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Mount Cameroon oil seeps and their rheological properties

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ABSTRACT: *The geology of the Gulf of Guinea, at the southeastern foot of Mount Cameroon presents a transition from a sedimentary terrain to a volcanic terrain marked by the presence of anactive Cameroon Mountain. The presence of seeps at the foot of this Mountain could serves as an indication for more onshore exploration in the area. Samples from these seeps were collected for rheological studies at temperatures ranging from 20.4°C to 60.1°C using a Brookfield DV-II Pro viscometer. Such studies were necessary to investigate the change in rheological properties of seeps after long exposure to the surface. The measurements provided for the percentage torque at given speeds, shear stress and the apparent viscosity data at various shear rates and at different temperatures. The seep samples exhibit a Newtonian behavior as the shear rate was varied from 0.17–32.64* s^{-1}*, and as such, the Newtonian model could be used to describe their rheological behavior. The viscosity of the seep sample reduced from 10918cP (at 20.4°C, 0.17* s^{-1}*) to 303.2cP (at 60.1°C, 21.42* s^{-1}*). The degree of viscosity reduction increases significantly from 0% to 97.2% over the investigated temperature range.*

KEY WORDS: *Seeps, heavy crude oil, rheological behavior, viscosity reduction, models*

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I. INTRODUCTION

Over so many decades, oil and gas seeps have been used as direct indicators is petroleum exploration. However, as time went on seeps became rarer due to due exhaustion of the near-surface deposits. Cameroon has been producing crude oil since 1976, but it is considered to be a small producer compared to other producers like Nigeria, Angola, Gabon and Equatorial Guinea, all in sub-Saharan Africa. Its production has been declining since it attained its peak production in 1986. This decline in production however, has halted in the recent years due to the discoveries in the Bakassi Peninsula of the Rio del Ray (RDR) Basin.

Over the past years, oil seeps have been noticed at the southeastern foot of Mount Cameroon. The geology of the Gulf of Guinea, at the vicinity of Mount Cameroon presents a transition from a sedimentary terrain to a volcanic terrain marked by the presence of the Cameroon Volcanic Line, amongst which is the active Cameroon Mountain, dividing the sedimentary terrain in this area into two basins; the Rio del Ray Basin to the northwest and the Douala-Kribi-Campo (DKC) Basin to the southeast. Considering that seeps are often linked to seismic activities, it is evident that the presence of seeps at the foot of Mount Cameroon, could be as a result of reactivation of faults (Baconet al., 2000) due to the active nature of the Mountain. This is illustrated by the oil seeps associated with cretaceous exotics shown in Figure 1.

Exploration works have continued in the RDR and the DKC Basins recently and have led to the discovery of new fields such as the Etinde Block in this area. The oil seeps at the foot of Mt Cameroon are found very close to this Etinde Block (Figure 2), a shallow water permit that cuts from the RDR to the DKC Basins.

I.1 Classification of Cameroon crude oils

Crude oils around the world have been classified into different groups based on API gravity and viscosity. Crude oils with API gravity less than 10° are denser than water while those with API gravity above 10° are lighter than water. Crude oils are further classified according to UNITAR (Meyer and De Witt, 1990) into light oils (API>20° μ<100cP); heavy oils (10°<API<20°, 100cP <μ<10,000cP); and bitumen (API<10°, 10,000cP <μ). According to the World Petroleum Congress (WPC) (Jamaluddin et al., 2018), crude oil is classified based on API gravity and viscosity into light oils (API>31.1°, μ<100cP), medium heavy (22.3 °<API<31.1°, μ<100cpP; heavy (10°<API<22.3°, 100cP <μ<10,000cP); extra heavy (API<10°, 100cP

<μ<10,000cP); and bitumen (API<10^o, μ>10,000cP). According to the API gravity and the sulfur content, there are two major types of crude oil produced from Cameroon oil fields. These include the Kole and the Lokele crude oils. Kole is a blend resulting from the production of half of dozen of oil fields and has the following characteristics: It has an API gravity of 30.98^o API, hence, a medium heavy crude according to the WPC classification, and the Sulphur level is 0.33; while the Lokele crude is a heavy crude oil with an API of 20.20^o, and Sulphur level of 0.450. Apart from the Kole and the Lokele crudes, Cameroon crude oils also include the Ebome crude (37.86^o API) and the Moudi crude (38^o API) both considered as light crude.

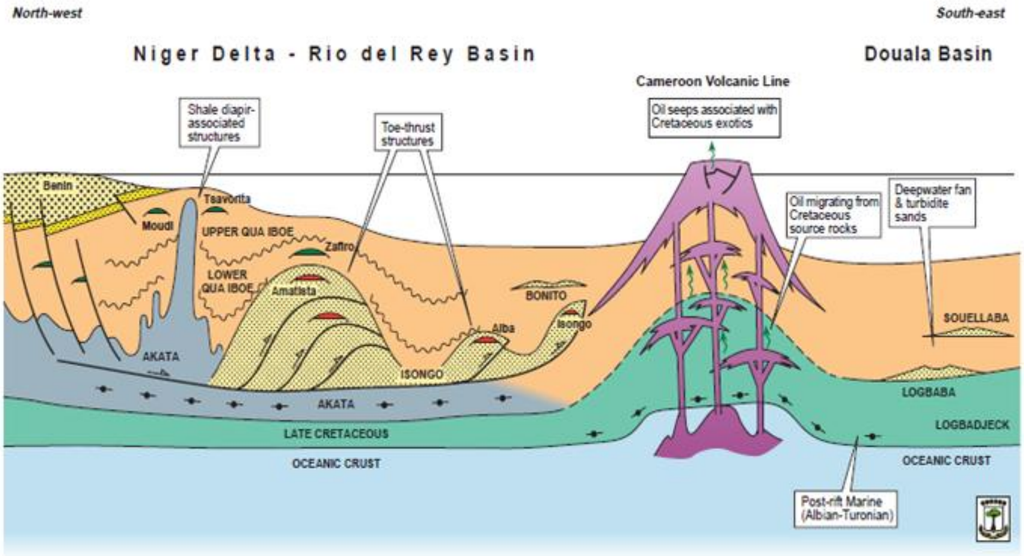

Figure 1 Bioko oil play types showing oil seeps association with the Cameroon Volcanic Line separating the Rio del Rey Basin and the Douala Basin.
Source: http://www.cmeyanchama.com/Documents/Guinee/pguinea_Hydrocarbons_and_Mining.pdf

Heavy crude has become an increasing important source of hydrocarbon in many parts of the world, including most Cameroon oil fields (the Lokele crude oil fields with API of 20.2^{o}API). The production of such resources from reservoir rocks into the wellbore and lifting up to the surface is a difficult task due to very high viscosities. Equally, transportation through pipelines to the refineries or to the world market could be a problem.

I.2 Effects of exposure of seep to the atmosphere

The exposure of crude oil seep to the surface may lead to the alteration of its physical and chemical properties by a range of physical, chemical and biological processes (Kennicutt, 2017). These processes are termed weathering. Biodegradation gradually destroys oil seeps (Bence et al., 1996), and affects the fluid properties (Miiller et al., 1987). Oil biodegradation raises oil viscosity and reduces oil API gravity. Apart from biodegradation, other processes could alter the properties of the seep. For example, water washing can affect the composition and fluid properties (Milner et al., 1977). Understanding oil alteration processes provides the key to predicting spatial variation in fluid properties such as viscosity and API gravity within an oil field. When seeps are exposed to the atmosphere, alteration takes place, during which some components and properties could be preserved. These could be used to infer where the seep originated.

A good number of works carried out on the rheological behavior of crude oil have been cited in the works of Petrus and Azuraien (2014). Rheological measurements of heavy crude oil have been carried out by Hasan et al., (2010) at a range of temperature from 25-75^{o}C. Apart from the investigation of the influence of temperature on rheological behavior of heavy crude oils, other modern methods have been documented that have also resulted to significant viscosity reduction. These include the use of micro-emulsions experimented by Yang (2019) which resulted to viscosity reduction above 90%, and the use of novel surfactants (Al Roomy, 2004; Kumar et al., 2016; Kumar et al., 2017) to improve on the transportability of heavy crudes. Little is known of the rheological properties of seeps in Cameroon. The seeps at the banks of a stream, at the southeastern foot of Mt. Cameroon have undergone serious biodegradation leading to the loss of all the light components (Hassanshahian and Cappello, 2013), thus cannot flow naturally. Knowledge of rheological properties of these seeps will be very important for the development of oil fields in this area since it will give a clue on the deterioration of these properties with time when exposed to the atmosphere, compared with those of a typical Cameroon crude oil such as the Lokele crude which has a viscosity of about 105.4cP at 20^{o}C. As such, it is necessary to investigate the rheological behavior of the samples collected from these seeps and to understand how long exposure to the atmosphere has influenced the viscosity of the crude relative to other Cameroon crude oils; and how the rheological properties will change as temperature is varied.

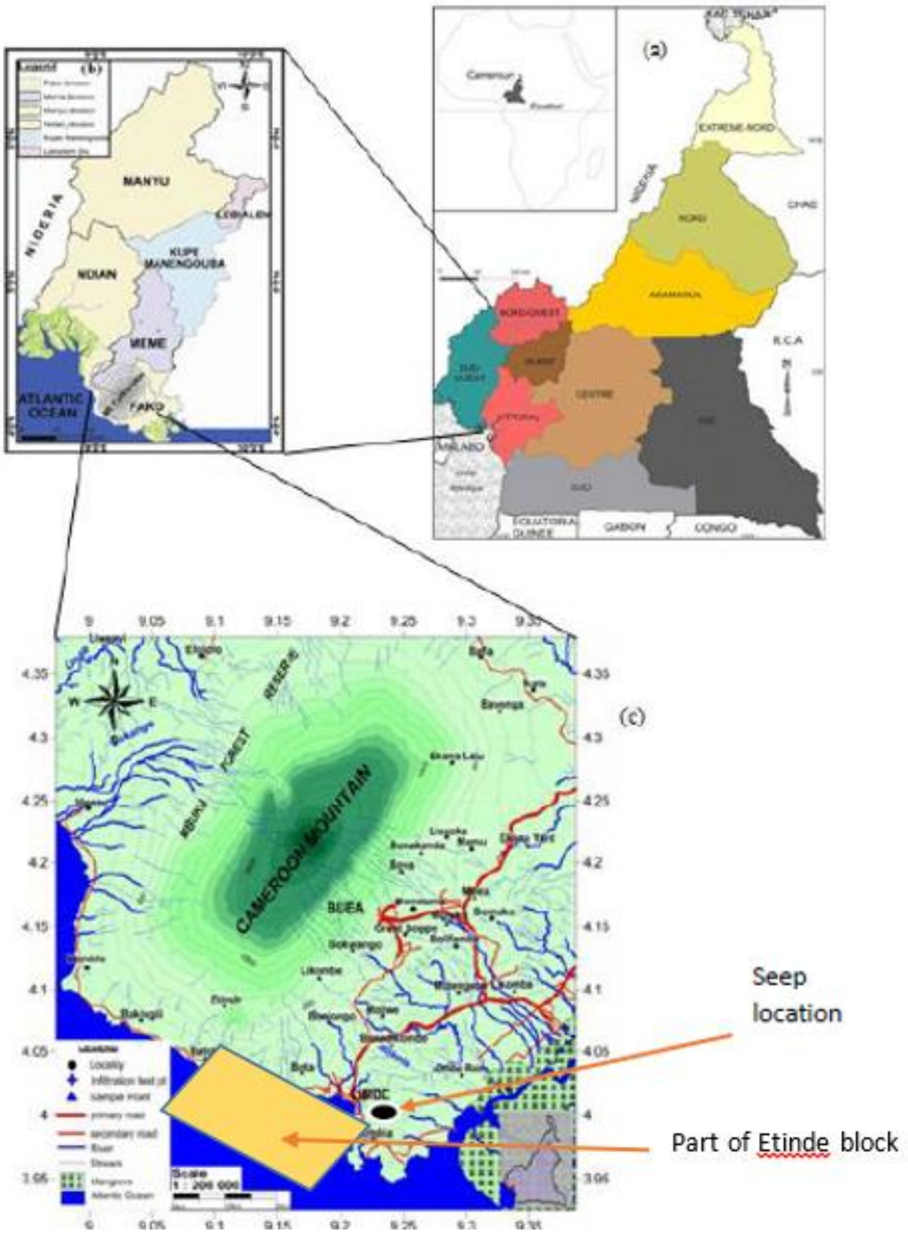

Figure 2 Location of seeps sites relative to the Etinde Block where exploratory drilling has begun since 2018

II. MATERIALS AND METHOD OF INVESTIGATION

II.1 Location of Seeps and Sample collection

Oil sample used for this study, was obtained from oil seeps at the foot of Mount Cameroon. The sites of the seeps are along the sides of stream in the MabetaNjanga forest(Figure 2).At the banks of the stream, high viscosity, less dense (relative to water) shiny black liquid had seeped from the ground and is floating on top of water (Plate 1).Two (02) liters of this black liquid (Plate 2) were collected for different analyses. Part of this liquid was packaged and sent to the VNIINeft special research laboratory in Russia for rheological analysis.

During sample collection, precaution was taken to avoid the entry of water into the sample collection bottles as much as possible. However, this could not be 100% successful as some water still found itself into the containers. The samples were allowed to rest in the sampling bottles for several days to promote more water entrapped in the seep sample to settle by gravity. The oil phase floating on top of the water was carefully transferred to another container. Such treatment was required because the study was focused on investigating the rheological properties of seep samples relative to those of the heavy oils produced in Cameroon oil fields.

Investigation of the influence of water content on rheological properties of the seep samples was not within the scope of the present study.

Plate 1 Patch of oil seep at the bank of MabetaNjanga stream

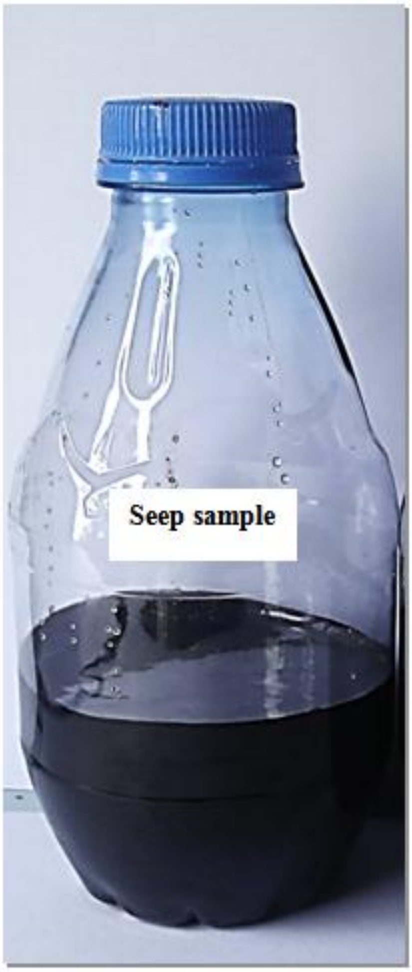

Plate 2 Seep sample sent for analysis

II.2 Method of Investigation: Determining the rheological properties

Any calculation involving the movement of fluids in either a porous medium or pipes requires a value for viscosity. The principal factors affecting viscosity of crude oil are crude oil composition, temperature, dissolved gas and pressure (Sutton, 2006).Different instruments exist for measuring viscosity. Some of these instruments give qualitative measurements while others have been designed to give quantitative measurements so that we could obtain absolute viscosity values (Bingham 1922).

In this study, A Brookfield DV-II Pro viscometer was used in the research laboratory of VNIINEFT to measure viscosity. The operational principle of this programmable viscometer entails driving a spindle (immersed in the crude oil sample contained in the sample container) through a calibrated spring. The spindle is inserted into the sample until the fluid level is at the immersion groove on the spindle shaft. The viscosity drag of the crude oil sample against the spindle is measured by the spring deflection. The speed (in rpm) is set and measurements taken on the screen pad of the programmable viscometer. In order to investigate the rheological behavior of the seeps sample, measurements were carried out which provided for the percentage torque at chosen speeds, shear stress and the apparent viscosity values at various shear rates and at different temperatures. The rheological parameters of the crude oil samples were determined following the procedure and guidelines prescribed in the Brookfield DV-II+ Pro manual (Manual No. M/03-165-C0508W). According to these guidelines, measurements were made within the torque range between 10 to 100%. Readings below 10% of the percentage torque scale were discarded to assure maximum accuracy.

III. RESULTS AND DISCUSSION

III.1TheSignificance of the Mount. Cameroon oil seeps

The presence of the seeps at the southeastern foot of Mount Cameroon could be linked to the reactivation of faults (Baconet al., 2000) considering the fact that these seeps are at the foot of an active mountain, and very close to the site, is the Tiko fault (Kervyn et al., 2014). Moving southward from the seeps site is the Etinde permit (in the shallow waters offshore), while northeastward of the seeps site is the Bomono permit. These seeps could serve as a clue for more exploration works onshore from the seeps site extending through Tiko plantations, moving across the Mungo River towards the Bomono permit, some tens of kilometers from the seeps site.

III.2 Rheological properties of seep samples

After investigating the rheological properties of the collected samples, the results presented in Table 1 and Appendix A were obtained. The parameters registered include the speed, n in revolutions per minute (rpm); percentage torque, M in %; shear stress, τ in dyne/cm^2; shear rate, $\dot{\gamma}$ in sec^{-1}; and viscosity, μ in cP. The density was also measured at room temperature and a value of (959.4 kg/m^3)(15.99 ^{o} API) was obtained. Based on the WPC classification (Jamaluddin et al. 2018), and UNITAR classification (Meyer and De Witt, 1990),this seep sample could be considered as heavy crude oil.

Table 1 -Rheological properties of seeps sample at a temperature of 20.4^{o}C

T=20.4 ^{o}C				
n, rpm	**M, %**	**τ, dyne/cm^2**	**$\dot{\gamma}$, 1/sec**	**μ , cP**
0.5	18.2	18.56	0.17	10918
1	36.2	36.92	0.34	10858
1.5	54.3	54.2	0.51	10838
2	72.3	73.73	0.68	10843
2.5	90.2	91.98	0.85	10810
2.7	97.4	99.33	0.92	10820

III.2.1 Rheograms of the seep sample at different temperatures

From the results presented in Table 1and Appendix A, rheograms were plotted (Figure3) to investigate the flow behavior of the crude oil sample at different temperatures. From Figure 3, it can be seen that the shear stress increases gradually and significantly with an increase in shear rate.

Using the least square method, some models were investigated that could describe the flow behavior of the seep sample. These models include the Bingham, the Power law and the Newtonian models described respectively by equations 1, 2 and 3 respectively.

$$\tau = m \cdot \dot{\gamma}^n \quad (1)$$
$$\tau = \tau_0 + \mu \cdot \dot{\gamma} \quad (2)$$
$$\tau = \mu \cdot \dot{\gamma} \quad (3)$$

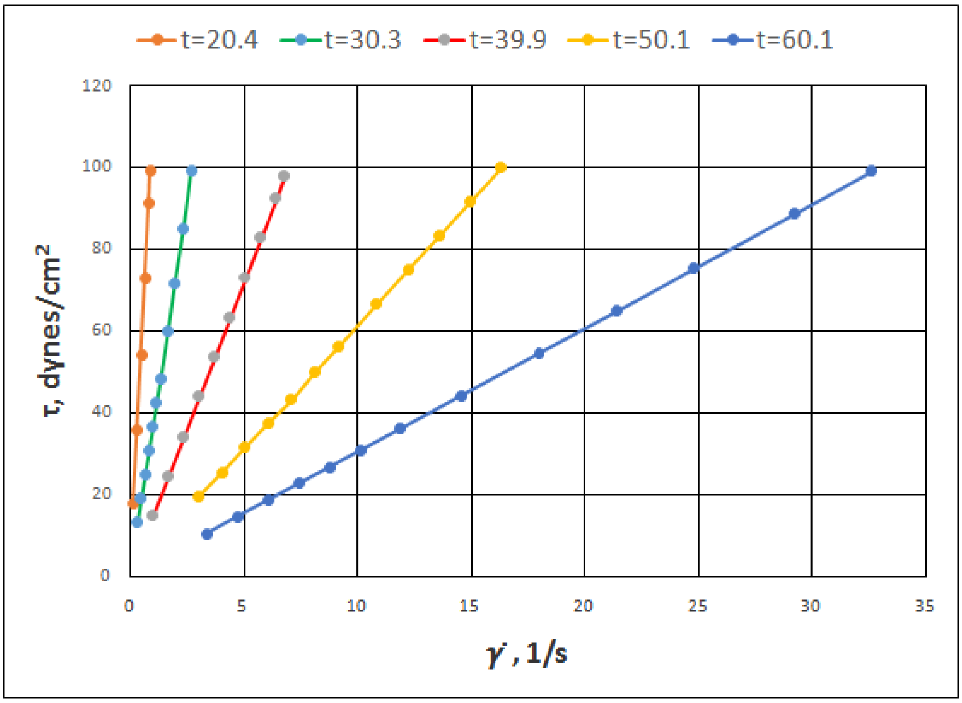

Figure 3 – Rheograms of seep sample at different temperatures

The results of the modeling analysis are reported in Table 2. In these equations, τ-applied shear stress in dyne/cm^2 and $\dot{\gamma}$ - the corresponding shear rate in s^{-1}; m and n are consistency index in cP and flow behavior index respectively; τ_o and μ are the apparent yield stress in dyne/cm^{2}and the apparent viscosity in cP.

Table 2 Modeling parameters of equations 1, 2 and 3

Temperature °C	**Bingham plastic Model**			**Power law model**			**Newtonian Model**	
	τ_o, dyn/cm^2	**μ, cP**	**R^2**	**m, cP**	**N**	**R^2**	**μ, cP**	**R^2**
20.4	-0.8718	108.69	0.9999	107.79	1.00	1	107.45	0.9998
30.3	0.4886	35.695	0.9992	36.586	0.96	0.999	35.974	0.9991
39.9	-0.0866	14.36	1	14.351	0.99	1	14.34	1
50.1	0.4423	6.0955	0.9999	6.4106	0.98	0.9997	6.135	0.9998
60.1	0.0676	3.027	1	3.072	0.99	1	3.03	1

From these results, the regression correlation coefficient, R^2, for the Power law model ranges from 0.999 to 1.0, the flow behavior index (n) values vary from 0.96 to unity (1.0).For the Bingham plastic model, the fluid requires a certain initial shear stress τ_o referred to as yield point below which the fluid will not flow. The Bingham model has regression correlation coefficient, R^2, ranging from 0.9992 to 1.0, but in some cases, a negative value of the yield stress is noticed from the model, which practically has no meaning. The Newtonian model was then verified and the model parameters for equation 3 presented in Table 2 were obtained. Looking at the model parameters obtained and presented in Table 2, it can be seen that for the investigated sample, the Bingham plastic model and the Power law model both reduce to the Newtonian model. The reported values of the flow behavior index (n) of the Power law model are very close to one (ranges from 0.96 to 1.0), while the values of the consistency index m of the Power law model, and the apparent viscosity of the Bingham model are very close to the values of viscosity obtained by the Newtonian model. This is an indication that the fluid under study is a Newtonian fluid.

III.2.2 Variation of viscosity with shear rate at different temperatures

Viscosity measurements werecarried out at different temperatures. The obtained results are presented on Table 1 and Appendix A for temperatures varying from 20.4^{o}C to 60.1^{o}C. At a temperature of 20.4^{o}C, viscosity decreases from 10918cP to 10820cP as the shear rate is varied from 0.17 s^{-1}- 0.92s^{-1}. At a temperature of 30.3^{o}C, viscosity decreases from 3959cP to 3644cP as the shear rate is varied from 0.34 s^{-1}- 2.72 s^{-1}. At a temperature of 39.9^{o}C, viscosity decreases from 1440cP to 1430cP as the shear rate increases from 1.02 to 4.42s^{-1}. At a temperature of 50.1^{o}C, viscosity decreases from 639.9cP to 613.9cP as the shear rate increases from 3.06 to 16.32 s^{-1}.At a temperature of 60.1^{o}C, viscosity decreases from 306.4cP to 303.4cP as the shear rate increases from 4.76 to 32.64s^{-1}. This could be misleading to think that the fluid is exhibiting a non-Newtonian behavior but the values presented in Table 2 are indications of Newtonian behavior.Also, by looking at the data presented in Figure 3, it can be easily concluded thesamples are Newtonian in the range of temperatures of the measurements. Even extrapolation ofthe data to zero shear rate shows that the trend passes through the origin.

III.2.2.1 Determination of the degree of viscosity reduction

The degree of viscosity reduction is determined relative to a certain reference viscosity. In this work, since the validity of the Brookfield DV-II Pro viscometer is limited to a minimum percentage torque range of 10%, the viscosity value at this M-value is considered as the reference value. For the studied temperature range, measurements were not taken at a 10% M-value for some of the temperatures considered. As such, in order to use it as the reference point, relationships were established between the percentage torque (M), and the shear rate ($\dot{\gamma}$), as well as the shear rate and the viscosity (μ). The variation of percentage torque (M), with the shear rate ($\dot{\gamma}$) and viscosity variations with shear rate investigated for the range of temperature from 20.4 to 60.1°C are presented in Figure 4 and Figure 5 respectively.

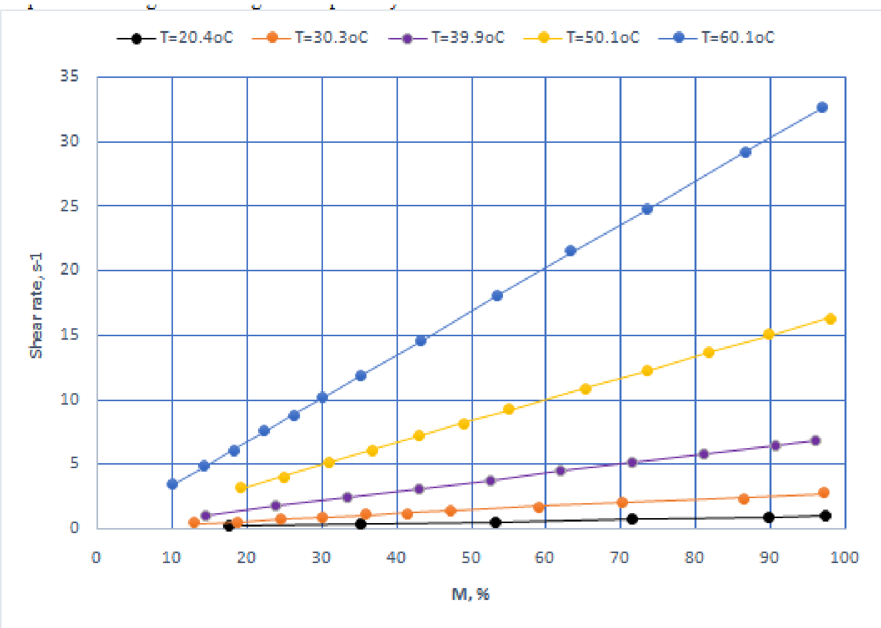

Figure 4 Modeling shear rate variations with percentage torque

these plots (Figures4 and 5), using the root mean square approach, the following equations (equations.4a-4e) were obtained to relate viscosity and shear rate for the different temperatures of investigation.

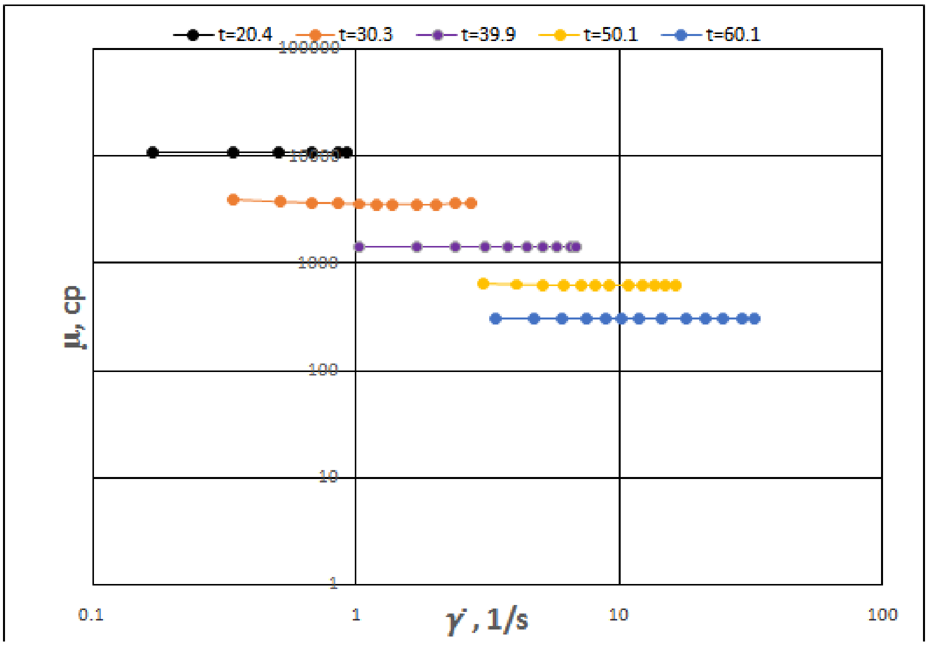

Figure 5 Modeling viscosity variations with shear rate at a temperature range of 20.4 to 60.1°C

Table 3 Model equations relating percentage torque, shear rate and viscosity

t, °C	Shear rate versus %Torque		Viscosity versus shear rate		Eq.
	$\dot{\gamma} = f(M)$	R^2	$\mu = f(\dot{\gamma})$	R^2	
20.4	$\dot{\gamma} = 0.0094M + 0.0081$	0.9999	$\mu = 10808\dot{\gamma}^{-0.005}$	0.9244	(4a)
30.3	$\dot{\gamma} = 0.0281M + 0.0004$	0.9987	$\mu = 196.2\dot{\gamma}^2 - 682.94\dot{\gamma} + 4100$	0.9108	(4b)
39.9	$\dot{\gamma} = 0.071M + 0.0062$	1	$\mu = 0.9261\dot{\gamma}^2 - 7.447\gamma + 1445.4$	0.744	(4c)
50.1	$\dot{\gamma} = 0.167M - 0.0957$	1	$\mu = 0.2921\dot{\gamma}^2 - 6.8691\dot{\gamma} + 650.83$	0.8025	(4d)
60.1	$\dot{\gamma} = 0.3369M - 0.0226$	1	$\mu = 0.0124\dot{\gamma}^2 - 0.5153\dot{\gamma} + 307.51$	0.8502	(4e)

These model equations (equations4a-4e) were used to forecast the viscosity values at a percentage torque of 10% at different temperatures within the range considered. The degree of viscosity reduction (DVR) was then computed according to eq. 5 (Ghannam and Esmail, 2006).

$$DVR\% = (\mu_r - \mu_c) * 100/\mu_r \qquad (5)$$

The results of DVR are presented in table 4 over a temperature range from 20.4°C to 60.1°C.

Table 4 DVR,% of seep sampleat a percentage torque of 10% versus temperature

t, °C	$\dot{\gamma}$at10%M	μ at 10%M, cP	DVR,%
20.4	0.1021	10,932.01	0
30.3	0.2814	3,923.36	64.1
39.9	0.7162	1440.54	86.8
50.1	1.5743	640.74	94.1
60.1	3.3464	305.92	97.2

In equation 5, μ_r is the reference viscosity at a percentage torque of 10% and temperature of 20.4°C, cP, and μ_c is the corresponding viscosity, cP. The results presented indicate that the DVR, % changes significantly from 0% to 97.2%. There might be several reasons linked to this significant reduction in viscosity. One of such reasons might be due to the effect of high temperatures on the chemical structure of heavy components (Hasan et al., 2010). Another reason for the significant reduction of viscosity could be as the result of the disentanglement and reorientation of the chain type molecules parallel to the driving force as explained by Ghannam and Esmail (2006), thus reducing viscosity. The influence of temperature on the viscosity of the seep sample is presented on Figure 6.

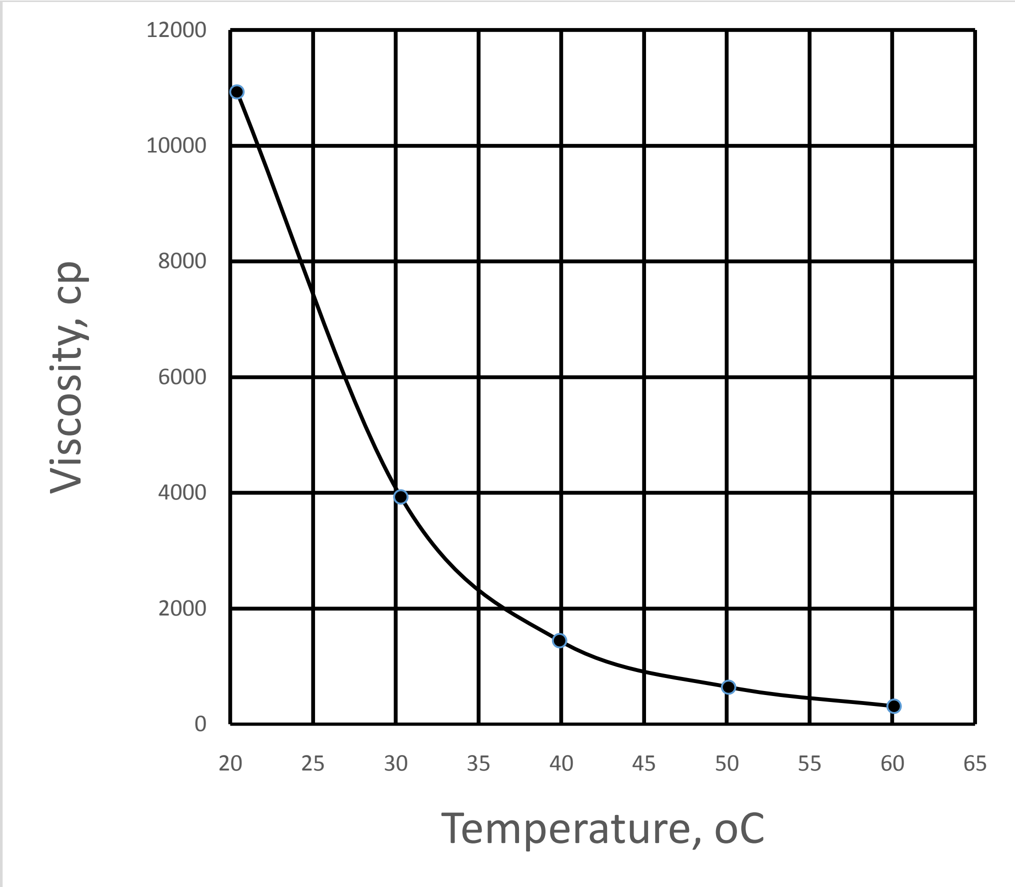

Figure 6 Viscosity variation with temperature

Temperature has much influence on the rheological behavior of fluids. Crude oils are equally very sensitive to temperature and any small variation in its value will result in significant change in viscosity. It was found that increasing the temperature gradually from 20.4 to 60.1 ^{o}C, the viscosity reduced significantly from 10932.01cP to 305.92cP. This indicates that the viscosity of crude oils depends so much on temperature (Santos et al., 2017) and formsthe basis of thermal enhanced oil recovery processes (Chuikinaet al., 2017; Green and Willhite, 1998).

III.2.2.2Thixotropic behavior of the Seep sample

An investigation was carried out on the influence of time on the rheological behavior of the seep sample at a temperature of 20.4^{o}C. The obtained results are presented on table 1 and Appendix A (a) and on Figure 7. The forward and the reverse processes did not coincide, leading to hysteresis of the flow plots. The viscosity of the sample decreases as the shear rate increases in the forward process. Upon reversal of the process, the viscosity continues to decrease as the shear rate decreases. This show that the seep sample exhibits thixotropic behavior (Ghannamet al., 2012) during which the structure in the seep sample is broken down over time and need time to recover.

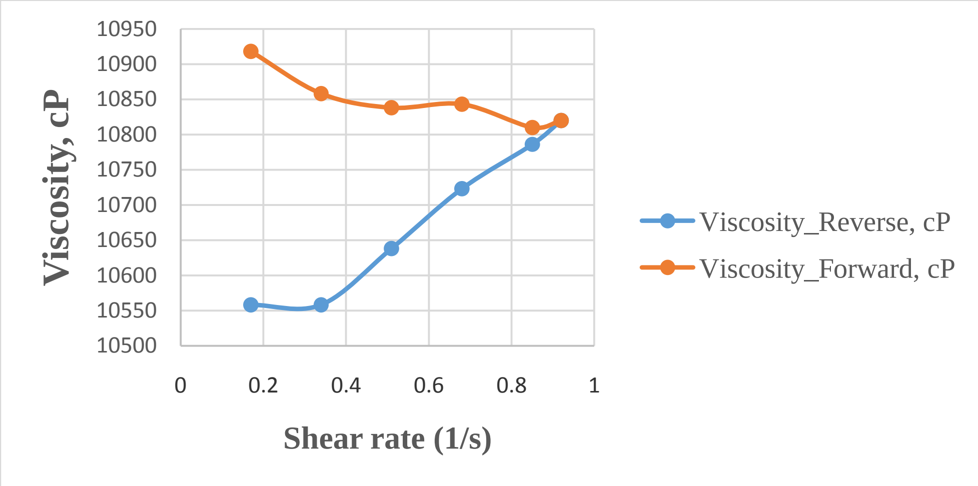

Figure 7 Thixotropic behavior of seep sample showing viscosity hysteresis

IV. CONCLUSION

From the results of this study, the following conclusions can be made:

- The presence of seeps in the given locations is linked to the breaching of a possible petroleum trap due to the active nature of Mount Cameroon separating two petroliferous basins.
- The properties (viscosity and API gravity) of the seeps at the foot of Mount Cameroon have been seriously altered due to their exposure to the atmosphere.
- The results obtained from the three investigated models show that the behavior of the seep sample could be adequately described by the Newtonian model.
- There is a very significant increase in the percentage viscosity reduction (DVR%). There are several reasons that could account for this,one of which could be the effect of high temperatures on the chemical structure of heavy components.
- During the forward and reverse investigation processes at a temperature of 20.4^{o}C, the sample exhibited a thixotropic behavior.

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Appendix A

Rheological properties of seeps sample at different temperatures of investigation

a)At temperature of 20.4^{o}C – Reverse process

T=20.4 ºC_ Reverse process				
n, rpm	**M, %**	**τ, dyne/cm^2**	**$\dot{\gamma}$, 1/sec**	**μ , cP**
0.5	17.6	17.95	0.17	10558
1	35.2	35.9	0.34	10558
1.5	53.2	54.25	0.51	10638
2	71.5	72.91	0.68	10723
2.5	89.8	91.58	0.85	10786
2.7	97.4	99.33	0.92	10820

b)At temperature of 30.3^{o}C

T=30.3 ºC				
n, rpm	**M, %**	**τ, dyne/cm^2**	**$\dot{\gamma}$, 1/sec**	**μ , cP**
0.5	13.1	13.36	0.34	3959
1	18.9	19.38	0.51	3779
1.5	24.6	25.09	0.68	3689
2	30.3	30.9	0.85	3635
3	35.9	36.51	1.02	3589
3.5	41.5	42.32	1.19	3556
4	47.3	48.13	1.36	3539
5	59.1	60.17	1.7	3539
6	70.4	71.79	2	3519
7	86.5	85.1	2.38	3646
8	97.2	99.12	2.72	3644

c) At temperature of 39.9^{o}C

T=39.9 ºC				
n, rpm	**M, %**	**τ, dyne/cm^2**	**$\dot{\gamma}$, 1/sec**	**μ , cP**
3	14.4	14.68	1.02	1440
5	23.9	24.37	1.7	1434
7	33.4	34.06	2.38	1431
9	43	43.85	3.06	1433
11	52.5	53.54	3.74	1432
13	62	63.33	4.42	1430
15	71.6	73.02	5.1	1432
17	81.2	82.81	5.78	1433
19	90.8	92.6	6.46	1433
20	96	97.9	6.8	1440

d) At temperature of 50.1^{o}C

T=50.1 ^{o}C				
n, rpm	**M, %**	**τ, dyne/cm^2**	**$\dot{\gamma}$, 1/sec**	**μ , cP**
9	19.2	19.58	3.06	639.9
12	25	25.49	4.08	624.9
15	31	31.61	5.1	619.9
18	36.9	37.63	6.12	614.9
21	43.2	43.2	7.14	616.1
24	49.1	50.07	8.16	613.6
27	55.1	56.19	9.18	612.1
32	65.5	66.8	10.88	613.9
36	73.7	75.16	12.24	614
40	81.8	83.42	13.6	613.4
44	90	91.78	14.96	613.5
48	98.1	100	16.32	613

e)At temperature of 60.1^{o}C

T=60.1 ^{o}C				
n, rpm	**M, %**	**τ, dyne/cm^2**	**$\dot{\gamma}$, 1/sec**	**μ , cP**
10	10.2	10.4	3.4	305.9
14	14.3	14.58	4.76	306.4
18	18.3	18.66	6.12	304.9
22	22.3	22.74	7.48	304
26	26.3	26.82	8.84	303.4
30	30.3	30.9	10.2	302.9
35	35.3	36	11.9	302.5
43	43.4	44.26	14.62	302.7
53	53.5	54.56	18.02	302.8
63	63.5	64.76	21.42	302.3
73	73.7	75.16	24.82	302.8
86	86.9	88.62	29.24	303.1
96	97.1	99.02	32.64	303.4

Fozao K.F. et al." Mount Cameroon oil seeps and their rheological properties"International Journal Of Engineering Research And Development , vol. 15, no. 1, 2019, pp 67-78