

Petroleum source rock characteristics of the Mesozoic units, Mekelle Basin, northern Ethiopia

Značilnosti mezozojskih plasti v Mekelle bazenu severne Etiopije kot izvornih plasti ogljikovodikov

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Abstract in English

The Mekelle Basin comprises carbonate and siliciclastic rocks which could have potential for petroleum as previous studies reported without enough evidence. This research is intended to assess source rock characteristics of selected samples from the Adigrat Sandstone, Antalo Limestone and Agula Shale. Four outcrop sections were investigated and fifteen limestone and shale samples were collected. TOC was deduced by Leco SC-632 carbon analyzer, and Rock-Eval pyrolysis was determined using Rock-Eval 6. The TOC values range from 0.11 wt.% to 0.42 wt.% for 80% of the samples which is less than the minimum requirements for source rocks. However, a few samples have TOC between 0.5 wt.% and 1.0 wt.%, indicating fair organic matter richness. The kerogen is mainly Type IV and inert. The S_1 (0–0.02 mgHC/g) and S_2 (0–0.07 mgHC/g) values are very low, with very high T_{max} (475–527 °C), indicating very poor potential with over-mature dry gas. Therefore, the analyzed samples have low organic content for hydrocarbon, implying that the studied units have no feasible source rock potential.

Keywords: Mesozoic units, Rock-Eval pyrolysis, Source rock, Thermal maturity, Total organic carbon

Introduction

Petroleum is considered as one of the geologic resources of Ethiopia and potential oil and gas occurrences are expected from the Ogaden,

Abstract in Povzetek

Mekelle bazen vsebuje karbonatne in siliciklastične kamnine, ki bi, glede na predhodne raziskave, lahko vsebovale ogljikovodike. Namen raziskave je določitev lastnosti izbranih vzorcev Adigratskega peščenjaka, Antalskega apnenca in Agulskega skrilavega glinavca. Raziskali smo štiri izdanke ter nabrali petnajst vzorcev apnenca in skrilavega glinavca. Vsebnosti TOC so bile določene z Leco SC-632 analizatorjem ogljika. RockEval piroliza je bila določena z uporabo Rock-Eval 6. Vsebnosti TOC v vzorcih so v razponu od 0,11 masnih odstotkov do 0,42 masnih odstotkov, kar je manj kot so najnižje zahteve za izvirne kamnine. Redki vzorci imajo vrednosti TOC med 0,5 in 1,0 masnega odstotka, kar nakazuje zmerno visoko vsebnost organske snovi. Kerogen je večinoma tipa IV in inerten. Vrednosti S_1 (0–0,02 mgHC/g) in S_2 (0–0,07 mgHC/g) so zelo nizke, z zelo visoko T_{max} (475–527 °C), kar kaže na zelo nizek potencial s prezrelim suhim plinom. Preiskani vzorci imajo tako majhno količino organske snovi za ogljikovodike, kar kaže, da raziskane enote nimajo pomembnejšega potenciala izvornih plasti.

Ključne besede: mezozojske enote, Rock-Eval piroliza, izvorna kamnina, termična zrelost, skupna količina ogljika

Blue Nile, Mekelle, Gambela and Southern Rift Basins [1]. Paleozoic shale units served as sources of hydrocarbon that fed sandstone and carbonate reservoirs and led to the formation of a significant amount of the world's oil and

gas resource [2] [3]. Large reserves of oil and gas were discovered within the Permian sandstone and carbonate reservoirs sourced mainly by Silurian shales throughout the Middle East (e.g., Iran, Iraq and Arabia) [4]. The Permian Calub Sandstone and Bokh Shale are also good reservoirs and source rocks respectively in the Ogaden Basin, Ethiopia [5, 6]. The middle to upper Jurassic formations which comprised limestone, dolostone, marl, shale and sandstone are also known to have the potential for petroleum occurrences [5–12]. The Ogaden Basin was intensively investigated and has become the focus of oil companies to look for petroleum due to potential discoveries of gas fields at Shilabo, Calub and Hilala [5]. And, the Blue Nile Basin was the second target and studied in terms of petroleum system [9, 13], whereas the petroleum potential of Mekelle Basin has not been studied except the discovery of oil shale deposits within the Paleozoic glacial sediments [14]. However, the presence of possible potential source rocks within the Mesozoic units was reported by different workers even if detailed evaluation of quality, quantity and maturity of the organic matters have not been carried out. These units include the Agula Shale and Antalo Limestone with brown to black micritic limestone, beds of mudstone, brown shale and greenish-black limestone interbeds [15–16]. The Mekelle Basin requires a detailed evaluation of hydrocarbon prospectivity [1]. Therefore, this study is aimed at evaluating the petroleum source rock potential of these limestone and shale units including the Adigrat Sandstone.

Geological setting

The evolution of the Mekelle Basin is thought to have a close relationship with the East Africa Mesozoic rift basins, developed following the breakup of Gondwana [17]. Subduction along the Tethyan margin was considered to be the cause for the development of tensional stress in the Gondwana plate and its eventual breakup (Figure 1a) [18]. The breakup process was also triggered by the Permo – Triassic mantle plume, situated beneath the Karoo province, South Africa, that thermally weakened the

lithosphere and contributed to the intracontinental rifting, widespread crustal extension and subsidence [18, 19]. These processes led to the development of the Permo – Triassic rift systems in the eastern part of Africa and created northwest-southeast trending aulacogen-like basins, reaching up to western and central Ethiopia [17, 20–22] (Figure 1b).

The sedimentation began in the late Paleozoic within these fault-controlled depositional environments [17, 19, 20, 23–28]. These rift-controlled sedimentary basins, in Ethiopia, include the Ogaden, Blue Nile and Mekelle Basins. The Mekelle Basin has also been considered as an intracontinental sag basin, formed due to cooling and thickening of a juvenile sub-continental lithospheric mantle and subsequent subsidence [29].

Some previous studies documented the petroleum potential of the Ogaden Basin [5, 6, 30–33]. [9, 13] investigated the hydrocarbon potential in the Blue Nile Basin. The Mekelle and Omo basins were investigated by [14, 34] respectively. The Mekelle Basin covers 8000 km² and comprises over 2000 meters thick Paleozoic to Mesozoic sedimentary successions [35] (Figure 2) which are considered to have geologically good properties to look for hydrocarbon [16].

The Paleozoic units comprise about 300 meters thick of glacial origin clastic rocks [36] which were, first, described and subdivided into glacial sandstone (Enticho Sandstone) and tillite facies (Edaga Arbi Tillite) [37]. The Edaga Arbi Tillite was later named Edaga Arbi Glacial which comprises tillite, siltstone and shale facies [35]. Enticho Sandstone was also subdivided into two members; Lower Enticho Sandstone and Upper Enticho Sandstone [38]. Detailed facies analysis revealed that the late Paleozoic sediments (Upper Enticho Sandstone and Edaga Arbi Glacial) were formed due to a wide range of glaciogenic processes and depositional environments including sub-aquatic environments with two major glacier advance-retreat cycles [39]. Oil shale deposit was discovered, sandwiched between the Enticho Sandstone and Edaga Arbi glacials and, in some places, underlying the Adigrat Sandstone which has an average mineable bed-thickness of 55 meters, covering an area

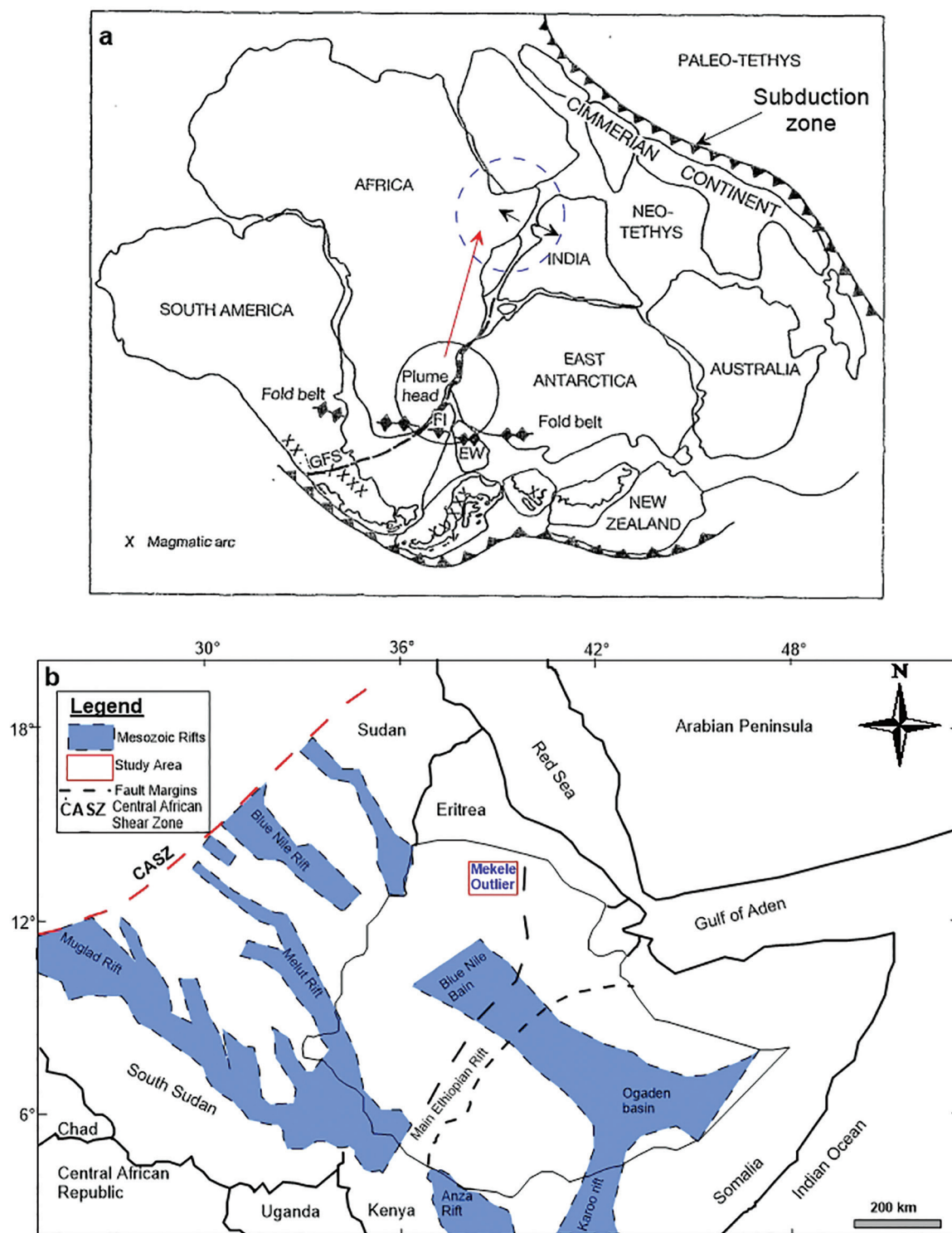


Figure 1: (a) Map showing Gondwana breakup (after [18]); (b) Mesozoic rift basins of the Horn of Africa including Ethiopia (after [21]).

of 30 km² with an estimated reserve of 4 billion tonnes [14]. The Triassic to middle Jurassic unit (Adigrat Sandstone) is about 300–650 meters thick and is considered to have a very

good reservoir potential for petroleum [15, 16, 35]. The unit comprises fine-grained to coarse-grained sandstones and interbeds of siltstone and clay which were deposited in continental

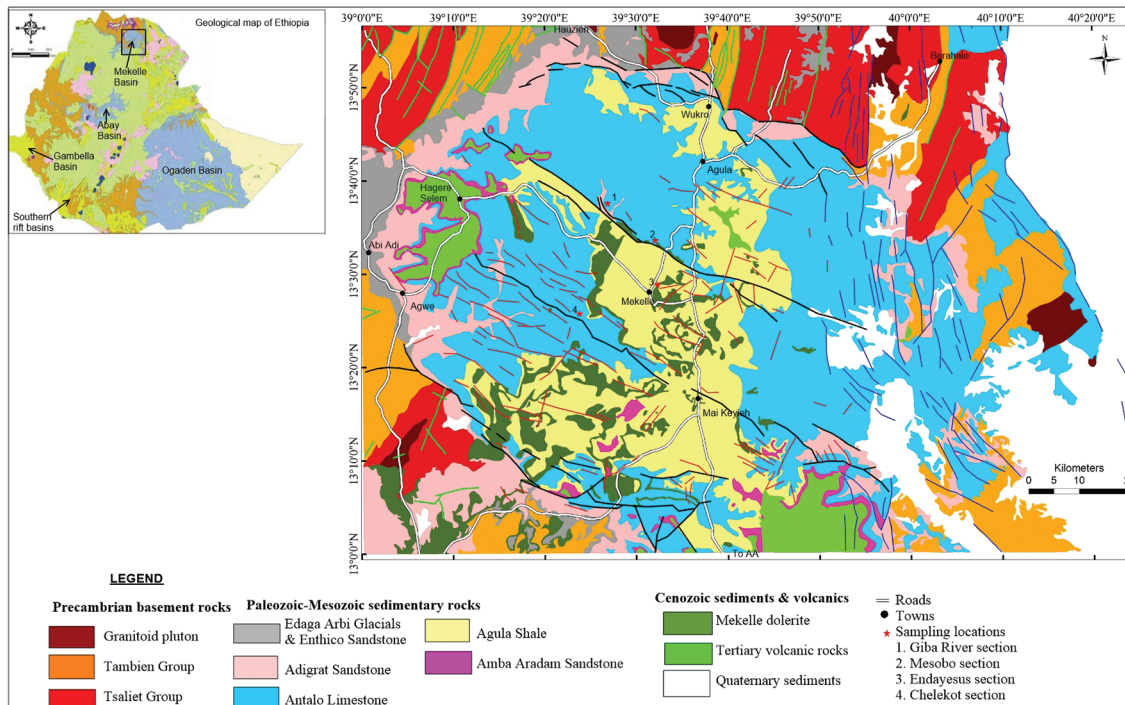


Figure 2: Geological map of the Mekelle Basin with sampling locations (after [42]). The inset map is a simplified geological map of Ethiopia (after [43]).

and shallow marine environments during the Triassic-middle Jurassic [35, 36].

The middle to upper Jurassic unit is carbonate (Antalo Limestone) with about 740 meters thick dominated mainly by yellow, white to black limestone with significant interbeds of marl, lenses of chert and cross-bedded sandstone [15–17, 35]. The brown shale and black limestone interbeds of the Antalo Limestone could serve as very good potential source rocks [16]. The unit has some reservoir potential [40]. The unit is also considered as a marine shelf carbonate facies, equivalent to the Mesozoic carbonate units of the Middle East Arabian Basins having potential for oil and gas occurrences [41]. In the Ogaden Basin, the marl and shale layers of Uarandab Formation are potential source rocks, with Type II kerogen, having petroleum potential that ranges from 2 kg/ton to 20 kg HC/ton of rock [5]. The black shales and mudstones of the Upper Hamanlei of the Blue Nile Basin, are also matured source rocks for oil generation, with TOC up to 7 wt.% and hydrogen index (HI) between 465 mgHC/g and 660 mgHC/g [9]. The Agula Shale is characterized by gray to black shale, marl and clay subunits with inter-laminae of black limestone,

gypsum and dolomite, and has 60 to 250 meters thickness that was deposited in lagoons under semiarid conditions [15] [35]. The Amba Aradam Sandstone is upper Jurassic-lower Cretaceous in age [15, 17] which conformably overlies the Agula Shale. It is 60–200 meters thick and comprises medium to coarse-grained white to pink color sandstone facies (at the northern part of the basin) and white sandstone and conglomerate facies with some clayey beds (at the southern part of the basin) [35]. It has been confirmed, from the present study, that a highly conglomeratic sandstone composed of very coarse pebble size and well rounded quartz grains is exposed in the southern part of the basin whereas in the northwestern part of the basin, it is very fine-grained with yellow, pink to reddish colors. This unit was deposited in fluvial-lacustrine depositional environments and is assumed to be a very good reservoir rock in the basin [16, 35].

Materials and methods

A total of fifteen samples made up of five black limestones and ten shales were collected from

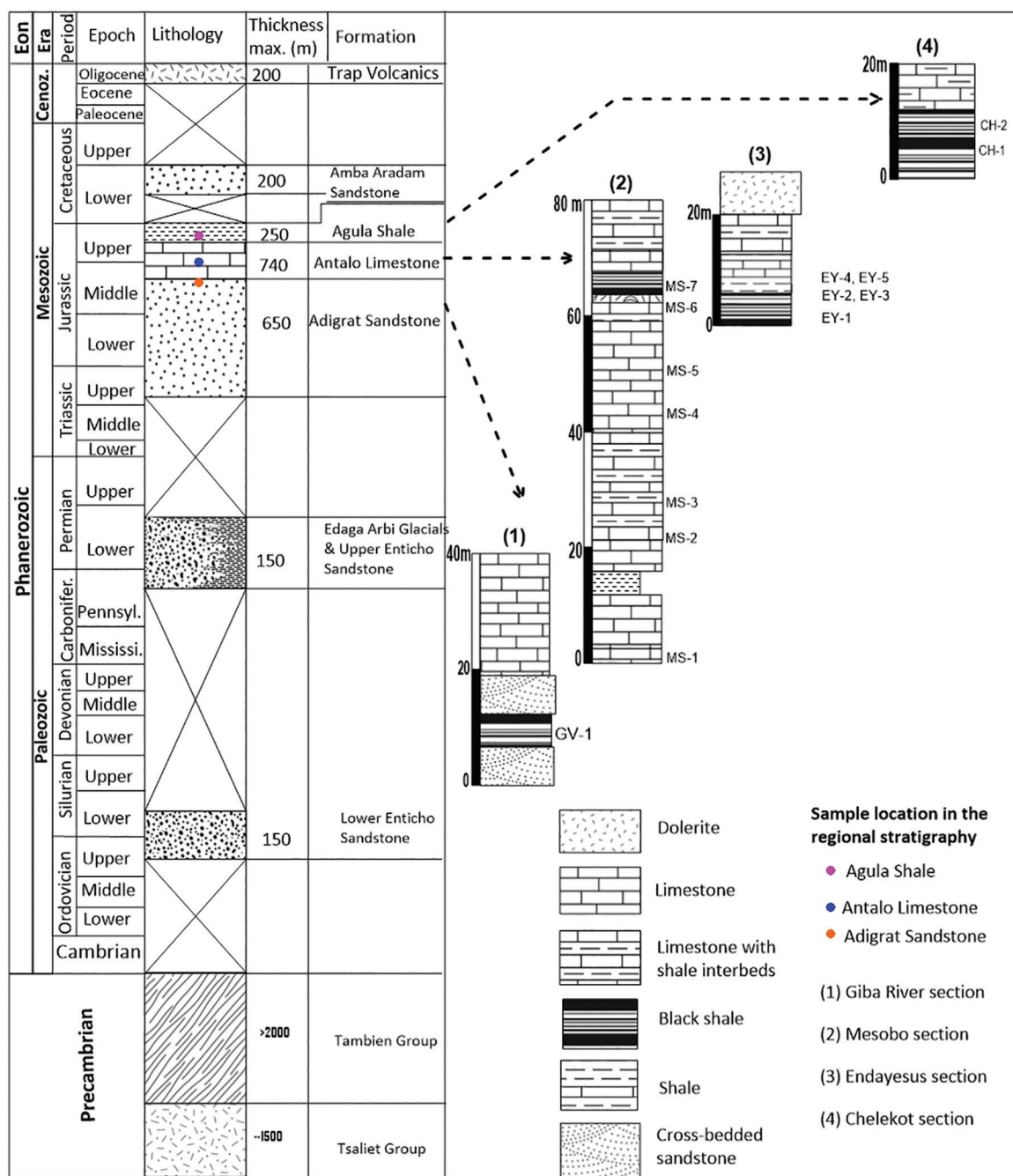


Figure 3: Lithologic logs showing the locations of samples collected for source rock characterization.

four outcrop locations for organic geochemical analyses. The samples were collected from the Adigrat Sandstone (one sample), Antalo Limestone (twelve samples) and Agula Shale (two samples). The petroleum potential of the samples was assessed from the Total Organic Carbon (TOC) and Rock-Eval pyrolysis. All laboratory procedures were carried out following the Norwegian Industry Guide to Organic

Geochemical Analyses, fourth edition [44], at the Applied Petroleum Technology Ltd, (ALS Oil & Gas), UK. About 100 mg of sample was pulverized and diluted hydrochloric acid (HCl) was added to the pulverized rock samples to remove carbonate. The samples were then introduced into the *Leco* combustion oven, and the organic matter was directly converted to carbon dioxide through combustion. The

Table 1: Outcrop samples collected for organic geochemical analyses.

Sample no.	Sampling location	Sample type	Formation
CH-1	13°25'36", 39°23'39", 1912 m asl.	limestone	Agula Shale
CH-2		shale	Antalo Limestone
EY-1	13°29'26", 39°29'07", 2113 m asl.	shale	
EY-2		shale	
EY-3		shale	
EY-4		limestone	
EY-5		shale	
MS-1	13°33'23", 39°30'36", 2094 m asl.	limestone	
MS-2		shale	
MS-3		shale	
MS-4		limestone	
MS-5		limestone	
MS-6		shale	
MS-7		shale	
GV-1	13°37'55", 39°24'51", 1818 m asl.	shale	Adigrat Sandstone

amount of carbon in the samples was measured, as carbon dioxide, by an infrared (IR) detector. A *Leco SC-632* carbon analyzer was used to measure the TOC and the amount of carbon was obtained and expressed in weight percent (wt.%). Rock-Eval pyrolysis was carried out using the *Rock-Eval 6* instrument. Jet-Rock 1 was run and checked against the acceptable range given in [44]. Different hydrocarbon components (S_1 , S_2 and S_3) were volatilized and determined, with the help of a Flame Ionization Detector (FID). The samples were placed in the oven and heated to a temperature of 300 °C for 3 minutes, and S_1 values were detected. The oven temperature was again increased to 650 °C, at a programmed rate of 25°C/minute to detect S_2 and S_3 values. Then, the pyrolysis products; S_1 , S_2 and S_3 peaks were normalized to the weight of the sample (mg HC/g sample). T_{max} values were also determined with the S_2 peaks.

Results and discussion

Field data

The investigated outcrop locations are Giba River, Mesobo, Enadayesus and Chelekot sections (Figure 3) where the studied layers from

the Adigrat Sandstone, Antalo Limestone and Agula Shale represent black limestone and shale (Table 1). About 70 meters thick black limestone with the associated shale layer was logged from the Mesobo section which is found approximately 5 km north of the Mekelle town (Figure 4a). The shale layers are gray to black, with variable thicknesses ranging from 10 cm to 3 m (Figure 4b). At the vicinity of Mekelle town, thickly bedded black fine-grained limestone (30 cm to 1.3 m in thickness) associated with cyclic layers of black to gray shale, was identified along a stream-cut which represents about 16 meters thick part of the Antalo Limestone (Figure 4c). The shale beds are relatively consolidated, slightly greenish to gray, with well-developed, very thin laminations. Fissility is observed within the loose to semiconsolidated layers, whereas the consolidated layers are characterized by conchoidal fractures. At the bottom of this outcrop, there is a very thick loose to highly consolidated black shale, with thickness ranging from 40 cm to 4 m (Figure 4d). Around Giba River which is located about 25 km northwest of Mekelle town, gray-black shale layers with thickness ranging from 5 cm to 10 cm were also identified from the upper part of Adigrat Sandstone

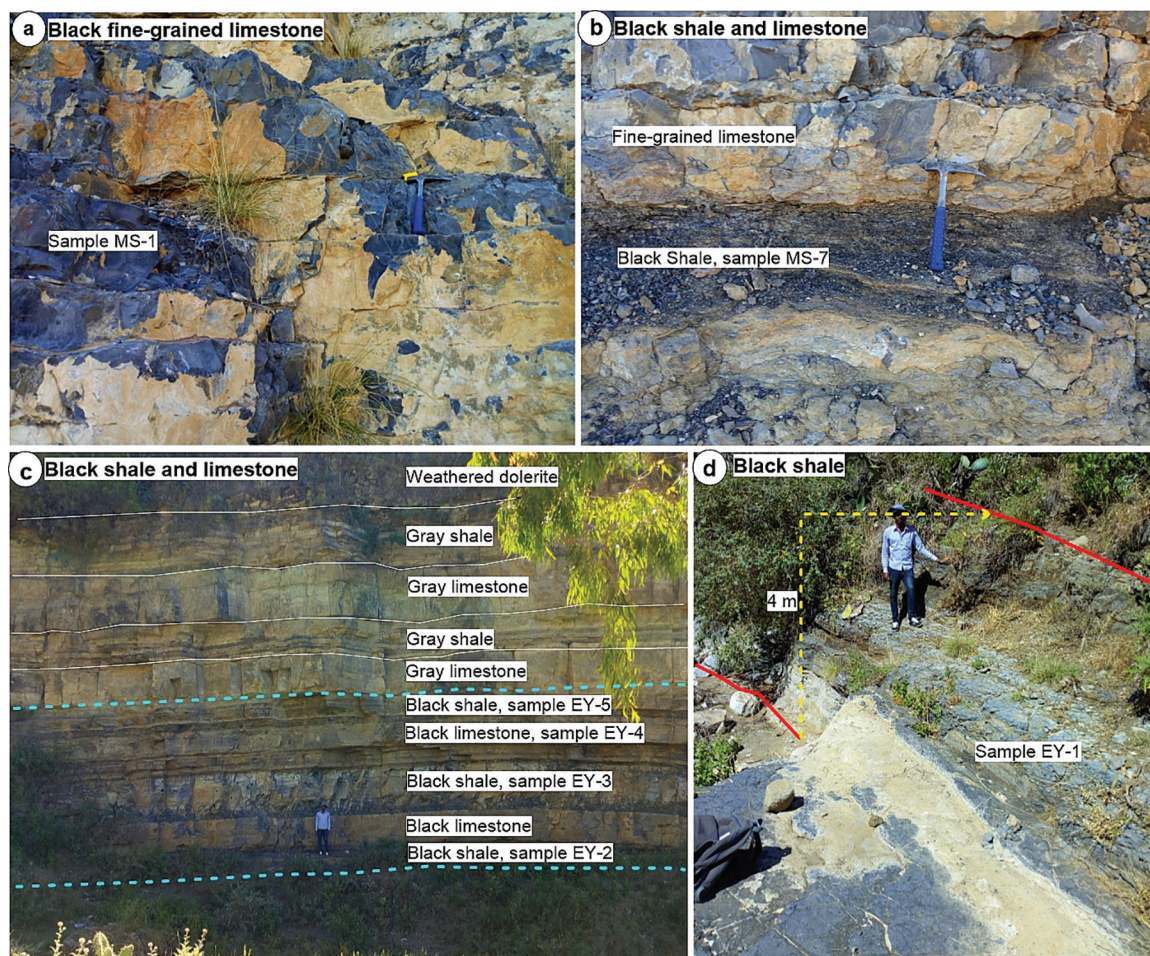


Figure 4: Outcrop photographs showing black shale layers and limestone beds within the Antalo Limestone at the central part of the Mekelle Basin. (a) thickly bedded black fine-grained limestone (Mesobo section, sample MS-1); (b) black shale within black micritic limestone beds (sample MS-7); (c) 16 m thick stream-side cliff exposure comprising limestone and shale beds (samples EY-2 to EY-5) around Mekelle town (Endayesus section); (d) Black shale along stream at the bottom of Endayesus section (sample EY-1).

(Figures 5a, b). Gray-black shale layers also represent a significant part of the Agula Shale (Figure 5c).

Organic geochemistry

The results of measured and calculated source rock parameters for fifteen (15) limestone and shale samples are shown in Table 2. Two shale samples of the Mesobo section (MS-2 and MS-7), have 0.50 wt.% and 0.92 wt.% TOC values respectively, whereas the remaining five samples (MS-1, MS-3, MS-4, MS-5, MS-6), have TOC between 0.10–0.41 wt.%. From the Endayesus section, only one shale sample (EY-2), has 0.77 wt.% TOC while the remaining four samples have TOC values ranging from 0.2 to 0.25 wt.%. A shale sample from

the underlying Adigrat Sandstone, in the Giba River section, recorded 0.42 wt.% TOC. In the Chelekot section, two samples from the overlying Agula Shale have 0.18 wt. % and 0.40 wt. % of TOC respectively. Only three samples (EY-2, MS-2 and MS-7) have TOC values above the 0.5% threshold [45]. The S_3 values which represent CO_2 content within the kerogen are relatively high compared to the S_1 and S_2 values (Table 2).

Organic matter richness

The most critical parameters such as; TOC and Rock-Eval S_1 and S_2 values for most of the studied samples are below the standard for any form of hydrocarbon generation, which are unlikely to be considered as petroleum

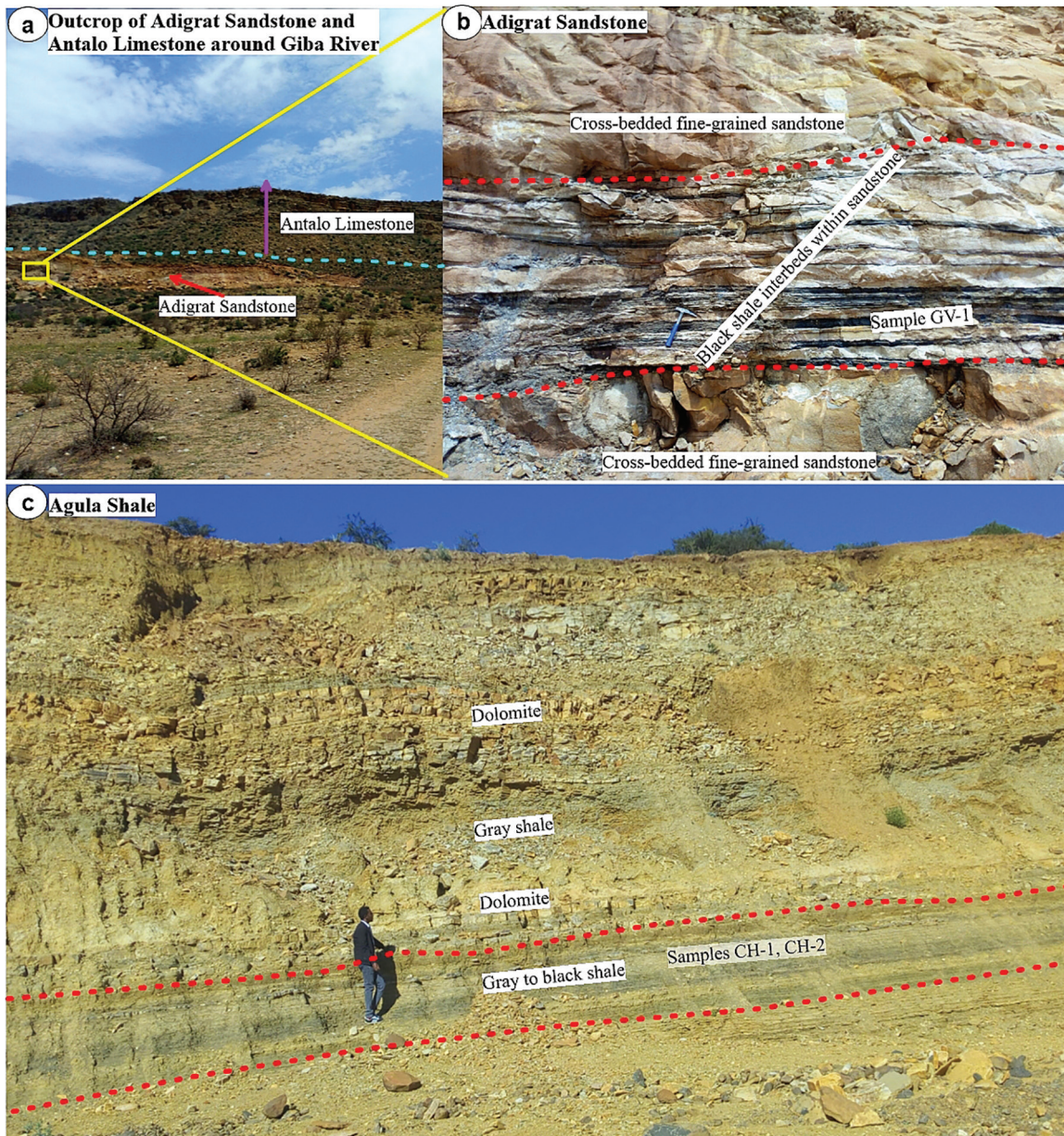


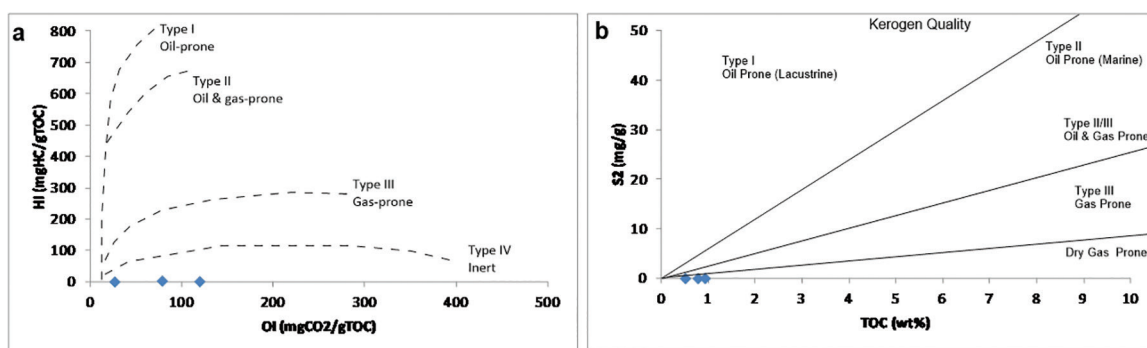
Figure 5: Outcrop photographs showing black shale layers within the Adigrat Sandstone and Agula Shale, at the central part of the Mekelle Basin. (a) lower part of Antalo Limestone conformably overlies the upper part of Adigrat Sandstone at Giba River section; (b) about 5–10 cm thick oil shale beds (sample GV-1) from the upper part of Adigrat Sandstone; (c) Some part of the Agula Shale at Chelekot section (samples; CH-1, CH-2).

source rocks. The total organic content (TOC) below 0.5 wt. % and S_2 values below 2.5 mg HC/g are generally considered as poor source rocks [46–49]. Twelve of the studied samples have TOC between 0.11–0.42 wt.% which is in the range of poor quality whereas three of the shale samples with 0.5–0.92 wt.% indicate fair organic matter richness. However, S_2 values are too low with very high pyrolysis T_{max} . The type of kerogen and its source organic matter has

been determined from a cross plot of hydrogen index (HI) and oxygen index (OI) (Figure 6a) by which Type IV kerogen with a high amount of organic carbon dioxide was identified for all of the analyzed limestone and shale samples. Type IV kerogen is derived from highly oxidized or reworked material of any origin [48, 50, 51]. The TOC and pyrolysis yield (S_2) cross-plot also show very poor quality organic matter [47, 50] (Figure 6b).

Table 2: Rock-Eval pyrolysis data of the analyzed samples.

Sample no.	Sample type	TOC (wt.%)	S ₁	S ₂	S ₃	T _{max}	HI	OI	PI	PP
CH-1	limestone	0.18	0.00	0.00	0.17	327	0	94	--	0.00
CH-2	shale	0.40	0.01	0.00	0.25	524	0	62	1.00	0.01
EY-1	shale	0.25	0.00	0.00	0.26	498	0	106	--	0.00
EY-2	shale	0.77	0.01	0.01	0.20	485	1.3	26	0.50	0.02
EY-3	shale	0.20	0.00	0.01	0.98	495	5	488	0.00	0.01
EY-4	limestone	0.21	0.02	0.07	0.64	475	34	309	0.22	0.09
EY-5	shale	0.23	0.00	0.00	0.26	496	0	111	--	0.00
MS-1	limestone	0.11	0.00	0.00	0.30	--	0	275	--	0.00
MS-2	shale	0.50	0.00	0.02	0.39	493	4	78	0.00	0.02
MS-3	shale	0.41	0.00	0.01	0.51	505	2.44	125	0.00	0.01
MS-4	limestone	0.10	0.00	0.00	0.28	484	0	294	--	0.00
MS-5	limestone	0.22	0.00	0.00	0.26	484	0	119	--	0.00
MS-6	shale	0.20	0.00	0.00	0.39	491	0	194	--	0.00
MS-7	shale	0.92	0.02	0.02	1.10	519	2	119	0.50	0.04
GV-1	shale	0.42	0.00	0.00	0.35	527	0	83	--	0.00

**Figure 6:** (a) Oxygen index (OI) and hydrogen index (HI) cross plot for the recognition of kerogen types (after [57]); (b) Kerogen type based on TOC versus pyrolysis yield (S₂) cross-plot, showing very poor quality organic matter for hydrocarbon generation (after [47]).

Organic matter maturity

The thermal maturity of the analyzed shale and limestone samples was determined from the Rock-Eval T_{max} which is the temperature at which the S₂ peak occurs during pyrolysis and can be correlated with the type of organic matter (kerogen) [46, 52–55]. The different levels of thermal maturity of the organic matters which are determined from T_{max} could qualitatively and quantitatively be expressed as immature (<435 °C), early mature (435–445 °C), peak mature (445–450 °C), late mature (450–470 °C) and post-mature (>470 °C) [48]. Therefore, thermal

maturity together with the other source rock parameters such as the total organic carbon (TOC) is significant to determine the quality of a given source rock [56]. The measured T_{max} value for one sample is 327 °C which shows an immature stage and nine samples have T_{max} that ranges 475–498 °C and four samples are in between 505–527 °C indicating post mature stage. The level of thermal maturity could also graphically be determined from T_{max} and hydrogen index cross plot (Figure 7a). Hence, the maturity level of the organic matter in all of the analyzed samples indicates a post-mature stage.

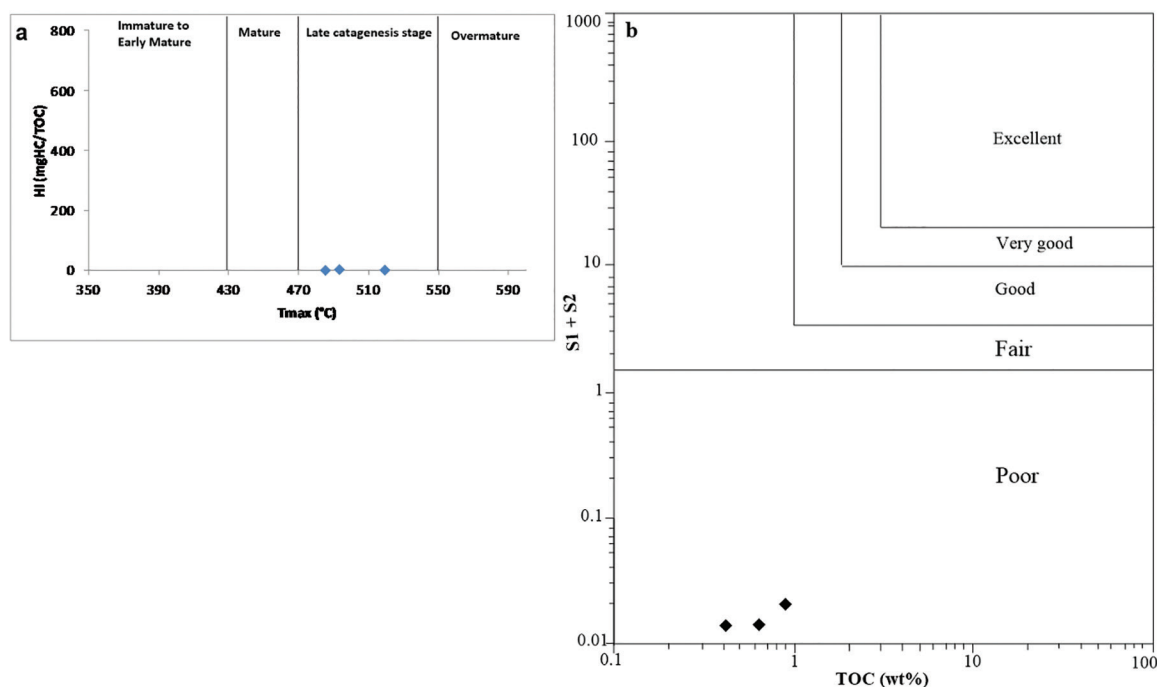


Figure 7: (a) Rock-Eval T_{max} versus hydrogen index (HI) plot showing the thermal maturity level of the organic matter (after [57]); (b) TOC versus $(S_1 + S_2)$ cross-plot, indicating poor hydrocarbon generating potential (after [47]).

Hydrocarbon generating potential

The hydrocarbon generating potential of source rocks is indicated with the sum of Rock-eval S_1 and S_2 values, which could be expressed qualitatively and quantitatively as; poor (0–3 mgHC/g), fair (3–6 mgHC/g), good (6–12 mgHC/g), very good (12–24 mgHC/g) and excellent (>24 mgHC/g) [46–48]. The S_1 values for most of the samples are 0.00 mgHC/g, with some samples having 0.01–0.02 mgHC/g values. S_2 values for nine (9) of the studied samples are 0.00 mgHC/g, whereas the remaining six (6) samples range from 0.01 to 0.07 mgHC/g. Therefore, both the S_1 and S_2 values indicate that the studied samples have a very low potential for any form of hydrocarbon generation. Cross plot of $S_1 + S_2$ vs TOC shows that the samples have poor oil generating potential (Figure 7b).

Conclusions

Field evidence showed that the studied units comprised black shale and black limestone beds which seem having adequate organic matter. However, the organic geochemical analyses

revealed low organic content of the analyzed samples, indicating that the black color of the samples is not a diagnostic feature of organic richness which could most probably be due to iron oxide impurities. The TOC values of a few samples indicate fair organic matter richness whereas about 80% of the samples have poor organic matter quality. The cross-plots of oxygen and hydrogen indices as well as S_2 versus TOC indicate Type IV and dry gas-prone kerogen. The T_{max} versus hydrogen index cross-plot shows that the organic matter is in a late catagenesis stage and thermally over-mature. Therefore, the source rock parameters indicate poor petroleum generating potential. However, since some outcrop samples of the Antalo Limestone have shown fair organic richness, further study is required, especially from core samples, to assure the source rock potential of this unit.

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References

- [1] World Bank (2016): Ethiopia Oil and Gas Sector Development: Support for Review and Update of Policy and Regulatory Framework. *Final Report*. The World Bank, 72 p.
- [2] Ehrenberg, S.N., Nadeau, P.H. (2005): Sandstone vs. Carbonate petroleum reservoirs: A global perspective on porosity-depth and porosity-permeability relationships. *American Association of Petroleum Geologists Bulletin*, 89(4), pp. 435–445.
- [3] Ahr, W.M. (2008): *Geology of Carbonate Reservoirs: The Identification, Description, and Characterization of Hydrocarbon Reservoirs in Carbonate Rocks*. John Wiley and Sons: New Jersey, 277 p.
- [4] Edgell, H.S. (1977): The Permian system as an oil and gas reservoir in Iran, Iraq and Arabia. *Proc. Second Iranian Geological Symposium*, pp. 161–201.
- [5] Hunegnaw, A. Sage, L., Gonnard, R. (1998): Hydrocarbon Potential of the Intracratonic Ogaden Basin, SE Ethiopia. *Journal of Petroleum Geology*, 21, pp. 401–425.
- [6] Tsegaye, S.G. Nton, M.E. Boboye, O.A., Ahmed, W. (2018): Geochemical Characteristics and Hydrocarbon Generation Modelling of Early Triassic to Late Cretaceous Formations within Ogaden Basin, Ethiopia. *Journal of Petroleum Science and Technology*, 8(4), pp. 58–75.
- [7] Carrigan, W.J. Cole, G.A. Colling, E.L., Jones, P.J. (1995): Geochemistry of the Upper Jurassic Tuwaiq Mountain and Hanifa Formation Petroleum Source Rocks of Eastern Saudi Arabia. In: *Petroleum Source Rocks*, Katz, B.J. (eds.). Springer-Verlag: Berlin, pp. 67–87.
- [8] Csato, I., Habib, A., Kiss, K., Koncz, I. (2001): Play concepts of oil exploration in Yemen: MOL's experience in 1996–2000. *Oil and Gas Journal*, 99(23), pp. 68–74.
- [9] Wolela, A. (2007): Source Rock Potential of the Blue Nile (Abay) Basin, Ethiopia. *Journal of Petroleum Geology*, 30(4), pp. 389–402.
- [10] Hakimi, M.H. Abdullah, W.H., Shalaby, M.R. (2010): Organic geochemistry and thermal maturity of the Madbi Formation, East Shabowah Oil fields, Masila Basin, Yemen. *Bulletin of the Geological Society of Malaysia*, 56, pp. 41–48.
- [11] Hakimi, M.H., Abdullah, W.H. (2014): Thermal maturity history and petroleum generation modeling for the Upper Jurassic Madbi source rocks in the Marib-Shabowah Basin, western Yemen. *Marine and Petroleum Geology*, 59, pp. 202–216.
- [12] Hakimi, M.H., Abdullah, W.H., Shalaby, M.R. (2012): Madbi-Biyadh/Qishn (!) petroleum system in the onshore Masila Basin of the Eastern Yemen. *Marine and Petroleum Geology*, 35, pp. 116–127.
- [13] Mammo, T. (2010): Delineation of sub-basalt sedimentary basins in hydrocarbon exploration in North Ethiopia. *Marine and Petroleum Geology*, 27, pp. 895–908.
- [14] Yihdego, Y., Salem, H.S., Kafui, B.G., Veljkovic, Z. (2018): Economic geology value of oil shale deposits: Ethiopia (Tigray) and Jordan. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 40(17), pp. 2079–2096.
- [15] Bosellini, A., Russo, A., Fantozzi, P.L., Assefa, G., Solomon, T. (1997): The Mesozoic Succession of the Mekele Outlier (Tigre Province, Ethiopia). *Memorie di Scienze Geologiche*, 49, pp. 95–116.
- [16] EMO. (2011): Petroleum Exploration in Ethiopia: Information and Opportunities. *Unpublished Report*, Ethiopian Ministry of Mines, Addis Ababa, pp. 1–20.
- [17] Kazmin, V. (1975): *Explanation of the geological map of Ethiopia*. Geological Survey of Ethiopia. *Bulletin*, 1, pp. 1–14.
- [18] Storey, B.C. (1993): Tectonic Controls on Gondwana break-up Models: Evidence from the Proto-Pacific Margin of Antarctica and the Southern Andes. *Second ISAG*, pp. 551–554.
- [19] Worku, T., Astin, T.R. (1992): The Karoo to Recent Rifting in the Western Branch of the East-African Rift System: A Bibliographical Synthesis. *Musée Royal de l'Afrique Centrale*, 83, pp. 63–82.
- [20] Binks, R.M., Fairhead, J.D. (1992): A plate tectonic setting for Mesozoic rifts of West and Central Africa. In: *Geodynamics of Rifting, Volume II. Case History Studies on Rifts: North and South America and Africa*, Ziegler, P.A. (eds.). *Tectonophysics*, 213, pp. 141–151.
- [21] Gani, N.D.S., Abdelsalam, M.G., Gera, S., Gani, M.R. (2009): Stratigraphic and structural evolution of the Blue Nile Basin, Northwestern Ethiopian Plateau. *Geological Journal*, 44, pp. 30–56.
- [22] Russo, A., Assefa, G., Atnafu, B. (1994): Sedimentary evolution of the Abay River (Blue Nile) Basin, Ethiopia. *Neues Jahrbuch Für Geologie und Paläontologie*, 5, pp. 291–308.
- [23] Bosellini, A. (1988): The continental margins of Somalia. *Geology and Geophysics of continental margins. American Association of Petroleum Geologists Memoir*, 53, pp. 185–205.
- [24] Coffin, M.F., Rabinowitz, P.D. (1988): Evolution of the Conjugate East African-Madagascan margins and the

- Western Somali Basin. *Geological Society of America, Special Paper*, 226, pp. 1–78.
- [25] Bosworth, W. (1992): Mesozoic and early Tertiary rift tectonics in East Africa. In: *Seismology and Related Sciences in Africa*, Ebinger, C.J., Gupta, H.K., Nyambok, I.O. (eds.). *Tectonophysics*, 209, pp. 115–137.
- [26] Worku, T., Astin, T.R. (1992): The Karoo sediments (Late Palaeozoic to Early Jurassic) of the Ogaden Basin, Ethiopia. *Sedimentary Geology*, 76, pp. 7–21.
- [27] Bosworth, W., Morley, C.K. (1994): Structural and stratigraphic evolution of the Anza rift, Kenya. *Tectonophysics*, 236, pp. 93–115.
- [28] Hankel, O. (1994): Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar. *Geologische Rundschau*, 83, pp. 703–710.
- [29] Alemu, T., Abdelsalam, M.G., Dawit, E.L., Atnafu, B., Mickus, K.L. (2018): The Paleozoic-Mesozoic Mekele Sedimentary Basin in Ethiopia: An example of an exhumed IntraCONTinental Sag (ICONS) basin. *Journal of African Earth Sciences*, 143, pp. 40–58.
- [30] Assefa, G. (1988): Potential hydrocarbon-generating rock units within the Phanerozoic sequence of the Ogaden Basin, Ethiopia: A preliminary assessment using the Lopatin model. *Journal of Petroleum Geology*, 11(4), pp. 461–472.
- [31] Worku, T. (1988): *Sedimentology, diagenesis and hydrocarbon potential of the Karoo sediments (Late Paleozoic to early Jurassic) Ogaden Basin, Ethiopia*. M. Phil. Thesis. University of Reading: UK, 222 p.
- [32] Geleta, S. (1998): *Biostratigraphy, depositional environment, basin evolution and hydrocarbon potential of the late Triassic to late Jurassic succession, Ogaden Basin, Ethiopia*. PhD Thesis. Institute und Museum für Geologie und Paläontologie: Tübingen, 78 p.
- [33] Oljira, T., Nton, M.E., Sonibare, O.O. (2020): Organic Geochemical Evaluation of Shale Units of Bokh Formation, Ogaden Basin, Ethiopia. *Open Journal of Geology*, 10, pp. 565–578.
- [34] Mammo, T. (2012): Analysis of gravity field to reconstruct the structure of Omo basin in SW Ethiopia and implications for hydrocarbon potential. *Marine and Petroleum Geology*, 29, pp. 104–114.
- [35] Beyth, M. (1972): Paleozoic-Mesozoic Sedimentary Basin of Mekele Outlier, Northern Ethiopia. *American Association of Petroleum Geologists Bulletin*, 56(12), pp. 2426–2439.
- [36] Bussert, R., Dawit, E.L. (2009): Unexpected diversity: New results on the stratigraphy and sedimentology of Palaeozoic and Mesozoic siliciclastic sediments in Northern Ethiopia. *Zentralblatt Für Geologie und Paläontologie*, Teil I, pp. 181–198.
- [37] Dow, D., Beyth, M., Hailu, T. (1971): Palaeozoic glacial rocks recently discovered in northern Ethiopia. *Geological Magazine*, 108, pp. 53–60.
- [38] Bussert, R., Schrank, E. (2007): Palynological evidence for a latest Carboniferous-Early Permian glaciation in Northern Ethiopia. *Journal of African Earth Sciences*, 49, pp. 201–210.
- [39] Bussert, R. (2014): Depositional environments during the Late Palaeozoic ice age (LPIA) in northern Ethiopia, NE Africa. *Journal of African Earth Sciences*, 99, pp. 386–407.
- [40] Adefris, D., Nton, M.E., Boboye, O.A., Atnafu, B. (2021): Aspects of Diagenetic and Sequence Stratigraphic Framework on Reservoir Potential of Antalo Limestone, Mekelle Basin, northern Ethiopia. *Nigerian Association of Petroleum Explorationists Bulletin*, 30, pp. 26–37.
- [41] Peterson, J.A. (1985): Geology and petroleum resources of central and east-central Africa. *Open-File Report 85-589*. United States Geological Survey, 48 p.
- [42] Arkin, Y., Beyth, M., Dow, D.B., Levitte, D., Haile, T., Hailu, T. (1971): *Geological Map of Mekele Sheet Area ND 37-11, Tigre Province*. Geological Survey of Ethiopia, Addis Ababa, 1p.
- [43] MoWR (2009): Water information and knowledge management project: strengthening water quality data generation and management. Draft Final Report, August 2009; 240 p.
- [44] Weiss, H.M., Wilhelms, A., Mills, N., Scotchmer, J., Hall, P.B., Lind, K., Brekke, T. (2000): NIGOGA-The Norwegian Industry Guide to Organic Geochemical Analyses [online]. Edition 4.0, Norsk Hydro, Statoil, Geolab Nor, SINTEF Petroleum Research and the Norwegian Petroleum Directorate, 102 p.
- [45] Tissot, B.P., Welte, D.H. (1984): *Petroleum Formation and Occurrence*. Springer-Verlag: Berlin, 699 p.
- [46] Krokstad, W., Schou, L., Leith, L.T., Vigran, J.O., Due, A., Andersen, W., Berg, T., Haugen, G., Vinge, T. (1986): *Source Rock Evaluation of Well 15/12-4. Hydrocarbon Characterisation of Oil, Cuttings and Cores*. Issue 16, 300 p.
- [47] Peters, K.E. (1986): Guidelines for evaluating petroleum source rock using programmed pyrolysis. *American Association of Petroleum Geologists Bulletin*, 70(3), pp. 318–329.
- [48] Peters, K.E., Cassa, M.R. (1994): Applied Source Rock Geochemistry. In: *The petroleum system-from source to trap*, Magoon, L.B., Dow, W.G. (eds.). *American*

- Association of Petroleum Geologists Memoir*, 60, pp. 93–120.
- [49] Al-Selwi, A., Joshi, M. (2015): Oil and Gas Research Source Rock Evaluation using Total Organic Carbon (TOC) and the Loss-On-Ignition (LOI) Techniques. *Oil and Gas Research*, 1(1), pp. 1–5.
- [50] Waples, D.W. (1985): *Geochemistry in Petroleum Exploration*. D. Reidel Publishing Company: Boston, 232 p.
- [51] McCarthy, K., Niemann, M., Palmowski, D., Peters, K. (2011): Basic Petroleum Geochemistry for Source Rock Evaluation. *Oilfield Review*, 23, pp. 32–43.
- [52] Espitalie, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J., Boutefeu, A. (1977): Rapid method of characterizing source rocks and their petroleum potential and degree of maturity. *Revue de l'Institut Francais du Pétrole*, 32, pp. 23–42.
- [53] Barker, C.E., Johnson, R.C., Poole, F. (1990): Rock-Eval pyrolysis data for petroleum-potential evaluation based on veil cuttings and core samples from Eastern Nevada collected during 1990. *Open-File Report 90-698*, pp. 1–15.
- [54] Stanley, R.G., Valin, Z.C., Pawlewicz, M.J. (1992): Rock-Eval pyrolysis and vitrinite reflectance results from outcrop samples of the Rincon Shale (lower Miocene) collected at the Tajiguas Landfill, Santa Barbara County, California. *Open-File Report 92-571. United States Geological Survey*, 27 p.
- [55] Lafargue, E., Espitalié, J., Marquis, F., Pillot, D., François, I., Préau, A.D.B. (1998): Rock-Eval 6 Applications in Hydrocarbon Exploration, Production and in Soil Contamination Studies. *Revue de l'Institut Français Du Pétrole*, 53(4), pp. 421–437.
- [56] Cooke, I.L. (2014): User Guide Total Organic Carbon (TOC) data. *Open Report, OR/14/056. British Geological Survey, Natural Environment Research Council (NERC)*. 14 p.
- [57] Van Krevelen, D.W. (1984): Organic geochemistry-old and new. *Organic Geochemistry*, 6, pp. 1–10.