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ECONOMIC EVALUATION, RECOVERY TECHNIQUES AND ENVIRONMENTAL IMPLICATIONS OF THE OIL SHALE DEPOSIT IN THE ABAKALIKI ANTICLINORIUM, SOUTHEASTERN NIGERIA

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An extensive geological mapping and geochemical studies of the oil shale deposit in the Abakaliki Anticlinorium, southeastern Nigeria were carried out to determine its areal extent, reserve estimate, recovery techniques and possible environmental impacts. The total area of the exploitable zones that is characterized by shale alternating with marl has been calculated to be 72.7 km^2 *by placing a 1,000 m by 1,000 m grid outlay on the mapped sections. Using an exploitable thickness of 34 m and an areal extent of 72.7 km*^{2}*, the oil shale reserve estimate is* 5.76×10^9 *tonnes. Moreover, using an average Fischer Assay yield value of 56.35 litre/tonne, the recoverable hydrocarbon reserve estimate is* 1.7×10^9 *barrels. Retorting recovery method is suggested for exploitation of local oil shale because of shallow upper soil and a relatively cheap cost of establishments. Low concentration of sulphur (between 0.33 and 0.74%) and trace elements such as Ba, Cd, Cu, Cr, Ni, Pb and Zn supports the economic viability of oil shale as refinery feedstock.*

Introduction

Nigeria is one of the developing countries endowed with numerous mineral resources and fossil fuels. Coal, crude oil, and natural gas are commonly known sources of fossil energy. There is little or no awareness as to the use of oil shale in Nigeria because of the early discovery of crude oil in the Niger Delta basin. Mid-Cretaceous oil shale deposits have been discovered in the Abakaliki Basin of the Benue Trough of Nigeria [1]. This oil shale

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was named “Lokpanta oil shale” based on outcrops in Lokpanta town situated near Awgu in southeastern Nigeria (Fig. 1).

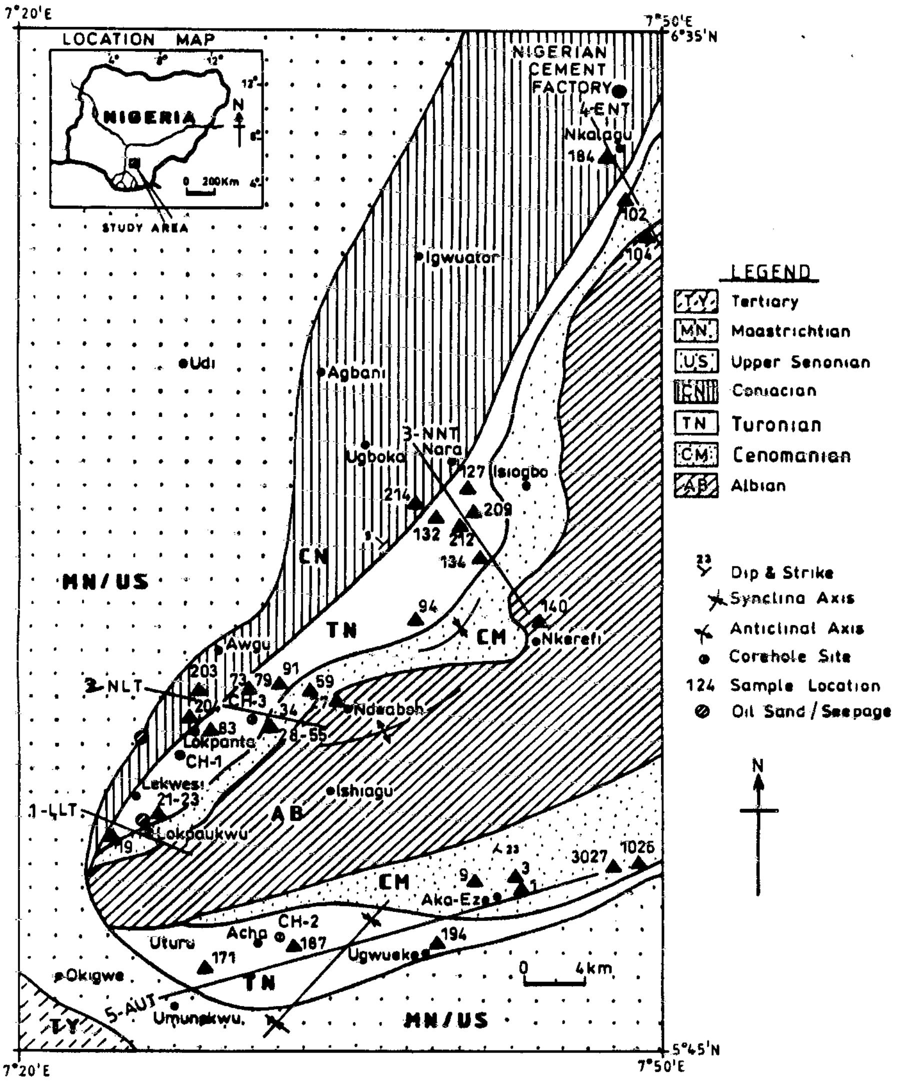

Fig. 1. Geological map of the Abakaliki anticlinorium, southeastern Nigeria showing sample location (modified from: *Ehinola et al.*, 2003)

Oil shales are rocks that yield oil upon pyrolysis [2]. Oil shale formation is the outcome of the transformation of organic material under water at relatively low temperatures, unlike coal formation which is a result of high pressure and high temperatures acting on organic material over long periods of time [3]. Known reserves of oil shale are present in Estonia, China, Brazil, Russia, the United States, and in several other countries [4]. In Jordan, oil shale is being used as raw material for oil production [2]. Hence, oil shale is a source of fossil fuel and may help to offset the expected exhaustion of petroleum reserves. However, oil shale is not widely used, especially for fuel oil production, due to the costs involved in production.

The way in which oil shale formation has taken place makes it high in components, which have a number of uses other than for fuel [3]. It can provide a wide range of chemical feedstocks for manufacturing the products such as adhesives, resins and plastics [3]. Powdered oil shale contains calcium compounds which, when added to acidic soil, will help to increase its pH value [5]. The ash from oil shale pulverized fuel combustion can be used in cement making, brick manufacturing, as asphalt filler in road construction, and also as hard core [6]. Oil shale ash, although alkaline in reaction, has been used as an amendment for spoil materials in reclamation work; particularly for acid colliery wastes [7].

Air and water pollution are rampant, especially in the areas where petroleum is being produced. Oil spillage and undesirable gaseous pollutants are common and associated with both conventional and unconventional oil. These problems may arise during exploration, drilling, production and transportation of oil shale [8]. Water and dust pollutions are the major environmental problems encountered during opencast mining and underground extraction of oil shale. At extraction of oil from oil shale, the air and water pollution could be minimized, if a good sanitary waste disposal method is employed and retorting of the shale is controlled.

The search for commercial crude oil within the Benue Trough in Nigeria has remained essentially a routine program of concern mostly to oil companies and research groups. The initial efforts were unsuccessful and prospecting for petroleum in the trough was abandoned completely in the late 1950s when oil was struck in the nearby Niger Delta Basin. However, abundant oil shale has been discovered in the area [1].

This study aims at providing information on areal extent, reserve estimate, recovery techniques and possible environmental impacts of oil shale, which have to be taken into account by the mining sector when aiming for sustainable development of such industry in Nigeria.

Methodology

The field mapping exercise in the Abakaliki Fold Belt covered an area of 1,105 km^2, which lies between latitudes 5º45′ N and 6º35′ N and longitudes 7º20′ E and 7º50′ E. The studied drillcore samples are taken from sites located near the towns of Lokpanta, Onoli-Awgu and Acha (see Fig. 1). The coordinates, the sample numbers, and the depths of the outcrop and core sections from which the samples were obtained are presented in Fig. 2.

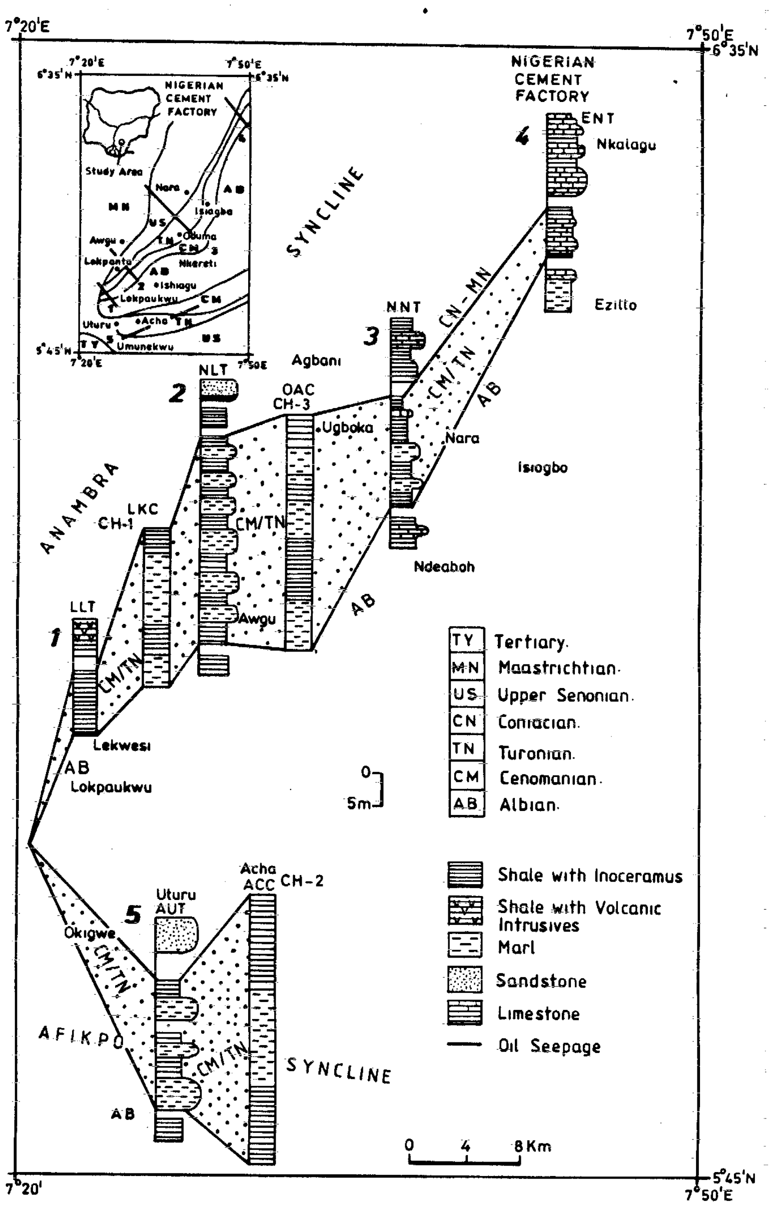

Fig. 2. Outcrop and core sections correlation in the Abakaliki Fold Belt (modified from: *Ehinola*, 2002)

To estimate the economic viability of oil shale, the following parameters were determined: the areal extent and thickness of the oil shale layer, oil yield and calorific value, and reserve estimate. The areal extent was determined using a grid outlay of 1,000 m by 1,000 m (Fig. 3) in areas with total organic carbon (TOC) values greater than 3 wt.% (sections B_1 and B_2 in Fig. 3). The area was calculated based on the areas of full squares (S), triangles (*T*) and trapezium (*Z*) and the difference in the combination of *S* and *T*, which is denoted by *C* (Appendix I).

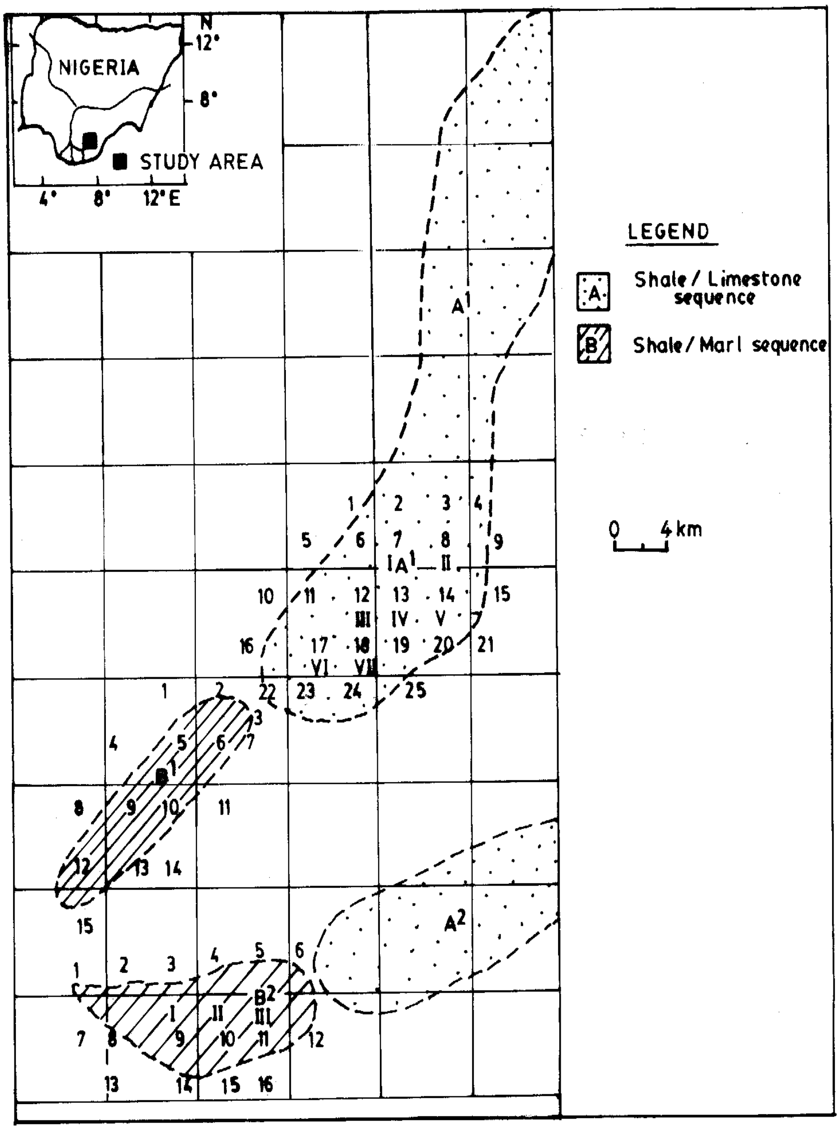

Fig. 3. Graphical grid layout of the mapped sections of the oil shale locations

The ratio of the overburden thickness to the thickness of the oil shale layer is one of the prominent economic conditions considered for profitable exploitation. The thickness of the shale layers was determined using the average thickness of the three boreholes sited in the study area (CH-1, CH-2 and CH-3 in Fig. 2).

The oil yield depends on the abundance of kerogen in oil shale (TOC), the nature of kerogen and source of the rock. The values of oil yields have been estimated using Fischer Assay (FAY) (Fig. 4).

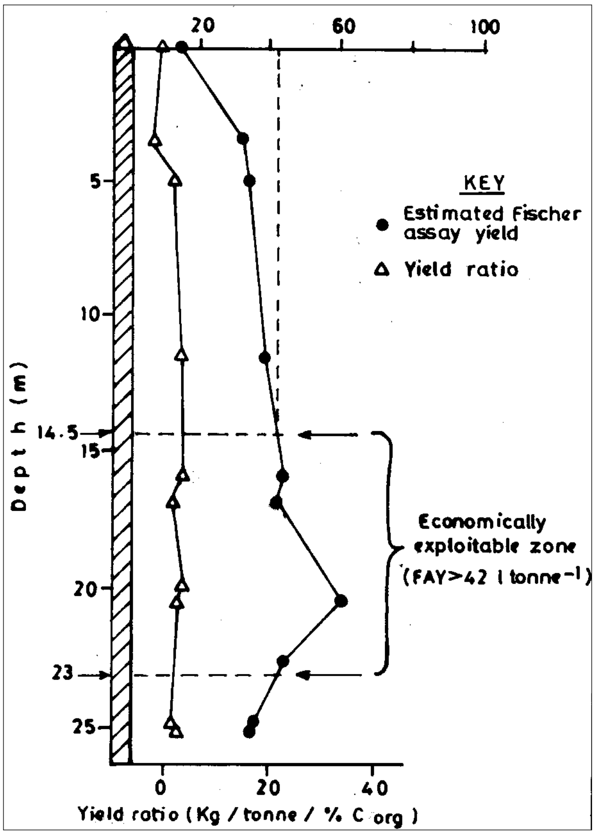

Fig. 4. Fischer assay yield estimate (after: *Ekweozor and Unomah*, 1990)

The average pyrolysis temperature of 500 °C is required to win oil from an oil shale. The energy to be provided for heating to that temperature is approximately 250 calories per gram of rock, and the calorific value of kerogen is 10,000 calories per gram [6]. Oil shales typically contain 5 to 20 wt.% organic carbon and yield about 10 to 30 gallons of oil per tonne, or 50 liters per tonne of rock [9]. Below the threshold of 2.5 wt.% organic carbon value, the rock cannot be a source of energy, and a lower limit of 5 wt.% organic carbon is frequently used. This corresponds approximately to an oil yield of 25 liters per tonne of rock [6].

The criteria used to determine the oil shale reserve are: minimum thickness, mean density and minimum oil content. The minimum thickness was determined from the core depth, while the minimum oil content was derived from the lowest TOC value. The average density was determined by fluid displacement using 11.0-g samples in a 100-ml measuring cylinder and

15.0-g samples in 500-ml measuring cylinder. Reserve is estimated using the equation

$$R_e = \text{Area} \times \text{Thickness} \times \text{Density}$$

where R_e is the reserve estimate (Appendix II).

Geochemical analysis involves the measurements of TOC, Rock-Eval pyrolysis and Atomic Absorption Spectrophotometry (AAS) using the procedure described in [10, 11]. This procedure is used to define the nature of kerogen, the degree of its maturation, hydrocarbon recovery potential, and whether any hydrocarbons remain or have migrated from oil shale.

Results and Discussion

Lithotypes

Oil shale beds in the upper Cenomanian to lower Turonian Eze-Aku Formation outcrop along a belt extending from Lokpanta to the Onoli-Awgu area in the western limb and the Uturu to Acha area in the eastern limb of Abakaliki anticlinorium, southeastern Nigeria (see Figs 1 and 2). The regional structure is an anticlinorium dipping northeast or southwest (NE-SW) at an average of 27º. The oil shale core is about 25 m thick at Lokpanta, 35 m at Onoli-Awgu and 40 m at Acha area (see Fig. 2).

Field examination of various lithotypes shows that Abakaliki shale is a light brown to dark grey massive shale. Eze-Aku shale is dark-grey to black, calcareous, platy and thinly laminated shale with *Inoceramus* impressions between the laminae. The shale alternates with marl units to form cyclothems. Oil smell and concentric nodules with pyritic nuclei are associated features of the oil shale interbeds [12]. Awgu shale is dark-grey, well bedded with limestone. The oil shale cores could be described as petroliferous with strong petroleum odor noticeable when samples are broken on bedding planes.

Discrimination of oil shale from other shales (Abakaliki and Awgu shales) based on color is not possible as the shales are generally black, dark-grey or dark-brown and highly laminated. However, such features as *Inoceramus* moulds, oil smell, concentric nodules with pyritic nuclei and cyclic or rhythmic occurrence of shale and marl beds characterize the oil shale strata [12].

The bedding of oil shale is highly significant because it shows lamination couplets, each consisting of a light grey marl layer of about 10 m on average and a dark to black shale layer of about 5-m thickness. The variation of average thicknesses of the shale/marl sequences in the three boreholes studied at Lokpanta (CH-1), Onoli-Awgu (CH-3) and Acha (CH-2) is 3/8 (0.38), 3.6/2.8 (1.29) and 10/7.5 (1.33) m, respectively (see Fig. 2). The difference in the thickness of the shale and marl layers was due to variable input to the basin with Lokpanta core having the highest marl content followed by Onoli-Awgu and Acha cores [10]. In fact, restriction of shale/marl sequence to the tip of Abakaliki anticlinorium could be a result of cyclic variation of water depth with time.

Calorific Value and Reserve Estimation

T_{max} values from Rock-Eval analyses of the samples from three boreholes in the study area range between 435 and 444 °C (Table 1) indicating that oil shale is marginally mature for petroleum generation. Low hydrogen index (HI), which is between 223 and 407 mg HC/gTOC, as well as the oxygen index (OI), which is between 15 to 176 mg CO_2/gTOC, indicate that the kerogen is of Types II/III (Fig. 5).

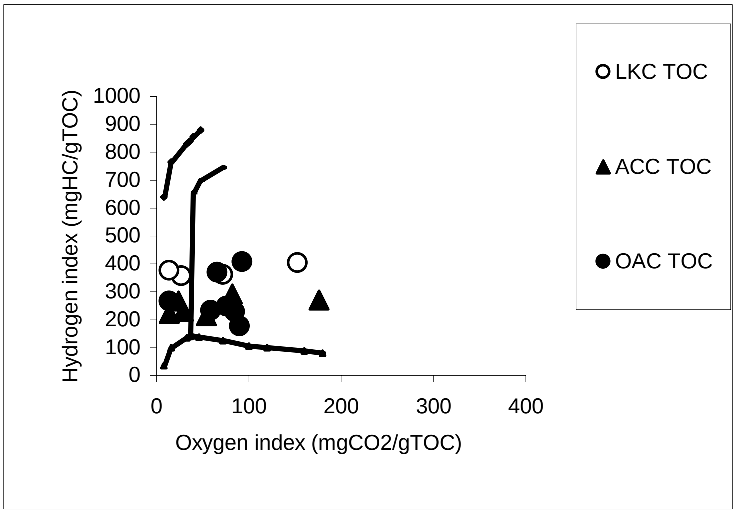

Fig. 5. Quantity and characterization of organic matter from outcrop and core samples in HI-OI diagrams. Shape of signs is proportional to TOC values in different boreholes

The hydrocarbon yield obtained at oil shale pyrolysis is between 6.31 and 25.31 kg/tonne. The TOC and FAY results used by Ekweozor and Unomah [1] were employed in estimating the oil yield and calorific value of oil shale (Table 1 and Fig. 4).

The TOC values for oil shale are between 1.8 and 6.04 wt. % (Table 1). These values are restricted to the tip of the Abakaliki Anticlinorium (B1 and B2 in Fig. 3). Since 1 g of kerogen has a calorific value of 10,000 calories, 4.2 wt.% (average value) of kerogen will give 420 calories/gram oil shale. However, the total area of the exploitable zones that is characterized by shale alternating with marl (B1 and B2 in Fig. 4) has been calculated to be 72.7 km^2 (Appendix I). Since the exploitable areas contain 5.76×10^{12} kg or 5.76×10^{15} g oil shale, the total excess energy expressed in calories for the area considered is $420 \times 5.76 \times 10^{15}$ or 2.42×10^{18} calories.

Table 1. **Rock-Eval Pyrolysis Data of Core Samples**

Sample No.	Depth, m	Age	TOC, wt%	T_{max}, °C	HI, mg HC/gTOC	OI, mg CO_2/gTOC	S_1, mg HC/g rock	S_2, mg HC/g rock	S_3, mg CO_2/g rock	S_2/S_3	$S_1 + S_2$	Production index k^{-1}	S_1/TOC, mg HC/gTOC
LKC-1	3.8	Turonian	4.4	435	361	72	0.65	16.07	3.2	5.02	16.72	0.04	0.15
LKC-2	9.4	Turonian	4.8	435	404	154	4.16	19.37	7.39	2.62	23.53	0.18	0.87
LKC-3	16.6	Turonian	2.2	436	357	27	2.13	7.86	9.41	0.83	9.99	0.21	0.97
LKC-4	25.5	Cenomanian	4.3	438	376	15	3.37	16.31	9.32	1.75	19.68	0.17	0.78
ACC-1	5.0	Turonian	2.7	443	214	55	0.58	5.73	1.47	3.89	6.31	0.09	0.22
ACC-2	12.0	Turonian	3.2	444	271	176	1.61	8.57	5.59	1.53	10.18	0.16	0.51
ACC-3	14.1	Turonian	1.8	441	223	15	1.05	4.03	3.88	1.03	5.08	0.21	0.58
ACC-4	22.5	Cenomanian	5.1	443	230	29	2.08	11.64	6.56	1.77	13.72	0.15	0.41
ACC-5	25.6	Cenomanian	4.3	443	293	58	2.13	12.57	6.79	1.85	14.70	0.14	0.51
ACC-6	36.7	Cenomanian	4.6	444	267	24	1.46	12.24	5.68	2.15	13.70	0.11	0.32
OAC-1	7.1	Turonian	5.4	440	248	76	0.87	13.51	4.17	3.23	14.38	0.06	0.16
OAC-2	11.3	Turonian	4.1	441	177	90	0.71	7.28	3.71	1.96	7.99	0.09	0.17
OAC-3	13.2	Turonian	5.8	436	407	93	1.56	23.75	5.43	4.37	25.31	0.06	0.27
OAC-4	15.1	Turonian	2.9	439	228	85	0.37	6.43	2.42	2.65	6.80	0.05	0.13
OAC-5	20.4	Cenomanian	3.6	438	266	15	0.99	9.55	4.12	2.31	10.54	0.09	0.23
OAC-6	24.5	Cenomanian	3.3	439	233	59	1.21	7.67	5.25	1.46	8.88	0.14	0.37
OAC-7	35.8	Cenomanian	3.6	438	369	72	1.85	13.29	6.22	2.13	15.14	0.12	0.51

Table 2. **Major and Trace Elements Results of the Ndeaboh-Lokpanta Traverse (NLT) and Core Samples**

	Sample number										
	NLT-39	NLT-51	NLT-63	NLT-72	NLT-204	LLT-21	NNT-212	ACC-1	ACC-4	OAC-2	LKC-2
	Age										
	Albian	Cenomanian	Turonian		Coniacian	Turonian			Cenomanian	Turonian	
	Formation										
	Abakaliki shale	Eze-Aku Shale			Awgu shale	Eze-Aku shale					
Oxides, wt%											
SiO_2	65.80	42.90	56.20	48.52	67.38	46.85	58.54	49.52	57.31	49.32	49.42
Al_2O_3	12.64	8.77	13.76	9.54	7.93	9.69	5.67	11.83	7.54	15.76	5.78
CaO	4.82	30.43	14.90	22.24	4.90	20.30	14.44	12.62	18.38	18.89	32.24
Fe_2O_3	6.61	7.99	8.60	8.90	3.35	10.22	5.29	12.78	6.15	7.99	5.19
MgO	2.40	1.54	1.62	1.21	1.42	2.71	1.85	4.25	2.32	1.02	1.90
MnO	2.75	0.22	0.75	1.26	3.20	4.21	2.68	1.54	1.25	0.98	0.71
K_2O	2.96	3.84	1.45	2.21	4.85	1.18	2.92	2.05	1.01	1.04	1.88
Na_2O	0.54	0.73	0.95	0.85	2.10	0.57	2.23	1.25	0.45	0.72	0.53
NO_2	0.27	0.19	0.59	0.43	0.13	0.06	0.15	0.25	0.31	0.63	0.25
SO_2	0.56	0.68	0.72	0.49	0.74	0.59	0.66	0.33	0.41	0.74	0.74
LOI*	4.71	2.71	0.49	4.36	4.00	3.54	5.57	3.58	4.87	2.91	1.09
Total	100.00	100.00	100.03	100.01	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Trace elements, ppm											
Ba	180	219	46	150	246	86	319	246	320	33	125
Cd	3.2	11	12	13	18	ND*	23	12	3	3	10
Pb	140	70	110	130	40	90	100	120	130	100	100
Cr	23	35	ND	37	40	40	140	ND	20	ND	40
Cu	32	64	10	70	20	20	90	10	60	30	50
Ni	95	98	110	120	210	100	180	130	200	110	100
Zn	930	715	220	210	100	180	1040	130	500	910	400

LOI = loss on ignition; ND = not detectable.

At estimating the oil shale reserve, minimum thickness, mean density and minimum oil content were determined (Appendix II). The minimum thickness of 33.8 m (average depth of the three boreholes in Fig. 2) was used while the average density is 2,342 kg/m^3. The volume of oil shale is calculated to be 2.46 km^3 or 2.46×10^9 m^3. However, the reserve is defined as the product of volume and density [10], the exploitable oil shale reserve is 5.76×10^{12} kg or 5.76×10^9 tonnes.

On the other hand, the hydrocarbon reserve is estimated FAY of 56.35 liter/tonne [10]. The hydrocarbon reserve estimation of the exploitable areas is 3.25×10^{14} liters or 7.1×10^{13} gallons or 1.7×10^{12} barrels (Appendix II).

Possible Recovery Techniques

The oil shale deposit in the Abakaliki Fold Belt of Nigeria may be extracted only by surface mining methods as the ratio of overburden to oil shale is very low (the average striping ratio is 2.5:1). This is one of the prominent economic conditions considered for profitable exploitation [2, 6].

The thickness of the overburden is maximum in Acha core (CH-2) section (3.5 m) and minimum in Lokpanta core (CH-1) section (1.7 m). The overburden is a soil composed of laterites and residuals, which are probably weathered products of Awgu shale and Owelli sandstones. The possible recovery techniques that could be employed include retorting and direct combustion (and, in special cases, gasification) based on commercial utilization or on economic basis. Retorting is suggested for oil shale recovery because of shallow upper soil and relatively cheap cost of establishments.

Environmental Implications

Exploitation of oil shale has a number of environmental impacts, some of which are similar to those of tar sand and coal. Since the deposit occurs near the surface, strip mining or open-cast mining would be the appropriate recovery technique. This technique uses large quantities of water, and there is a potential for noise, thermal and water pollution.

The surface mining techniques may contribute to the removal of the top fertile soil for farming and thereby results in the decrease of agricultural output. Since subsoil is of low quality to agriculture, an alternative place is needed to practice agriculture. The topsoil of the Abakaliki and its environs supports the growth of crops such as yams, rice, beans, cassava, maize, palm oil and oil seed (which is locally called 'ulie'). The people who live in the area derive their staple food from these crops and perhaps earn their income, too, from selling the farm products. Direct combustion could be the ideal method for oil shale exploitation if the land disruption would be minimized, and hence, the environment preserved for agriculture. Nevertheless, this method presents its own problems such as groundwater pollution and disturbance of ground water balance due to explosive needed to guarantee high permeability for movement of fluids. Spent oil shale and oil shale ash are difficult to wet, they may be saline, suffer from ion imbalance and have low fertility [13].

Gases like NO_2, CO_2 and SO_2 are poisonous and are ejected to the atmosphere during the retorting or heating of oil shale to recover oil [7]. The content of NO_2 and SO_2 in the samples analyzed ranged from 0.06 to 0.63% and 0.33 to 0.74%, respectively (see Table 2). These values are relatively low and may not have any serious effect on human health during extraction, storage and transportation [14]. The concentrations of some trace elements such as Ba, Cd, Cu, Cr, Ni, Pb and Zn are below the values recommended by the World Health Organizations [14, 15].

The comparison made between maximum concentrations measured in extractions of the Lower Toarcian oil shale from South Germany and those of the Abakaliki anticlinorium shows that the latters have the values indicating permissible level for extraction (Table 3). These concentrations cannot cause health problems such as catalytic poisoning during oil shale retorting. The high relative abundance of some of trace elements such as Pb (>100 ppm), Zn (500 ppm) and Cu (40 ppm) may have resulted from the Pb and Zn mineralization found within the Abakaliki anticlinorium [11].

Table 3. **WHO (1984) Recommendations, Maximum Concentrations Found in Extractions of the Lower Toarcian Oil Shale form S. Germany and Average Concentrations Found in the Whole Rock Samples from the Oil Shale Deposit from the Abakaliki Fold Belt, SE. Nigeria**

Elements	WHO (1984) Recommendations, mg/L	Highest concentration in extraction of Toarcian oil shale, Germany, mg/L	Average concentration (ppm) of the whole rock samples (calculated from Table 2)
Ba	NS*	0.904	0.35
Cd	0.005	0.002	0.001
Cu	1.00	0.015	0.014
Cr	0.05	1.06	0.001
Ni	NS	0.14	0.12
Pd	0.05	–	0.05
Zn	5.00	0.025	0.05

* NS = no value set.

Another main problem concerning the utilization of the oil shale deposit in the study area is, however, the supply of water needed for retorting as most of the streams dry up in the dry season. In Jordan, the need of water estimated for extraction of the El Lajjun oil shale deposit ranges from 14 to 22 million m^3 per year [2]. The scarcity of water in the study area may contribute a useful factor to be considered in technical planning of the retorting method of recovery.

Disposal of the waste generated by surface mining is always tedious because the waste products after the oil has been extracted are usually greater in volume than the original rock and thereby require a large area for waste dumping. For instance, in Jordan, where oil shale is currently being extracted 74,000 tonnes of shale, which has to be crushed to a particle size of less than 8 mm, the same amount of waste is produced every day [2]. This indicates that enormous volumes have to be moved in order to provide supplies to and to remove the waste from a retorting plant.

A lot of heat would be generated during extraction of oil from oil shale, which is disposed off by cooling with water. For example, 51,200 tonnes of the hot, fully retorted residues have to be handled during extraction of oil from Jordanian oil shale [2]. The release of treated water gives rise to thermal pollution that has serious effect on aquatic life. For instance, heat accelerates biological and chemical reactions and aggravates the diminution of dissolved oxygen [13].

Conclusion

In this research, an extensive geological mapping and geochemical studies of the oil shale deposit in the Abakaliki Anticlinorium, southeastern Nigeria were carried out to determine its areal extent, reserve estimate, recovery techniques and possible environmental impacts. An areal extent of 72.7 km^2, reserve estimate of 5.76×10^9 tonnes and recoverable hydrocarbon reserve estimate of 1.7×10^9 barrels have been calculated for oil shale. Retorting recovery method is suggested for oil shale, because of shallow upper soil and relatively cheap cost of establishments.

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APPENDIX I

Calculation of Oil Shale Areal Extent with Shale/Marl Sequence (TOC > 3 wt.%)

The area (A) is calculated based on the areas of full squares (S), triangles (T) and trapezium (Z), and the difference in the combination of the first two (C) (see Fig. 3). In this calculation, 25 small squares represent a full square (a cube), 3 trapeziums represent a square and 2 triangles represent a square.

- At the western limb (Anambra basin – B_1 of Fig. 3), the total exposed area of shale/marl (TOC > 3 wt.%) sequence is given by $A_1 = \Sigma B_1$

$$A_1 = \Sigma B_1 = \Sigma(a_1 + a_2 + a_3 + \ldots + a_n)$$

where n is the total number (n = 15) of square grids in the shale/marl sequence of B_1.

$A_1 = 4 + 12.5 + 4 + 4.5 + 23 + 15.5 + 0.5 + 4 + 23 + 19 + 1 + 17.5 + 15 + 0.5 + 6.5$

ΣB_1 is equal to 150.5 small squares and, consequently, to 6.02 full squares since 25 small squares make one full square.

Hence, the area of $B_1 = (6.02\text{ km})^2 = 36.24\text{ km}^2$.

- At the eastern limb (Afikpo syncline – B_2), the total exposed area of shale/marl sequence is denoted by: $A_2 = \Sigma B_2$
- $A_2 = \Sigma B_2 = \Sigma(a_1 + a_2 + a_3 + \ldots + a_n)$ where n is equal to 16
- $A_2 = \Sigma B_2 = 1.5 + 4 + 6.5 + 12.5 + 15 + 25 + 5 + 6.25 + 5.5 + 23 + 16.75 + 10.5 + + 2.5 + 3.25 + 13 + 0.75$

$A_2 = \Sigma B_2$ is equal to 151 small squares and, consequently, to 6.04 full squares since 25 small squares make one full square.

Therefore, the total area of $B_2 = (6.04\text{ km})^2 = 36.48\text{ km}^2$.

- For the B_1 and B_2, the total area is given as $A = A_1 + A_2 = (36.24 + 36.48)\text{ km}^2 = = 72.72\text{ km}^2$

Areal Extent = 72,720,000 m^2

Calculation of Oil Shale Volume with Shale/Marl Sequence (TOC > 3 wt.%)

The average thickness from the three bore holes is:

Average Thickness = (25.5 + 36 + 40)/3 =
= 101.5/3 = 33.83 m.

Oil Shale Volume = Area × Average Thickness =
= 72,720,000 m^2 × 33.83 m =
= 2,460,117,600 m^3

The average density of oil shale using fluid displacement = 2,342 kg/m^3

APPENDIX II

- **Reserve Estimation R_e**

$\boldsymbol{R_e}$ = Area × Thickness × Density =
= Volume × Density =
= 2,460,117,600 m^3 × 2,342 kg/m^3 =
= 5.762 × 10^{12} kg =
= 5.76 × 10^9 tonne

- **Hydrocarbon Reserve Estimation HR_e**

Since Fisher Assay yield (FAY) = 56.35 liter/tonne (after Unomah and Ekweozor, 1990) and oil shale reserve (R_e) = 5.76 × 10^9 tonne:

$\boldsymbol{HR_e} = R_e$ × FAY =
= 5.76 × 10^9 × 56.35 liter =
= 3.24 × 10^{11} liter =
= 1.7 × 10^9 barrel

- **Excess Heat Energy (Calorific Value) Estimation**

The total reserve estimate considered is 5.76 × 10^{15} g.

If 1 g of kerogen has calorific value of 10,000 cal, then 3 wt.% of kerogen per gram will have a calorific value of $3 \times 10{,}000/100 = 300$ calories per gram.

Therefore, the total excess energy in form of calories for the study area is:

$$\textbf{Calorific Value} = \\ = 300 \times 5.76 \times 10^{15} = \\ = 1728 \times 10^{15} \text{ calories}$$

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