New Frontiers in three-dimensional Geological Mapping and Applications for Solid Mineral Development in Nigeria[1]

Abel Idowu Olayinka
Department of Geology, University of Ibadan, Ibadan, Nigeria
aiolayinka@yahoo.com; idowu.olayinka@ui.edu.ng

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Introduction

I thank the Vice-Chancellor of Kwara State University, Malete, Prof Muhammed Mustapha Akanbi, SAN, the Dean, Faculty of Pure and Applied Sciences, Prof Emmanuel Oladipo Ajani and the Chairman of the Local Organising Committee, Dr Oluwasogo Olalubi for the kind invitation extended to me to present the First Public Lecture of the Faculty. The letter of invitation stated that this is the first in the series of annual Faculty Lectures as part of efforts in cultivating academic culture and maintaining an active academic environment in your University. This is a step in the right direction. Any University worth its salt must strive to maintain an academic culture. An academic culture is in this context somewhat an intangible asset which although you may not see you cannot but feel it. I congratulate the leadership of both the Faculty and the entire University and I am hopeful that this Lecture Series will be maintained in the coming years such that it would be mainstreamed into your academic calendar. We should put in place mechanisms to ensure that although this is the first Faculty Lecture it would not be the last.

The topic of our discourse today is “New Frontiers in three-dimensional Geological Mapping and Applications for Solid Mineral Development in Nigeria”. One can identify two main keywords in the topic, namely three-dimensional geological mapping and solid minerals.

Minerals are naturally occurring solid, crystalline, inorganic substances, which has definite chemical compositions and distinguished physical properties.

Mineral resources are mineral materials, organically-formed fossil fuels, water sources and other naturally endowed materials which are distributed within the earth. Some are deep-seated within the earth while some are hidden close to the surface; while some others exist exposed right at the surface, they are useful rock materials that is sufficiently concentrated in an accessible part of the earth-crust making it possible for it to be mined or extracted at a profit. The mineral resources of a country are its natural wealth upon which depend its development and prosperity. They include not only metalliferous deposits, but also non-metallic deposits. The materials for non-metallic mineral deposits may be solid, liquid or gas. Fortunately, Nigeria is a country blessed with a landscape or Geology that is very diverse, from the coastal end in the south to the very arid region in the north, the country presents a consistently changing and interlocking geomorphology of various Sedimentary Basins and Basement Complexes, this make it possible for the nation to have a good number of different mineral deposits since the processes that leads to their formation and localisation is related to surrounding geologic setting.

An attempt is made in this paper to provide an outline of the mineral resources of Nigeria, the importance of solid mineral resources to national development, the distribution and utilisation of the mineral resources, and the role of three dimensional geological mapping in resource evaluation.

Mineral Resources of Nigeria

The mineral resources of Nigeria can be grouped into the following:

1. Metallic mineral resources, which include:

   i. Precious Metals: Gold, Silver, Platinum
   ii. Ferrous and Allied Metals: Iron Ore, Manganese, Molybdenum, etc.
   iii. Non-Ferrous and Base Metals: Copper, Lead, Zinc, Tin, Cadmium, Tantalum and Columbium, Nickel, Chromium, etc.
   iv. Light Metals: Aluminium, Lithium, Magnesium, Bismuth, etc.
   v. Radioactive and Rare Earth Metals: Uranium, Terbuim, Lanthanium, Cerium

   and

2. Non-Metallic mineral resources like:
   i. Industrial Minerals: Mica, Barytes, Bentonite, Talc, Asbestos, etc.
   ii. Metallurgical and Refractory minerals: Zircon, Graphite, Dolomite,
   iii. Ceramic minerals: Clay, Feldspar, Wollastonite
   iv. Glass manufacturing materials: Glass sands and Quartz
   v. Fertilizer/Agricultural and Abrasive minerals: Limestone, Dolomite, Talc, Pumice, Garnet, Abrasive sands, Diatomite, Phosphate, etc.
   vi. Energy Minerals/Fossil fuels: Petroleum and Natural Gas, Bitumen, Coal, Lignite
   vii. Building Materials and Dimension stones: Marble, Limestone, Granite, Slate, Clay, Sand, Gypsum,
   viii. Gemstones: Aquamarine, Beryl, Amethyst, Tourmaline, Garnet,
   ix. Chemical minerals: Halite (rock-salt), Borax, Sulphur, Pyrites, Ochre
   x. Mineral water and Groundwater

A generalised geological map of Nigeria is presented in Fig. 1.

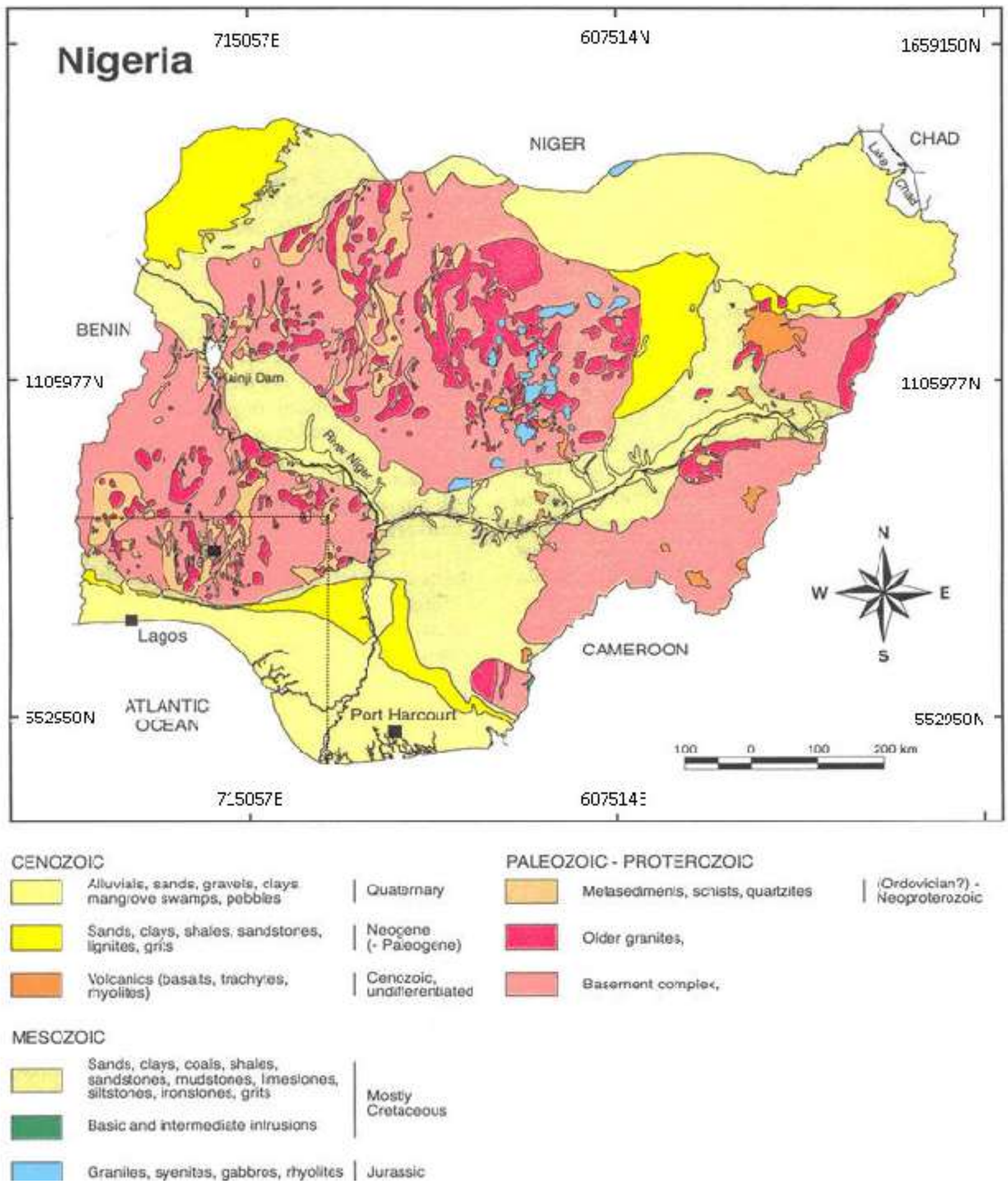

Fig 1:. Geological map of Nigeria (After NGSA, 2000)

In line of the foregoing explanations therefore; we can say **Solid Minerals** are the non-liquid/non-gaseous natural resources of a nation that serves as raw materials of many industries when extracted or mined profitably.

Importance of Solid Minerals to National Development

Most of the items we use and consume are gotten from mineral products or they are manufactured from or grown with minerals or mineral products. Virtually, no part of our lifestyle or development could be sustained without minerals. Minerals are utilized in every facet of our daily living from food production and processing, building, transport, communications, medicine, national security and Information technology. The Solid Mineral sector is a vast, latent, under-explored source of Economic Development that should be tapped to generate high economic yield, income, massive employment and foreign earning to our dear country. Tremendous opportunities for investments that will translate to great economic development abounds in the solid mineral sector in Nigeria and it is common knowledge that this sector contributed immensely to the economic development of Nigeria in the years before independence, in those days, Nigeria was a major producer and exporter of several natural commodities such as coal, tin, Iron-ore, Gold, Silver, Lead, Zinc and many more. All these mineral resources are found in Nigeria but they are not yet fully exploited. Nonetheless, opportunities exist for exploitation and exportation in the solid mineral sector, the earnings obtained here can be used to develop infrastructure, fund education, research, health facilities and agriculture.

The solid minerals industry have been neglected by the government over time. Mining involves the removal of minerals from the earth economically and sustainably ensuring minimum damage to the surrounding environment. Mining is necessary for nations to possess adequate/reliable supplies of minerals/materials to meet their economic and defense needs. But the neglect on the part of government has allowed the influx of illegal miners whose activities are characterized by unprofessional methods of mining, selling of highly priced minerals in their raw state at give-away prices, environmental degradation and pollution, smuggling and loss of revenue to government.

National development can be defined as the all-round balanced development of the different aspects or facets of a nation, such as political, economic, social, cultural and scientific facets. It includes maximum growth and expansion of industries, agriculture, education, social, religious and cultural institutions.

The above described progress of our national institutions and facets cannot materialiase without a strong economy, but to say Nigeria's economy is in a strong state at this moment will be tantamount to being economical with the truth. If we recall, the recently released 3rd Quarter (Q3) of year 2020 GDP report of the National Bureau of Statistics (NBS) stated that the Nation's economy has officially plunge into recession, as the country's GDP in real terms declined by -3.62% within the Q3 and this is the second recession, it came in close succession to the first which was recorded much earlier this year. The resultant effect of such closely timed cycles of recessions will lead to periods of Economic depression which is where we are in the country today. According to the Corporate Finance Institute "Economic depression is a steep and sustained long-term downturn in economic activity featuring high unemployment and negative GDP growth".

According to the report, the performance of the economy reflected the residual effects of the restrictions to movement and economic activity implemented across the country in early Q2 as a result of COVID 19 pandemic. The Corona virus pandemic no doubt has dealt a serious blow on the nation's economy, as both oil and non-oil sector including manufacturing, trade (wholesale and retail), aviation, tourism, real estate and even education have suffered major economic contraction. Several indicator flashpoint of economic depression observed in recent times include rising inflation, worsening unemployment rate, reduced purchasing power, increasing debt defaults, crash in price of crude oil at the international market and so on. The severity of this economic depression notwithstanding, analysts continue to dimension the recovery pattern for the Nigerian economy in 2021, several economists have proposed various other alternatives into which the nation's economy can be diversified among the available options is the Solid Mineral sector. Some recent data on economic indicators in Nigeria is presented in Table 1.

Table 1: Some recent economic indicators in Nigeria

	Year		
	2019	2020	2021 (Forecast)
Misery Index (%)		70.59	81.0
Unemployment (%)		27.1	35.1
Underemployment (%)		28.6	30.0
Average Inflation (%)	11.39	12.98	16.1
Average Oil Prices per barrel (US$)	64.16	42.89	
Average Oil Production (million barrels per day)	1.79	1.61	1.46 (Constrained by OPEC quota)
Gross Domestic Product Growth Rate (%)	2.27	-3.2	

Distribution and Utilization of Solid Mineral Resources in Nigeria

The Nigerian Extractive Industry and Transparency Initiative, NEITI report suggests that there are over 30 different kinds of solid minerals, precious metals and precious stones (Sapphire, Aquamarine, Topaz etc.) buried in Nigerian soil waiting to be exploited. Despite a good fiscal regime for mining, the development of the mineral sector has been hampered by several constraints such as the dearth of proven mineral reserves, illegal mining, the lack of infrastructure, the lack of mineral production and processing capacity, the smuggling of minerals out of the country etc. However, mineral exploration and production constitute significant parts of Nigeria's economy and remain keys to future economic growth.

Metallic minerals are usually combined in nature with other materials as ores, these must be treated generally with chemicals or heat to produce the metal or material of interest; with appropriate mining method, a well processed solid mineral and gemstone ends up being more attractive and valuable than a roughly or badly mined/processed one. A state by state account of the solid mineral deposits in Nigeria, as well as their uses is presented in Table 2.

Table 2: Distribution and Utilization of Solid Mineral Resources in Nigeria
(modified after www.slideshare.net)

S/N	Mineral	Location	Properties/Characteristics	Uses
1.	Coal and Lignite	Ebonyi, Edo, Enugu, Gombe, Imo, Kogi, Nasarawa, Plateau	accumulation of organic matter from plants (peat, lignite, bituminous coal, anthracite, graphite)	Energy generation, filtration, industrial application
2.	Uranium	Black shale of Dange Formation. Plateau, Taraba	Uranium is a radioactive material	used in nuclear defence systems; nuclear generation of electricity; in x-ray machines, atomic dating, and electronic instruments.
3.	Zircon	Lagos, Edo, Ondo	Zirconium metal is recovered from zircon	Used as refractory products that will withstand high temperature of 2,550°C. Also used in nuclear reactors. Ceramics, steel.
4.	Gold	FCT, Kaduna, Kano, Katsina, Kogi, Ogun, Kwara, Niger, Osun, Zamfara	gold is a rare, valuable and durable precious metal with a versatile use	jewellery, dentistry, medicine, coins, and applications for the aerospace industry; commonly alloyed with other metals to increase its strength and durability
5.	Silver	Ebonyi, Kano	a light precious substance	used for making jewellery, cell phone covers, fine silverware, coins and photography
6.	Platinum	Kuchiko, Niger state	the most precious and durable of all metals (it is very pure and it is rarer, denser and stronger than gold or silver)	used in jewellery industry
7..	Galena	Cross River,	Main ore for Lead; a	used especially in X-

		Ebonyi, FCT, Plateau, Zamfara	bluish-white soft malleable ductile plastic, or inelastic heavy metallic element	ray and gamma radiation shielding, pipes, cable sheaths, batteries, solder, and shields against radioactivity, ceramics, weights, and ammunition
8.	Chalcopyrite	Nasarawa, Ebonyi	Ore for Copper; a soft shiny and malleable metal. Chalcopyrite has a high copper content making it one of the mostly sought after solid mineral.	used as an alloy (bronze and brass); used to make coins, brass instruments, pipes and fungicides, electrical wiring etc
9.	Sphalerite	Cross River, Ebonyi, FCT, Plateau, Zamfara	Sulfide of Zinc (for zinc metal)	used as protective coating on steel, alloying metal with copper (brass). Also used in galvanizing iron, electroplating, metal spraying, automotive parts, electrical fuses, anodes, dry-cell batteries, nutrition, chemicals, roof gutters, cable wrapping, and pennies.
10.	Iron Ore	Kogi, Nassarawa, Katsina, Enugu	Fe metal (the fourth most abundant element in the crust)	used to manufacture steels of various types; magnets, auto parts, and catalysts.
11.	Nickel	Kaduna	Associated with Ultramafic rocks	A vital alloy for stainless steel, use in the chemical and aerospace industries
12.	Chromium	Zamfara	Obtained from the ore mineral Chromite $(Mg,Fe)(Cr,Al,Fe)_2O_4$	used in the production of stainless and heat-resistant steel, full-alloy steel, super alloys and other alloys.
13.	Cassiterite	Plateau, Kwara, Bauchi, Cross River, Kaduna,	Tin ore; Tin is a soft silvery-white, ductile and malleable metal	used in containers, as a protective coating, in tinfoil, and in soft

		Kano, Nasarawa,		solders and alloys.
14.	Copper	Nasarawa	Copper metal is obtainable from Native Copper. Copper is a good conductor of heat and electricity. It is very malleable and ductile in nature.	It is therefore use in electric cable, metal wares, jewelleries.
15.	Molybdenite	Plateau	Principal ore of molybdenum (MoS) found in pegmatites	used in stainless steels (21%), tool steels (9%), cast irons (7%), and chemical lubricants (8%); commonly used to make automotive parts, construction equipment, gas transmission pipes, and as a pure metal molybdenum is used as filament supports in light bulbs, metalworking dies, and furnace parts because of its high melting temperature (2,623°C).
16.	Wolframite	Bauchi, Kaduna, Kano, Kwara, Nasarawa, Niger, Zamfara	Ore of Tungsten	used in steel production, metalworking, cutting applications, construction electrical machinery, light bulbs, carbide drilling equipment etc.
17.	Bismuthinite	Kaduna	Major ores of bismuth	Majority is consumed in bismuth alloys, and in pharmaceuticals and chemicals; remainder is used in ceramics, paints, catalysts, and a variety of minor applications
18.	Gypsum	Ogun, Adamawa,	a soft white or grey mineral	used for making

		Edo, Gombe, Sokoto, Yobe	consisting of hydrated calcium sulphate	cement, plaster of Paris, fertilizer, wallboard, and glass. used in industrial or building plaster, prefabricated wallboard, cement manufacture, and for agriculture
19.	Bauxite (Aluminium)	Ondo, Plateau Delta, Benue and Ekiti	A silvery-white lightweight metal with malleable and durable property; it is soft and malleable	used in smartphones, tablets, laptops, and flat screen TV.
20.	Natural rock aggregates	All States of the Federation	Aggregates are composed of rock fragments **(**sand, gravel, and crushed stone); formed by weathering of igneous rocks like granite, it comes in various sizes of grain	used for making construction materials such as concrete blocks, bricks, pipes, mixing with asphalt and as construction fill
21	Baryte	Benue, Cross River, Nasarawa, Plateau, Taraba, Zamfara	Sulphate of Barium	used as a heavy additive in oil-well-drilling mud, paints, rubber, plastic and paper; production of barium chemicals; and glass manufacturing.
22.	Marble	Kwara, Oyo Nasarawa, Edo, FCT, Kogi,	A metamorphosed limestone	Used in Agriculture, Building, Dimension stone, Furniture, environmental industries
23.	Dolomite	Kogi, Ogun, Sokoto	Dolomite is the a near twin-sister rock to limestone.	used in agriculture, chemical and industrial applications, cement construction, refractories, and environmental industries.
24.	Diatomite	Borno, Yobe	A rock composed of the skeletons of diatoms, single-celled organisms with skeletons made of	Used mainly for filtration of drinks, such as juices and wines, others include

			silica which are found in fresh and salt water.	being used as filler in paints and pharmaceuticals and environmental clean-up technologies
25.	Clay	All States of the Federation	Weathering products of rocks.	used in the manufacturing of paper, refractories, rubber, ball clay, dinnerware and pottery, floor and wall tile, sanitary wear, fire clay, firebricks, foundry sands, drilling mud, iron-ore pelletizing, absorbent and filtering materials, construction materials, and cosmetics.
26.	Feldspars	All States of the Federation	A rock-forming mineral.	used in glass and ceramic industries; pottery, porcelain and enamelware; soaps; bond for abrasive wheels; cement; glues; fertilizer; and tarred roofing materials and as a sizing, or filler, in textiles and paper applications.
27.	Fluorite	Bauchi, Ebonyi, Plateau, Taraba	Compound of Fluorine	used in production of hydrofluoric acid, which is used in the pottery, ceramics, optical, electroplating, and plastics industries; as a flux in steel furnaces, and in metal smelting, carbon electrodes, emery wheels, electric arc welders, and toothpaste as a source of fluorine.
28.	Lithium	Kaduna, Nasarawa,	Source for lithium	For making lithium

	carbonate	Niger, Zamfara		Batteries used in smoke alarms, pacemakers, defibrillator machines, many other types of portable medical equipment, and in emergency communications equipment, including computers and cell phones.
39.	Mica	Ekiti, Osun, Kogi, Kwara, Nasarawa, Oyo	Mica minerals commonly occur as flakes, scales, or shreds in granitic rocks	used in electronic insulators, paints, as joint cement, as a dusting agent, in well drilling mud and lubricants, and in plastics, roofing, rubber, and welding rods
30.	Phosphate Rock	Ogun, Sokoto	A sedimentary rock	used to produce phosphoric acid and ammoniated phosphate fertilizers, feed additives for livestock, elemental phosphorus, and phosphate chemicals.
31.	Pyrite	Awe, Nasarawa	It is a ferrous sulphide but has resemblance to gold because of its bright metallic yellow colouration.	used in the manufacture of sulfur, sulfuric acid, and sulfur dioxide; pellets of pressed pyrite dust are used to recover iron, gold, copper, cobalt, and nickel
32	Silica Sand	Lagos, Ondo, Delta, Jigawa, Kano, Rivers	Pure white Beach sands	used in the manufacture of computer chips, glass and refractory materials, ceramics, abrasives, and water filtration, a filler in cosmetics, pharmaceuticals,

				paper, and insecticides; as a thermal insulator etc.
33.	Limestone	Kogi, Ogun Benue, Cross River, Ebonyi, Edo, Sokoto	A sedimentary rock composed of Calcium carbonate, normally deposited in marine environment.	used in cement manufacturing, construction, refractories, agriculture, chemical and industrial applications, water treatment, and environmental industries.
34.	Manganese	Katsina, Kebbi, Zamfara	Obtained from the ore minerals of Pyrolusite MnO_2, and Psilomelane $BaMn_9O_{18}*_2H_2O$.	Used in iron and steel production.
35	Talc	Ekiti, Kaduna, Kogi, Niger	Alteration product of Ultramafic rocks	Primary use, the production of paper. Ground talc is used as filler in ceramics, paint, paper, roofing, plastics, cosmetics, and in agriculture. Also used as baby (talcum) powder, deodorant, and makeup; used to carve figurines etc.
36	Gemstones	Bauchi, Kaduna, Kogi, Kwara, Nasarawa, Niger, Ogun, Oyo, Plateau, Taraba	Special beautiful, colourful and durable precious stones and semi-precious stones for personal adornment and aesthetic value	Jewelleries, ornamental stones, wall beautification, flooring, industrial abrasives, polishing.

Bauxite: is an ore of aluminum, it is usually converted to aluminum oxide which is used to make aluminum metal via heat and additives.

Rock-aggregates are mainly rocks and various materials that are employed for construction purposes such as building, dam and highway construction, railroad ballast, dimension stones, etc. they include rock materials like granites, basalt, dolerite, amphibolite, lateritic soils, sands, etc.

Barytes : used as an additive when producing drilling mud, also in the production of detergent, paints, explosives, rubber, paper and plastics; it normally finds application in glass manufacturing and the pharmaceuticals..

Bentonite Clay: Sodium-rich clay minerals used as component for drilling mud and for manufacturing of absorbent, soap, rubber, etc.

Bismuth: used as bismuth alloys in chemicals and pharmaceuticals, as well as paints, ceramics, bullets, metal alloys and cosmetics.

Bitumen: Sandstone heavily impregnated with hydrocarbon found in deposits such as Oil-sands or Tar sands, or obtained as residue in the refining of crude oil. It is primarily used for road surfacing and tarmac.

Clays: naturally occurring fine grained earthy materials that become plastic when mixed with small amount of water and when fired they are converted to a rock-like mass. They are used in the manufacturing of red-bricks, pottery, sanitary-ware, paper, spark plugs, textiles, insecticides, pharmaceuticals and refractories.

Cassiterite: also known as tin stone, used for the manufacture of tin plate and corrosion resistant alloys such as bronze, brass, solder.

Coal: a combustible, massive, organic sedimentary rock that over time has become an important source of energy.

Columbite: Columbite is Iron- Niobium oxide and it is naturally associated with Tantalite. They are used in forming alloys that are very useful in nuclear, aerospace and gas turbine engineering.

Gypsum: is a versatile industrial minerals, slightly soluble in water and has a wide range of varieties such as selenite, satinspar, rock gypsum, alabaster, gypsite, etc. Gypsum is an important material in the manufacturing of cement, ammonium sulphate fertilizer. It founds applications in the pharmaceutical, textile, paper and paint industries; it is also use in making plaster of paris (POP).

Feldspar: Potash feldspar is a hard silicate mineral, it has been found to be very useful in the manufacturing of automobile glass, floor and wall tiles, artificial teeth, fertilizers, abrassives among other uses. Commercial quantities are usually derived from pegmatite dykes.

Gemstones: include rocks and minerals normally applied for personal adornment and ornamental purposes because they possess distinctive physical properties which include brilliant lustre, transparency, attractive colours and other optical effects. They also have chemical stability (chemically inert) and durability. They have good polishing properties therefore the semi - precious ones e.g. corundum are used as abrasives.

Some locally available minerals requirements by industry in Nigeria are shown in Table 3 while Table 4 shows estimates of the local demand for some industrial minerals.

Table 3: Some Locally Available Minerals requirements by Industry (www.npc.gov.ng)

Industry	**Minerals Needed - Available Locally**

Oil	Barites, Bentonite, Mica, Gypsum, Soda Ash, Calcium Carbonate
Construction	Limestone, Gypsum, Clay, Granite, Marble, Bauxite
Agriculture	Phosphate, Limestone, Lime, Kaolin, Magnesite, Gypsum, Dolomite
Steel	Iron Ore, Limestone, Coal, Dolomite, Clay, Bauxite, Bentonite, Manganese, Molybdenum, Magnetite, Kyanite, Selenium, Tungsten, Nickel
Manufacturing	Kaolin, Talc, Limestone, Felspar, Quartz, Dolomite, Soda ash, Barytes, Diatomite, Tin, Titanium dioxide,
Cement works	Gypsum, Limestone, Marble

Table 4: Estimates of Local demand for some industrial minerals (www.npc.gov.ng)

S/N	Minerals	Proven Reserves	Annual National Demand (tons)	Medium Range Demand (4yrs) (tons)	Present Annual National Production (tons)	Shortfall Imports	Import price ($/ton)	Import value
1	Barytes	1000000	140000	20000	10000	130000	230	$29.9 million
2	Phosphate	800000	180000	250000	5000	175000	60/	$11.7 million
3	Gypsum	1700000	220000	300000	20000	200000	45	$9 million
4	Kaolin	30000000	250000	350000	25000	225000	60	$13.5 million
5	Marble	200000000	800000	1000000	50000	750000	100	$75 million
6	Coal	639000000	1000000	1500000	30000	970000	S25	$30 million

Geological mapping

Geological mapping is vital to the mining industry, but before any mineral exploration project can get under way, it's important to know exactly what you're working with – this means turning geological data into a readable, reliable format.

In a typical geological map, the rock units, faults and folds are plotted on a topographic map base, with different colours and symbols standing in for different features. The map may also shows the location of fossils and mineral deposits, along with the potential location of energy resources such as oil or coal.

It is a relatively straightforward idea, and it is far from being a new one. The oldest preserved geological map is the Turin Papyrus Map, which dates back to around 1150 BC. Designed to aid the pharaoh's quarrying expedition, the map shows the location of sandstone and gold deposits along with information including on the various rock types of the Wadi Hammamat region of Egypt.

In modern times, the process of geological mapping has been refined considerably. The first geological map of the US was created in 1809, followed six years later by the first geological map of the UK. In 1815, William Smith produced the geological map of England and Wales. This map could also be considered a three-dimensional (3D) map to the extent that it was accompanied by multiple cross-sections that depicted the subsurface. Since then, geological mapping has become a fundamental and core activity of the geoscience discipline, central to scientific understanding of landscape evolution, depositions of environment, and geologic history, and particularly its direct application to assessing water, energy, and mineral resources, engineering properties, hazard and risk assessments, and overall economic development potential. The British Geological Survey (BGS) has been carrying out extensive surveys since 1835 (Gay, 2019).

More recently, this long-established science has been going through an unprecedented period of change. We are seeing an increased availability of above and below-ground digital data that is of considerable value to geological mapping, and a range of new tools that allow us to access that data. Ultimately, better access to data enables more accurate and consistent results. This has clear implications for mining – as accurate geological map data can have many different uses within a commercial project. Moreover, the data that is used would be at a range of different scales and resolutions.

At a regional-scale, this map data could be used in conjunction with geophysical data to identify areas that may be geologically favourable for particular forms of mineralisation.

These data could be used to guide the regional exploration strategy and home in on areas that may deserve more detailed investigation.

The data may help identify more specific areas where rock and mineral sampling might be appropriate, and to provide a context to the sampling results.

At an even more detailed level, high-resolution geological mapping can delineate areas of likely mineralisation, helping mining companies target and prioritise their drilling activity. Geologists use digital field systems to validate the remote interpretation and record survey data. As well as its applications on the exploration side, geological mapping can be used at various other stages of a mining operation.

Geological map data may help inform the development of infrastructure associated with exploration or mining. The geological map data could also be used to understand some of the environmental considerations associated with mining activity, and to assess the availability of resources, for example groundwater, that the operation may require.

While there is no single, hard and fast method for developing geological maps, the process typically involves a number of steps. It is a **multidisciplinary process**, involving literature surveys, research, remote interpretation and fieldwork – increasingly facilitated through the use of digital tools and workflows. Geologists begin their mapping process at the office, working with a vast array of baseline information. We need to ensure we are bringing all that relevant information together and deriving the maximum value from it to help us understand what the geology is doing.

This is the first step in the digital mapping workflow. If we can't necessarily understand it upfront, we can use it to identify particular target areas that may require further investigation, such as through fieldwork or geophysical surveys."

Geologists in many countries are fortunate in that they have a huge quantity and diversity of baseline information available to them. This may take the form of digital elevation data, historical mapping information, geophysics, and a growing resource of borehole data from ground investigations. Increasingly, the baseline data includes advanced satellite imaging – unlike typical aerial photography, multispectral and hyperspectral satellite data includes information invisible to the naked eye, such as radiation from the infrared spectrum. There is a huge amount of information that we can bring together within digital environments, including through the use of immersive 3D visualisation. This allows creation of virtual geological environments and interpretations, that can be taken digitally to the field, the second step in the workflow.

Unlike a printed geological map, which is static, a digital geological map can be updated in real time. The idea is that, rather than making your fieldwork observations by hand, and transcribing them into a database at a later stage, you take a portable computer with you to the field. These devices include customised geographic information system (GIS) data entry software, tailored for geological surveying, allowing the relevant data to be recorded on the spot and analysed as soon as you return. They also include built-in GPS (or a wireless link to GPS), a portable long-lasting battery and an easy-to-read screen.

Geology and all geological structures are three-dimensional in space. Geology can be easily shown as four-dimensional when time is considered. Therefore GIS, databases, and 3D visualization software are common tools used by geoscientists to view, analyse, create models, interpret and communicate geological data. Consequently, as geologists we have to think in 3D, but conventional mapping approaches have often limited us to representing this in 2D. Digital advances have opened up the opportunity for us to capture and convey this 3D understanding more easily. Moreover, beyond thinking about the 3D geometry, it is important to understand how the subsurface behaves over time, which brings in the fourth dimension (4D). It is important that a geologist can operate between a field and digital environment almost seamlessly. Machine learning algorithms have a role to play in helping geologists make sense of the vast data sets that are available.

These days, creating the virtual interpretation and developing the final map tend to take place in three dimensions. Up until quite recently, geological maps were two-dimensional – they displayed the distribution of geological units at the surface and in cross sections showing the geology underground in a 2D plane. By contrast, 3D maps provide a sense of what is happening beneath the surface using 3D models that allow the geology to be viewed in all directions.

This gives geologists and users of the data the opportunity to develop more robust and conclusive interpretations and conclusions.

The application to regional geology, mineral resource exploration, groundwater, and engineering investigations is fairly new mainly because of the detail of mapping required to delineate subsurface materials, and the cost of obtaining the information (e.g., test-hole drilling and geophysical surveys).

An integration of developments in technology and mapping has led to the use of drone technology in many mapping expeditions. (Fig. 2)

Fig 2. Drone technology now used for geological mapping (After US Geological Survey.

Geological Mapping in Nigeria

The inauguration in 1903 and 1904 of the Mineral Surveys of Southern and Northern Nigeria by the Imperial Institute marked the beginning of official geological surveys in Nigeria. The results of this work were published between 1906 and 1914 in a series of pamphlets, "Colonial Reports—Miscellaneous ". This early reconnaissance work led to the discovery of the lignites in Benin Province, the coal in Onitsha Province, the iron ore of Lokoja, and the lead-zinc ores of Abakaliki. The Mineral Surveys came to an end before 1914 and it was not until 1919 that the Geological Survey of Nigeria was instituted. The new Survey's first tasks were the mapping of the Plateau Tinfields, and the investigation of the country along the Eastern and Western Railways. In 1928, the Survey undertook the actual exploitation of ground water by wells and boreholes and when the engineering side of its work was transferred to the Public Works Department in 1947, it had already sunk 2,000 concrete-lined wells and drilled 11 boreholes. Concurrently with this, systematic examination was made of the gold-bearing rocks in Sokoto, Zaria and Niger Provinces. At the outbreak of the Second World War in 1939, the Department diverted its attention to strategic minerals, the most important of which were tin, wolfram and tantalite.

The old Geological Survey of Nigeria (GSN) produced a geological Map of Nigeria in 1954, with a revised edition of 1: 2,000,000 in 1956. The GSN was replaced by he Nigerian Geological Survey Agency (ngsa.gov.ng) by an Act of Parliament in 2006 and it has produced Geological Sheet Maps on the scale of 1:100,000 and 1:250,000; Lineament Map on the scale of 1:2,000,000; Mineral Resources Map, Aeromagnetic Map; Gravity Survey map.

Some of the other major publications of the Geological Survey of Nigeria/Nigerian Geological Survey Agency include the following:

- **Minerals and industry in Nigeria with notes on the history of geological survey in Nigeria**
- **An illustrated review of the Geological Survey compiled from talks prepared for the Nigerian Broadcasting Corporation**
- **Nigeria geology and mineral resources** by F Dixey
- **Annual report of the Geological Survey for the year**
- **Annual report on the Geological Survey Department for the year**

The Nigerian Geological Survey Agency has since 2003 been publishing the Geological Map of Nigeria in digital format and incorporating GIS technology. This has made it possible to upgrade the map more frequently than was the case hitherto with new editions produced in 2004, 2006, 2008 and 2011.

The following digital products are available at the NGSA: Mineral Resources map; Fracture map of Nigeria; Regional maps-small-scale of Large areas 1:500,000: Map series- Large-scale Map 1:250,000; 1:100,000; Geochemical maps and Geotechnical maps; Corelog maps and Geodatabase.

The Nigerian Geological Survey Agency (NGSA) would have to develop a national geological model of the country's subsurface, that would display cross sections in a grid-like network. This would give decision-makers greater clarity in planning for the future such as in identifying potential energy and mineral resources and for understanding where the geology may be suitable for underground waste disposal or storage. Alo (2015) employed gravity and aeromagnetic data to characterize litho-structural features and estimate depth to basement in parts of the Anambra Basin and the Lower Benue Trough, South-East Nigeria. The study involved profile analysis, spectral or depth slicing techniques, source parameter imaging and 2.5-dimensional modelling. Similarly, Odunlami (2018) integrated remotely acquired geochemical and geophysical data with classical geological and geochemical datasets in delineating mineralised zones in Tegina area, North-central Nigeria. Studies such as these can go a long way into a better understanding of the 3D geology.

Conclusion and recommendation

Nigeria is enriched with a variety of solid minerals of various categories ranging from precious metals to various stones and industrial minerals. Statistically, the level of exploitation of these minerals is very low in relation to the extent of deposits found within the country. Part of the objectives of government policy on Solid Minerals should be to ensure the orderly development of the mineral resources of the country. A well-managed and established solid minerals sub-sector will definitely accelerate economic, social and political growth of the country by providing gainful employment and rise in national income earnings far exceeding the oil sector.

Solid minerals will provide local raw materials for industries and bring vital infrastructure and wealth to rural areas therefore the Federal Ministry of Solid Minerals should grant prospecting licenses to investors (both local and foreign) to participate in the exploitation of the vast mineral resources in Nigeria. Solid minerals have capacity to provide the all-important launching pad for the development of other sectors of the economy, it will also enable the oneness of the populace since minerals are located in every states of the Federation.

It is therefore expedient for government to fund the necessary agencies enabling them to produce needed information on the proven reserves of the federation, the sets of geological data acquired should be made available to the populace and investors in particular.

Nonetheless, the expected success of the mineral and metals industry in Nigeria lies in its ability to make local raw materials available for the use of the teeming small and medium industries thereby adding value to exportation.

It is important that the government of a country be committed to its mineral exploration activities, this, it can do by providing funds and making sure exploration and research develop at the same time.

Three-dimensional geologic mapping and modeling have long been a norm for oil and gas. Advances in data collection and digital processing now permit the application of methodologies previously limited to the petroleum industry, to mapping and modeling in 3D. Particularly beginning in the late 1990s, geological survey organizations (GSOs) began to more comprehensively map the thickness, extent, and properties of multiple strata, as well as selected deformed structures, in a 3D GIS environment. Developments were driven by considerable progress in digital methods, large databases of water-well and engineering boring logs, and new drilling and geophysical tools to acquire subsurface information. Advances in computer technology was coupled concurrently with escalating societal needs driven by land-use pressures requiring planners and health officials to make increasingly difficult decisions commonly revolving around groundwater resource evaluations and protection strategies. The situation can be particularly important in urban settings or expanding suburban areas, where there are thousands of data locations (e.g., water-well logs and engineering borings) that must be managed, evaluated, and compiled to construct accurate 3D geological maps and models at large scales. 3D geological models are quickly becoming the standard for assessing water and mineral resource potential, geological risk for both industry and government agencies, and economic development because they are effective tools to more easily explain and portray the often complex subsurface. They are also used frequently and successfully to assist with stakeholder engagement and communication. With the advent of powerful computers (past 25 years) to manage large data sets and manipulate the data to portray complex relationships, it has been feasible to map, model, and display geology in 3D. It is imperative that geoscientists understand what these tools can do to provide insight on sedimentary environments, stratigraphy, and geologic history, and more importantly, to better explain the complexity of geological information to non-geologists. Users also typically request the input data that was used to make the maps and models. Therefore, robust yet user friendly data bases with full metadata are also required, often along with a suite of interpretive or derivative products, as well as “user guides.”

Mining companies have a lot to gain from such developments. It is worth pointing out that if a geological map is inaccurate, the mining activities themselves could fail, resulting in a significant waste of resources.

Digital data help to speed up the process – important in commercial projects, where time is of the essence. Geologists will work with digital systems to make our work more effective and produce more robust and confident geological output.

Although geological mapping skills are decreasing, they are far from being lost altogether. As industries appreciate the value of experienced field mapping talent we can hope that the funding will follow, to ensure that this age-old at continues to be practiced for the benefit of not just geological disciplines, but other areas of society too. Geological cartographers may help find mineral veins for mining, or potential aquifers enabling them to provide water to parched communities, helping to achieve SDG 6 (clean water and sanitation). A technique with so much potential should not be allowed to be lost from the world.

It is recommended that the Nigerian Geological Survey Agency make the transition from a 2D to a 3D Geological Survey although this would require additional investments. This would entail integration of geological, geochemical, geophysical, remote sensing, GIS and borehole data. The geophysical surveys may include electromagnetic, seismic, radar, and borehole geophysical surveys.

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