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Kazalo

Historical Review

More than 90 years have passed since the University Ljubljana in Slovenia was founded in 1919. Technical fields were united in the School of Engineering that included the Geologic and Mining Division, while the Metallurgy Division was established only in 1939. Today, the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy are all part of the Faculty of Natural Sciences and Engineering, University of Ljubljana.

Before World War II, the members of the Mining Section together with the Association of Yugoslav Mining and Metallurgy Engineers began to publish the summaries of their research and studies in their technical periodical Rudarski zbornik (Mining Proceedings). Three volumes of Rudarski zbornik (1937, 1938 and 1939) were published. The War interrupted the publication and it was not until 1952 that the first issue of the new journal Rudarsko-metalurški zbornik – RMZ (Mining and Metallurgy Quarterly) was published by the Division of Mining and Metallurgy, University of Ljubljana. Today, the journal is regularly published quarterly. RMZ – M&G is co-issued and co-financed by the Faculty of Natural Sciences and Engineering Ljubljana, the Institute for Mining, Geotechnology and Environment Ljubljana, and the Velenje Coal Mine. In addition, it is partly funded by the Ministry of Education, Science and Sport of Slovenia.

During the meeting of the Advisory and the Editorial Board on May 22, 1998, Rudarsko-metalurški zbornik was renamed into "RMZ – Materials and Geoenvironment (RMZ – Materiali in Geookolje)" or shortly RMZ – M&G. RMZ – M&G is managed by an advisory and international editorial board and is exchanged with other world-known periodicals. All the papers submitted to the RMZ – M&G undergoes the course of the peer-review process.

RMZ – M&G is the only scientific and professional periodical in Slovenia which has been published in the same form for 60 years. It incorporates the scientific and professional topics on geology, mining, geotechnology, materials and metallurgy. In the year 2013, the Editorial Board decided to modernize the journal's format.

A wide range of topics on geosciences are welcome to be published in the RMZ – Materials and Geoenvironment. Research results in geology, hydrogeology, mining, geotechnology, materials, metallurgy, natural and anthropogenic pollution of environment, biogeochemistry are the proposed fields of work which the journal will handle.

Editor-in-Chief

Zgodovinski pregled

Že več kot 90 let je minilo od ustanovitve Univerze v Ljubljani leta 1919. Tehnične stroke so se združile v Tehniški visoki šoli, ki sta jo sestavljala oddelka za geologijo in rudarstvo, medtem ko je bil oddelek za metalurgijo ustanovljen leta 1939. Danes oddelki za geologijo, rudarstvo in geotehnologijo ter materiale in metalurgijo delujejo v sklopu Naravoslovnotehniške fakultete Univerze v Ljubljani.

Pred 2. svetovno vojno so člani rudarske sekcije skupaj z Združenjem jugoslovanskih inženirjev rudarstva in metalurgije začeli izdajanje povzetkov njihovega raziskovalnega dela v Rudarskem zborniku. Izšli so trije letniki zbornika (1937, 1938 in 1939). Vojna je prekinila izdajanje zbornika vse do leta 1952, ko je izšel prvi letnik nove revije Rudarsko-metalurški zbornik – RMZ v izdaji odsekov za rudarstvo in metalurgijo Univerze v Ljubljani. Danes revija izhaja štirikrat letno. RMZ – M&G izdajajo in financirajo Naravoslovnotehniška fakulteta v Ljubljani, Inštitut za rudarstvo, geotehnologijo in okolje ter Premogovnik Velenje. Prav tako izdajo revije financira Ministrstvo za izobraževanje, znanost in šport.

Na seji izdajateljskega sveta in uredniškega odbora je bilo 22. maja 1998 sklenjeno, da se Rudarsko-metalurški zbornik preimenuje v RMZ – Materiali in geookolje (RMZ – Materials and Geoenvironment) ali skrajšano RMZ – M&G. Revijo RMZ – M&G upravljata izdajateljski svet in mednarodni uredniški odbor. Revija je vključena v mednarodno izmenjavo svetovno znanih publikacij. Vsi članki so podvrženi recenzijskemu postopku.

RMZ – M&G je edina strokovno-znanstvena revija v Sloveniji, ki izhaja v nespremenjeni obliki že 60 let. Združuje področja geologije, rudarstva, geotehnologije, materialov in metalurgije. Uredniški odbor je leta 2013 sklenil, da posodobi obliko revije.

Za objavo v reviji RMZ – Materiali in geookolje so dobrodošli tudi prispevki s širokega področja geoznanosti, kot so: geologija, hidrologija, rudarstvo, geotehnologija, materiali, metalurgija, onesnaževanje okolja in biokemija.

Glavni urednik

Review paper

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Študij rudarstva in geotehnologije na Univerzi v Ljubljani od leta 1919 do danes

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Zgodovinski podatki o razvoju slovenske univerze prikazujejo veliko željo za ustanovitev visoke šole na slovenskih tleh. Iz podatkov je razvidno, da so že davno premišljevali o uvedbi študija tehničnih predmetov, kot sta mehanika in jamomerstvo. Ta zahteva se pojavi s strani Kranjskih deželnih stanov v letih 1786–1787, ki so se sklicevali na rudnike živega srebra v Idriji, rudnike železove rude in na tovarne v Sloveniji, da bi tehnično osebje v rudnikih in tovarnah opravljalo svoje delo zadovoljivo. Zahtevo so podprli z ustanovitvijo prve rudarske akademije na svetu leta 1765 v Freibergu na Saškem.

S prihodom Francozov v Ljubljano, ki so na tleh province Ilirije leta 1810 ustanovili Centralno šolo, je bilo omogočeno študirati inženirsko stroko. Študij naj bi trajal 4 leta, vendar ni nihče študija dokončal, ker je nova uredba ukinila študij za inženirje. Kljub večkratnim ponovnim poskusom, da bi Slovenija dobila univerzo, so se Slovencem te želje izpolnile šele po prvi svetovni vojni z razpadom Avstro-Ogrske monarhije.

V 19. stoletju je bilo rudarstvo v Sloveniji že precej razvito. Ob kovinskih rudnikih (Idrija, Mežica in drugi manjši), je imela Slovenija že pomembne premogovnike Senovo, Zagorje, Trbovlje, Hrastnik in Laško. Konec 19. stoletja pa se je pričela tudi proizvodnja lignita v Velenju. Strokovno osebje za te rudnike se je šolalo predvsem na avstrijski rudarski akademiji v Leobnu, vendar je bilo na domačih tleh slovenskih inženirjev sorazmerno malo.

Z ustanovitvijo Univerze v Ljubljani leta 1919, je zaživela tudi Tehniška fakulteta, ki je imela 5 oddelkov. Eden od teh je bil Rudarski oddelek. Slovenske narodnosti je bil samo en profesor in sicer dr. Karel Hinterlechner, ki je bil hkrati eden od ustanoviteljev ljubljanske univerze in prvi dekan Tehniške fakultete. Ostali učitelji so bili pretežno profesorji ruske narodnosti, ki so emigrirali iz Sovjetske zveze in so pred tem poučevali na rudarskih visokih šolah v Rusiji. Za ustanovitev Rudarskega oddelka v Ljubljani ima pomembne zasluge rudarski glavar Vinko Strgar. Na Tehniško fakulteto se je vpisalo 50 slušateljev, od tega 6 slušateljev za študij rudarstva. Vse do leta 1939 je bil Rudarski oddelek edini v tedanji Jugoslaviji in tudi na Balkanu. Leta 1939 so ustanovili Rudarski oddelek v Zagrebu, po drugi svetovni vojni pa še rudarske oddelke oziroma fakultete v Beogradu, Tuzli in Boru.

Tik pred drugo svetovno vojno je pričel Rudarski oddelek zidati stavbo. Uspeli so dokončati železobetonsko skeletno konstrukcijo do strehe. Gradnja je bila med vojno prekinjena. Stavba v kateri danes domuje Oddelek za geotehnologijo, rudarstvo in okolje na Aškerčevi 12 v Ljubljani je bila dokončana leta 1950.

Znano je, da je bil študij rudarstva od nekdaj heterogen. Razen povsem rudarskih predmetov kot so bili: tehnično rudarstvo, bogatenje mineralnih surovin, globinsko vrtanje, rudarsko merjenje in geofizika, transport in izvažanje v rudnikih, je zajemal študij še geološke predmete, naravoslovne predmete in predmete s področja strojništva in elektrotehnike. Spričo take pestrosti študijske snovi, marsikateri slušatelj ni uspel končati študija prej kot v pe-

tih letih, za večino pa je veljalo, da so porabili več časa.
Do leta 1931 je imel tedanji Rudarski oddelek dve rudarski organizacijski enoti – inštituta:
— Inštitut za rudarstvo,
— Inštitut za rudarska merjenje in geofizikalna raziskovanja.

V naslednjih letih se je Inštitut za rudarstvo reorganiziral v tri enote in tako so nastali štirje inštituti znotraj oddelka za rudarstvo in sicer:
— Inštitut za tehnično rudarstvo,
— Inštitut za separiranje in briketiranje rud in premoga ter za rudarsko gospodarstvo,
— Inštitut za rudarsko strojništvo,
— Inštitut za rudarska merjenje in geofizikalna raziskovanja.

Imena in naslovi teh enot so se večkrat menjavali in tako zasledimo tudi naslove: stolica, zavod in katedra. Po drugi svetovni vojni so zavodi dobili ime katedra, ki se je ohranilo do danes. Vse do šolskega leta 1949/50 je bil Rudarski oddelek v sestavu Tehniške fakultete Univerze v Ljubljani. Ko je bila leta 1950 ustanovljena Tehniška visoka šola, je Rudarski oddelek postal oddelek na Fakulteti za rudarstvo in metalurgijo. Tehniška visoka šola je združevala 6 fakultet. V tem obdobju se je prešlo na 10 semestrski študij. Sledilo je kar nekaj reorganizacij visokošolskega študija. V šolskem letu 1957/58 je Oddelek za rudarstvo prešel v sestavo Fakultete za rudarstvo, metalurgijo in kemijsko tehnologijo (FRMKT), s šolskim letom 1959/60 pa je oddelek prevzel ime Oddelka za montanistiko. Šolsko leto 1960/61 je prineslo bistvene novosti v študij rudarske stroke. Predvidene so bile tri stopnje študija, katerih vsaka posebej je trajala 4 semestre. Študenti prve stopnje so dobili naziv inženir rudarstva, druge stopnje diplomirani inženir rudarstva in tretje stopnje magister rudarske stroke. Obenem je prišlo do reorganizacije fakultete in nastala je Fakulteta za naravoslovje in tehnologijo (FNT). Vse do šolskega leta 1965/66 se študijski program ni spreminjal. S tem letom se je znova prešlo na štiri semestrski študij I. in II. stopnje in na tri usmeritve v II. stopnji: eksploatacija, bogatenje in merstvo z geofiziko. Z letom 1968/69 je bila prva stopnja študija ukinjena in prešlo se je na osem semestrski študij z navedenimi tremi osnovnimi usmeritvami. Zanimivo je, da je Oddelek za rudarstvo deloval znotraj Fakultete za naravoslovje in tehnologijo (FNT) vse do leta 1995, ko je bila ustanovljena Naravoslovnotehniška fakulteta (NTF), ki je združevala:
— Oddelek za geotehnologijo in rudarstvo,
— Oddelek za geologijo,
— Oddelek za materiale in metalurgijo,
— Oddelek za tekstilstvo,
— Oddelek za kemijsko izobraževanje in informatiko.

V obdobju med leti 1966 in 1995 ni prišlo do bistvenih sprememb v študijskem programu. Oddelek je imel v sestavi 4 katedre in sicer:
— Katedra za tehnično rudarstvo,
— Katedra za bogatenje mineralnih surovin,
— Katedra za rudarsko strojništvo, transport in elektrotehniko,
— Katedra za rudarsko merjenje in geofizikalno raziskovanje.

Študenti višjih letnikov so imeli možnost izbrati tri že omenjene osnovne usmeritve: eksploatacijo, bogatenje in merstvo z geofiziko. Zaradi vse večjega zanimanja stroke in gospodarstva na področjih podzemnih gradenj, ravnanjem z industrijskimi in komunalnimi odpadki, recikliranjem in izrabo alternativnih virov energije so na Oddelku za rudarstvo pričeli izvajati nov študijski program GEOTEHNOLOGIJA v šolskem letu 1993/94. Oddelek se je preimenoval v Oddelek za geotehnologijo in rudarstvo ter smiselno in vsebinsko preoblikoval štiri katedre:
— Katedra za tehnično rudarstvo in geotehniko,
— Katedra za mehansko procesno tehniko in bogatenje mineralnih in sekundarnih surovin,
— Katedra za rudarsko strojništvo, transport, elektrotehniko in računalništvo,
— Katedra za rudarsko merjenje in geofizikalno raziskovanje.

Univerzitetni študij geotehnologije in rudarstva je trajal 8. semestrov in se zaključi z izdelavo diplomske naloge v 9. semestru. Diplomanti so po uspešno končanem študijo pridobili naziv univerzitetni diplomirani inženir geotehnologije in rudarstva. V šolskem letu 1997/98 se je pričel izvajati Visokošolski strokovni program geotehnologije in rudarstva, ki je bistveno bolj usmerjen v pridobivanje aplikativnih znanj s področja stroke. Diplomanti po uspešno končanem študijo pridobijo naziv diplomirani inženir geotehnologije in rudarstva.

Z vstopom Slovenije v Evropsko skupnost, je Slovenija morala izvesti reforme na področju visokega šolstva. Univerza v Ljubljani je pričela reformo visokega šolstva na podlagi Bolonjske deklaracije iz septembra 2003. Na Oddelku za geotehnologijo in rudarstvo je bil v letu 2005 prenovljen študijski program v skladu z bolonjskimi smernicami in Merili za akreditacijo študijskih programov. Program je pripravljen po sistemu 3+2+3:

l stopnja (univerzitetni dodiplomski študij)	trajanje: 3 leta
2 stopnja (univerzitetni podiplomski študij, magisterij)	trajanje: 2 leti
3 stopnja (doktorski študij)	trajanje: 4 leta

Program smo pripravili po Merilih za akreditacijo visokošolskih zavodov in študijskih programov, ki jih je sprejel Svet za visoko šolstvo Republike Slovenije (Uradni list RS, št. 63/04, 10.09.2004). Študijski program Geotehnologija in rudarstvo daje naravoslovno in tehniško izobrazbo, ki sledi razvoju v okviru strok geoznanosti. Vedno bolj pa se v tem okviru izkazuje potreba tudi po drugih znanjih, na primer iz ekonomike in informacijsko komunikacijske tehnologije (IKT).

Program daje študentom potrebna teoretična in praktična znanja za reševanje konkretnih strokovnih problemov v praksi, hkrati pa jih uvaja tudi v osnove raziskovanja, ki so potrebne za nadaljevanje študija na naslednjih stopnjah.

S programom študenti pridobijo kompetence za neposredno zaposlitev na najširšem področju pridobivanja mineralnih surovin, primarne predelave, podzemnih gradenj, vrtalne tehnike, dela za izvajanje merjenj in sledenj v naravi, dela za vrednotenje in izvajanje posegov v naravi, sanacije degradiranih površin, ravnanje z okoljem, trdnimi odpadnimi snovmi, itn.

Pridobljena znanja in sposobnosti omogočajo uspešno delo na zahtevnejših strokovnih in tudi vodstvenih delovnih mestih tako v javnih kot tudi v zasebnih podjetjih.

Vsebina programa je prilagojena vsebinsko primerljivim študijskim programom s področja geotehnologije, geotehnike in rudarstva. Podobne študijske programe izvajajo na Montanistični univerzi v Leobnu – Avstrija, na Politehniki v Torinu – Italija, na Rudarski akademiji v Freibergu in Tehniški visoki šoli v Clausthalu – Nemčija. Poudarek je na študiju raznovrstnih aktivnosti, ki se odvijajo v zemeljski skorji z vključevanjem tehničnih in naravoslovnih znanstvenih polj. Težišča študijskega programa omogočajo mednarodno sodelovanje na interdisciplinarnih področjih, ki pokrivajo tehnično obravnavo gradnje podzemnih objektov, geotehnične gradnje, gospodarjenje z odpadki z vsemi pripadajočimi sklopi s področja okoljevarstvenega inženirstva, upravljanja podjetij in gospodarskih družb v zaokroženi celoti.

Leta 2015 se je oddelek zaradi vsebin poučevanja preimenoval v Oddelek za geotehnologijo, rudarstvo in okolje.

Danes je Oddelek za geotehnologijo, rudarstvo in okolje organiziran znotraj dveh kateder:

— Katedra za tehnično rudarstvo, geotehniko, geotermijo in urbano rudarjenje,
— Katedra za rudarsko merjenje in geofizikalno raziskovanje.

Do 31. decembra 2018 je na Oddelku za geotehnologijo, rudarstvo in okolje uspešno zaključilo študij naslednje število diplomantov:

STOPNJA ŠTUDIJA	ŠTEVILO DIPLOMANTOV
Univerzitetni študij	785
Študij I. stopnje	31
Visokošolski strokovni študij	77
Podiplomski študij, magisterij	62
Geotehnologija in rudarstvo VS - 1. stopnja	17
Geotehnologija in okolje UN - 1. stopnja	40
Geotehnologija – 2. stopnja	25
Doktorski študij	29

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Removal of Na_2SO_4 from a Filter Ash

Odstranjevanje Na_2SO_4 iz filtrskega prahu

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Abstract

In this paper, research on the possibilities of sodium sulphate (Na_2SO_4) separation from other substances in the filter ash sample is presented. The research material contains six components that differ in chemical composition and density. The possibilities of Na_2SO_4 separation using dry and wet methods were studied. The dry method was based on separation with a centrifugal air classifier at four cut size limits. The wet method was based on the dissolution of water-soluble components, filtration of insoluble components, and drying the products. The sulphur content of the individual products was determined using both methods. The aim of the research was to determine which method is more suitable for separation of the material in a way that most of the material would contain as little sulphur as possible and the rest of the material would contain concentrated sulphur. The wet method proved to be more successful. The product with mass fraction 33.1% of the total mass, obtained from the aqueous solution, contained 8.39% sulphur after filtration and drying. The water-insoluble component, with mass fraction 66.9% of the total mass, contained 0.56% sulphur. The dry method with the centrifugal air classifier proved to be less successful in comparison with the wet method. The particles containing Na_2SO_4 are very similar in size and density to the other components of the material, so the separation to the desired extent was not achieved.

Keywords: sulphur, centrifugal air classifier, filtration, filter ash, waste material.

Povzetek

V članku je predstavljena raziskava možnosti ločenja Na_2SO_4 od ostalih snovi v vzorcu filtrskega prahu. Preiskovan material vsebuje šest komponent, ki se med seboj razlikujejo po kemijski sestavi in gostoti. Preučevali smo možnost ločenja Na_2SO_4 s suhim in mokrim postopkom. Suh postopek je temeljil na ločevanju s centrifugalnim zračnim klasifikatorjem pri štirih mejah ločenja. Mokri postopek je temeljil na raztapljanju v vodi topnih komponent, filtraciji netopnih komponent in sušenju produktov. Po obeh izvedenih metodah smo določili vsebnost žvepla v posameznih produktih. Cilj raziskave je bilo ugotavljanje, s katero metodo doseči ločenje materiala tako, da bi večina materiala vsebovala čim manj žvepla, preostanek materiala pa bi vseboval koncentrirano žveplo. Kot bolj uspešna se je pokazala metoda z mokrim postopkom. Produkt z masnim deležem 33.1% od celote, pridobljen iz vodne raztopine, je po filtraciji in sušenju vseboval 8.39% žvepla. V vodi netopna frakcija, katere delež je bil 66.9% od celote, je vsebovala 0.56% žvepla. Suhi postopek z zračnim klasifikatorjem se je izkazal kot manj uspešen. Delci Na_2SO_4 so namreč po velikosti in gostoti dokaj podobni ostalim komponentam materiala, zato nismo dosegli ločenja v želenem obsegu.

Ključne besede: žveplo, centrifugalni zračni klasifikator, filtracija, filtrski prah, odpadne snovi.

Introduction

The construction industry in Slovenia is currently in expansion. Major repairs, reconstructions and renovations of residential, public and industrial buildings are underway. In connection with the increased number of buildings under construction, the production of construction materials is also increasing. Due to the demolition and reconstruction of buildings, the amount of construction waste is increasing, most of which have the potential of secondary use [1]. In the circular economy concept, waste is considered as raw material and could be reused in the production process. This avoids waste disposal and the associated environmental problems and reduces the need for new raw materials, in which sources are limited. The composition of construction waste has changed over the years. The construction waste whose use has spread in recent decades is increasing. Dry prefabricated materials such as gypsum boards and insulating materials which are the result of the energy efficiency concept and the introduction of new building materials and construction methods are included in this group.

In the European Union, 40.9 million tons of waste materials were generated in the field of construction and demolition in 2016, representing 36.4% of all waste, compared with 10.3% of industrial waste. The construction sector is thus the largest producer of waste in comparison with other economic sectors [2].

The European Commission Waste Directive also addresses waste hierarchy, which makes prevention of the top waste management priority, followed by preparation for reuse, recycling, recovery and landfill [3]. As a result, industrial companies are looking for new approaches to the waste management which are consistent with the environmental, social and economic sustainability [4].

As with most production processes, the production of building materials, whether using exclusively primary raw materials or adding secondary raw materials into the process, waste materials are produced as a by-product. Their quantity and composition depend on the type of technological process.

In the case of thermal treatment of materials, flue gases are mainly produced as by-products, carrying dusty ash particles with them. Mass fraction of heat treatment by-products may be significant in the intense production process. Products are frequently waste materials but can represent the potential for reuse in case of providing technological and environmental requirements. Some of these materials have one or more hazardous properties and may represent an environmental risk. If the material is characterised as hazardous waste, it represents a much higher cost to the waste producer or the payer to properly treat it than if the waste were considered to be a non-hazardous waste. Such materials may be prepared by mechanical and/or other processes to the extent that they are environmental friendly and reusable.

This study presents some methods for minimising sulphur content with mechanical processes in handling thermal treatment products, more specifically when handling filter ash containing a certain content of sulphur. By minimising the sulphur content, it is possible to achieve the removal of hazardous properties from waste which transforms waste from hazardous to non-hazardous type, thereby opening the possibilities of reuse or at least significantly reducing the cost of waste disposal.

Materials and Methods

The filter ash that is a subject of this research is a mixture of:

— Sodium bicarbonate ($NaHCO_3$),
— Sodium sulphate (Na_2SO_4),
— Coke,
— Limestone,
— Basalt (rock wool fibres),
— Ash.

In order to minimise the sulphur content of the filter ash, the aim of the research was to separate Na_2SO_4 from the other components or to concentrate sodium sulphate. One option was to perform the dry process separation using a centrifugal air classifier. Considering the fact that the research deals with the particulate matter, which was extracted from the flue gas by filters, it is logical that the maximum particle size in the sample taken was limited to about 50 μm. If the particles of the Na_2SO_4

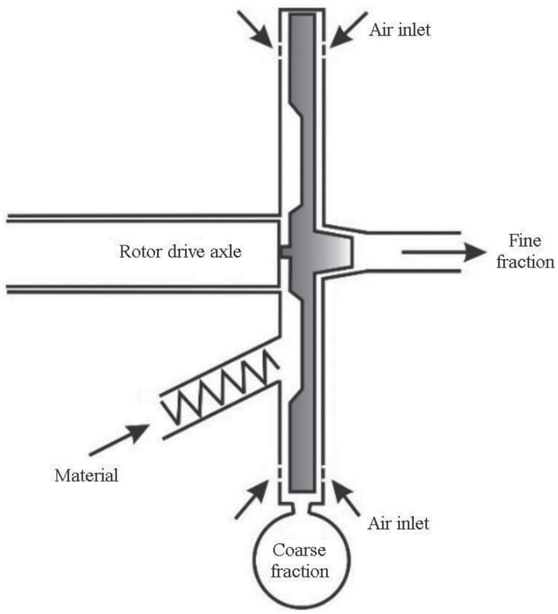

Figure 1. *Principle of operation of the centrifugal air classifier.*

Table 1. *Density measurements with a pycnometer*

Test no.	Density (kg/m^3)
1	2,445.8
2	2,579.5
3	2,539.5

component were present in a specific granulometric interval, there exists a possibility of separation with the centrifugal air classifier. Alternatively, a wet process could be performed in which the water-soluble Na_2SO_4 is separated from the other components by dissolving, filtration of insoluble components and drying the products.

A centrifugal air classifier is a device for separating particles according to their size and density. During the classification operation, the particles are under the influence of centrifugal force (F_c), drag force (F_d) and gravity (F_g) force. The centrifugal force field is generated by a rotor, which accelerates the particles towards the periphery of the classification zone where a coarse fraction is deposited. The air enters the classification zone tangentially, flows through the middle of the classification zone and removes finer particles on which the drag force of the air resistance is greater than the centrifugal force. The fine particles carried by the air stream are separated from the gas phase in the air cyclone. The material enters the classifier using a uniform dosing mechanism (dosing screw). The device principle is explained in Figure 1.

The definitions of the forces acting on particles are as follows [5]:

$$F_c = \frac{4}{3} \cdot \pi \cdot r_p^3 \cdot \rho_p \cdot \frac{v^2}{r} \tag{1}$$

$$F_d = c_D \cdot \rho \cdot \pi \cdot r_p^2 \cdot \frac{v_a^2}{a} \tag{2}$$

$$F_g = m \cdot (\rho_p - \rho) \cdot g \tag{3}$$

where r_p is particle radius, ρ_p is particle density, v is the peripheral velocity of the rotor, r is rotor radius, c_D is drag coefficient, ρ is the air density, m is mass of particle and g is gravitational constant.

The cut size of the classifier is the particle size limit at which the material is separated into a fine and coarse fractions. It depends on the rotor revolutions per minute (RPM), which creates the centrifugal field, and on the air volume flow through the classification zone. The required rotor RPM and the airflow for the selected cut size are determined from the diagram provided by the classifier manufacturer.

For the purpose of determining the operating conditions of the centrifugal air classifier, the sample density was measured using a pycnometer method. Since two components of the material ($NaHCO_3$ and Na_2SO_4) are water-soluble, in order to determine the density, we used isopropanol in which those components are insoluble or slightly soluble. First, we determined the density of isopropanol with a pycnometer (ρ = 784.8 kg/m^3). Following this, we performed three measurements of sample density, which are presented in Table 1.

The calculated mean density of the sample was 2,521.6 kg/m^3. In the next step, four different cut sizes were selected, namely 10, 20, 30 and 40 μm. For each cut size, the required rotor RPM and airflow quantity in accordance with

Table 2. *Determination of operating conditions for the centrifugal air classifier using the operating diagram of the classifier*

Cut size d_{TV} (mm)	RPM n (min^{-1})	Airflow Q (m^3/h)
10	8,900	46.1
20	5,200	49.8
30	4,100	50.9
40	3,500	51.5

the operating diagram of the device were determined (Table 2).

Na_2SO_4 is soluble in water, so it is possible to remove it from insoluble components by mixing the material in water at the appropriate temperature, and then filtration process is used to remove the insoluble residue, which is followed by the elimination of water-soluble substances, including Na_2SO_4, for which drying or a reverse osmosis process may be used.

Of the components contained in the input material, $NaHCO_3$ is also soluble in water, whose solubility at 35°C is approximately 120 g/L. The solubility of sodium sulphate in the water rises to 32.4°C (497 g/L), and decreases slightly at higher temperatures [6].

Sampling of Material

The material was sampled with a spoon. It was poured on a flat surface; a rectangle 1–2 cm high was formed and 5 × 6 even squares were drawn into it. Next, we took a spoonful of material from each quadrant to get four samples with about 250 g each for classification purposes. Sampling is shown schematically in Figure 2. The sulphur content of the samples was measured with an X-ray fluorescence (XRF) spectrometer and S = 3.38% for the initial sample.

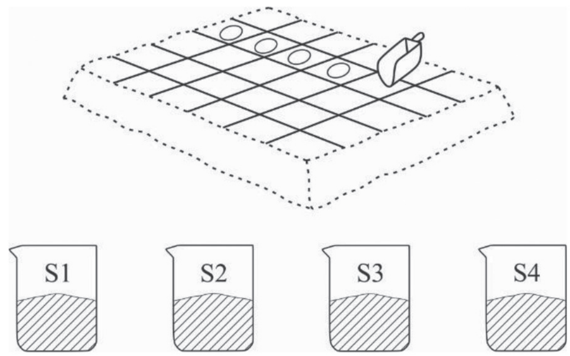

Figure 2. *Sampling with a spoon [after 7].*

Results and Discussion

Removal of Sulphur from Filter Dust by a Dry Process with Classification

The classification of the sample was performed four times, for each cut size individually. After each classification, the weight of the material of the coarse and fine fraction was determined by weighing. The data are presented in Tables 3–6.

Classification of sample 1 at the cut size of 10 µm yielded 21.8% fine fraction and 78.2% coarse fraction. This means that by weight 21.8% of the particles are smaller than 10 µm and 78.2% are larger than 10 µm.

When classifying sample 2 at the cut size of 20 µm, we found that about half of the particles were smaller than 20 µm and half were larger than 20 µm.

Classification of sample 3 at the cut size of 30 µm yielded 75.1% fine and 24.9% coarse fraction.

When classifying sample 4 at the cut size of 40 µm, the share of the fine fraction was 78.3% and the share of the coarse fraction was 21.7%.

The mean particle size of Na_2SO_4 can be, according to the sulphur content results, estimated to be around 20 µm. The most favourable result with air classification was obtained at a cut size of 10 µm, where the sulphur content in the fine fraction was 0.55%, but the mass share of the fine fraction was only 22.4% at this separation size. In all other cases, the sulphur content was not minimised.

The particles of the Na_2SO_4 component are quite dispersed in size and at the same time they are not significantly different in density from the other components in such a way that they can

Table 3. *Classification at a cut size of 10 µm*

Sample 1 (S1)	Mass (g)	Mass per cent (%)	Sulphur content (%)
	258.4	100.0	3.38
Fine fraction (1F)	56.3	21.8	0.55
Coarse fraction (1C)	202.1	78.2	4.19

Table 4. *Classification at a cut size of 20 µm*

Sample 2 (S2)	Mass (g)	Mass per cent (%)	Sulphur content (%)
	251.7	100.0	3.38
Fine fraction (2F)	128.9	51.2	3.30
Coarse fraction (2C)	122.8	48.8	3.44

Table 5. *Classification at a cut size of 30 µm*

Sample 3 (S3)	Mass (g)	Mass per cent (%)	Sulphur content (%)
	260.2	100.0	3.38
Fine fraction (3F)	195.4	75.1	3.71
Coarse fraction (3C)	64.8	24.9	2.32

Table 6. *Classification at a cut size of 40 µm*

Sample 4 (S4)	Mass (g)	Mass per cent (%)	Sulphur content (%)
	254.0	100.0	3.38
Fine fraction (4F)	198.8	78.3	3.49
Coarse fraction (4C)	55.2	21.7	2.81

be successfully separated from the other components by the air classifier.

Removal of Sulphur from Filter Dust by Wet Process

Approximately 100 g of sample was mixed with 800 mL of water. The suspension was stirred with a magnetic stirrer for 30 min, while it was heated to a temperature of about 35°C. The suspension was then poured into a Sartorius filtration cell equipped with a 0.2 µm aperture filter. The filtration was initially carried out at atmospheric pressure. The remaining fluid from the filtration cell was obtained using compressed air. The residue of the solid phase in the filtration cell (filter cake) was dried in an oven at 105°C until dry. The solution containing Na_2SO_4 was also processed to dryness in the oven. The process is schematically shown in Figure 3. After drying, both masses were determined. The weight of the filter cake of the water-insoluble solid phase was 72.5 g, while the mass in the water-soluble material was 35.9 g. The measured sulphur content of both samples is given in Table 7.

Table 7 shows that the sulphur content of the insoluble material is 0.56%.

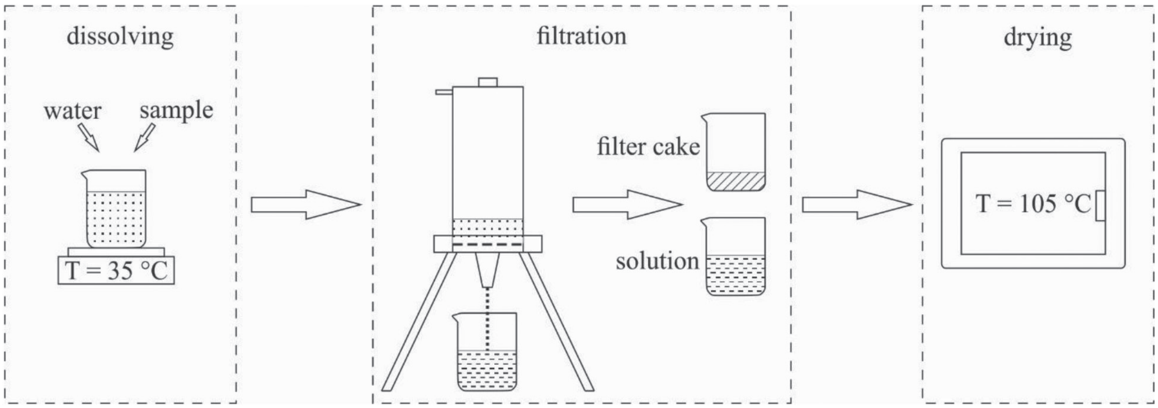

Figure 3. *Dissolution, filtration and drying of material.*

Table 7. *Results of an attempt to remove sulphur from filter ash by the wet procedure*

Sample 5 (S5)	Mass (g)	Mass per cent (%)	Sulphur content (%)
	108.4	100.0	3.38
Insoluble material (5I)	72.5	66.9	0.56
Soluble material (5S)	35.9	33.1	8.39

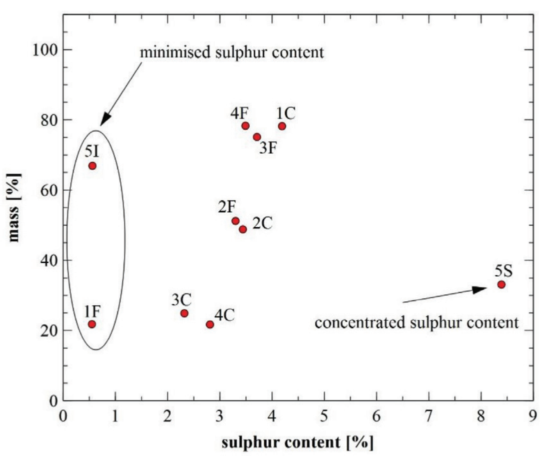

Figure 4. *Sulphur and mass content for different samples.*

In this case, it is the majority of the material (66.9%). Sulphur is concentrated in dissolved material, in which the sulphur content increased to 8.39%.

Figure 4 shows that only the 5I and 1F samples represent the minimisation of sulphur content, with the 5I sample having a much larger mass fraction than the 1F sample, which means that the separation using wet process is more optimal.

Conclusions

This article presents dry and wet methods of minimising the sulphur content in filter dust.

A dry method of sulphur minimisation would be a faster and more cost-effective method of sulphur removal in the industry but attempting to classify it at different cut sizes did not produce adequate results. With respect to the sulphur content, only a classification at the cut size of 10 μm would be appropriate, where the sulphur content in the fine fraction $S = 0.55\%$ was measured, but the share of this fraction was only 21.8%. The mass content of sulphur in the coarse fraction at this cut size was $S = 4.19\%$. In the case of all other cut sizes (20, 30 and 40 μm), the sulphur-containing particles are approximately evenly distributed between the fine and coarse fractions so that the sulphur content in both the fine and coarse fractions does not deviate significantly from the sulphur content of the starting sample.

Better results were obtained from the wet sulphur content minimisation process. In this part of the study, the sample was mixed with a sufficient amount of water, and the suspension was heated to the temperature necessary for maximum solubility of sodium sulphate in water. The water-soluble material, together with the insoluble residue, was filtered on a 0.2 µm aperture filter and then dried, and the sulphur content in the insoluble and water-soluble material was measured. The insoluble material represented about two-third of the total sample and had a sulphur content of $S = 0.56\%$, while the measured sulphur content in the rest of the material was $S = 8.39\%$.

Considering that a lot of energy is consumed in drying the material, a suitable solution for the industrial removal of Na_2SO_4 would include mixing of water and material while heating at 35°C, separation of the solid and liquid phase by filtration, elimination of Na_2SO_4 from the liquid phase by reverse osmosis and drying of the products.

By using reverse osmosis, drying volumes and energy consumption would be greatly reduced.

References

[1] Aleksanin, A. (2019): Development of construction waste management. In: *XXII International Scientific Conference on Advanced In Civil Engineering*, Tashkent, Uzbekistan, Volkov, A., Pustovgar, A., Sultanov, T., Adamtsevich, A. (eds.). E3S Web of Conferences.

[2] Eurostat [online]. European Commission [cited 1/15/2020]. Available on: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation.

[3] DIRECTIVE 2008/98/EC (2008). *Directive 2008/98/EC of the European Parliament and Council of 19 November 2008 on Waste and Repealing Cerain Directives*. European Parliament. Official Journal of the European Union, pp. 3–30.

[4] Shahbazi, S., Kurdve, M., Bjelkemyr, M., Jönsson, C., Wiktorsson, M. (2013): Industrial waste management within manufacturing: A comparative study of tools, policies, visions and concepts. In: *Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013)*, Shehab, E., Ball, P., Tjahjono, B. (eds.). Cranfield University: Cranfield, UK, pp. 637–642.

[5] Altun, O., Toprak, A., Benzer, H., Darilmaz, O. (2016): Multi component modelling of an air classifier. *Minerals Engineering*, 93, pp. 50–56. DOI:10.1016/j.mineng.2016.04.014.

[6] Bharmoria, P., Gehlot, P.S., Gupta, H., Kumar, A. (2014): Temperature-Dependent Solubility Transition of Na_2SO_4 in Water and Effect of NaCl Therein: Solution Structures and Salt Water Dynamics. *The journal of physical chemistry B*, 118, pp. 12734–12742. DOI: 10.1021/jp507949h.

[7] Stražišar, J., Knez, S. (2001): *Vaje in računski primeri iz mehanske procesne tehnike.* Univerza v Ljubljani, Naravoslovnotehniška fakulteta, Oddelek za geotehnologijo in rudarstvo: Ljubljana, 176 p.

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Hydrocarbon-Generating Potential of Eocene Source Rocks in the Abakaliki Fold Belt, Nigeria

Potencial za nastanek oglikovodikov v eocenskih izvornih kamninah nariva Abakaliki

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Abstract

Subsurface information on source rock potential of the Eocene shale unit of the Abakaliki Fold Belt is limited and has not been widely discussed. The total organic carbon (TOC) content and results of rock-eval pyrolysis for nine shale samples, as well as the one-dimensional (1D) geochemical model, from an exploration well in the Abakaliki Fold Belt were used to evaluate the source rock potentials and timing of hydrocarbon generation of Lower Eocene source rocks. The TOC content values of all the samples exceeded the minimum threshold value of 0.5 wt.% required for potential source rocks. A pseudo-Van Krevelen plot for the shale samples indicated Type II–III organic matter capable of generating gaseous hydrocarbon at thermally mature subsurface levels. The 1D burial model suggests that the Eocene source rock is capable of generating oil and gas at the present time. The modelled transformation ratio trend indicates that a fair amount of hydrocarbon has been expelled from the source rocks. The results of this study indicate that the Eocene source units may have charged the overlying thin Eocene sand bodies of the Abakaliki Fold Belt.

Key words: Abakaliki Fold Belt, generation, Eocene, basin modelling, hydrocarbon

Povzetek

Pod-površinske informacije o potencialu izvornih kamnin na območju eocenske enote nariva Abakaliki so omejene in niso bile predmet široke razprave. Za oceno potenciala izvornih kamnin in čas nastanka oglikovodikov nižjih eocenskih izvornih kamnin so bile uporabljene naslednje preiskave: skupni organski ogljik (TOC), rezultati pirolize Rock-Eval za devet vzorcev skrilavcev in 1D geokemični model iz raziskovalne vrtine. Vrednosti TOC so pri vseh vzorcih presegale minimalne mejne vrednosti 0.5 ut.%. Pseudo-Van Krevelen graf za vzorce skrilavcev nakazuje Tip II-III organske snovi, zmožne generiranja plinastega oglikovodika pod nivojem zrelosti organske snovi. 1D modeli predlagajo, da so eocenske izvorne kamnine zmožne generiranja nafte in plina v sedanjem času. Modeliran trend transformacijskega razmerja nakazuje, da je neka količina ogljikovodikov ušla iz izvornih kamnin. Rezultati raziskave prikazujejo, da so eocenske izvorne enote lahko napolnile prekrivajoče tanke eocenske peske na narivu Abakaliki.

Ključne besede: nariv Abakaliki, nastanek, Eocen, modeliranje bazena, ogljikovodik

Introduction

Petroleum exploration companies had drilled some wells in the Abakaliki Fold Belt in the 1950s and ’60s but had abandoned these because it was thought that magmatic intrusion in the belt did not favour hydrocarbon accumulation. However, in recent times, there has been a resurgence of interest in the search for petroleum in the belt [1]. The discovery of oil shale and indications of hydrocarbon in the Abakaliki Fold Belt (Figure 1) have shown that the basin has significant hydrocarbon potential [2, 3]. The Cretaceous source facies of the Abakaliki Fold Belt have, over the years, been considered as viable source units capable of generating hydrocarbons [1, 4].

Recent studies have shown that Eocene source rocks are immature with respect to hydrocarbon generation at the present outcrop level; but they have a fair-to-moderate potential to generate gaseous hydrocarbons at mature levels in the subsurface [5, 6]. Published works on deeply buried Eocene source rocks of the Abakaliki Fold Belt are rare. This study attempts to determine whether deeply buried Eocene source rock is responsible for charging the overlying Lower Eocene sandy facies of an exploration well (Ihuo-1 well) drilled in the Abakaliki Fold Belt by evaluation of the Lower Eocene source rocks (organic richness and kerogen type) and reconstruction of one-dimensional (1D) basin models. Modelling of the results allows for the assessment of Lower Eocene Bende/Ameki source rock in the Abakaliki Fold Belt, which will give a new perspective on the source potential and generative potential of the deeply buried Eocene source unit.

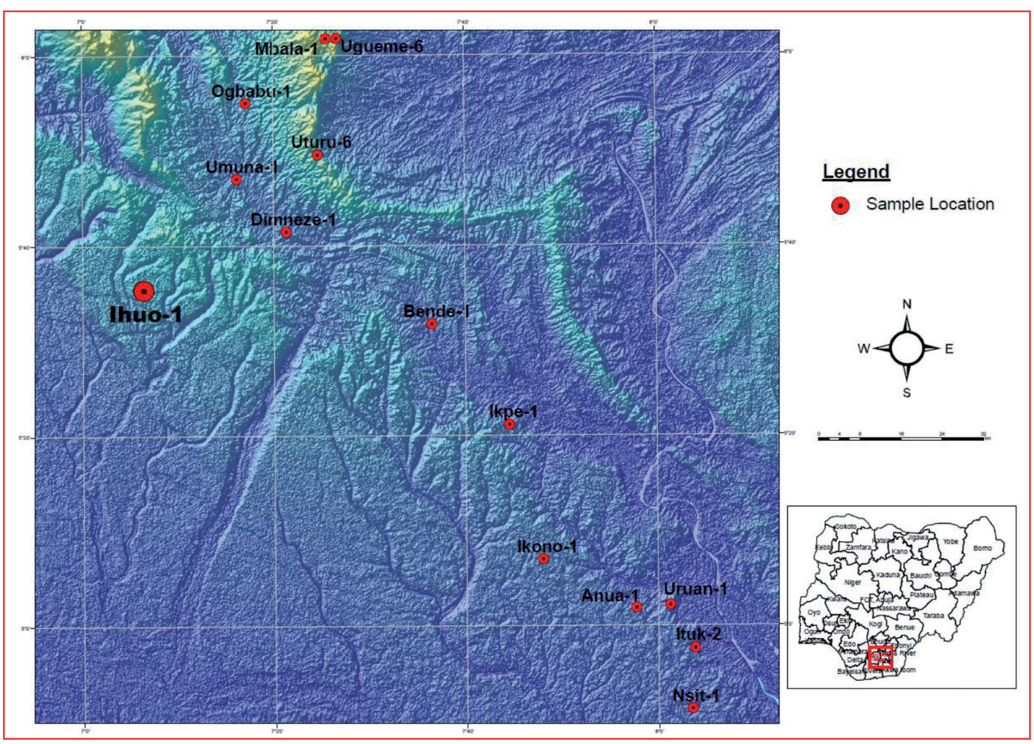

Figure 1: *Location of the study area showing the position of the Ihuo-1 well and other wells in the Abakaliki Fold Belt and the Calabar Flank. Insert: Map of Nigeria showing the location of the Abakaliki Fold Belt (marked by a red box), Southeastern Nigeria.*

Geological Settings

The Abakaliki Fold Belt consists of Cretaceous-to-Neogene sediments (Figure 2). Before the Santonian, the Abakaliki region was one of the most important depocentres in the Lower Benue Trough, with marine sediments ranging in age from Albian to Coniacian. The second

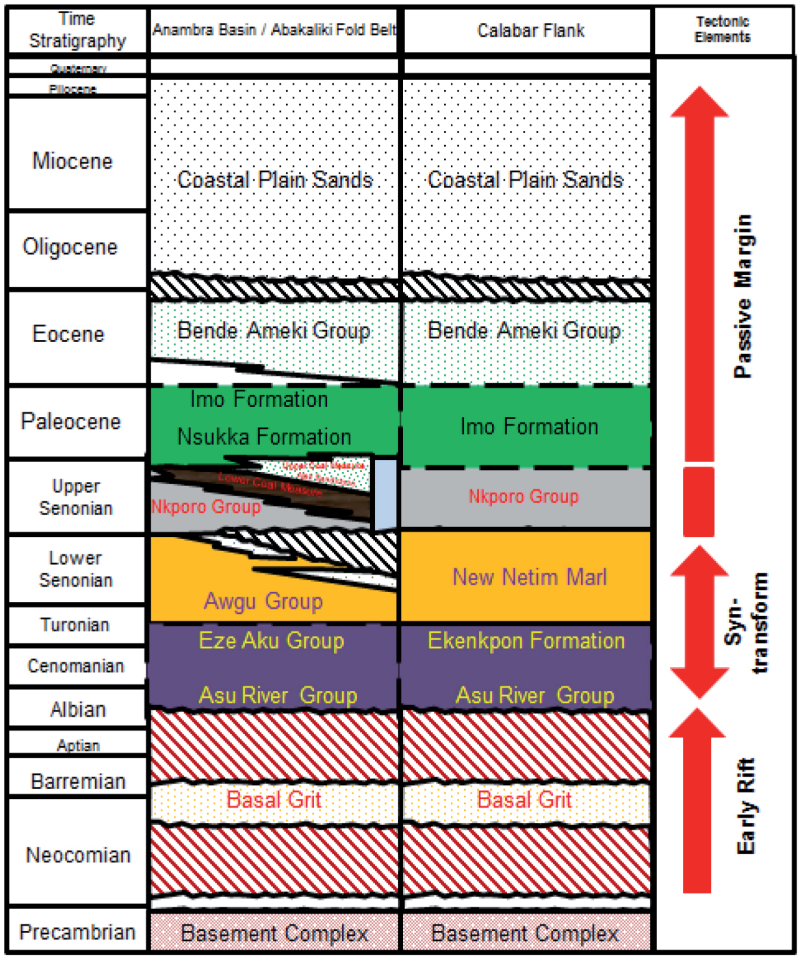

Figure 2: *A simplified regional section of the Cretaceous and Cenozoic stratigraphy of Anambra Basin, Abakaliki Fold Belt and Calabar Flank, with time stratigraphy and tectonic events [9–10].*

sedimentary phase occurred between the Upper Cenomanian and Middle Turonian and was associated with the deposition of Eze-Aku Shale and its lateral equivalents, namely the Amasiri and Makurdi sandstones [7]. The Lower Turonian Eze-Aku Shale in the Abakaliki Fold Belt underlies the Coniacian Awgu Shale [8].

The Campanian–Maastrichtian Nkporo Group overlies the Awgu Shale (Abakaliki Fold Belt) unconformably, above which are the Palaeogene–Neogene marine shales and regressive sandstones [11]. The Albian–to-Coniacian sediments were deposited before the Santonian compressional tectonic phase, which is reflected by basic volcanism and a disconformity [2]. It then implies that after the Santonian thermo-tectonic event, most of the source rock deposited earlier might have been overcooked due to high thermal effects; hence, the search for suitable hydrocarbon source rock in the Abakaliki Fold Belt should be in the subsurface post-Santonian (Eocene) sediments. The Nigerian Eocene sediments are well-dated marine deposits [12]. Eocene rocks that outcropped in Southeastern Nigeria constitute the subsurface Agbada Formation, which – according to previous research [13] – have been identified as the major source rock of petroleum in the Niger Delta Basin.

Materials and Methods

A total of nine ditch-cutting samples from shale interval depths ranging from 2204 m to 2557 m of the Ihuo-1 well, drilled by the Shell Petroleum Development Company (SPDC), located in the Abakaliki Fold Belt, were used in

Table 1: *Geochemical results of rock-eval/TOC analyses of Eocene samples in Ihuo-1 well*

Depth (m)	TOC (wt.%)	Rock-eval pyrolysis						
		S_1 (mgHC/gTOC)	S_2 (mgHC/gTOC)	$S_1 + S_2$	T_{max}	OI (mgHC/gTOC)	HI (mgHC/gTOC)	PI (mgHC/gTOC)
2204	0.8	2.7	2.58	5.28	442	171	323	0.51
2265	1.8	3.91	2.88	6.79	441	158	160	0.58
2320	1.5	3.70	2.40	6.10	439	156	150	0.61
2355	0.8	2.56	1.45	4.01	466	129	181	0.64
2375	0.7	6.52	3.28	9.80	455	557	469	0.67
2415	1.1	4.14	2.03	6.17	476	177	185	0.67
2510	0.9	1.60	0.83	2.43	469	17	92	0.66
2520	1.0	5.03	2.18	7.21	478	353	218	0.7
2557	0.8	2.53	1.21	3.74	480	116	151	0.88

Table 2: *Input for 1D basin modelling of the Ihuo-1 well as used in the present study.*

Layer name	Depth range (m)	Thickness (m)	Deposition period (Ma)	Erosion period (Ma)	Modelled TOC (wt.%)	Modelled HI (gHC/gTOC)
Overburden	0–28	28	0.2–0			
Mio-Oligocene (Coastal plain sands)	28–584	556	27–0.2			
Oligocene shaly sands	584–1328	744	28–27			
Upper Eocene (Bende/Ameki Formation)	1328–1426	98	37.6–34	34–28		
Mid-Eocene (Bende/Ameki Formation)	1426–1862	436	41.2–39	39–37.6		
Lower Eocene (Bende/Ameki Formation)	1862–2655	793	49–41.2		1	214
Lower Eocene (Bende/Ameki Formation)	2655–2710	55	54–49			
Lower Eocene (Bende/Ameki Formation)	2710–2863	153	56–54			
Palaeocene (Imo Shale)	2863–3228	365	66–56			
Maastrichtian (Nkporo Shale)	3228–3450	222	71.2–66			

Table 3: *Measured vitrinite reflectance values of Eocene stratigraphic levels in Ihuo-1 well.*

Well	Depth (m)	Vitrinite reflectance values
Ihuo-1	2204	0.80
Ihuo-1	2265	0.78
Ihuo-1	2375	1.03
Ihuo-1	2557	1.48

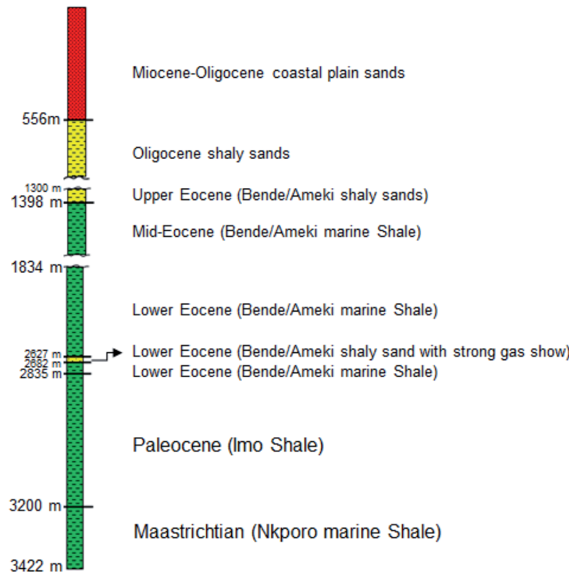

Figure 3: *Lithostratigraphy of Ihuo-1 well showing the different sedimentary intervals with relative ages. Note the gaps within the litholog, representing unconformity.*

the study. This work utilized the total organic carbon (TOC) content and rock-eval pyrolysis results (Table 1), in addition to the well data, of the Lower Eocene shale samples that were provided by the SPDC.

The sedimentation history of the basin is subdivided into a series of events of specified age and duration [14]. Accordingly, 1D basin modelling was carried out using Petromod 1-D^{Express} to determine the maturation and timing of hydrocarbon generation of the Lower Eocene source unit. The input data for the stratigraphic modelling included thicknesses, durations of deposition, ages and lithologies of the different sedimentary layers (Figure 3, Table 2). Palaeobathymetry values were obtained from the proprietary SPDC chart. The modelled vitrinite reflectance was correlated with the measured data in order to calibrate the hydrocarbon generation levels (Table 3). The source rock parameters, i.e. TOC content and hydrogen index (HI), used in the construction of the 1D models, were obtained from the well report (Tables 1 and 2). Average values of 1.00 wt.% TOC and HI of 214 mgHC (milligram hydrocarbon)/gTOC were applied during the modelling. The 1D model of the exploration well was simulated and the results are presented visually.

Results

Quality and Quantity of Organic Matter

The organic richness (i.e. TOC%) is a key parameter for the assessment of source rock potential. The data obtained from Table 1 shows that the TOC content of the Eocene shale unit ranges from 0.8 wt.% to 1.8 wt.% (mean value of 1.0 wt.%). The TOC values of all the samples exceeded the minimum threshold value of 0.5 wt.% required for potential source rocks [15]. A cross-plot of S_1 against TOC can be used to distinguish between allochthonous and autochthonous hydrocarbons (Figure 4), which shows that the analysed rock samples of the Eocene source rocks contain allochthonous (non-indigenous) hydrocarbons.

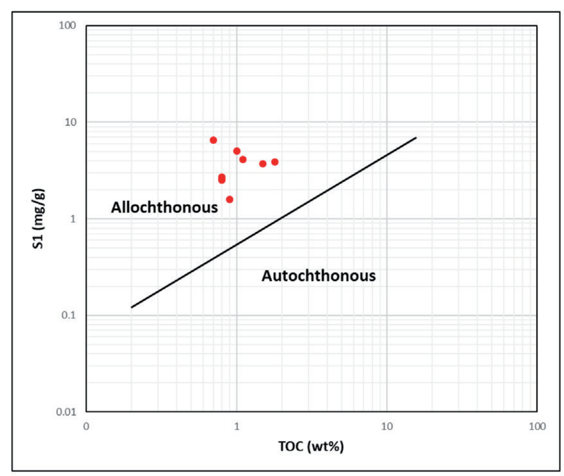

Figure 4: *Cross-plot of S_1 against TOC for the Eocene source rocks in Ihuo-1 well [16], used in distinguishing the hydrocarbon (potential) types. The red dots indicate the analysed samples.*

Generation Potential (GP)

Based on rock-eval pyrolysis, the hydrocarbon GP of a source rock can be estimated. The GP of a source rock is the summation of the S_1 and S_2 values. The GP of source rocks can be classified as poor, fair, good and very good with GP values <2, from 2 to 5, from 5 to 10, and >10, respectively [17]. A cross-plot of the GP (i.e. $S_1 + S_2$) against TOC suggests that the Eocene source rocks have fair-to-good source potential (Figure 5). In addition, the cross-plot of the HI against TOC shows that the source rocks are fair oil source rocks.

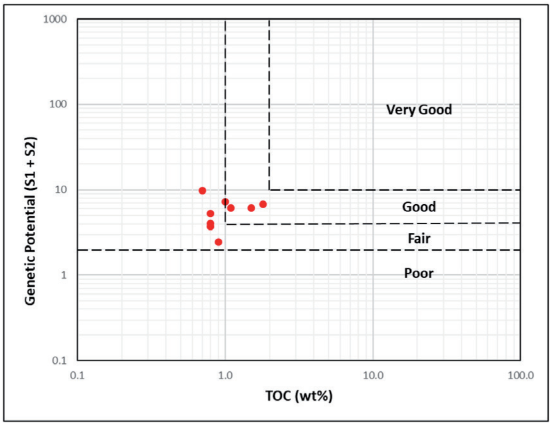

Figure 5: *Cross-plot of generation potential (GP) against total organic content (TOC) of Eocene source rocks in Ihuo-1 well [16], used to know the source potential of the sediment. The red dots represent the analysed samples.*

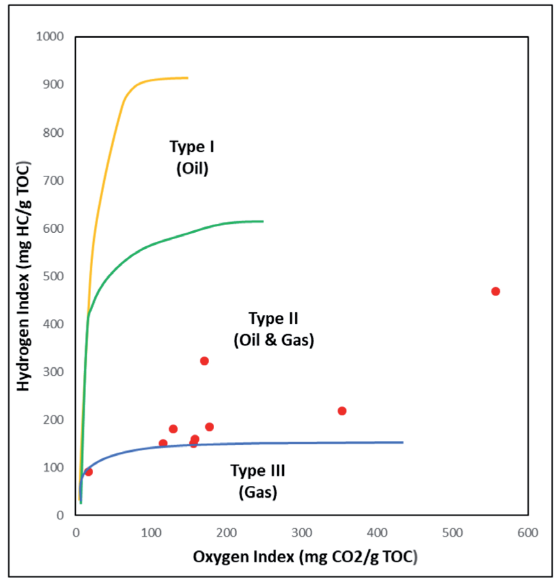

Figure 6: *Van Krevelen diagram for kerogen typing of Eocene shale samples in Ihuo-1 well [16], used to determine the kerogen types of the shale samples. The red dots represent the analysed samples.*

Kerogen Type of the Organic Matter

The original kerogen type of a source rock is a key element that aids in the forecast of oil and gas potential. HI values <150 mgHC/gTOC indicate potential for gas generation (chiefly Type III); HI values ranging from 150 to 300 mgHC/gTOC indicate potential for generation of mixed gas and oil (Type III and II, respectively), with mainly gas being generated. Kerogen with HI > 300 mgHC/gTOC has potential for more oil generation, with minor levels of gas (Type II); HI >600 mgHC/gTOC indicates Type I kerogen, which has the highest potential to generate oil [18].

Based on the data obtained in Table 1, the kerogen type was classified using the key parameters, such as HI, oxygen index (OI), and T_{max}. A cross-plot of HI against OI was used to construct a Van Krevelen diagram for the categorisation of kerogen types. The results obtained suggest that the rock samples of the Eocene shale unit are of kerogen Type II–III (i.e. potential for generating mixed oil and gas, with more gas being generated than oil) (Figure 6). A pseudo-Van Krevelen diagram was also constructed with a cross-plot of HI against T_{max} (Figure 7), which suggests a Type II–III organic matter type. The shale unit in Ihuo-1 well is characterised by average $S_1 + S_2$ yields of about up to 5.7 mgHC/gTOC rock and rather low average present-day HI value of <250 mgHC/gTOC rock (Table 1), thus indicating lower percentages of autochthonous organic matter [19].

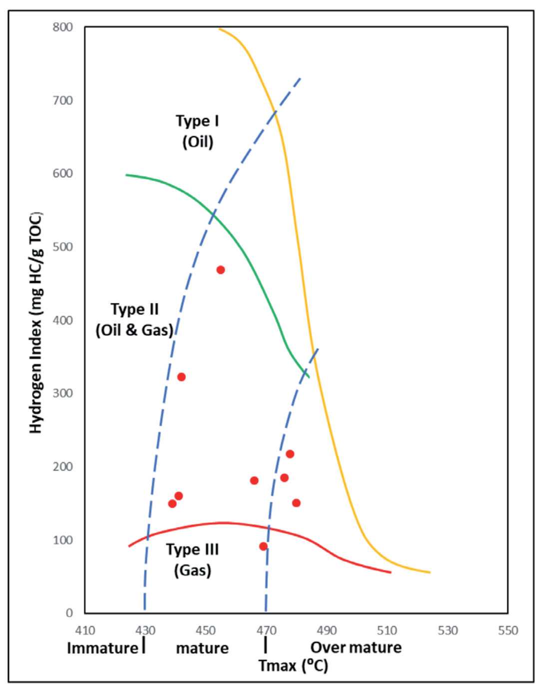

Figure 7: *Pseudo-Van Krevelen diagram of Eocene shale samples in Ihuo-1 well [20], used to determine the kerogen types of the shale samples. The red dots represent the analysed samples.*

Heat Flow and Thermal History

The reconstruction of thermal histories of sedimentary basins is always simplified and calibrated against maturity profile indicators such as vitrinite reflectance [21]. The heat flow values were determined based on the tectonic history of the basins and were defined by streaming modelled and measured thermal data (Figure 8).

Elevated heat flow values (Figure 9) were calibrated for Aptian-to-early Albian times because of the rifting associated with intensive magmatic activity, uplift and erosion [22] in the Abakaliki Fold Belt. Heat flow values (Figure 9) were reduced during the Cenomanian to account for the period of cooling following cessation of mantle upwelling [3]. High heat flow values were modelled for early-to-middle Turonian times to indicate extensional movements caused by the reactivation of mantle upwelling, accompanied by well documented rifting event in the Abakaliki Fold Belt [23–24]. Late Turonian to Santonian times were marked by indication of active tectonic phase of folding, faulting

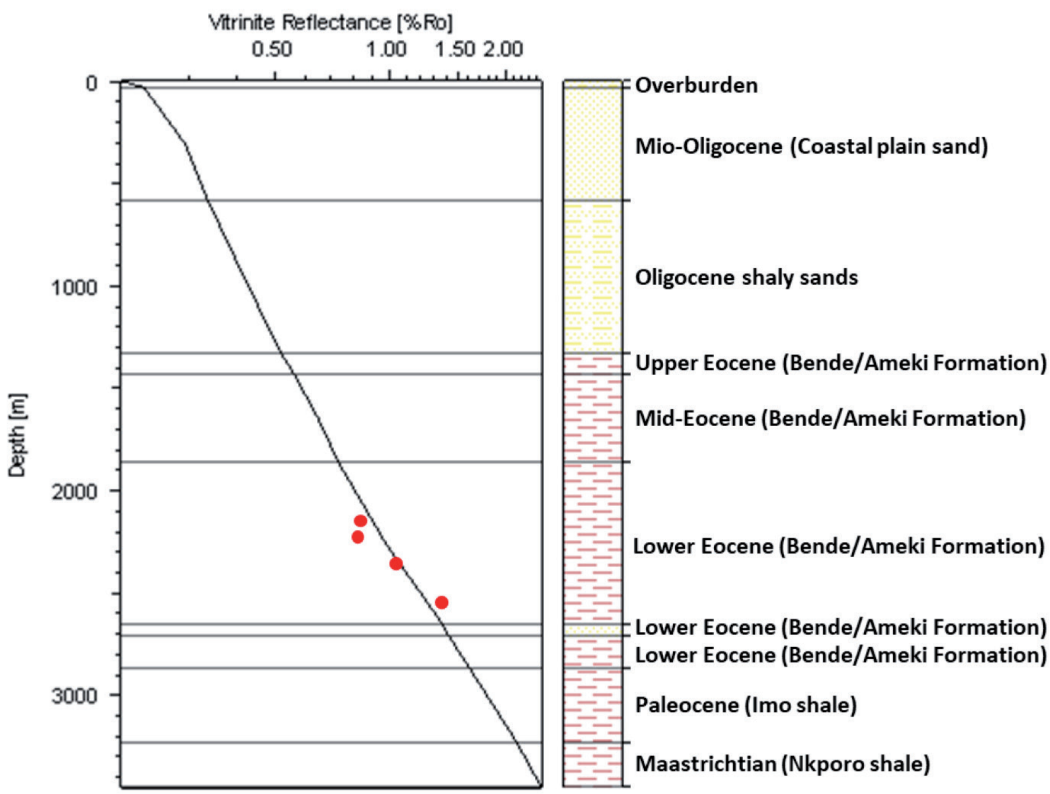

Figure 8: *Boundary condition used to model the most probable scenario for hydrocarbon generation in the Abakaliki Fold Belt. The figure indicates the heat flow trend for the Lower Eocene source rock.*

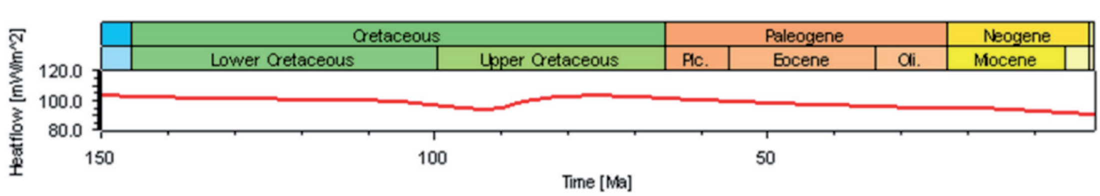

Figure 9: *Correlation of measured and modelled vitrinite reflectance data for Ihuo-1 well. The heat flow values were determined based on the tectonic history of the basins and were defined by streaming modelled and measured thermal data.*

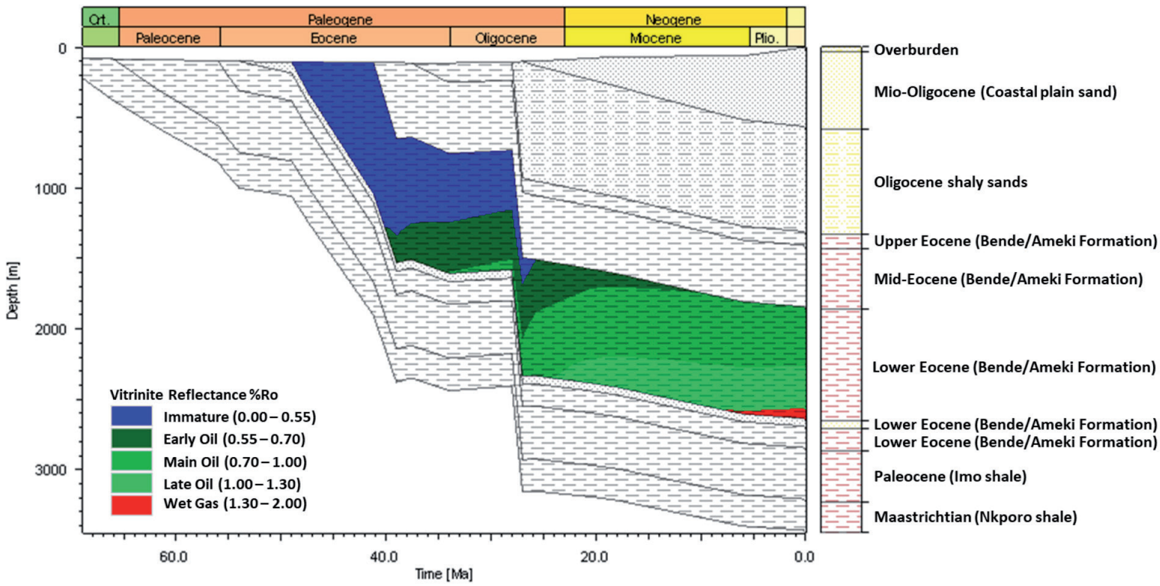

Figure 10: *One-dimensional history of the buried Eocene source unit in Ihuo-1 well extracted from the model. The coloured model indicates the modelled vitrinite reflectance maturity overlay.*

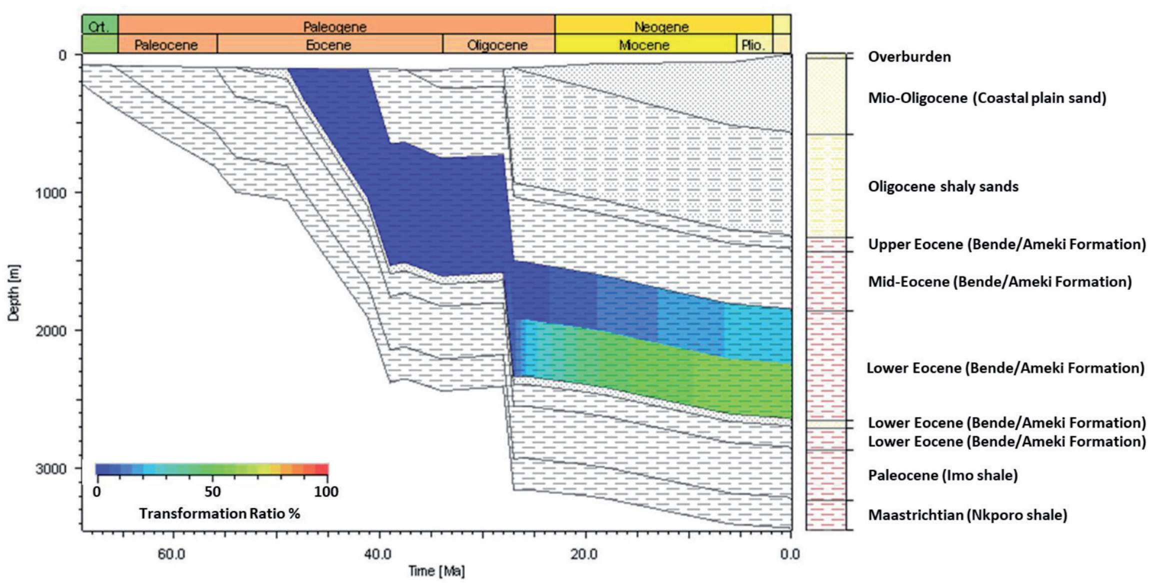

Figure 11: *Burial history of the Ihuo-1 well showing the transformation ratio overlay for the deeply buried Eocene source unit.*

and uplifting [25]. Thick series of hydrothermally altered Late Turonian-Coniacian basaltic sediment in the Abakaliki Fold Belt suggested an extrusive, rather than an intrusive, character, in which the volcanic activity occurred [26]. Santonian tectonism was followed by loss of thermal momentum associated with final cessation of mantle upwelling during Campanian to Palaeocene in the Abakaliki Fold Belt [3, 25].

Terminal tectonic event during late Maastrichtian had been reported [9, 27], where rifting, deformation and high heat flow from magmatic activity played an important role [28]. Thermal heat flow peak for Eocene tectonism was modelled based on intensive erosion [9] during the period.

Hydrocarbon Generation

The 1D charge modelling of the Ihuo-1 well used the [29] kinetic model to establish the hydrocarbon GP of the Eocene organic-rich shale bed. The top of the wet gas window was identified at about 2592 m, and this suggests that the Eocene shale unit is presently in the oil–wet gas generation phase. The maturity model (Figure 10) assumes that the source bed began hydrocarbon generation during Eocene times (40.58 Ma) and continues till date. The areas of crustal extension are commonly characterised by high heat flow (> 90 mWm^{-2}), volcanic activity and related thermal fluid circulation [30]. Elevated heat flow would have contributed to the maturation of the source unit (wet gas window) in the Abakaliki Fold Belt, as observed on the measured T_{max}.

Transformation Ratio

The modelled present-day transformation ratio value of the deeply buried Lower Eocene source samples in the exploration (Ihuo-1) well ranges from 25% to 59% (Figure 11). This suggests that a fair quantity of hydrocarbon has been expelled. The source rock intervals may have contributed to the charging of the Lower Eocene sand bodies in the Ihuo-1 well.

Discussion

The hydrocarbon source potential of the Lower Eocene (Bende/Ameki) shale is uncertain even with some oil and gas indications in the Abakaliki Fold Belt. Shales of the Cretaceous age (Turonian-Maastrichtian) have been previously considered as the major source rocks for the Abakaliki Fold Belt [1, 31, 32]. Although the Lower Eocene (Bende/Ameki) source rocks are of moderate-to-good quality, the source rocks must have generated and expelled hydrocarbon. This hydrocarbon source potential is attributed to the depth of burial of the Lower Eocene source rock. The herein-studied well, Ihuo-1 well, has the thickest sedimentary succession and source rock burial in the Abakaliki Fold Belt [9, 26]. More than 3000 m of sediment pile was deposited and Eocene source rock burial depth of >1800 m was observed in Ihuo-1 well. The Lower Eocene (Bende/Ameki) source rocks have the required depth of source rock burial for maturation.

The initial hydrocarbon generation phase commenced during the Eocene age with the generation of liquid hydrocarbon. The major phase of generation and expulsion of hydrocarbon started in the Oligocene age. The thermal maturity of Lower Eocene source rock is moderate to high, as observed in vitrinite reflectance data, suggesting that it is thermally mature for hydrocarbon generation. The thermal maturation of Lower Eocene source bed in the Ihuo-1 well may have been strongly affected by elevated heat flow (Figure 9). The areas of crustal extension are commonly characterised by high heat flow (>90 mWm^{-2}), volcanic activity and related thermal fluid circulation [30]. Rifting associated with intensive magmatic activity, uplift and erosion in the Abakaliki Fold Belt are more pronounced during the Cretaceous [22].

Strong indication of gas was found in Ihuo-1 well during drilling [9]. The origin of the gas indication in Ihuo-1 well is speculative, hence the need to carry out isotope geochemical analysis. The occurrence of gas within the thin Eocene reservoir is thought to have been sourced partly from Eocene organic-rich shales or deeply buried Cretaceous organic-rich intervals. Eocene-sourced oil and gas have been discovered in the Northern Delta depobelt [10]. The Northern Delta is the oldest mega-structure of the Niger Delta Basin and represents the transition depobelt between the Cretaceous succession of the Abakaliki Fold (including Anambra Basin) and the Niger Delta Basin.

Conclusions

Subsurface information on source rock potential of the Eocene shale unit of the Abakaliki Fold Belt is limited and has not been widely discussed. This study used results of rock–eval analysis and 1D basin models to evaluate Eocene shale samples from an exploration well (Ihuo-1 well) to evaluate the quantity and quality of the source rock, as well as reconstruct the timing of hydrocarbon generation.

TOC values and results of rock-eval pyrolysis for nine shale samples, as well as the geochemical model of Eocene Formation, from an exploration well in the Abakaliki Fold Belt, Nigeria, were used to evaluate and determine the source rock potentials and timing of hydrocarbon generation of Eocene source rocks. The TOC content values of all the samples exceeded the minimum threshold value of 0.5 wt.% required for potential source rock. The relationship between (S_1+ S_2) and TOC suggested that the Eocene samples could be regarded as having fair-to-good source potential. Van Krevelen plot for shale samples indicated Type II–III organic matter and showed that it can generate mixed oil and gas (with more of gas) hydrocarbon at thermally mature subsurface levels. This hydrocarbon source potential is attributed to the depth of burial of the Lower Eocene source rock.

The 1D burial model suggests that the Eocene source rock entered peak oil maturity in the Eocene, late oil maturity in the Oligocene and wet gas maturity during the Miocene age. The shale unit is capable of generating oil and gas at the present time. With transformation ratio ranging from 25% to 59% (with increasing depth), the shale unit has expelled fair amounts of hydrocarbon. The results of this study indicate that the Eocene source units may have fairly charged the thin Eocene sand bodies of the Ihuo-1 well.

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References

[1] Ekweozor, C.M. (1982): Petroleum Geochemistry: Application to petroleum exploration in Nigeria's Lower Benue Trough. In: *20th Anniversary proceeding, Nigeria Mining and Geosciences Society*, Oluyide, P. O., Mbonu, W. C., Onuogu, S. A., 19(1), pp. 122–129.

[2] Ehinola, O.A., Sonibare, O.O., Akanbi, O.A. (2005): Economic evaluation, recovery techniques, and environmental implications of the oil shale deposits in the Abakaliki Fold Belt, Southeastern, Nigeria. *Oil Shale*, 22(1), pp. 1–15.

[3] Oluwajana O.A., Ehinola O.A. (2018): Potential shale resource plays in southeastern Nigeria: Petroleum system modeling and microfabric perspectives. *Journal of African Earth Sciences*, 138, pp. 247–257.

[4] Unomah G.I., Ekweozor, C.M. (1990): First discovery of oil shale in the Benue Trough, Nigeria. *FUEL,* 69(4), pp. 502–508.

[5] Olajubaje, T.A., Akande S.O., Adeoye, J.A., Adekeye, O.A., Friedrich, C. (2018): Depositional Environments and Geochemical Assessments of the Bende Ameki Formation Potential as Petroleum Source Rocks in the Ogbunike Quarry, South-Eastern Nigeria. *European Scientific Journal*, 14, pp. 157–175.

[6] Nzekwe, I.E., Okoro, A.U. (2016): Organic and Trace Element Geochemistry of the Ameki Formation, South Eastern Nigeria: Implications and Hydrocarbon Generating Potential. *Journal of Applied Geology and Geophysics*, 4(4), pp. 12–20.

[7] Ehinola, O.A. (2002): *Depositional Environment and Hydrocarbon Potential of the Oil Shale Deposit from the Abakaliki Fold Belt, Southeastern Nigeria*. Ph. D. Thesis. University of Ibadan: Ibadan, 240 p.

[8] Petters, S.W., Ekweozor, C.M. (1982): Petroleum geology of Benue Trough and southeastern Chad basin, Nigeria. *Am. Assoc. Petrol. Geol. Bull*, 66, pp. 1141–1149.

[9] Murat, R.C. (1969): *Geological Data Book of Southern Nigeria,* Unpublished Report of Exploration Department of Shell-BP.C Nigeria, 26 p.

[10] Oluwajana, O.A., Ehinola, O.A., Okeugo, C.G., Adegoke O. (2017): Modelling hydrocarbon generation potentials of Eocene source rocks in the Agbada Formation, Northern Delta Depobelt, Niger Delta Basin, Nigeria. *Journal of Petroleum Exploration and Production Technology*, 7(2), pp. 379–388.

[11] Ehinola, O.A., Sonibare, O.O., Javie, D.M., Oluwole, E.A. (2008): Geochemical appraisal of organic matter in the mid-cretaceous sediments of the Calabar

Flank, Southeastern Nigeria. *Eur. J. Sci. Res.*, 4(23), pp. 567–577.

[12] Reyment, R.A. (1965): Aspects of the Geology of Nigeria. *Am. Assoc. Petrol. Geol. Bull*, 66, p. 1141.

[13] Short, K.C., Stauble, A.J. (1967): Outline of Geology of Niger Delta. *The American Association of Petroleum Geologists Bulletin*, 51, pp. 761–779.

[14] Underdown, R., Redfern, J. (2008): Petroleum generation and migration in the Ghadames Basin, North Africa: a two-dimensional basin-modeling study. *The American Association of Petroleum Geologists Bulletin,* 92(1), pp. 53–76.

[15] Tissot, G.P., Welte, D.H. (1984): *Petroleum Formation and occurrence*, 2nd edition, Springer: Berlin, 702 p.

[16] El Nady, M.M. Ramadan, F.S., Hammad, M.M., Lotfy, N.M. (2015): Evaluation of organic matters, hydrocarbon potential and thermal maturity of source rocks based on geochemical and statistical methods: Case study of source rocks in Ras Gharib oilfield, central Gulf of Suez, Egypt. *Egyptian Journal of Petroleum*, 24, pp. 203–211.

[17] Hunt, J. (1996): *Petroleum Geochemistry and Geology*, 2nd edition, W.H. Freeman and Company.

[18] Waples, D. (1985): *Geochemistry in Petroleum Exploration*. Inter. Human Resources and Develop. Co.: Boston, 232 p.

[19] Bustin, R.M. (1988): Sedimentology and characteristics of dispersed organic matter in Tertiary Niger Delta: Origin of source rocks in a deltaic environment: *The American Association of Petroleum Geologists Bulletin*, 72, pp. 277–298.

[20] Amer, A.M., Che, A.A. (2009): Characterization of the Black Shales of the Temburong Formation in West Sabah, East Malaysia. *European Journal of Scientific Research*, 30(1), pp. 79–98.

[21] Yahi, N., Schaefer, R.G., Littke, R. (2001): Petroleum generation and accumulation in the Berkine basin, eastern Algeria. *The American Association of Petroleum Geologists Bulletin*, 85(8), pp. 1439–1467.

[22] Benkhelil, J., Guiraud, M., Ponsard, J. F., Saugy, F. (1989): The Bornu Benue Trough, the Niger Delta and its Offshore: Tectono-sedimentary Reconstruction during the Cretaceous and Tertiary from Geophysical Data and Geology. In: *Geology of Nigeria*, Kogbe, C.A. (ed.). Elizabethan Publ. Co.: Lagos, pp. 277–309.

[23] Olade, M.A. (1975): Evolution of Nigeria's Benue Trough (Aulacogen): A tectonic model. *Geological Magazine*, 112(6), pp. 575–583.

[24] Nwachukwu, J.I. (1985): Petroleum prospects of the Benue Trough, Nigeria. *The American Association of Petroleum Geologists Bulletin*, 69(4), pp. 601–609.

[25] Kogbe, C.A., (1989): Paleogeographic History of Nigeria from Albian Times. *Geology of Nigeria*, pp. 257–274.

[26] Baggelaar, H., Van Morkhoven, F.P.C.N., Gutjahr, C.M. (1954): *Owerri Geological Report No 116 Compilation Paleontological and Biostratigraphical Results, Southern Nigeria*. Unpublished Shell Internal Report, 35 p.

[27] Odigi, M.I., Amajor, L.C. (2009): Brittle deformation of the Afikpo Basin, Southeastern Nigeria: evidence for a terminal Cretaceous extensional regime in the Lower Benue Trough. *China J. Geochem*., 28(4), pp. 369–376.

[28] Odigi, M.I. (2011): Diagenesis and reservoir quality of Cretaceous sandstones of Nkporo Formation (Campanian) southeastern Benue trough, Nigeria. *J. Geol. Min. Res*, 3(10), pp. 265–280.

[29] Sweeney, J.J., Burnham, A.K. (1990): Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *The American Association of Petroleum Geologists Bulletin*, 74, pp. 1559–1570.

[30] ÇiftÇi B., Temel, R., İztan, Y. (2010): Hydrocarbon occurrences in the western Anatolian (Aegean) grabens, Turkey: Is there a working petroleum system? *The American Association of Petroleum Geologists Bulletin*, 94(12), pp. 1827–1857.

[31] Agagu, O.K., Fayose, E.A., Peters S.W. (1985): Stratigraphy and sedimentology of the Senonian Anambra Basin of eastern Nigeria Nig. *Journ. Min. Geol*., 22, pp. 25–36.

[32] Ekine, A.S., Onuoha, K.M. (2010): Seismic Geohistory and Differential Interformational Velocity Analysis in the Anambra Basin, Nigeria. *Earth Sci. Res. J*., 14(1), pp. 88–99.

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Assessment and Analysis of Precambrian Basement Soil Deposits Using Grain Size Distribution

Ocena in analiza predkambrijskih nahajališč zemljin z uporabo porazdelitve velikosti zrn

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Abstract

The article presents the grain size distribution of soil samples from the Precambrian basement within the purview of the textural properties, deduced transportation history and the numerical assessments using statistical parameters. The fourteen soil samples collected from the study area were subjected to sieve analysis in the laboratory for the determination of their grain size distribution. The statistical parameters' study includes the graphic mean, skewness, sorting and kurtosis. The result of the analysis of the soil samples ranged from coarse to fine-grained samples, moderately and poorly sorted, positively and negatively skewed and the kurtosis also shows leptokurtic as the most dominant which suggests the samples poorly distributed and moderately sorted at the centre of the grain size distribution. These results also suggest the geological environment of the soil samples could be responsible for the poorly and moderately sorted exhibited by the samples deposited in the location.

Key words: Deposition, Grain size analysis, Kurtosis, Skewness, Provenance

Povzetek

Članek predstavlja porazdelitev velikosti delcev vzorcev zemljine iz predkambrijske osnove znotraj namena proučevanja teksturnih značilnosti, zgodovine transporta in numerične ocene z uporabo statističnih parametrov. Na štirinajsti vzorcev zemljine iz preiskovanega območja je bila opravljena laboratorijska sejalna analiza z namenom določitve porazdelitve velikosti delcev. Statistična parametrična raziskava vključuje: grafično srednjo vrednost, asimetrijo, razvrščanje in sploščenost. Rezultati granulometrične analize kažejo na grobe do fine vzorce zemljin, ki so srednje do slabo sortirane. Vzorci imajo pozitivno in negativno asimetrijo. Sploščenost kaže na najbolj pogosto koničasto porazdelitev, ki predlaga slabo porazdeljene in srednje sortirane vzorce v sredini porazdelitve velikosti delcev. Rezultati prav tako kažejo, da je geološko okolje vzorcev zemljine lahko razlog za slabo in srednjo sortiranost.

Ključne besede: odlaganje, preiskava velikosti delcev, sploščenost, asimetrija, poreklo

Introduction

The grain size analysis is one of the tests that can be performed to determine the percentage of different grain size contained within the soil. It provides very useful information on the classification of sedimentary environment and the transportation of the sediments. The grain size distribution provides good quantification for soil studies and reveals the weathering characteristics of sedimentary processes and provenance [1–4]. The results of Abuodha [5] have helped to clarify the sedimentary environment and its transport dynamism.

The benefits of mathematical representation of grain size analysis cannot be overemphasised which include the soil classification using the best-fit parameters. Second, the mathematical equation can be used as the basis for analysis related to estimating the soil–water characteristic curve. Third, a mathematical equation provides a method of representing the entire curve between the measured data points [6]. Representing the soil as a mathematical function also provides increased the flexibility in searching for similar soils in the database.

The development of computerized data analysis has enhanced the knowledge of the calculation of different statistical parameters to determine the transportation history of the sediments as in the kurtosis, the average size of grain, sorting and skewness. They are designated by different methods and characterised the particle-size distribution in sediments [7–9]. Various researchers [10–18] have established different formulae for the statistical parameters but the most widely used among the formulae are those proposed by Folk and Ward [19].

The measures of quartile, phi scale among others are some of the frequently used statistical measures of grain size distribution. Seven different points on the cumulative frequency curve are directly selected (at 5, 16, 25, 50, 75, 84 and 95 percentiles) for the computation of the parametric statistics [20]. Sediment transportation is the movement of organic or inorganic particles (sediments) by water, the sediments can also be carried by gravity, glaciers and fluid in which the sediment is entrained. Most mineral sediments are as a result of weathering and erosion [21]. Transportation of sediments was often responsible for the intermixing of geologic features by carrying mineral particles away from their origin [22].

According to Adegoke and Layade [23], a geophysical investigation had been carried out within Gbede, the study area which revealed the proximity of the iron ore in form of magnetite and hematite to the ground surface. Vents, supposedly the ore source, were also identified in the area which shows the presence of the ore in the area as a result of sediment transportation that took place for years irrespective of the geological constituent of the area. This research is aimed at analyzing the grain size of the soil samples collected from the study area in other to classify the samples based on their textural properties and determine the transportation history of the samples.

Geology and Description of the Study Area

The study area is located in Gbede of Surulere L.G.A of Oyo State, Southwest Nigeria. It is accessible through Ogbomoso – Gambari – Ilorin road, and is about 30 km from Ilorin Airport. The area is bounded within latitudes 8˚17’37.7” and 8˚17’49.8’’ North and between longitudes 4˚20’45.9’’ and 4˚20’58.8’’ East. It has an undulating topography with an average elevation of 370 m above the mean sea level. Past studies [24–25] have identified the hydrogeology of Sub-Saharan African as represented in Nigeria into four provinces; the Precambrian basement rocks, volcanic rocks, unconsolidated sediments and consolidated sedimentary rocks. However, the province of the Precambrian basement is located on the study area, and it comprises crystalline and metamorphic rocks.

Materials and Method

Sample Collection

Grain size analysis can be determined using various analytical techniques among which were sieving methods adopted for this research. The low investment, ease of handling and high accuracy make the sieve analysis a commonly used procedure to determine the soil texture. Fourteen fresh samples were collected at different locations using Soil Auger. This Auger used at a different point was properly rinsed before and after each sample collection for good analysis. A small polythene bag was used to transport the samples to the laboratory to begin the sieving procedure and further analysis. For proper identification, each polythene bag was labelled GB1 to GB14 (GB means Gbede, while the figures represent the number of strata being sampled).

Sieve Analysis

A weighing balance was used to weigh 100 g of each sample already arranged according to their depth. Since collected samples were fresh at the point of collection, it was then oven-dried at 70°C so that it will be free from trace moisture and thereafter passed through the mechanical sieving process using the Ro-tap shaker. The result of this sieving was tabulated and analysed. From the histogram chart, the cumulative frequency weight percent plotted against grain size (Phi) were generated and statistical parameters such as graphic mean, standard deviation skewness were computed from the graph. Seven points were identified as percentiles (5, 16, 25, 50, 75, 84 and 95 percentiles) and the results presented in Tables 1–6, respectively. The trend of grain size distribution was then determined from the total average value of each computed parameter. Appendices 1 and 2 represent the histogram and cumulative arithmetic curve plotted together from each sample.

Results and Discussion

Graphic Mean

Graphic mean is one of the statistical parameters to understand the transport history of the sediments. It depends on the size of available sediments and the amount of energy impacted to the sediments. The result of the classification of samples with graphic mean is presented in Table 1 while Figure 1 shows the variogram of the mean for the soil samples.

$$Mz = \emptyset \frac{16 + 50 + 84}{3} \quad (1)$$

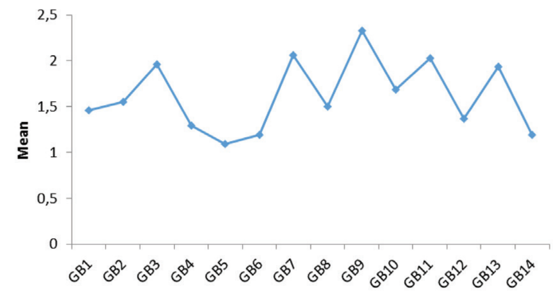

Figure 1: *Variogram of the mean for the sample location.*

Table 1: *Classification of the graphic mean.*

Graphic mean	Classification
Ø – 1 to Ø 0	Very coarse sand
Ø 0 to Ø 1	Coarse sand
Ø 1 to Ø 2	Medium sand
Ø 2 to Ø 3	Fine sand
Ø 3 to Ø 4	Very fine sand

On the basis of the classification of as given different researchers [26–28] and using Equation (1), the range from 1.09 to 2.33 was obtained and the average value for the distribution within the analysed samples was 1.61. The two sediments category identified from the study area were coarse-grained and fine-grained sediments. The range values of the coarse grained are from 0.6 to 1.0, which suggests the samples were transported farther than other groups, while the value of fine-grained samples is greater than 2 which is a result of low energy of transportation that is associated with coarse conglomeratic of soil [29].

Sorting (Standard Deviation)

Sorting indicates how effective the depositional medium in separating different classes of grains. The expression for graphic standard deviation is given in Equation (2) followed by its interpretation as shown in Table 2. According to [30], the various ranges of sorting in sandstones indicate the various environments of the sand.

$$\sigma_1 = \emptyset \frac{(84 - 16)}{4} + \emptyset \frac{(95 - 5)}{6.6} \quad (2)$$

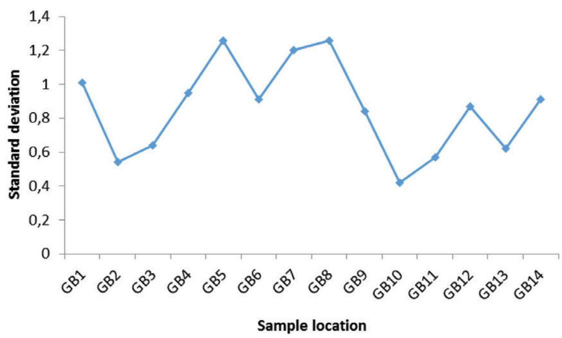

Figure 2: *Variogram of standard deviation of the soil samples.*

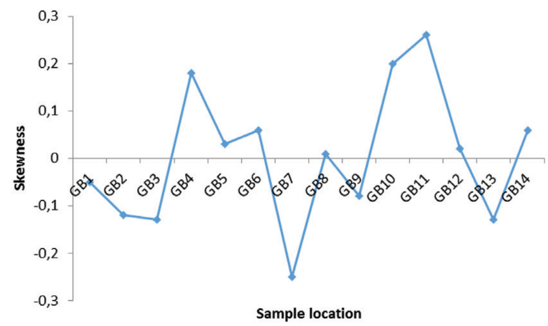

Figure 3: *Variogram of graphic skewness for the sample locations.*

Table 2: *Graphic Standard deviation with classes of sorting.*

Graphic Standard Deviation	Classes of Sorting
Ø 0.35 to Ø 0.50	well sorted
Ø 0.50 to Ø 0.71	moderately well sorted
Ø 0.71 to Ø 1.00	moderately sorted
Ø 1.00 to Ø 2.00	poorly sorted

Table 3: *Classification scale describing the skewness.*

Classification scale	Skewness
Ø 0.1 to Ø 0.3	Fine skewed
Ø −0.1 to Ø 0.1	Near symmetrical
Ø −0.3 to Ø −0.1	Coarse-skewed

Figure 2 shows the range of sorted values lies between 0.54 and 1.42. This statistical calculation revealed two different categories, namely moderately sorted and poorly sorted. But moderately sorted is the most dominant, suggesting the samples were transferred farther away from the point of collection. From the result, the classification class of 0.71–1.0 represented the moderately sorted grain, while the latter category is within the range of 1.0–2.0. The energy and transportation of sediment distance are all functions of the distance of sorting values; therefore, the more the sediment is transferred from the source, the more the sample is moderately sorted and the closer the sediments to the source, the poor the samples sorted.

Skewness

Another parameter for the transportation history of sediments is Skewness and its determined using Equation (3) with the results presented in Table 3. It simply determines or measures symmetry in the scatter of distribution as well as degree of lopsidedness of a curve (Figure 3). Skewness is directly related to the fine and coarse tails of the size distribution, and hence suggestive of energy of deposition.

$$S_{k1} = \frac{(\emptyset 16 + \emptyset 84 - 2\emptyset 50)}{2(\emptyset 84 - \emptyset 16)} + \frac{(\emptyset 5 + \emptyset 95 - 2\emptyset 50)}{2(\emptyset 95 - \emptyset 5)} \quad (3)$$

On the basis of the result of this parameter calculated, all the sediments are positively and negatively skewed. The values ranged from −0.01 to 0.26. The most significant classifications identified are near symmetrically skewed (from −0.1 to 0.1) and finely skewed samples ranged from 0.1 to 0.3. This is an indication that samples are transported from various sources. The positive and negative values are the confirmation that the sediments were transported to and away from the source.

Kurtosis

The kurtosis is the peakedness of the distribution and measures the ratio between the sort-

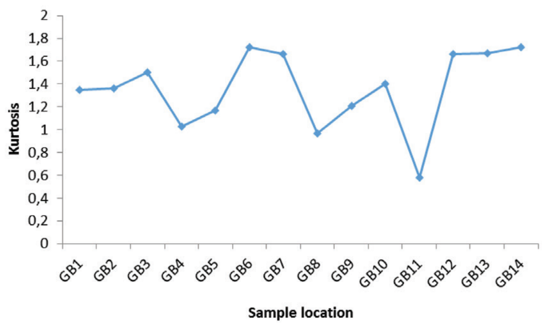

Figure 4: *Variogram of Kurtosis of sample location.*

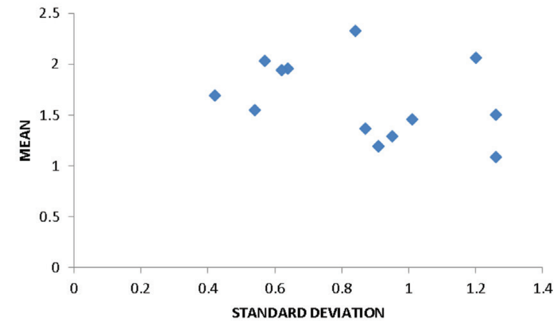

Figure 5: *Cross Plot of mean against standard deviation [30].*

Table 4: *Classification scale and description of Kurtosis.*

Classification scale	Kurtosis
<Ø 0.67	Very Platykurtic
Ø 0.67 to Ø 0.90	Platykurtic
Ø 0.90 to Ø 1.11	Mesokurtic
Ø 1.11 to Ø 1.50	Leptokurtic
Ø 1.50 to Ø 3.00	Very leptokurtic

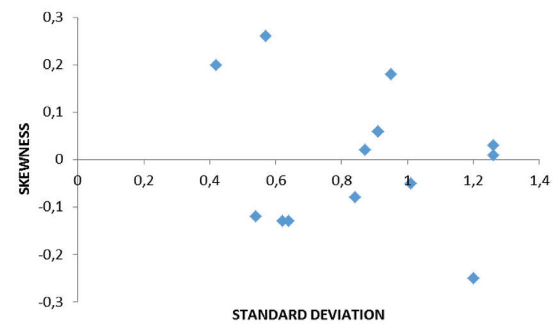

Figure 6: *Cross Plot of Skewness against standard deviation.*

ing in the tails and central portion of the curve as given by Equation (4). The result of the classification scale for kurtosis is presented in Table 4 while the range of Kurtosis is 0.58–1.72 as shown in Figure 4. From the classifications (platykurtic, leptokurtic, very leptokurtic and mesokurtic), the classes of leptokurtic are the most predominant in the study area with 50% of the samples. This implies the central portions are better sorted at the tails and strongly suggests that the samples are located at the water concentrated zone.

$$K_G = \frac{(\text{Ø}95 - \text{Ø}5)}{2.44(\text{Ø}75 - \text{Ø}25)} \qquad (4)$$

The Cross Plot Analysis

A graph of graphic mean values versus standard deviation, skewness against standard deviation as shown in Figures 5 and 6 respectively was used to determine the paleoenvironment of deposition of the soil samples from grain size analysis. Therefore, the graphical plots depict that all the samples analysed from the study

Table 5: *Comparative result of the Grain Size Analysis for soil samples in phi (Φ).*

Sample	Mean	STD	Skewness	Kurtosis
GB1	1.46	1.01	−0.05	1.35
GB2	1.55	0.54	−0.12	1.36
GB3	1.96	0.64	−0.13	1.50
GB4	1.29	0.95	0.18	1.03
GB5	1.09	1.26	0.03	1.17
GB6	1.19	0.91	0.06	1.72
GB7	2.06	1.20	−0.25	1.66
GB8	1.50	1.26	0.01	0.97
GB9	2.33	0.84	−0.08	1.21
GB10	1.69	0.42	0.20	1.40
GB11	2.03	0.57	0.26	0.58
GB12	1.37	0.87	0.02	1.66
GB13	1.94	0.62	−0.13	1.67
GB14	1.19	0.91	0.06	1.72
Average	**1.62**	**0.95**	**4.3E-3**	**1.36**

Table 6: *Description of the Soil samples with Grain Size Analysis.*

Sample points	Descriptions
GB1	Medium sand, poorly sorted, ear symmetrical and leptokurtic.
GB2	Medium sand, moderately well sorted, coarse-skewed and leptokurtic.
GB3	Medium sand, moderately well sorted, coarse-skewed and leptokurtic.
GB4	Medium sand, moderately sorted, fine skewed and mesokurtic.
GB5	Medium sand, poorly sorted, near symmetrical and leptokurtic.
GB6	Medium sand, moderately sorted, near symmetrical and very leptokurtic.
GB7	Fine sand, poorly sorted, coarse-skewed and very leptokurtic.
GB8	Medium sand, poorly sorted, near symmetrical and mesokurtic.
GB9	Fine sand, moderately sorted, near symmetrical and leptokurtic.
GB10	Medium sand, moderately sorted, fine skewed and leptokurtic
GB11	Medium sand, moderately sorted, near symmetrical and leptokurtic
GB12	Medium sand, moderately sorted, near symmetrical and very leptokurtic.
GB13	Medium sand, moderately well sorted, coarse skewed and very leptokurtic.
GB14	Medium sand, moderately sorted, near symmetrical and very leptokurtic.
Average	**Medium sand, moderately sorted, near symmetrical and leptokurtic**

area were deposited by the transitional environment of geological effects [31]. The multiple directional patters of the paleoenvironment of deposition of soil samples were suggested to be responsible for the moderately sorted impact on the soil samples.

Conclusion

The transportation history of the soil deposit of the Gbede area has been assessed and analysed using grain size distribution through statistical parameters of mean, standard deviation, skewness, kurtosis and cross plot analysis, respectively. The geological environment of the soil samples could be responsible for the poorly and moderately sorted characteristics, and near symmetrical and leptokurtic nature exhibited by the samples deposited in the location [32]. All locations are characterised by soil samples input from a mineral source.

Acknowledgement

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References

[1] Kranck, K., Milligan, T.G. (1985): Origin of grain size spectra of suspension deposited sediment. *Geo-Mari Letter*, 5, pp. 61–66.

[2] Kranck, K., Smith, P.C., Milligan, T.G. (1996a): Grain-size characteristics of fine-grained unflocculated sediments I: "one round" distributions. *Sedimentology*, 43, pp. 589–96.

[3] Lång, L.O., Stevens, R.L. (1999): Source, transport and weathering influences upon grain-size and heavy mineral trends in glacial deposits of south-western Sweden. *GFF*, 121(2), pp. 45–53.

[4] Kranck, K., Smith, P.C., Milligan, T.G. (1996b): Grain-size characteristics of fine-grained unflocculated sediments II: "multi round" distributions. *Sedimentology,* 43, pp. 597–606.

[5] Abuodha, J.O.Z. (2003): Grain Size Distribution and Composition of Modern Dune and Beach Sediments, Malindi Bay Coast, Kenya. *Journal of African Earth Sciences,* 36, pp 41–54.

[6] McLaren, P. (1981): An interpretation of trends in grain size measures. *Journal of Sedimentary Petrology,* 51, pp. 611–624.

[7] Folk, R.L. (1966): A review of grain-size parameters. *Sedimentology*, 6, pp. 3–93.

[8] Grzegorczyk,M.(1970):Metodyprzedstawianiauziarnieniaosadów [Methods of presentation of grain size distribution of sediments]. *PraceKomisji-Geograficzno-Geologicznej*, 10(2), pp. 38–40.

[9] Racinowski, R., Szczypek, T., Wach, J. (2001): Prezentacja i interpretacja wyników badań uziarnienia [Presentation and interpretation of the grain-size distribution of Quaternary sediments]. University of Silesia Press, Katowice, 146 pp.

[10] Trask, P.D. (1932): Hydrological investigative work by petroleum companies. *Transactions, American Geophysical Union,* 13(1), pp. 306–307, doi: 10.1029/TR013i001p00306.

[11] *Krumbein*, W.C., Pettijohn, F.J. (*1938*): *Manual of Sedimentary Petrography*. Appleton Century Crofts: New York, 549 p.

[12] [12] Otto, G.H. (1939): A modified logarithmic probability graph for the interpretation of mechanical analyzes of sediments. *Journal Sedimentary Petrology*, 9, pp. 62–72.

[13] Dudley, R.J. (1977): The Particle Size Analysis of Soils and its Use in Forensic Science - The Determination of Particle size Distribution within the Silt and Sand Fractions. *Journal of the Forensic Science Society*, 16, pp. 219–229.

[14] Inman, D.L. (1952): Measures for describing size of sediments. *Journal of Sedimentary Petrology*, 19, pp. 51–70.

[15] McCammon, R.B. (1962): Efficiencies of percentile measures for describing the mean size and sorting of sedimentary particles. *Journal of Geology,* 70, pp. 453–465.

[16] Kane, W.T., Hubert, J.F. (1962): FORTRAN program for the calculation of grain-size textural parameters on the IBM 1620 computer. *Sedimentology*, 2, pp. 87–90.

[17] Sawyer, M.B. (1977): Computer program for the calculation of grain-size statistics by the method of moments: U.S. Geological Survey Open-File Report 77–580, 15 p.

[18] Gupta, S.C., Larson, W.E. (1979b): A model for predicting packing Density of soils using particle-size distribution. *Soil Science Society of America Journal*, 43, pp. 758–764.

[19] Folk, R.L., Ward, W.C. (1957): Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology,* 27, pp. 3–26.

[20] Folk, R.L. (1974): *The petrology of sedimentary rocks*. Hemphill Publishing Co.: Austin, Texas, 182 p.

[21] Nichols, G. (1999): *Sedimentology and Stratigraphy*. Blackwell Science Ltd.: Oxford. 355 p.

[22] Czuba, J.A., Magirl, C.S., Czuba, C.R., Grossman, E.E., Curran, C.A., Gendaszek, A.S., Dinicola, R.S. (2011): Sediment load from major rivers into Puget Sound and its adjacent waters: *U.S. Geological Survey Fact Sheet 2011–3083*, 4 p.

[23] Adegoke, J.A., Layade, G.O. (2019): Comparative depth estimation of iron-ore deposit using the Data-Coordinate Interpolation Technique for airborne and ground magnetic survey variation. *African Journal of Science, Technology, Innovation and Development*, 11(5), 663–669, doi: 10.1080/20421338.2019.1572702.

[24] Alagbe, O.A. (2005): *Integration of Electrical Resistivity Techniques and Lineament analysis in Hydrogeological investigation of parts of Ogbomoso, South – Western Nigeria*. M. Tech Thesis. Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

[25] MacDonald, A.M., Davies, J. (2000): A brief review of groundwater for rural water supply in Sub-Saharan Africa. *B.G.S. Technical Report.* W.C./00/33.

[26] Udden, J.A. (1914): Mechanical composition of clastic sediments. *Bulletin of the Geological Society of America,* 25, pp. 655–744.

[27] Brown, A.G., (1985): Traditional and multivariate techniques in the interpretation of floodplain sediment grain size variations. *Earth Surface Processes and Landforms*, 10, pp. 281–291.

[28] Wentworth, C.K. (1922): A scale of grade and class terms for clastic sediments. *Journal of Geology,* 30, pp. 377–392.

[29] Murray, R.C., Solebello, L.P. (2002). In: *Forensic Science Handbook (volume I)*, Saferstein R. (ed.). Prentice-Hall: Upper Saddle River, New Jersey.

[30] Friedman, G.M. (1962): On sorting, sorting coefficients, and lognormality of the grain size distribution of sandstone. *Journal of Geology*, 70, pp. 737–756.

[31] Gupta, S.C., Larson, W.E. (1979a): Estimating soil-water retention Characteristic from particles size distribution, of organic matter percent, and bulk density. *Water Resources Research,* 15(6), pp. 1633–1635.

[32] Passega, R. (1964): Grain size representation by CM patterns as a geological tool. *Journal of Sedimentary Petrology*, 34, p 4.

APPENDIX 1: Typical result of sieve analyzes for sample points GB1 and GB2.

Sample No: GB1
Raw Wt: 100 grammes
Total Wt: 99.93 grammes
Loss (grammes): 0.07 grammes

Sieve {mm}	Phi {ø}	Raw wt or individual {gm.}	Corrected wt {g}	Cum wt {g}	Cum wt {%}	Ind wt {%}
2.00	-1.00	2.80	2.80	2.80	2.80	2.80
1.18	-0.25	6.80	6.80	9.61	9.61	6.80
0.85	0.25	1.11	1.11	10.71	10.72	1.11
0.60	0.75	11.60	11.60	22.31	22.33	11.61
0.425	1.25	22.15	22.15	44.46	44.49	22.17
0. 30	1.75	21.58	21.61	66.07	66.12	21.62
0.25	2.00	10.50	10.51	76.58	76.63	10.52
0.15	2.75	11.94	11.92	88.50	88.60	11.93
0.10	3.25	10.45	10.40	98.90	98.97	10.41
0.075	3.75	0.32	0.32	99.22	99.30	0.32
0.063	4.00	0.300	0.31	99.53	99.60	0.31
Pan	-	0.40	0.40	99.93	100.00	0.40

Sample No: GB2
Raw Wt: 100 grammes
Total Wt: 99.92 grammes
Loss (grammes): 0.08 grammes

Sieve {mm}	Phi {ø}	Raw wt or individual {gm.}	Corrected wt {g}	Cum wt {g}	Cum wt {%}	Ind wt {%}
2.00	-1.00	0.30	0.30	0.30	0.30	0.30
1.18	-0.25	1.26	1.26	1.56	1.56	1.26
0.85	0.25	2.00	2.01	3.57	3.57	2.01
0.60	0.75	4.13	4.12	7.69	7.70	4.12
0.425	1.25	17.40	17.45	25.14	25.16	17.46
0. 30	1.75	36.60	36.65	61.79	61.84	36.68
0.25	2.00	25.27	25.27	87.06	87.13	25.30
0.15	2.75	9.90	9.91	96.97	97.05	9.92
0.10	3.25	0.95	0.94	97.91	97.99	0.94
0.075	3.75	0.50	0.50	98.41	98.49	0.50
0.063	4.00	0.61	0.61	99.02	99.90	0.61
Pan	-	0.91	0.90	99.92	100.00	0.90

APPENDIX 2: Typical results of histogram and frequency cumulative curve of different points.

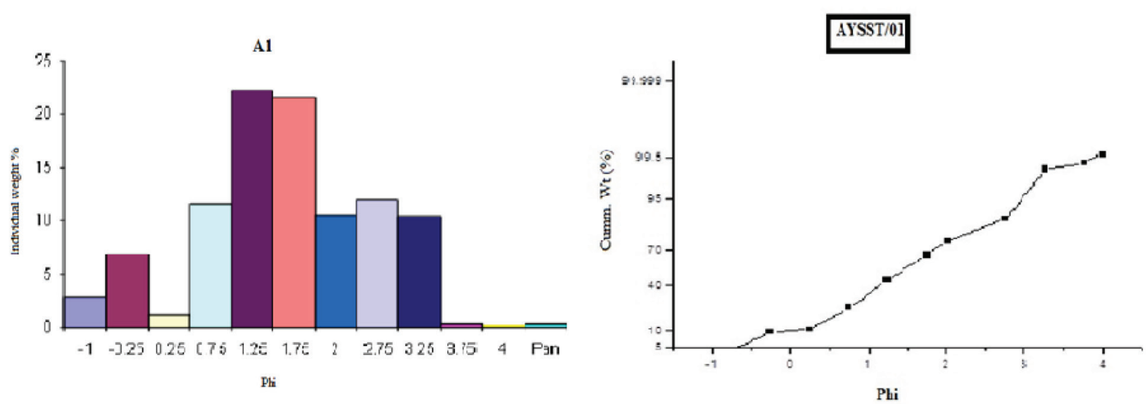

Figure 1: *Histogram and frequency Cummulative curve for sample GB1.*

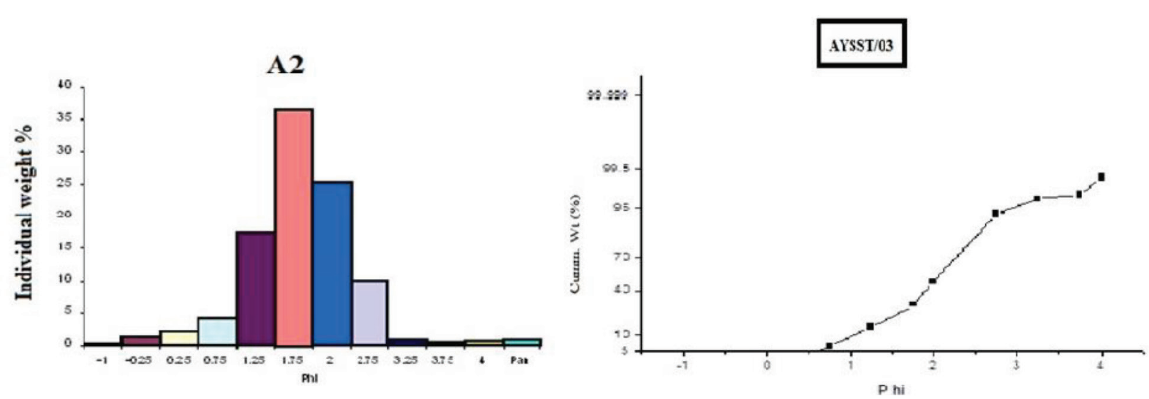

Figure 2: *Histogram and frequency Cumulative curve for sample GB2.*

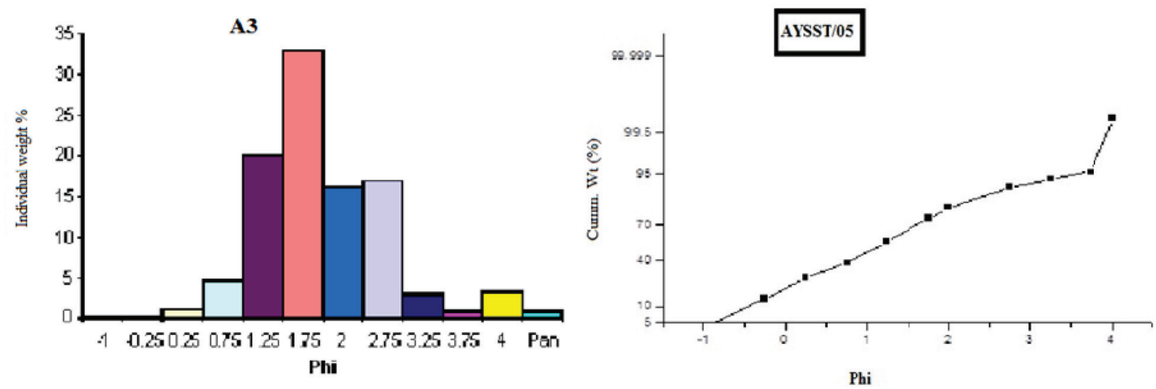

Figure 3: *Histogram and frequency Cumulative curve for sample GB3.*

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Spatial Resistivity Mapping of Ureje Dam Floor, Southwestern Nigeria

Prostorsko upornostno kartiranje dna jezu Ureje, JZ Nigerija

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Abstract
Ureje Dam, Ado-Ekiti has witnessed drastic reduction in the water storage capacity of its reservoir. It became imperative to determine the possible cause(s) of the reduction in storage capacity. Geophysical investigation involving the vertical electrical sounding technique of the electrical resistivity method was conducted in the upstream part of the dam. Five lithologic units that include the mud/suspended materials, such as sandy clay, clay, weathered/fractured bedrock and fresh bedrock, were delineated. The respective resistivity and thickness range of the units are 2–19 ohm-m; 147–206 ohm-m, 2–38 ohm-m; 47–236 ohm-m and 455–1516 ohm-m and 0.4–1.9 m; 0.5–2.5 m; 1.0–12.2 m; 7.3–16.4 m and ∞. The thickness of suspended materials, resistivity/thickness of weathered layer and the presence of near-surface impervious layer were used as the main indices for the spatial demarcation of the dam axis in terms of vulnerability to loss of impounded water. Using the cumulative response of the indices, the study concluded that the eastern to southeastern parts of the dam axis showed the highest indications of vulnerability to loss of impounded water.

Key words: Drastic reduction, vulnerability, spatial demarcation, impounded water.

Povzetek
Jez Ureje na območju Ado-Ekiti se sooča z drastičnim zmanjšanjem kapacitete zadrževanja vode. Določitev mogočih vzrokov za zmanjšanje kapacitete zadrževanja je postalo nujno. V gor-vodnem delu jezu so bile izvedene geofizikalne preiskave z navpičnim električnim sondiranjem. Razmejenih je bilo pet litoloških enot, ki so vključevale blato/suspendirane materiale; peščeno glino; glino; preperelo/razpokano podlago in svežo podlago. Pripadajoče upornosti in debeline plasti za omenjene enote so 2–19 ohm-m; 147–206 ohm-m, 2–38 ohm-m; 47–236 ohm-m in 455–1516 ohm-m ter 0.4–1.9 m; 0.5–2.5 m; 1.0–12.2 m; 7.3–16.4 m in ∞. Debelina suspendiranih materialov, upornost/debelina preperele plasti in prisotnost neprepustne plasti blizu površine so bili uporabljeni kot glavni indeksi za prostorsko razmejitev osi jezu v smislu ranljivosti glede izgube zajezene vode. Z uporabo kumulativnih odzivov indeksov preiskava zaključuje, da vzhodni do jugovzhodni deli osi jezu kažejo najvišje znake ranljivosti na izgubo zajezene vode.

Ključne besede: drastično znižanje, ranljivost, prostorska razmejitev, zajezena voda.

Introduction

Ureje dam, Ado-Ekiti was constructed over 50 years ago with the sole aim of providing potable water for the populace of Ado-Ekiti and its environs. At construction, the dam lake had an initial production capacity of 10,000 m^3 volume of water per day. The production capacity has, however, dwindled over the years and has reduced abysmally in recent times. This research aims to investigate the possible cause(s) for the reduction in reservoir water, which has negative impact on the living standard of the people. Dam lake floors are susceptible to the accumulation of sediments after several years of construction. This is due to the transportation of sediments through the streams and rivers that serve as feeders to the lake. The volume of sediments deposited is a function of the rate of flow of the streams and the progressive deposition increases the volume of sediments in the dam lake floor [1].

The initial storage capacity and functions of the dam reservoir have been compromised by the increase in the volume of sediments with the attendant reduction in the production capacity of the dam. Unpublished reports from local fishermen at the Ureje dam site indicate that there has been a rise in the level of the dam floor in some portions of the dam lake. This rise in the level of the dam floor could be attributed to the appreciable deposition of sediments. Apart from the accumulation of sediments, the nature of subsurface materials and anomalous seepages may contribute to the loss of dam reservoir water [2–4]. Subsurface geologic structures such as faults, fracture zones, basement depressions, and so on, if present beneath, a dam reservoir floor may also inhibit the storage capacity of the dam reservoir [5–8].

Geophysical methods, especially the electrical resistivity (ER) method, have been used in dam site investigation [2, 3, 9, 10, 11]. ER method is a non-destructive technique that is capable of detecting internal erosion processes and detection of anomalous seepage [12–14] during pre-construction feasibility studies, post-construction integrity assessment and post-failure investigations. ER method has proven its performance and adequacy in the characterization of the potential paths of water seepage from dams [10, 12]. For example, [15] successfully carried out geophysical surveys at the Marathon Dam site near Athens, Greece, to detect possible degraded areas that are potentially liable to water infiltration or leakage. They also evaluated the dynamic properties of the subsurface materials and evaluated the quality of the concrete in the dam interior using this technique. [16] employed geoelectrical measurement to identify seepages through embankments and dams. [17] successfully used electrical resistivity tomography (ERT) technique at Abu Baara earth dam in northwestern Syria to delineate potential pathways of leakage that occur through the subsurface structure close to the body of the dam. [18] investigated water seepage of earth dams in Cordeirópolis, São Paulo in Brazil using the direct current ERT technique with Wenner electrode array configuration.

This study, therefore, aims at investigating the upstream part of the Ureje dam floor to unravel the subsurface features that may be undermining the production capacity of the dam.

Location, Geology and Geomorphology

Ureje Earth Dam is located in Ado-Ekiti, Ado Local Government Area of Ekiti State, Southwestern Nigeria. The geographic coordinates of the dam site are between latitude 7^{o} 35.74′ and 7^{o} 36.26′ N of the equator and longitude 5^{o} 12.45′ and 5^{o} 13.01′ E of the Greenwich meridian (Figure 1).

Geologically, the dam site lies on charnockite (Figure 2), a member of the Precambrian Basement Complex rocks of Southwestern Nigeria. Although the rock is concealed within the immediate vicinity of the dam, charnockites are classified in terms of structures as gneissic charnockites, foliated charnockites and coarse-grained charnockites [19].

The topography at the site is gently undulating with elevation above mean sea level varying between 400 m and 418 m. The surrounding hills roll towards the dam artificial lake. The area surrounding the dam site is covered with thick vegetation typical of the tropical rain forest vegetation belt of Nigeria. Two seasons occur in the area, namely the wet season

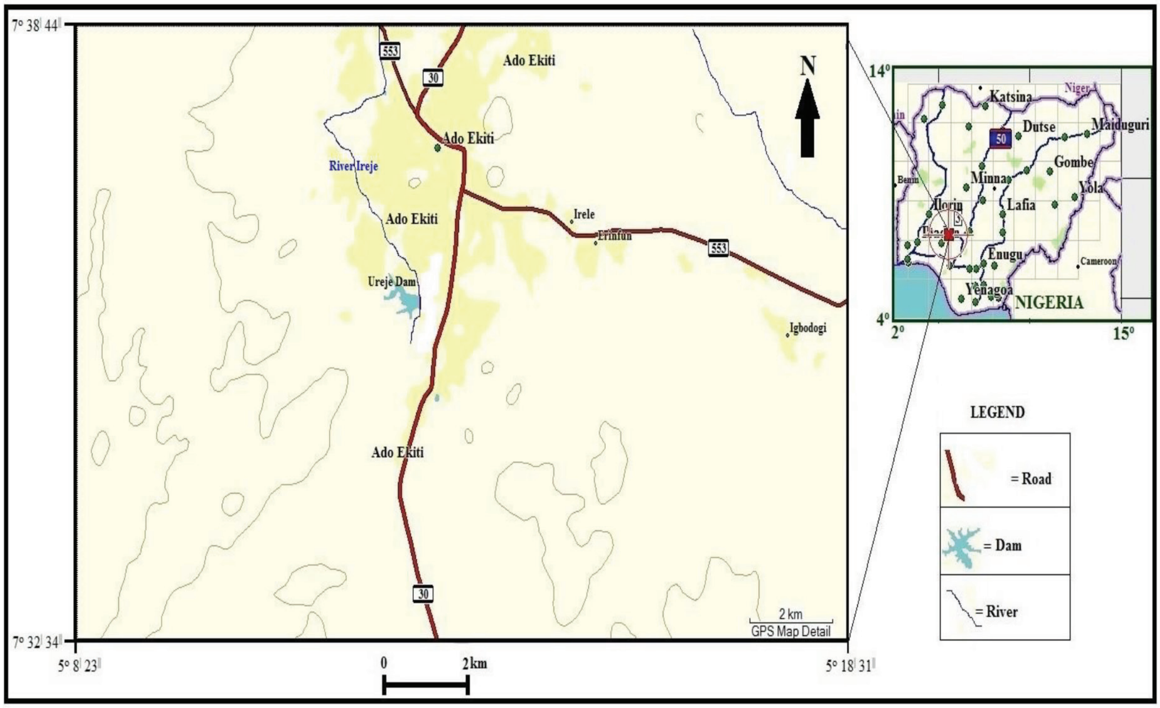

Figure 1: *Location Map of the Study Area.*

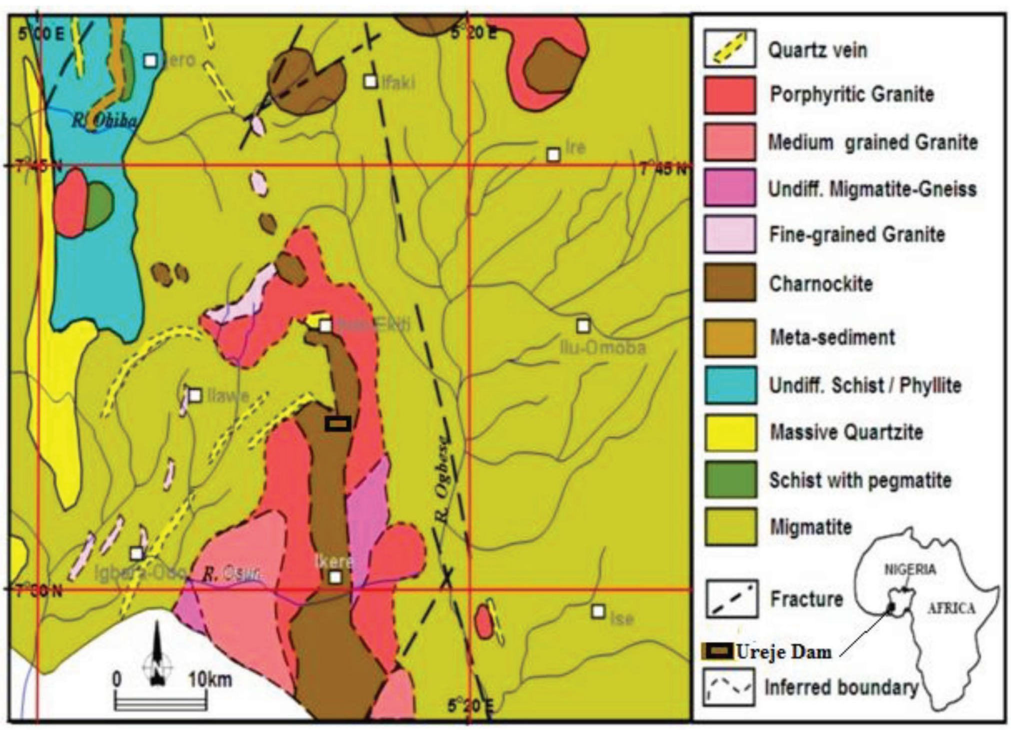

Figure 2: *Geological Map of the Area Around Ado-Ekiti Showing the Ureje Dam site (After [20]).*

(April–October) and the dry season (November–March).

Methodology

The ER method of geophysical prospecting was used in this study. The vertical electrical sounding (VES) technique, which involved the use of the Schlumberger electrode array, was adopted. Twenty-five (25) VES stations were occupied (Figure 3) and the half current electrode spacing (AB/2) varied from 1 to 50 m. The geographic coordinates of the VES locations were taken using the Garmin® Global Positioning System (GPS). All measurements were taken on the dam floor with the aid of three wooden canoes on which measuring apparatus was mounted. VES data were processed by plotting apparent resistivity against half-current electrode spacing (AB/2). The resulting depth sounding curves were interpreted qualitatively by visually inspecting them for classification. The quantitative interpretation involved segment-by-segment matching of field curves with master curves and auxiliary point charts. The parameters obtained from that process were used to constrain the 1-D computer-aided forward modelling on the IPI2Win® platform. The smoothed geoelectric parameters obtained from the iteration process were thereafter used to generate 2-D geoelectric sections in which deduced geoelectric/lithologic units were correlated. The same parameters were also spatially interpolated, and relevant maps were generated.

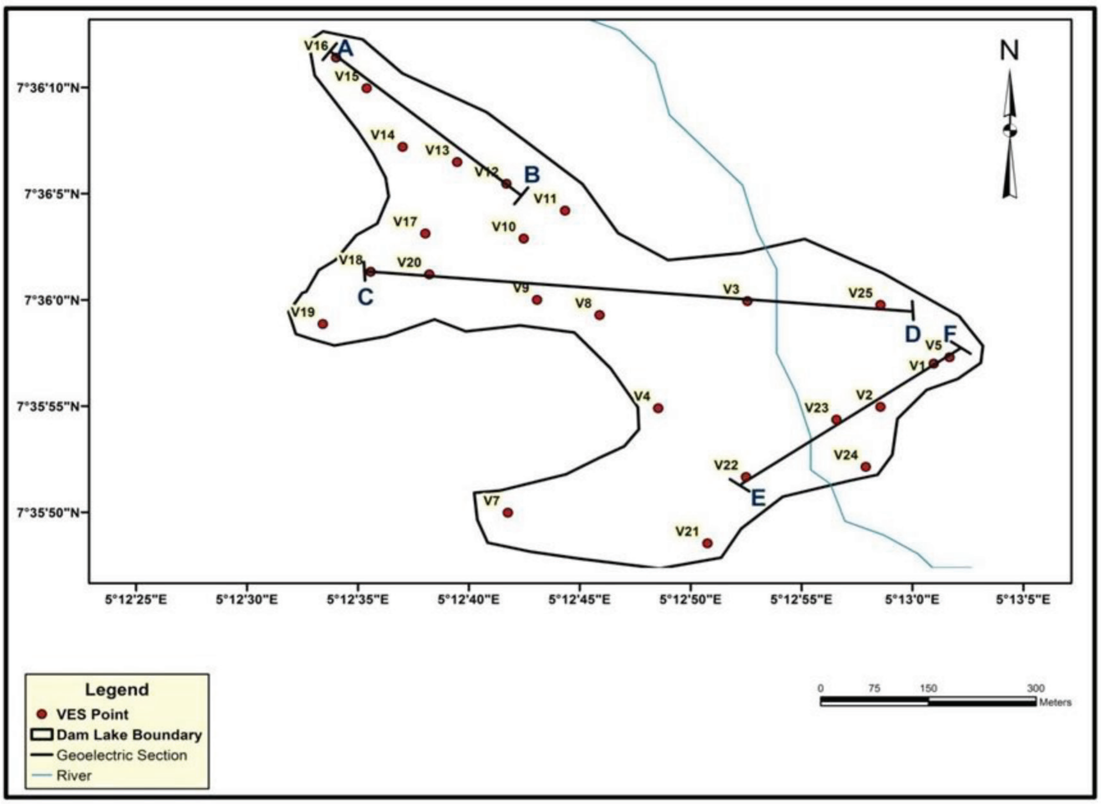

Figure 3: *Geophysical Data Acquisition Map.*

Results and Discussion

Depth Sounding Curves

The interpreted depth sounding curves (Figure 4a–d) in the dam lake shows that they are characterised by 3–5 geoelectric layers. The lithology is generally made up of mud/suspended materials, sandy clay, clay, weathered/fractured bedrock and fresh bedrock. The curve types include A, K, KH and KHA with A–type

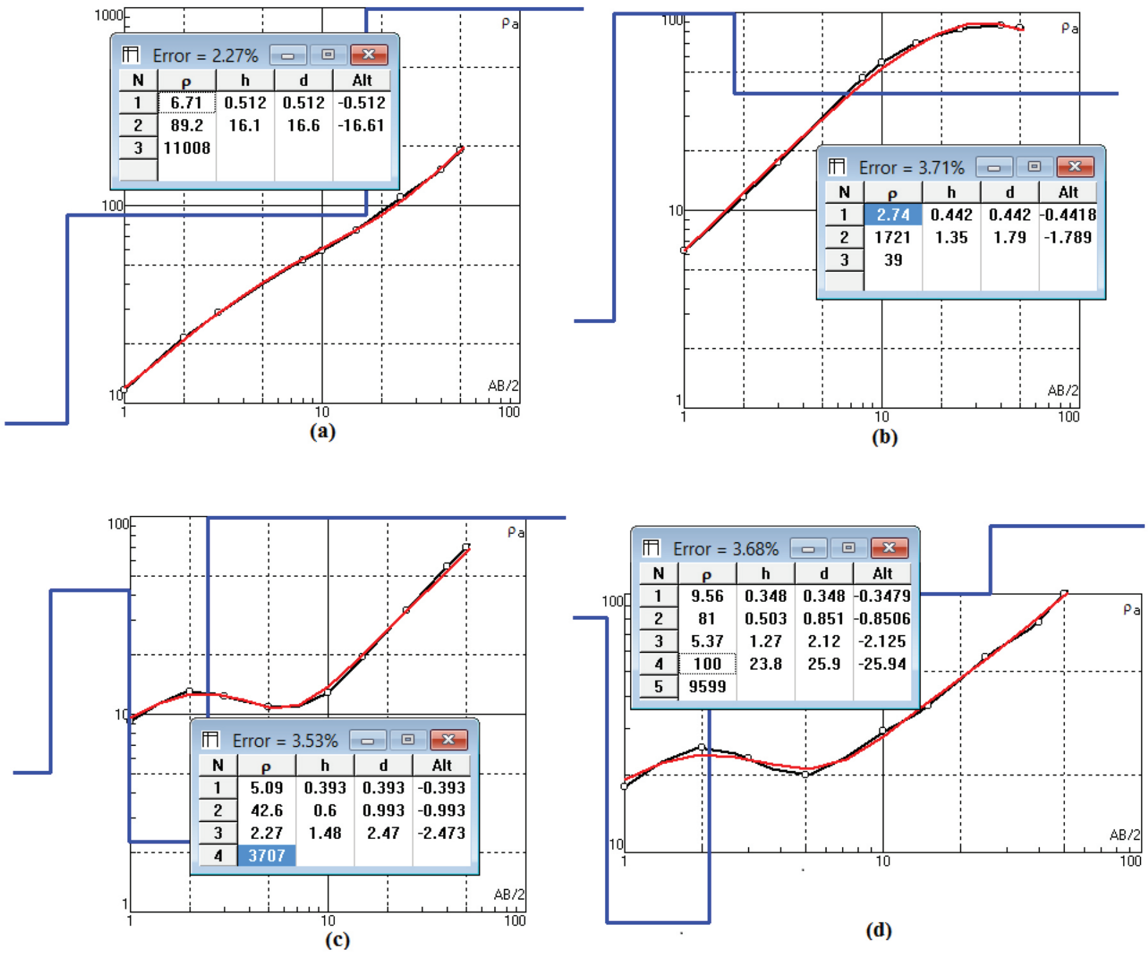

Figure 4: *Typical Depth Sounding Curves. (a) A – Type, (b) K – Type, (c) KH – Type and (d) KHA – Type.*

Table 1: *Colour Chart of the Distribution of the Depth Sounding Curves.*

VES LOCATIONS			KEY	
1	10	19	$p_1 > p_2 > p_3$	= A-Type Curve
2	11	20	$p_1 \langle p_2 \rangle p_3$	= K-Type Curve
3	12	21	$p_1 \langle p_2 \rangle p_3 p_4$	= KH-Type Curve
4	13	22	$p_1 \langle p_2 \rangle p_3 < p_4 < p_5$	= KHA-Type Curve
5	14	23		
6	15	24		
7	16	25		
8	17			
9	18			

curve being the dominant curve. The summary of the VES type-curves and their distribution within the 25 sounded positions are presented in Table 1.

Geoelectric Sections

The geoelectric sections (Figure 5a–c) generated from approximately linearly existing VES locations show that there are a maximum

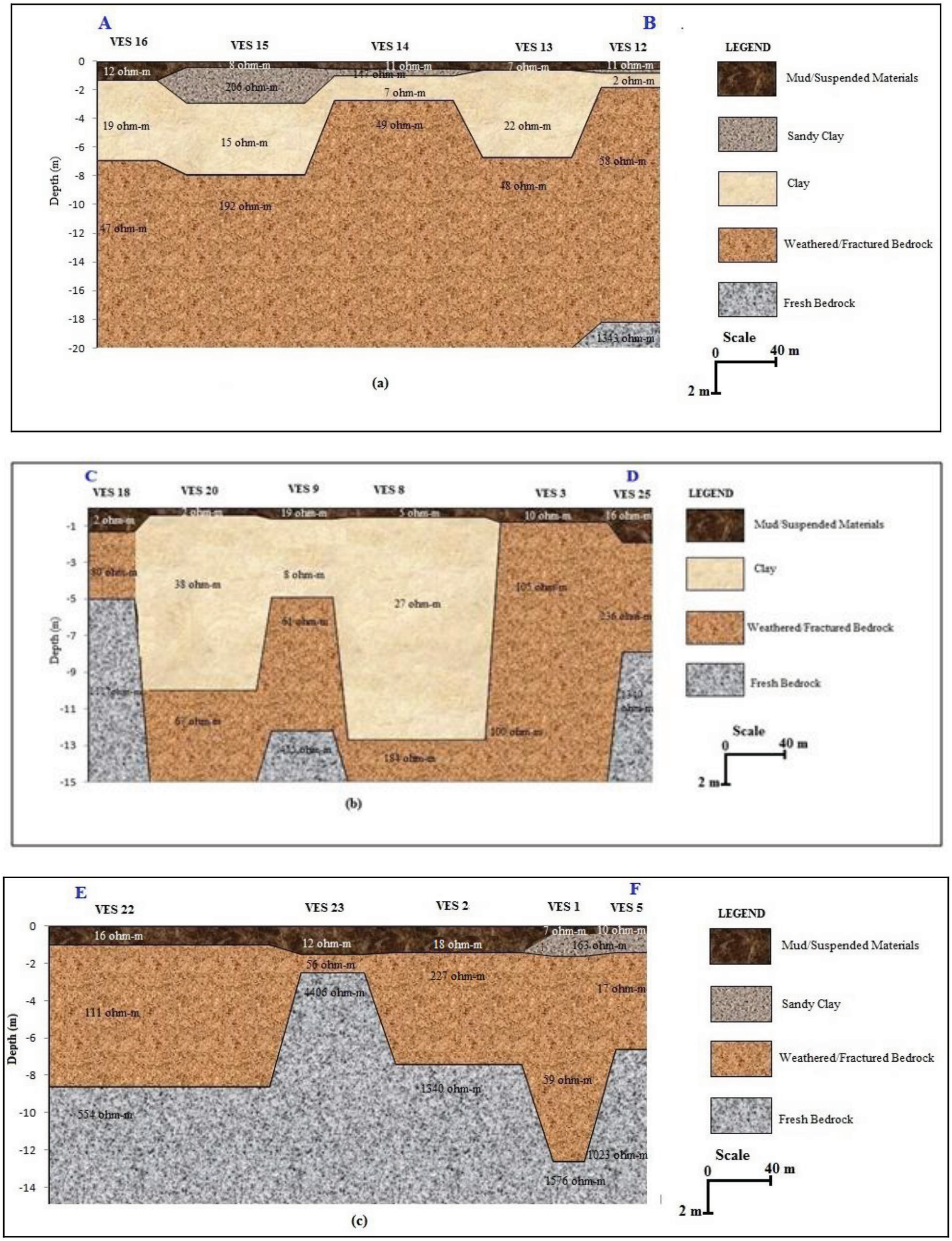

Figure 5: *Geoelectric Sections Beneath the Dam Floor (a) Section A – B (b) Section C – D, (c) Section E – F.*

of five (5) geoelectric units beneath the Ureje dam lake. The geoelectric units were calibrated in terms of apparent resistivity and five lithologic units were identified. The lithologic units, in order of their occurrence, include mud/suspended materials, sandy clay, clay, weathered/

fractured bedrock and fresh bedrock. Each of the lithologic units has their implication(s) on the overall storage capacity of the dam reservoir. The mud/suspended materials is characterised by resistivity values generally less than 20 ohm-m and its thickness varies from 0.4–1.9 m. An increase in the cumulative volume of the mud/suspended materials could inhibit the storage capacity of the reservoir.

The sandy clay layer with resistivity values greater than 100 ohm-m present in VES 12, 14 and 15 (Figure 5a) and VES1 and 5 (Figure 5c) constitutes a liability to the reservoir. This is because the relatively high porosity associated with sandy clay materials can enhance the seepage of impounded water into the subsurface. On the other hand, the clay unit where significantly thick, (Figure 5a and 5b) is advantageous to the dam reservoir as it will inhibit the percolation of water into the subsurface due to very poor permeability characteristics of the clay materials.

The weathered/fractured bedrock unit is a threat to any engineering structure/facility due to its incompetent nature. The threat becomes greater when it is near the surface and is not overlain by any impervious medium as found in Figure 5c and some portions of Figure 5b. Also, the weathered/fractured bedrock is an aquiferous unit in a typical Basement Complex environment, and as such, the Ureje dam lake may be losing water to the groundwater in zones associated with near-surface weathered/fractured bedrock and without overlying impervious layers.

The fresh bedrock is a relatively resistive layer with impervious characteristics. The bedrock ordinarily has the capacity to support the foundation of any engineering structure especially containment facilities such as dams. However, the potential could be inhibited if it is deeply seated and with undulating topography – most especially depressions. The basement bedrock beneath the Ureje dam as seen in Figure 5a to 5c is generally deeply seated with exceptions of VES 18 and VES 23. The depth of occurrence of the bedrock varies between 7 m and 18 m and as such has minimal importance as far as the containment of impounded water is concerned.

Spatial Vulnerability Indices

The general vulnerability of the Ureje dam lake to reduction in volume/loss of impounded water was assessed using three main indices [9, 10] which include:

i. the thickness of suspended materials,
ii. the resistivity of weathered layer,
iii. the presence of near-surface impervious (clay) layer.

The dam lake was demarcated based on the thickness of suspended materials, such that areas having thicknesses less than the mean thickness (0.77 m) of suspended materials under the bluish colour band in Figure 6 are classified as having a low vulnerability to the reduction in volume/loss of impounded water. Areas having thickness values greater than 0.77 m (identified by the reddish colour band) are classified to be highly vulnerable to loss of impounded water.

As shown in Figure 7, areas within the dam lake characterised by weathered layer resistivity values greater than 100 ohm-m are classified to have a higher vulnerability to the loss of impounded water due to the sandy nature of the weathered materials inferred from the resistivity values. However, areas under the greenish colour band associated with relatively low resistivity values possess low vulnerability to loss of impounded water.

As mentioned earlier, the presence of a near-surface impervious (clay) layer beneath a dam lake has the potential to inhibit the percolation of impounded water into the subsurface. Zones devoid of clay substratum (purple colour band) in Figure 8 are classified to possess high vulnerability. Other areas are potentially less prone to loss of impounded water due to the presence of clay.

Cumulative Spatial Vulnerability Assessment

The indices earlier discussed were spatially overlaid to generate the cumulative index map (Figure 9) of the dam lake to assess its general vulnerability to loss of impounded water. The map shows that the eastern to southeastern portions of the dam lake constitute zones with the highest indications of high vulnerability to loss of impounded water. Such zones are also present in other locations within the lake. It is interesting to note that the zones are mainly as-

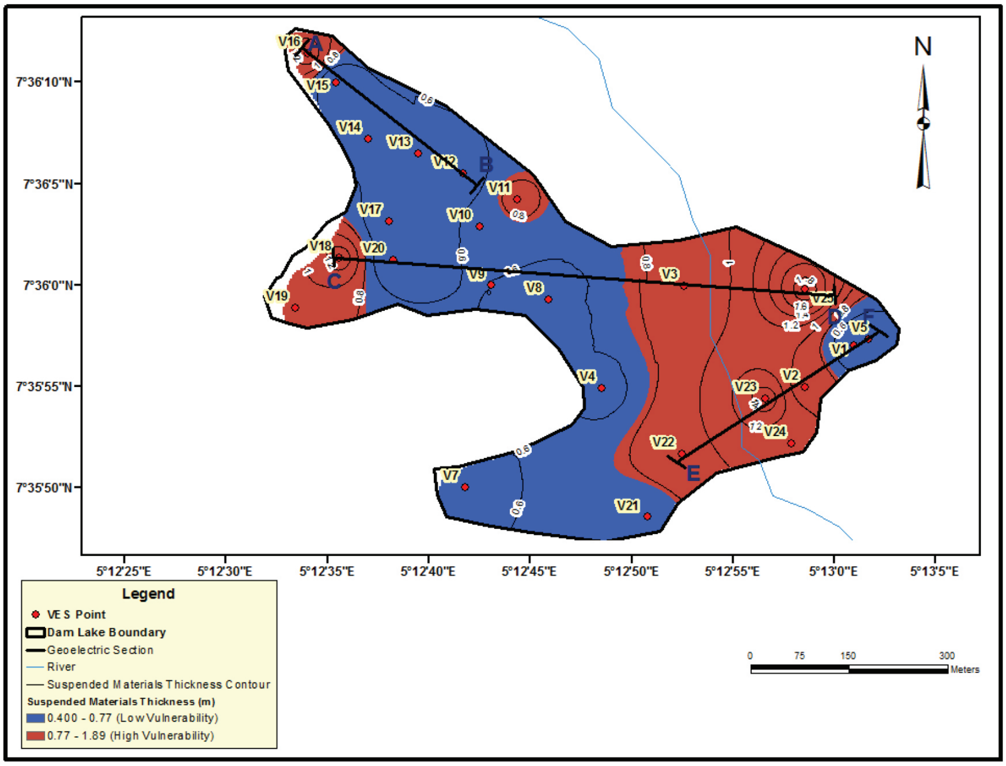

Figure 6: *Spatial Vulnerability Assessment from Thickness of Suspended Materials.*

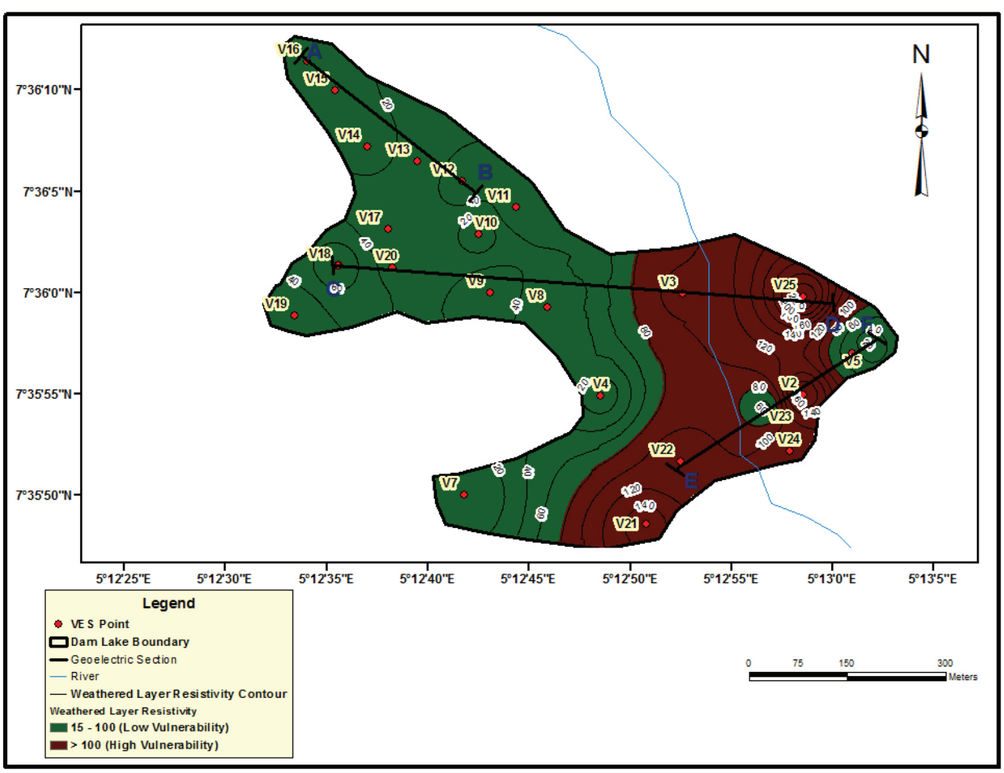

Figure 7: *Spatial Vulnerability Assessment from Resistivity of Weathered Layer.*

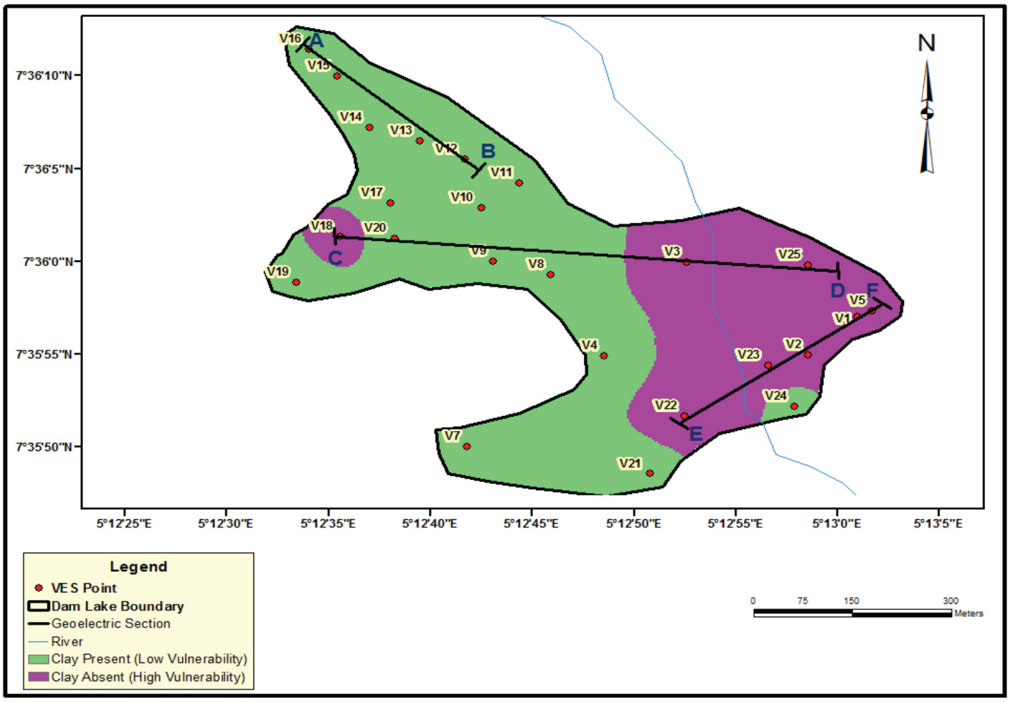

Figure 8: *Spatial Vulnerability Assessment from Presence of Near-surface Clay Substratum.*

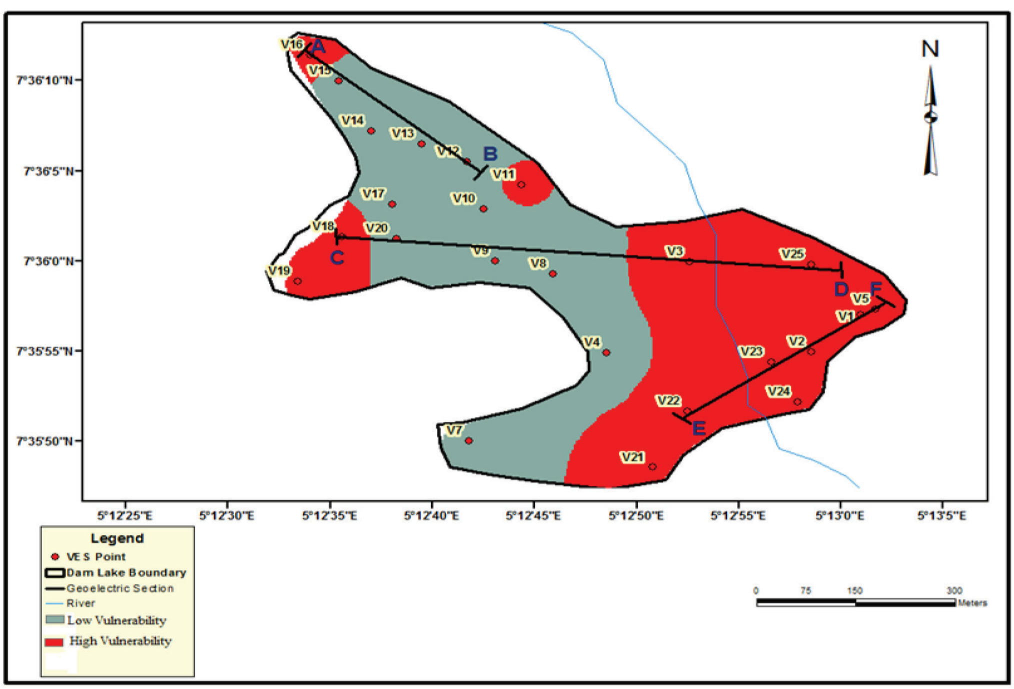

Figure 9: *Cumulative Spatial Vulnerability Map.*

sociated with the boundaries of the lake with most occurring around the water intake section through which the river straddles. On the other hand, areas under the bluish colour band represent zones adjudged to be less prone to the loss of impounded water as far as the indices deployed are concerned.

Conclusions

The cause of the drastic drop in the quantity of impounded water in the Ureje dam lake in Ado-Ekiti southwestern Nigeria has been investigated using the ER method of geophysical prospecting. The VES field technique was deployed via the Schlumberger electrode array. Twenty-five locations were depth sounded within the dam lake, and three geoelectric sections were constructed to cut across a sizeable number of VES locations for correlating their resistivity parameters. Five subsurface geoelectric layers were delineated within the lake. These include the mud/suspended materials, sandy clay, clay, weathered/fractured bedrock and the fresh bedrock. The thickness of the suspended materials, weathered layer resistivity and the presence of near-surface clay substratum were used as the main indices for the loss/reduction in the volume of impounded water. Areas classified as having high vulnerability to the loss of impounded water are those having attributes such as the thickness of suspended materials greater than the mean thickness of 0.77 m; weathered layer resistivity greater than 100 ohm-m and absence of near-surface clay substratum. On the other hand, zones characterised by a thickness of suspended materials less than the mean thickness of 0.77 m; low resistivity values and presence of clay substratum were considered to be less prone to the loss of impounded water. The general characteristics of the vulnerability indices indicated that the eastern–southeastern axis and some localised zones of the dam lake possess the highest cumulative vulnerability to the loss/reduction in the quantity of impounded water. Conclusively, therefore, the Ureje dam lake may have been losing most of its impounded water in the eastern–southeastern areas of the dam lake.

References

[1] Snyder, N.P., Rubin D.M., Alpers C.N., Childs J.R., Curtis J.A., Flint L.E., Wright S.A. (2004): Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California. *Water Resources Research*, 40(11), W11301, doi:10.1029/2004WR003279.

[2] Aina, A., Olorunfemi, M.O., Ojo, J.S. (1996): An Interpretation of Aeromagnetic and Electrical Resistivity Methods in Dam Site Investigation. *Geophysics,* 61(2), pp. 349–356.

[3] Eluwole, A.B., Olorunfemi, M.O. (2012): Time-Lapsed Geophysical Investigation of the Mokuro Earth Dam Embankment, Southwestern Nigeria, for Anomalous Seepages. *Pacific Journal of Science and Technology,* 13(1), pp. 604–614.

[4] Olorunfemi, M.O., Idornigie, A.I., Fagunloye, H.O., Ogun, O.A. (2004): Assessment of Anomalous Seepage Conditions in the Ope Dam Embankment, Ile-Ife, Southwestrn Nigeria. *Global Journal of Geological Sciences,* 2(2), pp. 191–198.

[5] Johri M., Zoback M.D., Hennings P. (2014): A scaling law to characterize fault-damage zones at reservoir depths. *AAPG Bulletin*, 98(10), pp. 2057–2079.

[6] Mansour K., Omar K., Ali K., Zaher M.A. (2018): Geophysical characterization of the role of fault and fracture systems for recharging groundwater aquifers from surface water of Lake Nasser. *NRIAG Journal of Astronomy and Geophysics*, 7(1), pp. 99–106.

[7] Song S., Feng X., Rao H., Zheng H. (2013): Treatment design of geological defects in dam foundation of Jinping I hydropower station. *Journal of Rock Mechanics and Geotechnical Engineering,* 5, pp. 342–349.

[8] Wieland M., Brenner R.P., Bozovic A. (2008): Potentially active faults in the foundations of large dams part i: vulnerability of dams to seismic movements in dam foundation. In: *The 14th World Conference on Earthquake Engineering*, Beijing, China.

[9] Ajayi, O., Olorunfemi, M.O., Ojo, J.S., Adegoke-Anthony, C.W. (2006): Integrated geophysical and geotechnical investigation of a damsite on River Mayo Ini, Adamawa State, Northern Nigeria. *Africa Geoscience Review,* 12 (3), pp. 179–188.

[10] Olorunfemi, M.O., Ojo, J S., Sonuga, F.A., Ajayi, O., Oladapo, M.I. (2000): Geoelectric and Electromagnetic Investigation of the Failed Koza and Nassarawa Dams Around Katsina, Northern Nigeria. *Journal of Mining and Geology,* 36 (1), pp. 51–56.

[11] Sjodahl, P., Dahlin, T., Johansson, S. (2003): Resistivity Monitoring for Leakage Detection at Hallby Embankment Dam. In: *9th Meeting of Environmental and Engineering Geophysics,* Prague, Czech Republic.

[12] Cho I.K., Yeom J.Y. (2007): Cross line resistivity tomography for the delineation of anomalous seepage pathways in an embankment dam. *Geophysics,* 72(2), pp. G31–G38, doi: 10.1190/1.2435200.

[13] Lin C.P., Hung Y.C., Wu P.L., Yu Z.H. (2014): Performance of 2-D ERT in investigation of abnormal

seepage: a case study at the Hsin-Shan earth dam in Taiwan. *Journal of Environmental and Engineering Geophysics,* 19(2), pp. 101–112.

[14] Sjödahl P., Dahlin T., Johansson S. (2010): Using the resistivity method for leakage detection in a blind test at the Røssvatn embankment dam test facility in Norway. *Bulletin of Engineering Geology and Environment,* 69(4), pp. 643–658.

[15] Karastathis V.K., Karmis P.N., Drakatos G., Stavrakakis G. (2002): Geophysical methods contributing to the testing of concrete dams. Application at the Marathon Dam. *Journal of Applied Geophysics,* 50, pp. 247–260.

[16] Benes, V., Tesar M., Boukalova, Z. (2011). Repeated geophysical measurement—The basic principle of the GMS methodology used to inspect the condition of flood control dikes. *Trans. Ecol. Environ*.,146, pp. 105–115.

[17] Al-Fares W. (2014). Application of Electrical Resistivity Tomography Technique for Characterizing Leakage Problem in Abu Baara Earth Dam, Syria. *International Journal of Geophysics, 2014*, 9 pages, doi:10.1155/2014/368128.

[18] Camarero P.L., Moreira C.A. (2017): Geophysical investigation of earth dam using the electrical tomography resistivity technique. *REM: Int. Eng. J., Ouro Preto*, 70(1), pp. 47–52.

[19] Rahaman, M. (1988): Recent Advances in the Study of the Basement Complex of Nigeria. *Precambrian Geology of Nigeria*, pp. 11–41.

[20] Talabi, A., Tijani, M. (2013): Hydrochemical and Stable Isotropic Characterization of Shallow Grounwater System in the Crystalline Basement Complex Terrain of Ekiti Area, Southwestern Nigeria. *Applied Water Science,* 3(1), pp. 229–245.

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[3] Blindow, N., Eisenburger, D., Illich, B., Petzold, H., Richer, T. (2007): Ground Penetrating Radar. In: *Environmental Geology – Handbook of Field Methods and Case Studies, Knödel*, K., Lange, G., Voigt, H.J. (eds.). Springer: Berlin, pp. 283–335.

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[4] Benac, Č., Gržančić, Ž., Šišić, S., Ružić, I. (2008): Submerged Karst Phenomena in the Kvarner Area. In: *Proceedings of the 5th International ProGEO Symposium on Conversation of the Geological Heritage*, Rab, Croatia, Marjanac, T. (ed.). Pro GEO Croatia: Zagreb, pp. 12–13.

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[5] Rošer, J. (2010): *Study of the effects of sediments on seismic ground motion in the city of Ljubljana using the microtremor survey method*. Ph. D. Thesis. University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geotechnology, Mining and Environment: Ljubljana, 278 p.

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[6] ISO/ICS 17892-10:2018. *Geotechnical investigation and testing – Laboratory testing of soils – Part 10: Direct shear tests*. International Organization for Standardization: Genova.

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[7] CASREACT – Chemical reactions database [online]. Chemical Abstracts Service, renewed 2/15/2000 [cited 2/25/2000]. Available on: *http://www.cas.org/casreact.html*.

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