An integrated study involving detailed lithofacies analysis and source rock evaluation were carried out to reconstruct the paleoenvironment and assess the petroleum potentials of the Ikom–Mamfe embayment, southeastern Nigeria. Sedimentological field mapping involving detailed description of lithologic characteristics and facies characterisation was carried out. Geochemical studies were carried out to determine the quantity of organic matter total organic carbon (TOC), soluble organic matter (SOM), the organic matter quality (organic matter type) and level of maturity. Results show that the dominant vertical succession of the various lithofacies indicate a general finning upward succession with basal massive pebbly sandstone, medium to coarse grained sandstones with intercalation of shale and mudstones. Seven lithofacies A to G, were identified. These include: conglomerates, massive pebbly sandstone, trough cross-bedded sandstone, planar cross-bedded sandstone, shale/mudstone facies. These facies were compared with established standard facies association for determining paleoenvironment of deposition. The facies analysis carried out pointed to fluvial (alluvial – braided) depositional system as the environment of deposition. TOC values range from 0.05 – 4.13 wt% indicating poor to excellent and SOM range from 200 – 6000 ppm indicating also poor to excellent. The amount of pyrolizable carbon derived as S1 and S2 peaks suggested that the source rocks possess organic matter capable of generating hydrocarbons. Hydrogen and oxygen indices (HI and OI) ranged from 0.24 to 656 and 0.53 to 61.90 mg/gTOC respectively. Analyses of the evaluated source rock shows that the hydrocarbon potential of the study area is lean and typically of a reworked terrestrial deposit of fluvial depositional system.

Keywords: Petroleum potentials, organic matter, mudstone facies, cross bedding, fluvial system

INTRODUCTION

Sedimentary environment of deposition is determined by detailed study of the characteristics of the sediments. These are hinged upon by the different environmental factors upon which the sediments from their provenance to their depositional site have been through e.g. physical, biological and chemical factors and/or a combination of all these (Tucker 2003; Okon 2015; Essien and Okon 2016; Quasim et al 2017). It is also important to note that post-depositional modifications (diagenesis and tectonic adjustments, in some cases) leave imprints on the final rock exposed for study, therefore care is to be taken to properly decipher the depositional setting amidst these factors. The Mamfe basin straddles the border between south – eastern Nigeria and Western Cameroon. It extends from the Southern Benue Trough, where it is bounded at the NE and SW by the Bamenda and Oban Massifs of about 500m elevation (Figure 1) to the south.

*Corresponding Author: Emmanuel Etim Okon, Department of Geology, University of Calabar, Calabar, Cross River State, Nigeria. E-mail: etyboy911@yahoo.com; Tel: +234 8030841340
Previous studies show that the Cameroon sector has received more attention, notably Dumort, 1968; Eben 1984; Eyong 2003; Eyong et al. 2013; Eseme et al., 2002; Hell et al. 2000; Kangkolo, 2002; Ndougsa et al., 2004; Nouayou 2005; Tabod, 2008; Tokam et al. 2010; Njoh et al. 2015; Bassey et al. 2013, Abolo 2008; Ajonina, 2016 while the Nigerian sector has attracted relatively few studies like those of Olade 1975, Fairhead and Okereke 1987, 1988, Fairhead et al. 1991; Petters et al.,1987; Reyment 1965, Bassey 2012; Oden 2012; Bassey et al. 2013; Obi et al. 2013; Oden et al., 2015 which lead to paucity of geological information. Studies involving facies analysis and stratigraphic subdivision of sedimentary basin are commonly carried out to subdivide the basin infill to connote their age relationship and depositional environment. When this is established, further studies on such platform may yield success into associated economic potentials of the basin. For the Ikom-Mamfe embayment, only few biostratigraphic studies and been carried out and these studies where available are centred on outcrop exposures and few road cuts.

In spite of these studies, not so much centred on the sedimentological and stratigraphic framework/development of the embayment. This has informed the need for this research paper, essentially to investigate the lithofacies and assess the petroleum potentials of parts of the embayment. To achieve this goal, detailed geological mapping was carried out to document the various geological features (rock types, lithology, grain size distribution/facies trend, sedimentary structures, etc.), also geochemical analysis of the mud rock facies within the study area to assess their petroleum potential.
Geology of the study area

The Mamfe Basin is regarded as a side rift/half graben on the eastern flank of the Southern Benue Trough, Nigeria. It is bordered to the north by the Bamenda Massif and to the south by the Oban Massif. It extends into the southwestern part of the Republic Cameroon to the east where it is bordered by uplift of the Cameroon Volcanic Line (CVL). Based on some of its notable structural styles, for example, its fold axis parallel to basin axis and attendant magmatic intrusions, it is regarded as being similar to those of the Benue Trough and suggests that both basins have a closely related tectonic framework and geodynamic evolution (Ajonina et al., 2001). Thus, the basin is generally regarded as one of the three sub basins that make up the Southern Benue Trough. These sub basins from east to west are Mamfe, Abakaliki, and Anambra Basins.

The age of the Mamfe basin has been a subject of debate since studies begun within the basin largely due to paucity of biostratigraphic controls and complete lack/insufficiency of exploratory well in the basin. However, judging from the sedimentary fills of the WCARS which range in age from Neocomian to Recent and consists mostly of siliciclastics and volcanoclastics sediments of predominantly Cretaceous age, deposited in fluvial, lacustrine, marine, and deltaic settings. Ajonina (2016) proposed a Neocomian age for the basin (Figure 2).

Reyment (1965) described the Mamfe Formation as thickly folded and faulted series of massive arkosic sandstones and grits having intercalations of marlstones, arenaceous limestones and shale. He erected the type section at the bank of the Cross River near Mamfe Town, Cameroon Republic. The lithostratigraphic subdivision of the Mamfe embayment is composed of sediments that range in age from Aptian – Albian with thickness of about 4000m (Petters et al., 1987), collectively referred to as Mamfe Formation (Reyment, 1965; Dumort, 1968; Whiteman, 1982). The sedimentary package lies unconformably on the Pan-African crystalline basement complex composed predominantly of gneisses, schists and granitoids.

The formation is dominantly made up of sandstone, shale, mudstone, conglomerate and limestone/marble units constituting the basal unit of the Asu Rive Group (Petters et al., 1987). Petters et al., (1987) further described the Mamfe Formation sediments as coarse grained to pebbly, finning upward sequence with well-developed cross bedding and contains plant remains. The mud rocks alternate with medium grained sandstones in the upper part of the formation and often the sandstone pinch out in the grey friable shales. Earlier attempts to subdivide the sedimentary rocks of the Mamfe Formation, Abolo (2008) proposed a three-member subdivision: Etuko/Okoyong Member, Nfaitok Member and Manyu Member. Bassey et al., (1982, 1987, 2013) further described the Mamfe Formation sediments as coarse grained to pebbly, finning upward sequence with well-developed cross bedding and contains plant remains.
al. (2013), rather preferred a two-member subdivision: the Manyu and Kesham members respectively. Due to these plaguing inconsistencies in stratigraphic nomenclature, Ajonina (2016) suggested an upgrade of the members to formation status and presented the following: an older Etuko Formation overlain by Mamfe Group (represented by Nfiatok, Manyu and Okoyong Formations) and overlying Ikom-Munaya Formation. However, because these formations are not fully consistent with the stratigraphic code for erecting formations, it is best to stick to the Mamfe Formation until adequate data set and well controls across the basin is available to constrain proper subdivision if necessary. The occurrence of brine springs in the Ikom-Mamfe embayment, suggesting a possible marine influence during deposition was reported by Petters et al, 1987 but stated the fluvialite origin of the formation was overwhelming.

MATERIALS AND METHODS

Detailed field mapping was carried out across the study area using a topographic map (part of UGEP Sheet 314) as a guide. A total of 15 outcrops were visited and 53 samples collected for laboratory analyses. All the outcrop and river sections were measured and their lithologic characteristics were documented. This facilitated the erection of vertical sedimentary section, taking into account the colour, grain size, sedimentary structures, bedding forms/types, bed thicknesses and nature of their contacts. The lithostratigraphic facies analysis of this study was carried out from general field observations comprising description of rock types in the study area, with emphasis on the texture, colour, bed thickness, grain shape and sizes, sorting, grain size trends and sedimentary structures. On the basis of the above, lithologic log sections were constructed for outcrops from different locations (Figure 3).

Figure 3: Map of the study area showing the various lithologic sections

Miall (1978) facies model was instrumental in the erection of the facies succession for the study area (Table 1). The comparison was based on similar lithologic characteristics and the information obtained, was put together to interpret the depositional environment of the study area.

Rock samples were collected at representative units for further laboratory characterization/analyses, especially the mudrocks (shale and mudstones). These were described and subjected to geochemical analysis (Total Organic Carbon – TOC, Soluble Organic Matter - SOM and Rock Eval Pyrolysis) to evaluate the organic richness, maturity and hydrocarbon generative potentials.

A total of 15 shale samples were subjected to TOC analysis using the Walkley-Black titration method. This involved the protocol referred to as "wet oxidation method" where by 0.5g of the sample is pulverized and subjected to chronic oxidation. After heating, excess potassium dichromate ($K_2Cr_2O_7$) was titrated against ferrous ammonium sulphate. The difference between the initial and residual potassium dichromate is a measure of the organic content of the sample. This is calculated using the relation:

$$\%TOC = 10 \times (1 - T/S) F$$
Table 1: Facies and characteristic structure of sediments and depositional environment (After Miall, 1978)

<table>
<thead>
<tr>
<th>Gmm</th>
<th>Matrix - supported, massive gravel</th>
<th>Weak grading</th>
<th>Plastic debris flow (high-strength, viscous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gmg</td>
<td>Matrix - supported gravel</td>
<td>Inverse to normal grading</td>
<td>Pseudoplastic debris flow (low strength, viscous)</td>
</tr>
<tr>
<td>Gci</td>
<td>Clast - supported gravel</td>
<td>Inverse grading</td>
<td>Clast - rich debris flow (high strength), or pseudoplastic debris flow (low strength)</td>
</tr>
<tr>
<td>Gcm</td>
<td>Clast - supported massive gravel</td>
<td>-</td>
<td>Pseudoplastic debris flow (inertial bedload, turbulent flow)</td>
</tr>
<tr>
<td>Gh</td>
<td>Clast - supported, crudely bedded gravel</td>
<td>Horizontal bedding, imbrication</td>
<td>Longitudinal bedforms, lag deposit, sieve deposits</td>
</tr>
<tr>
<td>Gt</td>
<td>Gravel, stratified</td>
<td>Trough cross beds</td>
<td>Minor channel fills</td>
</tr>
<tr>
<td>Gp</td>
<td>Gravel, stratified</td>
<td>Planar cross beds</td>
<td>Traverse bedforms, deltaic growths from older bar remnants</td>
</tr>
<tr>
<td>St</td>
<td>Sand, fine to very coarse, maybe pebbly</td>
<td>Solitary or grouped, trough cross-beds</td>
<td>Sinuous-crested and linguoid (3-D) dunes</td>
</tr>
<tr>
<td>Sp</td>
<td>Sand, fine to very coarse, maybe pebbly</td>
<td>Solitary or grouped, planar cross-beds</td>
<td>Traverse and linguoid bedforms (2-D dunes)</td>
</tr>
<tr>
<td>Sr</td>
<td>Sand, very fine to coarse, may be pebbly</td>
<td>Ripple cross-lamination</td>
<td>Ripples (lower flow regime)</td>
</tr>
<tr>
<td>Sh</td>
<td>Sand, very fine to coarse, may be pebbly</td>
<td>Horizontal lamination, parting or streaming lineation</td>
<td>Plane-bed flow (critical flow)</td>
</tr>
<tr>
<td>Sl</td>
<td>Sand, very fine to coarse, may be pebbly</td>
<td>low angle (15°) cross-beds</td>
<td>Scour fills, humpback or washed-out dunes, antedunes</td>
</tr>
<tr>
<td>Ss</td>
<td>Sand, fine to very coarse, may be pebbly</td>
<td>Broad, shallow scour</td>
<td>Scour fills</td>
</tr>
<tr>
<td>Sm</td>
<td>Sand, fine to coarse, maybe pebbly</td>
<td>Mass, or faint lamination</td>
<td>Sediment-gravity flow deposits</td>
</tr>
<tr>
<td>Fl</td>
<td>Sand, silt, mud</td>
<td>Fine lamination, very small ripples</td>
<td>Overbank, abandoned channel, or waning flood deposits</td>
</tr>
<tr>
<td>Fsm</td>
<td>Silt, mud</td>
<td>Massive</td>
<td>Backswamp or abandoned channel deposits</td>
</tr>
<tr>
<td>Fm</td>
<td>Mud, silt</td>
<td>Massive, desiccation cracks</td>
<td>Overbank, abandoned channel, or drape deposits</td>
</tr>
<tr>
<td>Fr</td>
<td>Mud, silt</td>
<td>Mass, roots, bioturbation</td>
<td>Root bed, incipient soil</td>
</tr>
<tr>
<td>C</td>
<td>Coal, carbonaceous mud</td>
<td>Plant, mud films</td>
<td>Vegetated swamp deposits</td>
</tr>
<tr>
<td>P</td>
<td>Paleosol carbonate (calcite, siderite)</td>
<td>Pedogenic features: nodules, filaments</td>
<td>Soil with chemical precipitation</td>
</tr>
</tbody>
</table>

where: %TOC = Percentage Total Organic Carbon
T = Sample Titration (Vol of ferrous ammonium sulphate used for titration)
S = Standard or Blank titration
F = Factor derived from the relation
F = ([1.0 x 12] / 4000 x 1.72 x 100 w)
And w = weight of the samples in grams;
1.0N = Normality of K₂Cr₂O₇; 10 = Vol of K₂Cr₂O₇

The final results were compared with the chart of Peters, 1986. Soluble organic matter was determined for the shales using axiotrophic mixture of acetone and methanol (ratio 9:1). Refluxing technique whereby the solvent is made to be in prolonged contact with the sample such that a complete extraction is established. The setup was left to stand for 24 hours. After complete extraction, the weight of the extract was determined and used to calculate the SOM as shown below:

SOM = weight of extract/weight of sample x 1000000.

Using the data generated from the TOC and SOM analysis, 8 samples were selected and subjected to Rock Eval pyrolysis (Figure 4). This analysis was carried out at Weatherford Laboratories, Texas, USA.

![Figure 4: Schematic diagram of Rock-Eval pyrolysis process (adapted from Okon, 2011)](image-url)
RESULTS

Lithostratigraphic Facies Analysis

The observations made in the field with emphasis on the variations in colour, rock types, texture, bed thicknesses, grain shape and sizes, sorting and sedimentary structures formed the basis for the lithofacies inference which facilitated the identification of the various depositional environments. Comparing the lithofacies based on similar characteristics with that of Miall (1978), seven (7) lithofacies were identified as follows: conglomerate facies (Gmm), massive pebbly sandstone facies (Sm), trough cross-bedded sandstone facies (St), planar cross-bedded sandstone facies (Sp), fine to coarse grain sandstone facies (Sh) and mudstone/shale facies (Fl).

The codes used here were drawn from their similarities to the Miall (1978) facies characterization.

Conglomerate Facies (Gmm)

This consist of brown, poorly sorted matrix supported polymictic conglomerate exposed around Obubra constitute conglomerate facies. It is analogous to the Miall (1978) facies code Gmm interpreted as plastic debris flow deposit. Its boulder to pebble sized quartz clasts are thought to be products from redeposition (second cycle sedimentation) into the part of Southern Benue Trough (Afikpo/Mamfe Basin) resulting from the uplifted Abakaliki Anticlinorium following the Santonian event.

Several cycles of deposition were mapped and the average thickness of each bed was approximately 1.2m (Figure 5). The overall thickness of this unit is approximately 10m thick in exposed sections. This facies succession was not observed in all sections studied but notably occur overlying the black shale facies, where observed.

Massive pebbly sandstone facies (Sm)

The pebbly sandstone facies consist of a light grey to white coloured arkosic sandstone observed almost throughout the study area. It occurs at the basal section of the sediment pile and generally lack well defined satisfaction. This lack of clearly defined stratification has been attributed to the absence of traction transport, whereby sediments were subjected to rapid deposition. The characteristics suggest is dumped very rapidly without subsequent reworking to form a homogenous mass. A crude fining – upward succession was however observed based on sediment grain size, in the upper part but capped with a thin conglomerate layer (lag deposit) and scour under surface before the beginning of another cycle. The massive pebbly sandstone faces (facies A) of the study is similar to Miall’s (1978) facies (Sm) which is interpreted as sediment gravity flow, with occasional lag and scour surfaces.

Trough cross bedded sandstone facies (St)

The trough cross bedded sandstone facies is characterized by dark-grey to brown, medium to coarse grain sandstone (Facies B). The cross beds are stacked on top of each other, resulting in multi-story pattern of cosets. This is comparable with Miall (1978) facies code (St) interpreted as sinuous-crested and linguoid dune sands in channel deposit. The characteristic suggests it resulted from a unidirectional traction current migration of sinuous crest (ripple marked) sands (Cant and Walker, 1976, Allen, 1970).

The planar cross bedded sandstone facies in the study area is reddish, brown to light brown in colour, medium to coarse grain (Facies C), generally exhibit a finning – upward succession (Figure 6). The facies are similar to facies code (Sp) of Miall, 1978. Such characteristics are typical of transverse and linguoid bedforms in braided stream sub-environments.

Figure 5: Vertical section of the polymict conglomerate

Figure 6: Planer cross bedded sandstone facies (SP)
Table 2: Result of the rock eval pyrolysis of Mamfe Formation sediments

<table>
<thead>
<tr>
<th>S/N</th>
<th>Sample No.</th>
<th>Sample Type</th>
<th>Location</th>
<th>Formation</th>
<th>TOC wt%</th>
<th>SOM (ppm)</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S1+S2</th>
<th>Tmax</th>
<th>HI</th>
<th>OI</th>
<th>S2/S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IHR22A</td>
<td>Outcrop</td>
<td>Ihurumektet</td>
<td>Mamfe Fm</td>
<td>0.05</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>IHR 22B</td>
<td>Outcrop</td>
<td>Ihurumektet</td>
<td>Mamfe Fm</td>
<td>0.41</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>IHR 22C</td>
<td>Outcrop</td>
<td>Ihurumektet</td>
<td>Mamfe Fm</td>
<td>0.52</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>IHR22D</td>
<td>Outcrop</td>
<td>Ihurumektet</td>
<td>Mamfe Fm</td>
<td>0.16</td>
<td>1000</td>
<td>0.03</td>
<td>1.05</td>
<td>0.04</td>
<td>1.08</td>
<td>541</td>
<td>656</td>
<td>25</td>
<td>26.3</td>
</tr>
<tr>
<td>5</td>
<td>IHR22E</td>
<td>Outcrop</td>
<td>Ihurumektet</td>
<td>Mamfe Fm</td>
<td>0.57</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>IY23A</td>
<td>Outcrop</td>
<td>Iyametet</td>
<td>Mamfe Fm</td>
<td>0.77</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>IY23B</td>
<td>Outcrop</td>
<td>Iyametet</td>
<td>Mamfe Fm</td>
<td>0.52</td>
<td>1000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.22</td>
<td>0.02</td>
<td>327</td>
<td>1.92</td>
<td>42.3</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>IY 23C</td>
<td>Outcrop</td>
<td>Iyametet</td>
<td>Mamfe Fm</td>
<td>0.06</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>OH 1 A</td>
<td>Outcrop</td>
<td>Ohana</td>
<td>Mamfe Fm</td>
<td>0.41</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>OH 2</td>
<td>Outcrop</td>
<td>Ohana</td>
<td>Mamfe Fm</td>
<td>0.21</td>
<td>200</td>
<td>0.01</td>
<td>0.02</td>
<td>0.13</td>
<td>0.03</td>
<td>386</td>
<td>9.52</td>
<td>61.90</td>
<td>0.2</td>
</tr>
<tr>
<td>11</td>
<td>OCH 7</td>
<td>Outcrop</td>
<td>Ochon</td>
<td>Mamfe Fm</td>
<td>0.36</td>
<td>300</td>
<td>0.01</td>
<td>0.01</td>
<td>0.12</td>
<td>0.02</td>
<td>-1</td>
<td>2.78</td>
<td>33.33</td>
<td>0.1</td>
</tr>
<tr>
<td>12</td>
<td>ND 13A</td>
<td>Outcrop</td>
<td>Nde</td>
<td>Mamfe Fm</td>
<td>0.91</td>
<td>1000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.04</td>
<td>0.02</td>
<td>376</td>
<td>1.09</td>
<td>4.39</td>
<td>0.3</td>
</tr>
<tr>
<td>13</td>
<td>OKHI5B</td>
<td>Outcrop</td>
<td>Okagh</td>
<td>Mamfe Fm</td>
<td>1.87</td>
<td>6000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>-1</td>
<td>0.53</td>
<td>0.53</td>
<td>1.0</td>
</tr>
<tr>
<td>14</td>
<td>AJ21 A</td>
<td>Outcrop</td>
<td>Ajasor</td>
<td>Mamfe Fm</td>
<td>4.13</td>
<td>1000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
<td>0.02</td>
<td>-1</td>
<td>0.24</td>
<td>1.45</td>
<td>0.2</td>
</tr>
<tr>
<td>15</td>
<td>IK 17B</td>
<td>Outcrop</td>
<td>Ikom</td>
<td>Mamfe Fm</td>
<td>0.61</td>
<td>2000</td>
<td>0.02</td>
<td>0.01</td>
<td>0.07</td>
<td>0.03</td>
<td>405</td>
<td>1.64</td>
<td>11.48</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Fine - coarse grained sands (sh)**

The fine - medium and medium - coarse grained sandstone facies of this study occurs as mainly brown to occasionally light-brown in colour (Facies D), exhibiting a fining - upward trend. The fine - coarse grained sandstone facies can be compared to the facies code (sh) of Miall (1978). It is characterized by plane bed condition as they transit from one grain size to another with occasional crude laminations defined mostly by colour variations is interpreted as channel sands facies.

**Mudstone - shale facies (FI)**

The mudstone-shale facies (E and F) of the studying area is dark to grey in colour (Figure 7). Individual occurrence of these facies is up to 0.5m thick and is occasionally sandy (fine size). This is analogous to facies code (FI) of Miall (1978). In all the locations that the mudstone-shale facies occur, it appears gradational and non-erosional with facies (A) and facies (D). Its texture (silt-clay size grains) suggests accumulation under suspension and this points to abandoned, waning flood-phase deposits.

**Organic Geochemistry**

The results of Total Organic Carbon, TOC, Soluble Organic Matter, SOM, and Rock - Eval pyrolysis from the study area are presented in Table 2. The results show that values for TOC range from 0.05 - 4.13wt% with a mean value of 0.07wt%. The minimum threshold value of 0.5wt% established for clastic sedimentary rocks, wherewith they may generate hydrocarbon (Tissot and Welte, 1984) and source quantitative scale of Peters (1986) was adopted in this study. Using this as a basis for classification, the source rocks range from poor source rock through fair source rock to very good source rock potential (Table 2). Samples collected especially from Okagh and Ajasor have good and very good source potentials respectively. Soluble organic matter in rocks are also used to characterized the organic matter quantity Phillipi (1965), prepared a cut off scale for characterizing source rocks (Table 3), and using the scale, some of the values indicate fair to very good concentration of soluble organic matter (SOM) in the samples. Organic richness alone may not be sufficient for assessing the petroleum generation potential of any given source rock. Temperature plays an important role for the source to attain maturity. In this study, the type/quality of organic source rock and the maturation status of the potential source rock was based on the hydrogen Index (HI), Oxygen Index (OI) and Tmax obtained from the rock – eval pyrolysis respectively.

The rock-eval analysis data allows the derivative of HI which is roughly the equivalent of H/C and OI that is also roughly the equivalent of the O/C (Espositie et al, 1977, Peters, 1986). The HI and OI data are commonly plotted on a modified Van Krevelen diagram (Tissot and Welte, 1984) which clearly demarcates Type 1 – 1V Kerogen).

![Figure 7: Typical highly fissile shale facies](image)

Lithofacies Analysis and Petroleum Potentials of Parts of Ikom-Mamfe Embayment, South-Eastern Nigeria
DISCUSSIONS

Facies and facies sequence (depositional environments interpretation)

The study of the distribution and characteristics of sedimentary facies present aid in the identification of certain unique characteristics present in modern depositional settings, which when extended to their ancient counterpart facilitates interpretation of depositional environment (Middleton, 1978, Quasim et al., 2017). Two facies associations were observed namely: A-B-C and E-F (Figure 8) within the study area. Notably, each of the association depict well defined erosional base characterized by scour surface and succession that generally fines upward. The significance of scour surface forming the base of individual sedimentation units is logically starting point for reconstructing the history of sedimentation (Visher, 1972).

Essentially, within this study area, the facies succession starts with the massive pebbly sandstone facies (A) at the base, followed by trough and planer cross bedded sandstone facies (B) and (C), medium to coarse grained sandstone facies (D), shale/mudstone facies (E and F), and finally the massive conglomeratic sandstone facies (G). From the lithofacies model (Figure 8) the Mamfe Formation has a finning upward succession typical of fluviatile origin. Visher (1972) suggested that the characteristics produced by uni-directional flow must be present before a fluval interpretation can be considered and it was observed in the medium - grained trough/planar cross bedded sandstone facies (B and C). A very important aspect to note is the 5.5m thick deposit of polymict conglomerates with size varying from granules through cobbles and boulders near Obubra (Loc 6) and was interpreted to be of alluvial origin. Ascribing alluvial origin to the deposit is based on the thickness of the deposit which is regarded as debris flow deposit. The facies (G) in combination with the braided stream gives an overall alluvial-braded stream fluvial depositional system for the study area. Facies (D) is interpreted as active channel deposit while facies (E and F) mudstone/shale facies are typical overbank deposits.

The massive conglomerate (G) and fissile shales are believed to have been deposited unconformably on the Asu River Group sediments in the Ikom-Mamfe Embayment following the Santonian deformational episode and uplift of the Abakaliki Anticlinorium (Southern Benue Trough) giving rise to sediments in their second cycle of deposition (Figure 8).

Based on the observed characteristics, with the Miall (1978) model as a guide, the Mamfe Formation is likened to the Donjek type of braided river depositional profile because the sedimentation cycles are marked by definite boundaries with thin conglomerate layer and scour surfaces with a general finning – upward successions. This facies succession is comparable with sediments of the Lower Member of the Guanajuato Conglomerate (Puy-Alquiza et al 2017) interpreted to have been deposited in alluvial fans setting associated with braided fluvial system. For hydrocarbon accumulations to be substantial in the Ikom-Mamfe basin, the understanding of the environment of deposition vis-a-vis the migration dynamics need to be understood correctly. Facies analysis point to fluvial setting for the sedimentary pile, however there is evidence of some marine incursion at some point and the post depositional tectonics of the basin have produced structure that lends positive support to the potential presence of hydrocarbon in the basin. Although the quantity of organic matter from this study reflect lean organic matter, there are sporadic increases in organic matter from place to place (especially around Okagha and Ajasor). The plot of Hydrogen Index (HI) against Oxygen Index (OI) show that all samples, but one sample (IHR 22D) plotted in the Type III-IV kerogen field (Figure 9), suggesting sources of organic matter from a fluvial environment. Although reports of lacustrine sediments exist in the literature (Njoh et al.,2015; Abolo, 2008) in the Cameroon sector of the Mamfe basin, that may have been responsible for the characteristics of the sediment that plotted in the Type II field.

Table 3: Soluble Organic Matter Interpretation for source rock potential (after Phillipi, 1965)

<table>
<thead>
<tr>
<th>SOM (ppm)</th>
<th>Description of Source Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Very Poor</td>
</tr>
<tr>
<td>150</td>
<td>Poor</td>
</tr>
<tr>
<td>500</td>
<td>Fair</td>
</tr>
<tr>
<td>1500</td>
<td>Good</td>
</tr>
<tr>
<td>5000</td>
<td>Very Good</td>
</tr>
<tr>
<td>&gt;5000</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Figure 8. Correlation Panel for the lithologic sections from west to east of Ikom-Mamfe Embayment in the study area.
It is important to note that since samples from this study were collected mainly from outcrops, there is a possibility of occurrence of lacustrine sediments which maybe deeply buried and inaccessible, more so, the outcrop samples may have been subjected to some degree of weathering, even though deliberate efforts were made in the field to collect the most unaltered samples.

Hydrocarbon Source Potential (SP)

The hydrocarbon source potential (SP) of the samples range from 0.02 - 1.08mg HC/grock with an average value of 0.16mg HC/grock (Table 2). From the criteria used by Tissot and Welte, (1984) and Dymann et al (1996), the samples fall below the pre-requisite for hydrocarbon oil source rocks. Therefore, the yield potential of the present in the rock suggest little or no oil source potential.

To further buttress this, a bivariate cross plot of S2 against TOC, this plot showed that the kerogen has lean organic matter character except one sample that plotted in the oil prone field (Figure 10). Further assessment based on thermal maturity using pyrolysis method (Tmax) show a range from 327 to 541°C. This implies that the sediments are thermally immature (Peter and Cassa,1984; Dow 1977; Peter, 1986), except one sample (IHR 22D) which attained a Tmax value of 541°C and falls above 470°C, indicating that the kerogen has reached the post mature stage. It is also very important to point out the occurrence of intrusives in close proximity to samples used in this study, and this could have influenced the high Tmax value.

SUMMARY AND CONCLUSION

The facies analysis and petroleum generative potential of parts of Ikom-Mamfe embayment were investigated with the purpose of carrying out paleo-environmental reconstruction and assessment of the petroleum potential. The study strongly points to the fact that the sediments were deposited in a fluvial depositional environment. The lithofacies generated facilitated paleo-environmental inference. The various facies encountered range from conglomerate / massive pebbly sandstone, trough/planar cross bedded sandstone, fine-medium grained sandstone and mudstone/shale facies, all showing unidirectional flow characteristics and exhibiting essentially fining upward succession. This is typical of sediments belonging to alluvial-braided fluvial depositional system.

Also, evaluation of the kerogen for hydrocarbon source potential revealed that the TOC and SOM were poor to good. The organic matter was mostly derived from different sources including continental and possibly lacustrine environments. The thermal history of the analysed samples seems not to have supported hydrocarbon accumulation in the basin. This position can be further strengthened when subsurface samples from deep wells are made available for study in this basin.

As a concluding remark, it is important to note that outcrop samples alone were used for this study, and may not, on their own, be adequate to provide a deep insight on a detailed stratigraphic sequence and petroleum generating potential of the basin. It is recommended that where possible, a drilling campaign where drill core samples or even ditch cuttings could be analysed for the entire vertical section of the basin (from its shallowest parts to the deepest parts) is carried out. This would go a long way to adequately constrain the age, depositional history and much more reliably access the petroleum source potentials.
ACKNOWLEDGEMENTS

I will like to express my profound gratitude to the anonymous reviewers whose critical review comments have greatly improved the quality of this manuscript.

REFERENCES

Abolo MG (2008) Geology and Petroleum potential of the Mamfe basin, Cameroon, Central Africa. Geosciences Review (Special publication 01 & 02), 65-78


es science, specialitGeophysique Interne, Universite de Yaounde I

Obi DA, Obi EO and Okiwelu AA (2013) Basin configuration and intrasediment intrusive as revealed by aeromagnetics data of south east sector of Mamfe basin. Journal of Applied Geology and Geophysics.1:01-08

Oden, MI (2012) Barite veins in the Benue trough: Field characteristics, the quality issue and some tectonic implications, Environment and Natural Resources Research, 2(2):21 - 31


Reyment RA (1965), Aspects of Geology of Nigeria: Ibadan, Nigeria, University of Ibadan Press


Tokam AK, Tabod CT, Nyblade AA, Julia J, Wiens, DA and Pasyanos ME (2010), Structure of the crust beneath Cameroon, West Africa, from the joint inversion of Rayleigh wave group velocities and receiver functions. Geophysics International Journal 10:1-16


Accepted 28 June 2018


Copyright: © 2018 Essien et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are cited.