UNIVERSITY OF PORT HARCOURT

PETROLEUM & MINERALS UNDER MY LAND, NONE IN YOURS: HOW COME?

An Inaugural Lecture

by

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Finally, I thank the Almighty God for giving me life and for making it possible for me to gain a little modest insight to a tiny little bit of His wondrous work of nature.

DEDICATION

Dedicated to my parents, the late Mazi Daniel Oji Oti and Mrs. Eunice Nwaugbo Oti

PETROLEUM & MINERALS UNDER MY LAND, NONE IN YOURS: HOW COME?

Vice-Chancellor, Deputy Vice-Chancellors, Registrar and other Principal Officers, Provost College of Health Sciences, Deans of Faculties, Distinguished Professors and Scholars, Great Students of Unique Uniport, Distinguished Guests, Ladies and Gentlemen.

INTRODUCTION

One day several years ago when I was still generally being referred to as Dr. Oti, my then 7-year old son returned from school looking quite puzzled, a little embarrassed and with a little frown on his brows. Upon setting down his school bag, he came up straight to me, looked at me hard in the eye and said "Papa, is it true that you are a Doctor of Stones?" I was completely taken by surprise and nearly thrown off balance as to how best to formulate a response. Until that moment no one had ever described what I did for a living as such. In order to gain a little time while I quickly pondered how best to describe my profession to, well, not exactly a layman, not even a 'layboy' – but a 'laychild' – I asked him how this 'doctor of stones' matter had come about in the first place. Innocently, he said that a group of pupils had been discussing the matter at school while generally reviewing their parents' various occupations. Being mostly children of university dons most of their parents were either academics or medical doctors or university administrators. So, almost every adult around them were 'doctor this' or 'doctor that'. To them, however, a doctor was someone you went to when you took ill, and in fact many of them even knew that there are doctors for different categories of illnesses or patients. They also knew that I was a 'doctor' as well, but somehow though they had heard that the objects with which I worked were not humans, not even animals for that matter, but instead were rocks, stones, minerals and the like, but exactly what I did with them no one seemed to know. Common sense, however, told them that my job could only be one thing: Doctor of Stones. My son didn't seem to have liked the sound of it all and wanted to know directly from me what all of this meant.

I told my son that, well ..well, you see, my boy, there is quite some truth, more or less, in what your friends had said at school, but well .. it's not quite as simple as that. Then came the obvious follow-up question that had made him uneasy all day long: Do rocks and stones get ill? Do you treat them? Exactly what do you do with them? Why are you *their* doctor?

Today, as then, I am going to try to explain to you why and how rocks – and the mineral treasures they hold - in deed our very Planet Earth itself (for after all it is made up essentially of rocks and minerals) have been the focus of my study and research since 1971 – the past 37 years. This apparently lengthy time span notwithstanding, I may not be able to tell you a great deal about my science. This would sound like a paradox knowing that I received my PhD some twenty-eight years ago and have been full professor of geology for about half of that time. But you see, as one Russian scientist once put it, specialization in any field of knowledge is essentially *knowing* *more and more about less and less*. So, today, I fear that it just might well be that I now know a modest little bit about quite a very little bit. And that is why I will try, as much as I can, to tell you that very little bit which my peers tell me that they think I know, or ought to know, from my studies and research.

But, lest this remark about knowledge be misconstrued I would like to quickly align myself with Virginia Woolf in humility, who when speaking through the voice of Bernard in her 1964 work, *The Waves*, said:

> 'To speak of knowledge is futile. All is
> experiment and adventure. We are forever
> mixing ourselves with unknown quantities.'

The topic of this Inaugural Lecture may well have read: **Geological Controls on the Occurrence of Petroleum and Minerals –** but I feared that it might have sounded a little too austere for a mixed audience, apart from necessitating the use of too much of technical jargon. I have therefore deliberately coined it the way I have done to read *Petroleum & Minerals Under My Land, None in Yours: How Come?* Both mean essentially the same thing, but it is hoped that this light-hearted form will facilitate a confluence of town and gown as we explore the science underlying the geological distribution of resources of the earth, over which man has absolutely no control whatsoever. In doing so, I shall restrict myself mainly to the science; I leave details of the equally interesting socio-political and economic aspects to the relevant and more competent experts.

Mr Vice Chancellor, sir, this planet Earth on which we humans find ourselves has not always been there. Nor has it remained static and unchanged since its origins. In his 1987 essay titled *Deep Time and Ceaseless Motion* Stephen Jay Gould elaborates on the dynamic processes which our planet has been going through since its coming into being. The Earth has continued to undergo subtle but far-reaching changes; mostly the changes are slow and almost imperceptible, often they could be quite drastic, violent and catastrophic. Its physical appearance today is different from how it has looked at different epochs (or time chunks) in its long and complex geological history. It has changed and continues to change literally in every, and any, sense of the word – physically, chemically, and biologically. Nor have the origins and distribution of its economic minerals and energy fuels (petroleum, coal, uranium, etc) been a random and disorderly affair. The geologic and rock cycles ensure the distribution and re-distribution of these resources in space and time, in an orderly and predictable manner.

Today we have ocean where land once was, and vice versa; mountain ranges have been thrown up from former deep ocean floors; continents have drifted from where they once were into new positions and new configurations, and in fact are still on the move.

Since coming into existence some 4.6 billion (4,600,000,000) years ago, our Planet Earth has experienced so many, many things. If our primordial earth were to see itself in a mirror today, chances are that it would not recognize itself. It has been bombarded from outer space by countless meteorites and cratered mercilessly in the process (although most of the scars have long vanished); millions of tons of cosmic dust have continued to rain onto it; the average day length is now much longer (thanks to tidal friction caused by the moon’s gravitational attraction which has resulted in a slower velocity of earth’s rotation); an atmosphere has not only developed and evolved around it, but in deed huge water masses called Oceans have evolved – in turn setting the stage for the appearance of life and the accumulation of biomass - and thence to some fossil fuels such as coal, petroleum and natural gas. At certain stages during this long history various life forms have held sway but had suddenly disappeared into extinction (the so-called *Great Dyings*, such as experienced by the famous Dinosaurs and the less famous Ammonite cephalopods at the end of the Cretaceous Period some 65 million years ago; or even the more devastating mass extinction at the end of the Permian period some 225 million years ago that wiped out as much as half of all the families of marine organisms!).

A common fossil fuel, coal, for example, that helped to give rise to the Industrial Revolution two centuries ago, a revolution that marked the watershed in mankind’s march toward modern civilization (and which, by the way, helped to free the black race from slave labour), has not always been there. First plants had to conquer land by adapting from living in water to living on land during the so-called Carboniferous Age (some 340 million years ago), and thence develop enough biomass for coal to form when submerged in anoxic (or oxygen-free) conditions in swamps. Petroleum and natural gas, which are also fossil fuels, have originated from dead microscopic organisms trapped and buried with very fine-grained (mud or clay) sediments in oxygen-free conditions under ancient sea floors where they became gently heated up or ‘cooked’ under pressure, in subterranean ‘geological kitchens’. In these fuels, the ultimate source of energy can be traced back to the sun’s energy trapped directly or indirectly through photosynthesis by once-living, but long-dead organisms, hence the term – ***fossil***.

But where did rocks come from? What are they? Of what are they made? Have they always been there or did they have a beginning? If they were ‘born’ at some point in time, then how old are they? Can we ascribe some age to a lifeless inert object such as a rock or stone? If so, are some of them still being ‘born’ now at this moment in time? Have they changed or evolved through time? If you studied them could they reveal their essence and tell their own story as to how they originated and what they have ‘experienced’ through time? (You will have noticed the word *Time* popping up persistently: Geology is saturated with time, and Geologic Time is truly *deep* – as an instant or moment to a geologist may well be a few million years - as we shall see).

Now, if some of these rocks contain evidence of once-living organisms, as they in fact often do, can they give us clues and insights into the history of life on our planet, and in deed into the origin of life itself on Earth? How did useful economic minerals and petroleum come to be associated with rocks, in deed come to reside ‘inside’ them? These are certainly intriguing questions which have captured mankind’s curiosity since ages. However, to answer some of these questions we must first make recourse to the origin of the earth itself, to the solar system, to other stellar systems (stars and their associated planets), to galaxies and to the universe, since the earth is part of the family of celestial or ‘heavenly’ bodies constituting the Universe. But here we must be very brief, as this is outside the scope of this lecture – belonging as it does to the realm of astrophysics, astronomy and cosmology.

SCIENTIFIC VIEWS ON THE ORIGIN OF THE UNIVERSE

Beautiful is what we see
More beautiful is what we understand
Most beautiful is what we do not comprehend

Nicolaus Steno, Danish priest, physician/anatomist and geologist -1673

"…. Because of his intellectual ability, man is privileged to ask questions and search for answers in any given field of culture and nature…"
Gisbert Freiherr zu Putliz (former President, Univ. of Heidelberg), 1986, on the occasion of the 600th Year anniversary celebrations of the University of Heidelberg.

We cannot begin to discuss the origin of the Earth without first addressing the question of the origin of our Solar System (that is, a nearby star which we call the Sun, together with the planets, including our Planet Earth, orbiting around it, and with the planetary moons orbiting around the planets themselves). Nor can we begin to discuss the origin of the Solar System without first looking into the origin of the Universe itself. This is because our Earth is an integral part of the Solar System, while the solar system is itself an integral part of our Milky Way Galaxy, a galaxy among hundreds of billions of other galaxies each comprising billions and billions of stars (suns) with their individual planetary satellite systems! What this boils down to is that our planet Earth is but one little planet orbiting around a medium-sized star at the periphery of a medium-sized galaxy, amidst a nearly infinite number of galaxies in the Cosmos. Or put another way, our Earth may be analogous to just one tiny grain of sand amidst trillions of trillions of other grains of sand in the Sahara desert, amidst hundreds of billions of other Sahara deserts! Indeed, a speck, in a speck, in a speck, in a speck, in a speck….!!

Under such humbling status and scenario for our dear little planet it is tempting to ask: Is the Earth special in any unique way as we anthropocentric humans inhabiting it tend to think it is? Or is it just vanity on our part to think so? Is there intelligent life – in deed, any type of life for that matter – out there somewhere on another planet in our own galaxy or in any of the other hundreds of billions of galaxies? But these questions, interesting and intriguing as they are, cannot be treated within the scope of this inaugural lecture, but suffice it to say that the search for life in the near universe, intelligent or otherwise, is on.

Now, what are the scientific thoughts on the origin of the Universe - this magnificient hierarchy of galaxies, stars, planets and moons?

Thoughts on the Origin of the Universe:
From Babylonian Court Mystics to Greek Philosophers to Religious Adherents to Modern Astronomers and Astrophysicists

René Descartes (1596-1650), the great 17th Century French philosopher, mathematician and scientist had this to say in one of his major works, Discourse on Method:

> "One cannot conceive anything so strange and so implausible that it has not already been said by one philosopher or another."

Descartes also said:

> "If you would be a real seeker after the truth, it is necessary at least once in your life you doubt, as far as possible, all things."

Strange as it might sound, modern scientific ideas on the origin and structure of the Universe and the cosmos stem from philosophy. But long before the Greek philosophers, however, the systematic observation of the sky and celestial phenomena (such as comets, shooting stars, and most impressive of all – solar eclipse!) had long been established in Babylon and Assyria by mystico-religious observers who worked for mighty kings and whose paid job it was to interpret celestial phenomena as supernatural signs and omens given by the gods to these great kings. Consequently, to be of continued relevance and to wield enormous power in the kings' courts these mystics and magicians were not interested in the development of thought in the scientific direction of naturalistic explanations, as this would render them dispensable and disposable (Panchenko, 2004). Instead, and understandably, they chose to explain celestial phenomena with 'cock and bull stories' which these superstitious kings wanted to hear in the first place!

Now, enter the Greek philosophers and thinkers from about the 600 BCs, and the story began to change drastically and radically with the sheer power of intellectual thought and reasoning. The ancient Greeks lived in republican city states and had no awesome kings to worry about. Consequently, they were free to apply intellectual rigour to any subject matter they fancied, including their observations of the natural world and natural phenomena such as what went on in the heavens (comets, eclipses, etc) above them, and mundane natural things and societal issues here on earth. According to Panchenko (2004), these early Greek philosophers who were typically from the upper stratum of society often possessed some special knowledge in what would later be called mathematics, astronomy and logic, and so their ideas were not to be dismissed lightly. Thales in the 580s BC was able to successfully explain solar eclipses by reasoning that it occurred when the moon moved into a position where it screened the sun from an observer on earth, and therefore if one knew the relative orbital motions of these heavenly bodies one could easily predict when an eclipse would occur. And astonishingly he did manage to predict one, putting the whole belief of divine command for such phenomena into serious question. From then on it was only a question of time for Socrates in 340 BC to prove convincingly that the earth was not flat, as was widely believed, but spherical. He based his argument on such simple observations as the inferred shape of the earth from its shadow on the moon during lunar eclipses when the earth came between the sun and the moon; the position of the North Star that appeared overhead at the North Pole but low in the horizon when observed from the equator; and thirdly, the fact that one first sees the sails of a ship coming over the horizon at sea before seeing the rest of the ship's body. But like the ancient Assyrian and Babylonian metaphysicists and diviners, Socrates and the other

Greeks believed that the earth was stationery and at the centre of the universe, that is that the universe was geocentric, and that all the stars, the sun, the planets and the moon moved around it in their respective orbits.

Ptolemy, in the second century AD, further developed the geocentric Aristotelian model by supposing that the Earth, at the centre of the Universe, was surrounded by eight spheres each of which respectively bore the moon, the known planets, and finally the so-called fixed stars. But this theory of celestial spheres implied that the universe had a boundary, and although no one knew what lay beyond the assumed boundary, some reasoned that that would be the logical place for Heaven to be located.

Many years later, however, in 1514, the Polish priest Nicholas Copernicus put forward his heliocentric model in which the sun, not the earth, was stationery and at the centre of the universe and that the earth and other planets orbited around it in circular orbits! A risky, heretical claim to make in the Middle Ages, and by none other but by a catholic priest for that matter, Copernicus was so scared to identify himself openly with his theory for fear of reprisal by the Church. For how could anybody in his right mind, it was reasoned, not see that the Earth, where we supposedly specially created humans reside, was the centre of the Universe? So, to save his life, poor Corpenicus opted largely for the underground with his model.

About a hundred years later, the German, Johannes Kepler, and the Italian, Galileo Galilei – two high profile astronomers of the period – concluded that Corpenicus - if one discountenanced the sun being static and at the centre of the universe - was right after all (although Galileo was later punished by the Church for his effrontery). In addition, Kepler introduced the idea of elliptical orbits, not circular ones, as elliptical orbits matched the observations more accurately. In 1609, Galileo used the then newly invented telescope to observe that Jupiter had its own moons which orbited around it, demonstrating that everything in the universe did not have to orbit around the earth, and therefore discrediting the Aristotelian/Ptolemaic geocentric model, once and for all time (Hawking, 1995).

In 1687, Isaac Newton published his *Philosophiae Naturalis Principia Mathematica*, in which he, among other scientific achievements, postulated his theory and law of universal gravitation which controlled how bodies (stars, planets, etc) move in space and time, and which showed how these bodies followed elliptical paths.

But all of these breakthroughs notwithstanding, no one knew and still no one knows how large the universe was or is, what its large-scale structure was or is, whether or not it has always been there or not, or whether or not it had a beginning, and if so what, if anything, was there before it. Nonetheless, these questions are crucial to our dear little planet Earth and its ultimate origin and ultimate fate.

Not until 1924 did our modern picture and understanding of the universe and our place in it begin to take shape. For it was in that year that the American astronomer, Edwin Hubble, show that apart from our own Milky Way Galaxy (defined in the night sky by a band of stars across the dark background of the heavens) there are many other galaxies separated by enormous tracts of empty space. Not only did Hubble calculate the distances to several other galaxies in light years (light travels at a velocity of

300,000 km per second!), he also inferred the composition and temperature of their individual stars using the spectra of the light they emit. Furthermore, by observing their spectra, Hubble made the ground-breaking discovery that their spectra are red-shifted, that is the galaxies were *receding* from us in whatever direction we looked in space. What made this discovery so ground-breaking and fundamental is that it implies one and only one thing: the Universe is *expanding*! In 1929, Hubble further found that the farther away a galaxy is the faster it is moving away. Which facts lead to yet another inescapable conclusion: if the universe is not static but is expanding, it is logical to conclude that at a certain point back in time the galaxies were closer together – in fact, so close that all the matter in the universe was concentrated at a point of infinite density from where the sudden explosive expansion began. Modern science calls that event point the *Big Bang* – the moment of Creation! At the Big Bang singularity all known laws of physics break down and cannot describe the events of that initial state; therefore scientists do not have the tools to even try to inquire into it (Hawking, 1995).

Now, two key questions remain unanswered: what *caused* the Big Bang? What was *before* the Big Bang? Science does not know, period. But that is just as well, for our Creator must have set limits to what we humans can ever know about Creation, His work. And as many scientists themselves acknowledge, it is futile to attempt to read the Mind of God.

Our nearest star, that is the Sun, is thought to have been 'born' some 4.5 to 5 billion years ago. Astronomers tell us that stars form from the little bit of primordial matter in the universe which forms clumps, which together with primordial hydrogen gets so compressed under gravity that it eventually ignites nuclear fusion, a process in which hydrogen nuclei merge to form helium and heavier elements. As this releases energy the star starts to glow. In deed there are baby stars, young stars, middle-aged stars (such as our Sun, which has an additional 5 billion years to go till death when its hydrogen fuel burns out), old stars, red giants, white dwarfs, etc., with the last two categories already in their death throes. When they die, they suffer a violent explosive death called a *supernova* (or star burst). When our Sun dies, our Earth must also necessarily die. This is because the sun powers everything on earth; without it there will be no life on earth. There will be no rotation or revolution of the earth. The Earth and the other planets in our solar system will be extinguished. The earth and her sister planets will go into a dark and endless frozen slumber, if not consumed outright into the possibly ensuing ***black hole*** (although a black hole would be unlikely due to the restraining *Chandrasakar limit* imposed by our Sun's size).

The Aztecs of ancient Mexico revered and worshipped the Sun – represented by a sun god, *Huitzilopochtli*, who needed to be nourished daily with living human hearts – so much so that every morning, without fail, one to several victims - mostly captured brave young warriors in their prime - were seized and their hearts violently ripped out, live, and offered to the rising sun in sacrifice! Of course, this necessitated endless wars to ensure the uninterrupted supply of ritual food for the sun!

Now back to our dear little Planet Earth. How old is it? When did it appear in the Cosmos, not minding its relatively miniature size. From the available evidence, scientists believe that our planet Earth, together with all the other planets in our solar system (Mercury, Venus, [Earth], Mars, Jupiter, Saturn, Uranus, Neptune and Pluto) have a common origin with the Sun, our nearest star and came to being some 4.6 billion years ago.

THE LARGE-SCALE INTERNAL STRUCTURE AND COMPOSITION OF THE EARTH

Our age cannot look back to earlier things
Except where reasoning reveals their traces.

Lucretius, 99BC-ca.55BC, Roman poet and philosopher, On the Nature of Things (De Rerum Natura)

Although no one has ever been inside the earth deeper than the deepest mines (less than three kilometers, or so, deep), let alone as far as the center, nonetheless geophysicists and geologists have a fairly good idea of what it looks like right to the center, 6,378 km deep. The insights gained have come largely from the behaviour of earthquake (seismic) waves traveling through the earth and how they are reflected and refracted at certain boundaries within the earth. Other insights have been gleaned from direct comparison with meteorites (chunks and debris of asteroids, rocky and iron-rich materials that reach the earth - most spectacularly as meteors or ‘shooting stars’ - from other parts of our solar system). Firstly, the earth’s structure shows that there is a density layering – with the heaviest materials making up the central portion while the lightest ones make up the rim. Secondly, the deeper you go the hotter it becomes (geothermal gradient), with temperatures reaching some 4,300°C at the centre. Thirdly, it is not solid all through; some layers are semi-solid and plastic, while at least one layer is completely liquid.

If we were able to slice the earth into two equal halves we would see that the inside is roughly similar in many respects to a boiled egg sliced into two. We would see that it consists of three main concentric layers: ***crust***, ***mantle*** and ***core***, each of which has a different chemical composition, density and temperature regime. The crust (analogous to the egg shell) is solid and brittle, and in comparison to the other layers is relatively very thin (in fact skin-deep for a planet that has a diameter of 12,756km), averaging about 30-50km on continents, and only as thin as about 5km or less under the oceans.
The crust is the main component of the lithosphere (from *lithos*, Greek for stone) made up of ordinary light and dark coloured silicate rocks which we see at the surface and in mines.
Under the crust and reaching a depth of 2,900km is the mantle (analogous to the egg white), a plastic, semi-solid, essentially dark coloured rock material which is as hot as 3,700°C, is mobile and can flow. (This situation of solid crustal rocks floating as rafts on a semi-solid mobile upper mantle material has grave and far-reaching consequences for many geological processes and products, such as the drifting apart of continents and other aspects of what geological jargon calls **Plate Tectonics** which controls, among others, the occurrence and distribution of minerals and petroleum, as we shall see later).
Below the mantle and extending to the very center of the earth at a depth of 6,378km, is the core (analogous to the egg yolk), which is composed of metallic material (iron-nickel alloy), and therefore very dense and heavy. However, the core is differentiated

into a liquid outer core and a solid inner core, and as the earth rotates the liquid outer core spins, generating the earth's magnetic field.

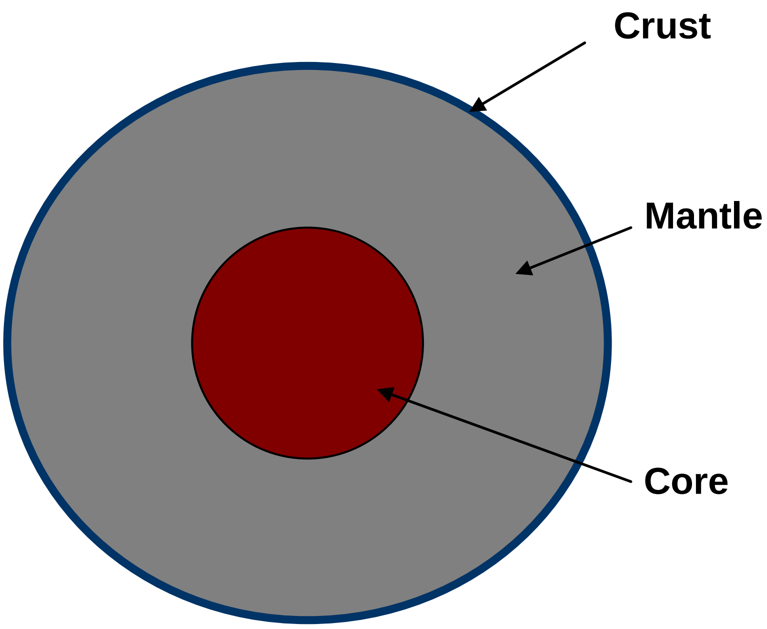


Fig.1. Very Simplified model of the Earth, showing the three main constituent layers: crust, mantle and core

Plate Tectonics: The good, the bad and the ugly aspects

First, the bad and the ugly: Earthquakes which cause mass deaths of humans and other species; fiery volcanic explosions, intense crustal rock deformation and with it the destruction of man-made constructions such as houses, roads, power plants and other utilities; tsunamis (monstrous ocean waves) such as occurred in Asia on 26 December 2004 killing hundreds of thousands of persons, etc, etc. These are some of the bad and ugly aspects.

The awesome and magnificent: Rifting, faulting, horizontal crustal displacements, continents splitting, breaking up and tearing apart, and set off wandering!
Continents drifting apart and slamming violently into each other and throwing up grand mountain ranges at their edges in the process; new oceans opening up in the middle of continents! These are grandiose and awe-inspiring geological events.

The good: Geological basins forming, receiving sediments and generating petroleum, natural gas, coal and other energy and economic minerals; sedimentary, magmatic and metamorphic processes running in high gear to concentrate and accumulate metallic and non-metallic ore minerals, all to the benefit of mankind! Surely, these are some of the good aspects.

All of these geological phenomena and processes have one thing in common: their driving mechanism which earth scientists call ***Plate Tectonics***. Now, let us examine Plate Tectonics a little closer.

Until not too long ago (the mid-1960s), many aspects of geological observations just did not "jive", to use a local Nigerian metaphor for the words 'add up' or 'fit'. Too many things seemed quite puzzling and unrelated; but there ought to be an over-arching theory that could explain these puzzles, for there is so much order in the universe and in nature for things to happen in an arbitrary manner. Why, for example do the western coastline of Africa (Nigeria, Gulf of Guinea) and the eastern coastline of South America (Brazil) seem to fit perfectly, if they were brought together like in a jig-saw puzzle? Why does the earth have long extensive linear mountain chains in certain places eg. the Rocky mountains in the western part of North America (Canada & the USA) which stretches south to dovetail with the Andes also in the western coastline of South America; also we have the Alpine (Alps) mountains which stretch all the way across central and eastern Europe; then the magnificent and majestic Himalayas bestriding much of Asia, and so on? Why do earthquakes occur repeatedly only in certain parts of the world, and not in others, again following some consistent lines of locations? Why, if you looked at a map of the world, do you see a string of volcanic islands dotted in the middle of the oceans, forming archipelagoes, atolls, etc. – beautiful islands which form the basis of a flourishing international tourist industry, especially in the Pacific? Why do hydrocarbons (oil & gas) and other mineral resources occur in certain places, and not in others?

Today, earth scientists believe they know why – and we will try as much as possible to strip the discussion of unnecessary technical jargon. Remember that we have just discussed the simplified structure of the earth and have shown that the rigid crust floats on a semi-liquid mobile mantle. However, the crust itself is not a single continuum but consists of several individual, very huge, rock plates (about 20 of them or so, of which only about eight are the major ones). These so-called lithospheric plates - or ***plates*** for short - because they float, they may be moving away from each other (in which case their motion relative to each other is said to be *divergent*), or they may moving towards each other (*convergent*), or moving past each other (*strike-slip* or *transform*). As we can well imagine, all kinds of terrible and frightful things would be happening at their common boundaries, either by way of collisions and crushing deformations, extensions, or horizontal displacements, and so on, with attendant severe consequences for us little mortals and whatever we may have constructed. But the underlying reasons for all of these movements is that in the middle of the oceans, the sea floor has a linear chasm (called mid-ocean ridges) where new molten crust continuously rises up and solidifies into a ridge-like structure (propelled by heat-driven convection currents in the upper mantle), thereby pushing both sides of the chasm (so to speak) apart, resulting in the so-called sea-floor spreading (or divergent plate motion), which translates to the phenomenon popularly called '***Continental Drift'***. Now, if the sea floor in spreading due to the addition of new crustal or lithospheric material and the earth still maintains its constant size, it follows that some of the older crust must necessarily have to be consumed and vanish somewhere else. And because, although thinner, the oceanic crust is made up of denser or heavier rocks (thoeleitic basalt), they end up descending under the lighter but thicker granitic continents at the continental margins, in the so-called *subduction zones*.

What all of this boils down to is that there is plenty of trouble at the convergent, divergent and strike-slip (or transform) plate boundaries where huge amounts of energy must necessarily be dissipated as earthquakes, hence the nightmarish scenarios described above under the *bad and the ugly*. Although no country is completely immune from earthquakes, because even the middle parts of continents may once have been split but now healed plate boundaries (and hence could always be reactivated like an old healed wound), we in Nigeria are lucky to find ourselves within a relatively stable **craton** (or very, very ancient little-changed crystalline basement rock 'foundation'). Our dear country Nigeria is consistent in having bad international press in almost everything, but luckily not when it comes to earthquakes. Perhaps, our great, great ancestors had a hunch to locate us in a relatively safe area of the planet, for it will be horrible to imagine adding catastrophic earthquakes, active volcanoes spewing fire and brimstones, and murderous tsunami waves, to our seemingly endless list of problems. Things are already bad enough without them.

But plate tectonics was kind to Nigeria (or now with hindsight, was it really?) in that it created our geological basins where our huge oil and gas reserves were generated and geologically trapped, in addition to ensuring that we have more than our fair share of other mineral resources within our borders. How did it do it?

First, let us look at the basic principles.

Before 200 million years ago the continents clustered tightly together in a configuration of a universal landmass or super-continent called ***Pangea***, which started to break up and evolve and drift to the present configuration of individual normal continents of the present day (Fig.2). Subsequent geological events on the whole planet have been dominated by this break-up of Pangea. For example, North and South America on the one hand, separated from Europe and Africa respectively, opening up the Atlantic Ocean in the process. Australia, popularly called *Down Under*, moved far away from its then position in the Antarctic (South Pole region) to its present position under Southeast Asia. India, also then in the Antarctic, rotated northeastwards to collide with proto-Asia, throwing up the Himalayas. Africa, on its part, moved up north to collide with Europe (throwing up the Alps). Among other developments the different types of geological basins or tectonic sinks (a basic requirement for the accumulation of sediment, and with it oil and gas, as well as many other mineral resources) formed worldwide in the process.

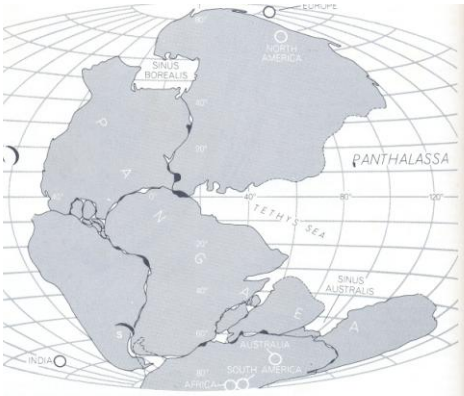
But the bottom line of these developments which are of immediate interest to us in this lecture, is what happened to the area defined by what was to later become our dear Nigeria in all this rifting, tearing apart, separations, drifting, collisions, and what have you.

Figure 3 shows us that the area defined by Brazil was tightly hugging the area defined by Nigeria (the types and ages of rocks on both sides are very similar, and hence confirm this), but more importantly the rifting and separation gave rise to the Benue

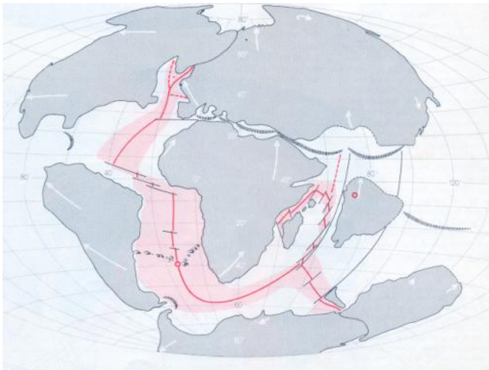
Trough and the Niger delta basins, and all the mineral and petroleum resources located in them (Burke et al. 1971; Burke, 1976; Olade, 1975; Olade and Morton, 1985; Whiteman, 1982; Weber and Daukoru, 1976)

Without the rifting and separation of Africa and South America, caused by plate tectonics, there would have been no South Atlantic Ocean and therefore no Gulf of Guinea. Consequently, none of the Gulf of Guinea countries (Angola, Gabon, Cameroons, Nigeria, Benin, Ivory Coast, Ghana, etc. would have had continental shelf basins in which oil and gas could have formed and accumulated!

A. 200 million years ago



B. 65 million years ago



C. Present day

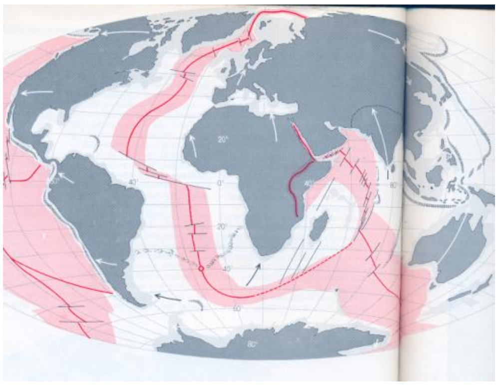


Figure 2. Break-up of the universal landmass or super-continent, Pangea, through rifting, separation and drifting. A. Pangea as it must have looked 200 million years ago before separation into the individual components of today's continents. In the process, the Atlantic Ocean was born, and North and South America separated from Europe and Africa. B. 65 million years ago. C. Present day. After Dietz and Holden (1970).

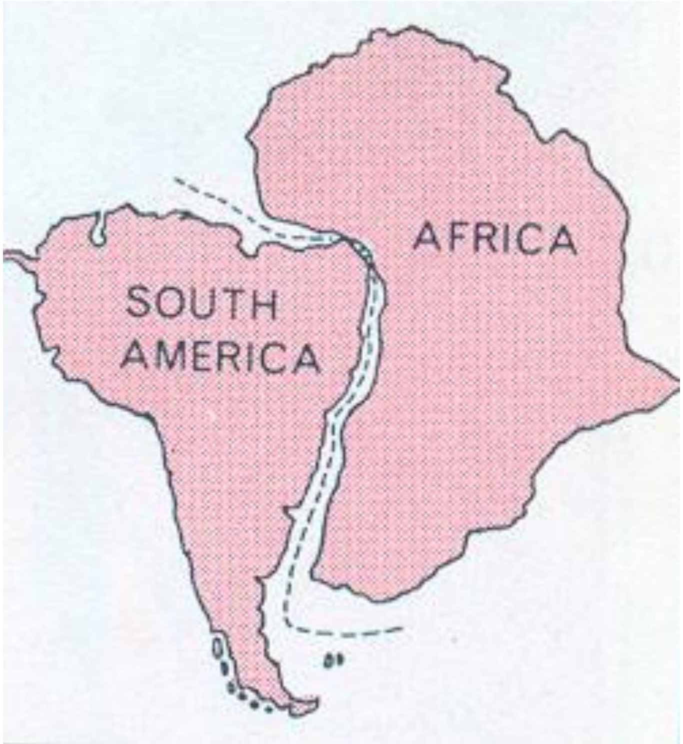


Figure 3. Original positions of South America and Africa 200 million years ago before the rifting and separation of both continents. Separation created the South Atlantic Ocean and Gulf of Guinea, which events paved the way for the geological evolution of the Niger Delta and its huge oil and gas resources. In addition, an aborted rift system cut into what was much later to become Nigeria, creating the Benue Trough and its associated mineral resources.

Minerals

Over 2,500 different mineral species are known to mankind and these have been analysed, identified and described from different parts of the world. Not all of them are 'economically useful' to man; some merely constitute the various ordinary rocks which make up the earth crust and upper mantle, whereas others are exotic-looking enigmatic curiosities with as yet no known economic benefit, except perhaps for horoscope reading and other metaphysical applications.

A mineral is a solid naturally occurring inorganic substance (though not necessarily of inorganic origin), with a definite, or more commonly characteristic range, of chemical composition and distinctive physical properties. Minerals are crystalline, that is they have a solid chemical lattice in which the atoms have a definite, regular and characteristic geometric arrangement (except a few exceptions such as opal which is amorphous or non-crystalline).
However, in a broad non-technical usage, the term mineral includes all inorganic and organic substances which are extracted from the earth for use by man and these include the mineral fuels such as petroleum. Nigeria is endowed with some of these minerals, many of which occur in economically viable quantities and quality, and which can be extracted commercially for profit (Aliyu and others, 1996; MSMD, 1999). In Nigeria they are popularly but inaccurately called 'solid minerals', as all minerals are by definition necessarily solid.

Nigeria is richly endowed with these so-called 'solid minerals'. The Ministry of Solid Minerals Development lists 33 (thirty-three) different types of solid minerals which occur in about 450 locations across the country and which are in various stages of exploration and exploitation.

Before zeroing-in on how and why we have oil & gas in certain parts of Nigeria, and what is responsible for the reasons why some communities have it under their land or coastal waters while others do not, let us quickly look at four common sedimentary mineral deposits associated with the rifting which gave rise to the Benue Trough and Niger Delta basins. It should be noted, however, that there are many other mineral deposits which are not of sedimentary origin, but of igneous and metamorphic origin. These are outside the scope of this inaugural lecture.

The few examples will include three simple, popular, 'everyman's mineral used not only by big companies for industrial purposes, but by simple average Nigerians for routine domestic, traditional or cosmetic applications. The examples are:

Example 1: The industrial mineral deposit of **limestone** (chemically calcium carbonate CaCO3, which may consist of any or mixtures of the carbonate minerals calcite, aragonite and low Mg-calcite). – This rock is not only used in its own right as the main raw material in the manufacture of Portland cement, but is perhaps, more importantly, also an oil & gas reservoir rock in many parts of the world so much so that, in fact, about half of the world's oil reserves are located in them and their closely related dolomites. (A *reservoir rock* is a porous and permeable rock in which commercially important oil and gas accumulations are found and produced from).

Example 2: The metallic ore deposits of **Lead/Zinc** which usually occur together as suphides of these elements. **Galena** (or lead suphide, PbS) is the commercial mineral source of the metal lead. Consider all the lead pipes used by plumbers to supply our homes with water. In fact, the word Plumber is derived from the Latin word *plumbium* which means lead. Apart from its other industrial applications such as in the manufacture of batteries, local rural women in Nigeria grind it into powder for use as eye-lid cosmetic called "*tiro*". **Sphalerite** (or Zinc sulphide, ZnS), on the other hand, is the mineral ore from which the metal zinc is produced. Again, consider all the zinc roofing sheets of our houses which shelter and protect us from the elements, as well as its wide use in many other industrial applications.

Example 3: A precious **Gemstone** mineral called *Sapphire* (when blue) or *Ruby* (when red), both of which are varieties of the mineral, corundum, Al_2O_3 (the second hardest mineral after diamond), which occurs initially in sedimentary, igneous or metamorphic rocks but which is concentrated into so-called sedimentary placer deposits by lateritic weathering of basalts (a dark volcanic rock) in parts of northern Nigeria, among other places.

Example 4: An evaporite mineral known mineralogically as **Trona** (a sodium sesquicarbonate) but which is locally called '***Akanwu***' in southern Nigeria, or '***Kanwa***' or '***Kaun***' in northern Nigeria. Trona is an important source of soda ash which has wide applications in the chemicals industry, but in Nigeria much of it is mainly used in our kitchens to prepare special delicacies which we will discuss shortly.

These minerals have been chosen, not randomly, but based on five main reasons: firstly, the scope of this inaugural lecture precludes a consideration of all the minerals known to man. Secondly, they all occur in Nigeria. Thirdly, apart from the fossil fuel minerals (petroleum, coal, bitumen, tar sands, oil shale, etc), the chosen four minerals are worthy representatives of other classes of economic mineral groupings such as the industrial minerals, the metallic ore minerals and gemstones. Fourthly, we simply want to use them to illustrate how geological processes lead to the localized concentration of minerals in certain specific places, such as under your land, whereas the next neighbourhood may be completely barren of them. Furthermore, some of these, especially the industrial minerals (limestones and evaporites) are intimately linked with oil and gas deposits. Finally, the present inaugural lecturer has spent a significant part of his academic career researching into, and writing about some of them.

Limestones (Carbonate Rocks & Carbonate Petroleum Reservoirs)

Apart from its simple and direct use in the industrial manufacture of cement for construction purposes, there is more to limestones than ordinarily meets the eye. It is used in many industrial applications such as in the manufacture of Iron & Steel, in Sugar Refining, Water Treatment, Glass Manufacture, Construction Industry, Agriculture, Paint Manufacture, Paper Mills, Animal Feed, Tanning Industry, etc. Its metamorphosed (changed by heat and pressure, but particularly heat in contact metamorphism) variety is called Marble, which is widely used as ornamental and dimension stones, or as polished slabs and tiles.

But all of these applications are perhaps dwarfed by its impact and role in the Oil & Gas Industry where it is intimately involved in the occurrence of petroleum and gas. This accounts for the reasons why petroleum geoscientists are so fascinated by carbonate rocks. But why do geoscientists want to be able to predict their occurrence, type and distribution in the subsurface far ahead of exploratory drilling of an oil well? This is because about half of the world's petroleum reserves are found in them (the other half occur in sandstones). The Middles East countries (Saudi, Arabia, the United Arab Emirates, Iraq, Iran, etc.) are home to most of the world's oil & gas reserves and in these countries the oil & gas occur mainly in carbonate rocks (reservoirs). Apart from acting as reservoirs to petroleum, carbonate rocks may in certain circumstances act as so-called source rocks (rocks in which petroleum is formed from entombed microscopic dead organisms) if conditions are right, as we shall see a little later. Furthermore, they are host rocks to a number of metallic ore minerals in the so-called *stratabound or*es (the ores are bound in sedimentary rock beds) or *stratiform ores* (the ores themselves form layers or beds of strata).

Not surprisingly, therefore, the very first research publication (Oti & Müller, 1979) of this inaugural lecturer was devoted to carbonate petrology (although his academic mentor's interest was largely responsible for this). But beside academic interest, the other main the reason for going into that field of sedimentological research at that particular point in time was that certain problems in carbonate petrology were topical and of immediate practical concern. Worldwide at that time, in the years following the great Middle East Oil Embargo of 1973 by the Arab countries as a fall out of their war with Israel, there was great urgency among researchers in academia and the oil industry to fully understand the origin, distribution in time and space, mineralogy, stratigraphy, reservoir geology and diagenesis of carbonate rocks. Diagenesis (or post-depositional changes) in carbonate sediments and rocks was of particular concern because of its impact that could improve or impair the crucial petrophysical properties of porosity & permeability, and hence the ability of the rocks to be good or bad oil & gas reservoirs, among others. It also includes the phenomenon which sedimentologists call dolomitization (chemical changes that could convert a tight impervious limestone into a very porous and permeable magnesium-bearing one by the isomorphous substitution of Calcium ions by Magnesium ions in the solid rock mineral lattice). Now, back to that first little paper. This inaugural lecturer was extremely proud of that first contribution to knowledge which was the result of his 1977 Masters thesis on the Microstructure and Petrophysics of Recent Ooids. His supervisor and other senior researchers at the Institute of Sedimentary Research in Heidelberg thought the work was worthy of presentation at the 1978 Congress of the International Association of Sedimentologists which took place in Jerusalem, and so his supervisor took him to that congress where the then young doctoral student presented it (Oti & Müller, 1978). After the presentation, followed by the usual applause, four African gentlemen were among those who walked up to congratulate me. It turned out that they were participants from Nigeria who came on behalf of the Nigerian National Oil Company (which later became the NNPC). They were surprised and proud to learn that I, too, was their fellow Nigerian, and I felt quite elated. But why this mention of that very first research paper? The reason is that this inaugural lecturer was so inspired, encouraged, and emboldened by his apparent ability to join the fray in scientific research and discourse, to make modest contributions in solving scientific problems, and to confidently present his findings at a major international conference of experts, at that relatively young age, that he decided then and there to pursue a career in academics! Perhaps, without that first beckoning call to the excitement of academic research work he might have been lured away to a more economically rewarding industry when Elf and Shell came calling in early 1980 in Heidelberg, and would consequently not be standing here today giving this inaugural lecture.

The Unique and Wonderful Characteristics of Carbonate Rocks

All rocks – igneous, metamorphic and sedimentary - are formed by physical and chemical processes. But the formation of most carbonate rocks has another critical dimension, in addition. That dimension is the involvement of life. Although, in some instances carbonate rocks can form in evaporative settings, where only physico-chemical processes prevail and lead to their precipitation out of sea or lake water, but more often than not, there is the input of life – either directly or indirectly. Many plants and animals are important as limestone-builders because after their death their calcareous (or calcium carbonate) skeletal remains, can accumulate to form limestones. This is due to the fact that some of them, through their physiological activities, are calcifying, in that they extract calcium carbonate directly out of ambient sea water to form their exoskeletons, tests and shells which contribute to carbonate sediments and rocks when the organisms eventually die (Oti & Müller, 1981). On the other hand, others organisms - plants in particular - extract dissolved carbon dioxide from sea or lake water through photosynthesis, and this leads to the inorganic precipitation of calcium carbonate which then forms carbonate sediments and rocks.

Consider the so-called Coral Reefs, for example, which form in shallow waters close to the coastlines of many countries and which have led to countless shipwrecks when unsuspecting ships sail into them. Even in Greek mythology - Homer’s epic, for example - Odysseus the Greek warrior, whose latin name was Ulysses, would have fared a lot better without his tragic shipwrecks occasioned by none other but the gods and their treacherous reefs! Not even his ingenuity with Trojan horses could have prepared him well enough to cope with reefs. Also, many treasures unjustly seized by sea pirates centuries ago but which now lie unclaimed on the bottoms of the world’s oceans due to the sinking of the pirate ships have reefs as the ultimate Nemesis.

But as far as petroleum is concerned reefs are a blessing. Reefs are not only built by corals, but also by numerous other calcareous plants and animals such as green algae (eg. *Halimeda*, *Penicillus* – *Udotea*, *Dasyclads*, etc), red algae, especially the so-called coaralline algae (eg. *Lithothamnium*, *Goniolithon*, *Porolithon*, *Corallina*, etc), the marine invertebtrate animals such as Echinoderms (or sea stars or sea urchins), Molluscs (oysters, gastropods and others), etc, and animal colonies such as Bryozoans, and so on. The list is long.

The important thing is that ancient buried reefs are some of the best carbonate reservoirs for oil & gas deposits and they represent an excellent example of what the petroleum explorationist would call a stratigraphic trap, because it is a very porous and permeable carbonate build-up (bioherm) which is surrounded by impermeable mudstones leading to an ideal situation where you have reservoir rock and a so-called source rock (the mother rock in which petroleum is formed) in close juxtaposition. They therefore constitute prime exploration targets for oil & gas.

Other carbonate rocks may also be excellent reservoirs as well. The reason is that no matter how tight and impervious they might be when they are initially formed as rocks, they are more often than not later transformed to very porous and permeable reservoir rocks through the process of **diagenesis** (Oti, 1980; Oti, 1982; Oti, 1985; Oti & Ogbuji 1986; Oti & Müller, 1985), to the extent that the tight limestones may transform altogether into another type of carbonate rock called Dolomite, itself a petroleum 'gusher', under certain circumstances. Diagenesis include all low temperature and low pressure physical, chemical and biological changes that act upon a sedimentary rock from the moment they are deposited until the onset of metamorphism when the rocks are further and radically changed again by enormous heat and pressure.

Apart from reef organisms other carbonate rocks are formed by blue-green algae (eg Cyanophytes) where they form algal mats (so-called boundstones) and stromatolites (that look like giant mushrooms but composed of carbonate rock). Another important group of calcareous plants belong to Phylum Chrysophyta (or Coccolithophorids) and form deep-sea carbonate rocks called Chalk which consists of submicroscopic coccospheres and coccoliths. They are so very small - about 5μm in diameter - that they sink extremely slowly, needing about 10 years to reach the deep (5,000 meters) ocean floor, first as very soft carbonate ooze, which later hardens as chalk, through diagenesis. Chalks are also excellent carbonate reservoirs for oil & gas and some of the world's giant oil fields (eg. in the North Sea) are made up of them. Some other allochems or calcareous components that form further excellent carbonate rock reservoirs include ooids or oolites (Oti & Müller, 1979) which are rounded carbonate grains that look like the roe or eggs of fish (but have nothing to do with fish at all) that form in turbulent shallow seas, as well as pelloids or fecal pellets excreted by crabs and other organisms in quiet lagoons. In most cases, carbonate sediments and rocks consist of diverse components, some of which are listed above, but in some cases they may consist of just one type of component, eg. ooids only (for oolitic limestone) or mollusk shells only (for coquina limestone) or foraminifera (for foraminiferal limestone), etc. Or they may consist of very fine-grained submicroscopic inorganic carbonate particles called micrite (or lime muds).

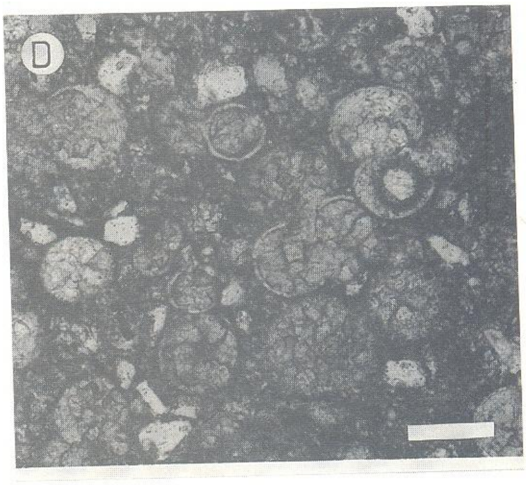


Figure 4. Thinly sliced limestone rock (less than 30 microns thick) from the Nkalagu Limestone deposit (Enugu State), entirely made up of microscopic-sized, foraminiferal (protozoan) skeletons consisting of calcium carbonate. These unicellular animals lived and floated in the Cretaceous sea (from Atlantic Ocean waters) which covered the Nkalagu area some 80 million years ago. (From Oti, 1990d).

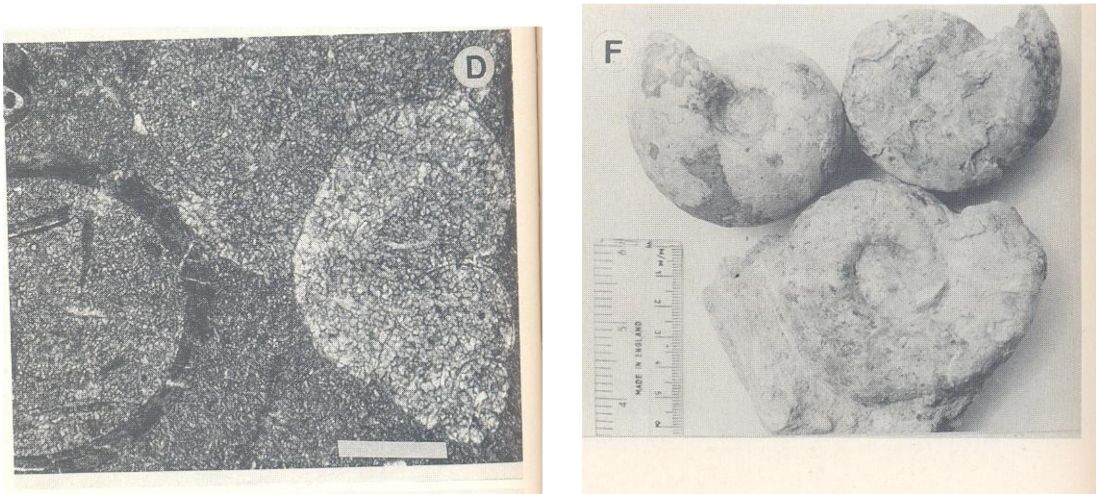


Figure 5. **Left**: Thinly-sliced limestone rock from the Ashaka Limestone, Bauchi State, revealing the calcium carbonate skeletal relics ('ghost') of a juvenile marine gastropod (snail). **Right**: Whole specimens of ammonite (an extinct Cephalopod and great, great ancestors of modern squids and octopuses), also from the same Ashaka Limestone in Bauchi, Nigeria. Both lived in the sea (Atlantic) that transgressed far into northern Nigeria and covered parts of Bauchi State, other states, and beyond, during the Cretaceous period some 80 million years ago, but selflessly contributed their carbonate skeletons to form the limestones we now mine to manufacture cement. (From Oti, 1990c).

During the geological period called the Cretaceous (from Latin *creta*, for chalk) which lasted from 145 to 65 million years ago, there was particularly widespread deposition of carbonate sediments from the oceans because many calcareous organisms such as the nannoplankton Coccolithophores flourished and died to form chalk and other carbonate sediments. These sediments later lithified or hardened to form carbonate rocks.

The area which was to be later known politically as Nigeria also witnessed widespread carbonate sedimentation. All that was required is warm shallow seas and the presence of some of the marine organisms and conditions already discussed. But we have carbonate rocks in only certain parts of Nigeria, not in all parts. What this implies is that the Atlantic Ocean must have extended (or transgressed) inland to only those places in past times, although the ocean has receded (or regressed) from those places a very long time ago. Let us start from the South: we have limestones in such places, for example, as Ewekoro/Shagamu in Ogun State in the southwest, Arochukwu/Ohafia in Abia State, Obotme in Akwa Ibom State, Nkalagu and Odomoke in Enugu State, Mfamosing and Odukpani in Cross River State, Igumale, Ogbolokuta and Yandev in Benue State, Ashaka and Kanawa in Bauchi State and Kalambaina in Sokoto State (although the Ewekoro and Sokoto deposits are different in that they formed later on a passive continental margin, the Dahomey basin, and in an intracratonic inland basin, the Iullemedden basin, respectively).

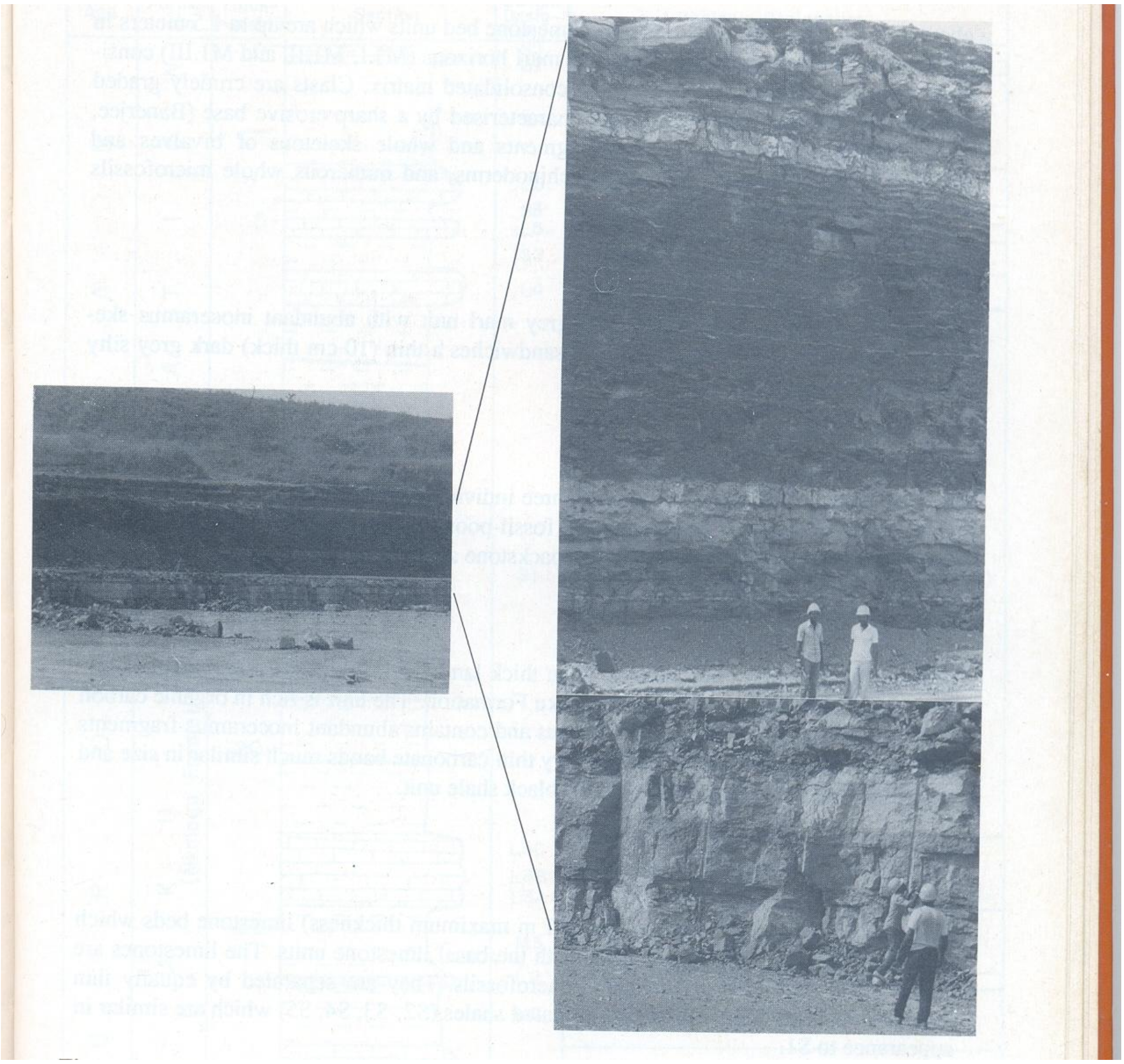


Figure 6. Open cast mine at the Nkalagu Limestone quarry at Nkalagu, Ebonyi State: left – overview; right – close up. (From Oti, 1990c).

Most of the marine organisms which were discussed earlier participated in the formation of these limestone deposits in Nigeria and are in deed entombed in the rocks. Now, however, if you climbed a mountain and found sea shells and marine fishes fossilized in rocks on the mountain top, you have no choice but to accept that that mountain top was once the bottom of a vanished sea or ocean. Geologists call this type of reconstructive reasoning '*paleoenvironmental or paleogeographic reconstruction'*, and it is based on another fundamental geological principle which states that '*The present is the key to the past*'. If squids and fish live and swim in the sea today, it is reasonable to assume that in the past they also lived and swam in the sea, not on land or in the air. Geological jargon calls this '**The Uniformitarian Principle**'. Following this principle, we are able to deduce that the Atlantic Ocean inundated the interior of

Nigeria from the coast and extended inland far beyond Nigeria, and most probably across North Africa by way of a 'trans-Saharan seaway', depositing carbonate sediments (which later hardened into carbonate rocks) as it progressed on its way. The enabling environment was provided by the rift basin (Benue Trough) which was created when South America separated from Africa along a so-called triple junction. Two arms of this triple junction were successful in separating both continents and opening up the South Atlantic Ocean, but the third arm failed to fully develop and ended up as a 'dwarf', the Benue Trough. Nonetheless, the Atlantic waters moved into it and left the marine sediments such as the carbonate rocks found all along the graben or incision. (Oti, 1983; Oti, 1985; Oti, 1988; Oti, 1989; Oti, 1990a; Oti,1990b; Oti, 1990c; Oti, 1990d; Oti & Koch, 1990). So, apart from the exception of the coastal Dahomey basin (Ewekoro) or the inland intracratonic Sokoto basin (Kalambaina) both of which were also formed by plate tectonics, if your village or community is not located anywhere along the route of that Cretaceous sea way, which route was itself dictated by plate tectonics that was responsible for creating the rift basin in the first place, it is futile to dream of having limestone deposits under your land in Nigeria.

The Metallic Ore Mineral deposits of Lead & Zinc

When I was a boy I remember that many rural women wore a cosmetic make-up called '*Tiro*' (or '*Otanjele*' in some parts of SE Nigeria). It was used very much like the modern eye-pencil in darkening the hair on the eyelids and eye-brows. I do not know if some of the ladies here today are wearing tiro, but I have a hunch that they are not. Of course, at the time I had no clue what tiro consisted of, just as I have no clue today what the modern eye-pencil consists of. Many years later in the mid-1980s, when I was doing field work somewhere around Ishiagu in Ebonyi State, I saw and recognized the mineral, *galena*, or lead sulphide PbS, being sold by rural women in the village market. I was curious to know why galena was being sold and bought in the open market by rural women. Upon inquiry, I was informed that it was a cosmetic! Firstly, my mind went to the possible safety implications. Administering lead on any part of the human body may not be the safest of habits. It could in fact be quite dangerous as lead could be toxic above certain concentrations in the human body. But then I reckoned that if they had experienced any adverse effects through several generations, the habit would have been discontinued.

But *tiro* aside, lead and zinc are important metals for the manufacturing of several goods used by modern society. They are important components in alloys. Lead is used in the manufacture of batteries, lead foils, electrical cables, bearings, etc and in glass making. Zinc, on the other hand, is widely used in the manufacture of alloys, as protective coatings for other metals, in dry cell batteries, etc.

Deposits of lead and zinc ores usually occur in association, that is, they occur together in an intimately tight textural fabric. Such associations are termed **paragenesis**, and petrographic study (microscopic study with a polarizing microscope) will often unravel

the timing and sequence of their precipitation in the host rock, and consequently throw light into how they formed geologically.
But how did they come to be deposited in and hosted by the subsurface sedimentary rocks in many areas along the narrow belt of the Benue Trough, that is from Ishiagu and Abakaliki areas in southeastern Nigeria through Benue State to Taraba, Plateau and Bauchi States?

To answer this question let us take a closer look at an example of a present-day rift basin in its embryonic stages with a nascent 'baby' ocean. Our example is the Red Sea which separates Egypt/Sudan from Saudi Arabia. The sea water at the bottom of the rift is a hot brine, due to the high heat flow (or geothermal gradient) and hot **hydrothermal** fluids from the deep seated faults and fractures right below the bottom of rift system that gave rise to the Red Sea basin. It is an active spreading boundary between the African and Arabian plates. If you came back there in a few million years from now the present-day narrow Red Sea would have widened to a brand new, full-blown ocean. But for now, the important thing is that the crustal activity is bringing up so-called hydrothermal fluids laden with dissolved metals such as lead and zinc which are precipitated in the sediments at the bottom of the sea. Also, simultaneously, the overlying sea water is percolating down into the hot upwelling new sea floor and dissolving out metals and re-precipitating them within the sediments. This scenario, coupled with extrusive magmatism, occurred in the Benue Trough several million years ago during its active rifting stage in the late Jurassic to Cretaceous times, and today lead and zinc ores are mined from hydrothermal veins (cracks, fractures and fissures) in shales (hardened mudstones) and limestones, and according to the Ministry of Solid Minerals Development (1999) the Nigerian Mining Corporation estimates proven reserves of over 711,000 tonnes in the Abakaliki area alone. Again, we see that geological processes have lead to these deposits being found exactly where they are, and apart from revenues that will accrue to the Nigerian nation from large-scale mining and export of these minerals, the rural women in these areas would at least, if nothing else, continue to have 'resource control' over the local *tiro* trade.

Figure 7. Galena (PbS): Typical habit and texture in host Limestone and Shales

The Gemstone Sapphire

In Nigeria, this category of mineral resources have their primary occurrence in alkaline basalts (volcanic rocks) mostly in northern Nigeria - in Kaduna, Plateau and Nasarawa States. Gemstone mining is a flourishing industry in parts of Northern Nigeria, but most of the miners are local, small scale, individual miners called artisanal miners.
But the gemstones are not extracted by the local artisanal miners directly from the basalts themselves which are hard igneous rocks. These local, mostly rural, miners (who until recently, have variously been branded 'illegal miners' by the authorities – colonial and Nigerian) do not understand the geological basis of mineral deposits and mining operations, nor do they have the requisite technology. Instead, geological process of weathering have softened and loosened the initial very hard rocks to very soft so-called lateritic soils in which these very hard gemstones have accumulated as secondary residual deposits, waiting to be picked (or harvested, so to speak) with relatively little effort, close to the ground surface.

Lateritisation is a widespread geological weathering phenomenon in the humid tropics which has been operating for several million years, and have been known to impact such diverse areas of national economies such as mineral resources occurrence and distribution, agricultural production or the lack of it (if the soils are completely leached of nutrients required by plants), construction industry – particularly for roads and buildings; indeed this geological phenomenon could be the driver for wealth or outright poverty and disease!

But let us focus on the mineral resources potential aspects of lateritisation, a variety of chemical weathering of rocks. In my recent research book (Oti, 2007), several aspects of this geological phenomenon were investigated and reported upon. Although, lateritisation leads to the geological concentration of certain mineral deposits such as iron ore, aluminium ore (bauxite), nickel ore, gold, gemstones, etc., it can have negative aspects. In particular – and paradoxically – the very fact that they are the products of deep in-situ weathering also constitutes them into a mapping nuisance for the geologist because they mask or 'blanket' the underlying bedrocks. This makes geological mapping, and hence the appraisal of the mineral resources potential of a region extremely difficult, if not outright impossible. Therefore, we sought through our studies to try to establish geochemical benchmarks and trace element 'fingerprints' inheritable by laterites from their hidden parent rocks that could betray the identity of the unseen parents, as well the mineral resources which are derived as fall-outs from the accompanying changes (Oti, 1987; 1990e, 1990f; 1995; 2007a, 2007b, 2007c, 2007d, 2007e).

One of the several mineral resource fall-outs emanating from lateritisation which may be of interest to us, particularly those interested in jewelry, is the precious stone or gemstone sapphire (Henn, 1986; Kiefert and Schmetzer, 1987), which occurs widely in parts of Northern Nigeria (Figure 8).

Figure 8A. Villagers, artisanal miners and prospectors recovering sapphire gemstones from lateritic soils in Northern Nigeria in 1987

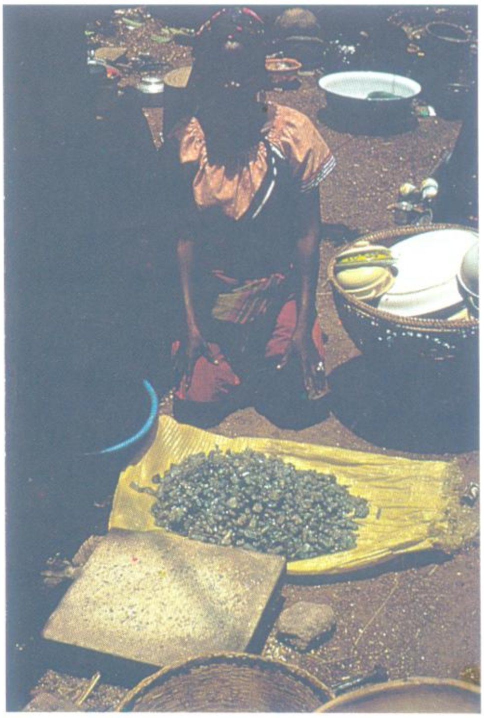


Figure 8B. Raw Sapphire Gemstones being sold in a local market near Kaduna, Northern Nigeria (from Kiefert & Schmetzer, 1987)

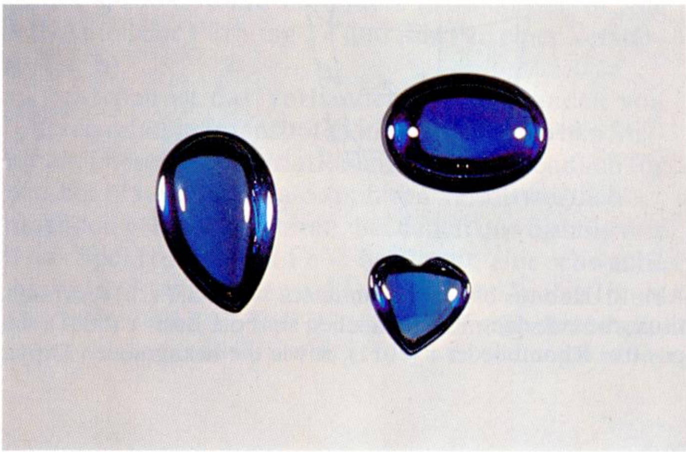


Figure 8C. Cut and polished blue sapphire jewelry from above raw gemstones from Northern Nigeria (from Kiefert & Schmetzer, 1987)

Blue sapphires are one of the four most-valued gemstones known to mankind, besides rubies (red sapphires), emeralds (green gemstone variety of beryl) and diamonds. It was already known and valued even in ancient biblical times. For example, in Exodus – in the Old Testament of the Holy Bible - it is the gemstone on the *ephod*, thought to have represented the tribe of Issachar, one of the twelve tribes of Israel.

> Excerpts: "….that they make Aaron's garments to consecrate him for my priesthood. These are the garments which they shall make: a breastpiece, an ephod, a robe, a coat of checker work, a turban, and a girdle; they shall make holy garments for Aaron your brother and his sons to serve me as priests. … And you shall set it in four rows of stones. A row of sardius, topaz and carbuncle shall be the first row; and the second row an emerald, **a sapphire**, and a diamond; and the third row a jacinth, an agate, and an amethyst; and the fourth row a beryl, an onyx, and a jasper…. There shall be twelve stones with their names according to the names of the sons of Israel…" (Exodus 28:3-4, 17-21).

In astrology or horoscope reading (not to be confused with astronomy which is the physical science that deals with the origin, composition, properties, etc. of stars and the universe), blue sapphire is associated with the planet Saturn, while yellow sapphire is associated with Jupiter. People who believe in birthstones will tell you that sapphire is associated with the month of September. If you have been married for a long time, your 45th wedding anniversary is known as the Sapphire Anniversary. And so on...

Now, let us take a close look at Sapphire. It is the gemstone variety of the mineral Corundum, chemically aluminium oxide (Al_2O_3), the second hardest natural substance known to man, after diamond. It occupies the 9th position on the so-called Moh's hardness scale (denominated from 1 to 10), ranked just below diamond which has the 10th and highest position. It crystallizes in the trigonal (or three-sided) system of symmetry, in crystal habits (or shapes) of hexagonal prisms (or six-sided barrel shaped rods, with flat or pyramid-shaped terminations). It may be colourless, but more often

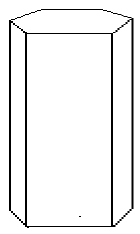


Figure 9. Typical hexagonal prism shape of natural crystal of sapphire

than not it is coloured by impurities of metallic elements such as iron, titanium, chromium, vanadium, etc. Because it is colour that makes ordinary corundum to become a valuable gemstone, this would appear to be a rare instance where impurity is desired over purity. Corundum can be colourless, or ***red*** due to chromium oxide impurities (in which case it is the gemstone *Ruby*), or ***blue*** due to impurities of iron and titanium oxides (and called *Sapphire*), or other colours such as orange, red, violet, indigo, green, brown, mauve or even black. In Nigerian sapphires, like sapphires from elsewhere, the blue coloration is the due to absorbed impurities of iron and titanium oxides either as compounds, or combined in very tiny crystallites of yet another mineral called ilmenite, which finds its way into host sapphire crystal as inclusions. In deed, the phenomenon of crystallite inclusions has resulted in the spectacular and most invaluable property of ***asterism*** found in the so-called Star Sapphires, where oriented, intersecting tiny inclusions of the mineral, rutile, cause a magnificent six-pointed star-light effect in the sapphires (eg. the magnificent and priceless 563-carat “Star of India”).

However, because of its hardness ordinary corundum has wide application in industry as well. It is used as an abrasive, as refractories in high temperature furnaces and kilns, as a non-slip surface treatment for tiles, etc. Apart from its natural occurrence as a mineral it is manufactured artificially for these and many other industrial uses. For example, it is manufactured in large crystal *boules* many inches across, useful for different industrial applications such as in the semiconductor industry (wafers or substrates for growth of Gallium nitride semiconductors), infra red and laser optical components (the first laser ever produced was based on ruby, the red variety of corundum), the production of very durable, scratch-resistant faces of designer watches, etc, etc.

Sadly, though, fake imitations of natural sapphires can be synthetically produced by the technology of flame fusion, and can look so real that it is almost impossible for the non-expert to tell the difference. In some cases, it could be quite tricky for the expert gemologist. Even the colour nuances, the crystallite inclusions, metallic oxide impurities can, and are routinely artificially replicated. Well, I do not know if these technologies for faking this wondrous work of nature are as yet available locally here in Nigeria - only time will tell.

The Evaporite Mineral, Trona (*Akanwu, Kanwa or Kaun*)

In the South Eastern and South South States of Nigeria, some of the much cherished and relished delicacies of their cuisines are *Isiewu* (goat head), *Ugba* (sliced oil bean seeds), and *Nsisa* (thinly sliced cassava, alias ‘tapioca’), etc. The common denominator of these delicacies is their content of the evaporite mineral, ***Trona***, locally called *Akanwu*. Basically, Akanwu is used in the saponification of palm oil to transform it to an indescribably pleasant taste. Folklore has it that in one of these States (I hear it is Imo, but I am not sure), a man finds the ultimate satisfying experience if only he is served *Ugba* and some palm wine to wash it down! I gather that the *Ugba* itself (or the *Isiewu*) is of little consequence in itself; what matters is the *Akanwu* used in preparing it!
Beyond these, *Akanwu* is also widely used as a tenderizer to quickly soften tough menu items such as beans, dry stockfish, etc.

The chemists and biochemists certainly know all about the kinetics of the reactions involved; what concerns us here is the geology and mineralogy of the mineral locally called *Akanwu*, *Kanwa* or *Kaun*

Trona (*Akanwu*) is an evaporite mineral which precipitates in shallow lakes undergoing strong evaporation. These are the so-called ***Playa*** or saline or salt lakes. Lakes can only be present if there is a geological basin to host it. Many of such basins are inland intracratonic ***sag basins*** formed by Plate Tectonics. These basins form when there is localized heat (*mantle plume*, in geological jargon) from below the mantle slowly heating up the relatively thin overlying earth crust. The end result is the sagging of the crust to form a lacustrine (or lake) basin in which the evaporation of the water mass occurs with the accompanying precipitation of all kinds of salt minerals, which eventually leads to the lake becoming saline. When the lake becomes very saline, it becomes so salty that no normal living things (plants, animals, even fish), except perhaps specially adapted forms, can survive in it. A good example is the Dead Sea in Israel, called the *dead* sea because of this phenomenon. Also the water density increases so much that even if you cannot swim, you cannot sink and drown because whether you like it or not you must float, as your body density is much smaller (lighter) than that of the salt water. If and when you visit Israel go to the Dead Sea and swim; if you are unable or unwilling to swim you can simply lie and float on the water while you read a book or newspaper! This inaugural lecturer tried it in 1978, and found it to be a wonderful experience. It is also believed that the hypersalinity has positive medicinal value for some dermatological skin conditions – so, enjoy the double benefit of floating effortlessly while you heal!

Searles Lake, in Death Valley of the United States is perhaps one of the world’s most famous places for present day precipitation of trona, to the extent that a city which sprang up at the shores of the saline lake is itself called Trona. There the mineral is the direct source for the industrial production of sodium carbonate, unlike other places in the world where the product is produced through the indirect method of the Solvay Process. Other places where trona is mined include Lake Tangayinka in East Africa, and in Namibia.

Nearer home here in Nigeria, it occurs as one of the evaporite minerals deposited in the ancient Lake Chad basin millions of years ago. Lake Chad used to be very much more extensive in area than it is presently, and so deposits of trona are found in states as far afield as Borno, Yobe, Taraba and Adamawa in northeastern Nigeria, with notable deposits in Manga, Tula, Geidam, Yusufari, Kukawa and Kazaure, from where again mostly local artisanal miners are involved in its exploitation and trade. With so much *akanwu* being consumed domestically in Nigeria's kitchens alone (let alone export in the ECOWAS subregion and overseas), there could be quite some substantial financial reward in that mineral resource, to some day warrant some agitation for 'resource control' and the derivation principle, when oil ceases to take centre stage. Again, only time will tell.

Trona, chemically a sodium sesquicarbonate or $Na_3H(CO_3)_2.2H_2O$, is colourless, greyish, yellowish white, or pale brownish. It is transparent to transluscent, vitreous and may be glistening. It is relatively soft, with a hardness on the Moh's scale of 2.5, unlike corundum (sapphire) which has a harness of 9.

The industrial uses of the partly refined product of trona, sodium carbonate (soda), are many and include applications in the manufacture of glass, soaps, detergents, paper, etc. It is also used in petroleum refining, production of alumina from bauxite and in water treatment.

Trona is a typical example of a lacustrine evaporite mineral which we have chosen as *everyman's mineral* because of its domestic usage by all and sundry in Nigeria. There are many other evaporite minerals which have much greater economic significance. These are mainly the marine evaporites, and they include the minerals **halite** (rock salt, or common salt, NaCl), **sylvite** (or KCl, used widely in the manufacture of fertilizer), and **carnallite** ($KCl.MgCl_2.6H_2O$). Others are **anhydrite** ($CaSO_4$) and **gypsum** ($CaSO_4.2H_2O$), etc. Gypsum is used as an additive in the manufacture of cement, and also as the main raw material in Plaster of Paris (POP) for our decorative ceilings and to fix our bones when fractured, among other uses.

But the petroleum geologist will argue that the greatest and most important use he or she sees in evaporites is their ability to form **salt domes** - large, deep-seated, mushroom-shaped, subsurface geological diapiric structures that trap oil & gas. Salt domes form when the overburden (or the weight of overlying geological formations) trigger off plastic deformation in the salt beds, due to differential loading, which lead to the irreversible 'mushrooming' of the salt beds. In the process, the previously overlying horizontal beds of sandstones, limestones and shales become so deformed that they form structural (and possibly stratigraphic) traps for oil & gas. Therefore, the existence of a salt dome in an oil mining acreage is a prime exploration target for the petroleum geologist.

Furthermore, because of their plasticity which makes them mobile salt domes are considered geologically suitable – at least theoretically - as repositories for the disposal of nuclear wastes generated from nuclear power stations. To accomplish this, a borehole is drilled deep into the salt dome, the highly radioactive wastes are then emplaced within the salt body and then sealed off. Eventually, the mobile salt gobbles it up like an octopus and entombs it forever. Forever, that is until tectonics throws it up near the surface where the salt will dissolve and the radioactive wastes can contaminate the groundwater. But it will take several million years in the future for that to happen – and by then, it is conveniently assumed, that scenario will no longer be the problem of us current humans on Planet Earth! Some developed countries tried to do just that but met with stiff opposition from environmental activists – the so-called 'Greens'. In the mid-to-late seventies in Germany, for example, I remember that that led to several demonstrations and clashes. I suspect that some of my German classmates at the time participated actively - to help protect future unborn generations - but never gave me any hint of their involvement, except for some tell-tale battle bruises, which they never quite successfully explained away. Eventually, the program was shelved - to everyone's relief.

Figure 10. Trona, locally known as '*Akanwu*', from Northern Nigeria. The mineral is widely used locally in Nigeria and other parts of Africa in preparing local culinary delicacies, and as a tenderizer to quickly soften tough food items being boiled.

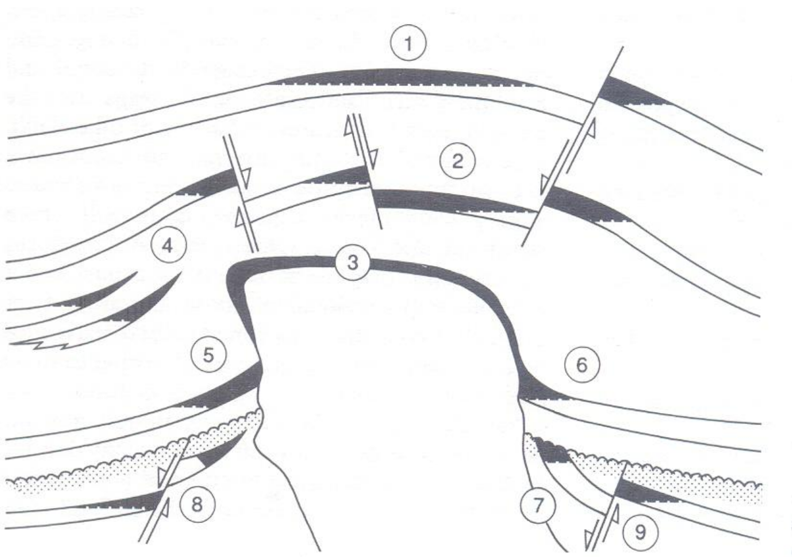


Figure 11. A Salt dome (diaper) with its myriad of associated petroleum trap types (1-9).
Note: black = oil accumulations. From Halbouty (1979).

"……There are enormous challenges ahead, not least in the exploration, production and delivery of fuels to an energy-hungry world……"
Eivald Røren, President World Petroleum Council, 2005

Petroleum

On petroleum resources, Mr Vice Chancellor, ladies and gentlemen, please permit me to use metaphors in setting the stage for our brief discourse:

It all starts off with a geological sink (**basin**) which has accommodation space to receive water and all types of different sediments, some of them minerals and the others, organic matter (from microscopic dead organisms). Then, this cauldron of a mixture gets buried under more sediments (overburden) and gets gently cooked up by heat under pressure to the point that the organic matter matures first into **kerogen**, and from there begins to form (*generate*) oil and gas. But at this point, the heat and pressure (but particularly, the pressure) forces or compels (*compacts*) the particular type of sedimentary rock (**source rock**) containing the organic matter to expel the generated oil & gas from its pores due to lack of space to hold it any longer, just like a water-soaked sponge will expel its contents when squeezed. It then begins to move or wander (*migrate*) without any pre-planned destination – often, for several kilometers - until it stumbles into some ample space that can hold it (a porous & permeable sedimentary rock called a **reservoir rock**), but which unfortunately is booby-trapped (by structural or stratigraphic geometrical configuration or a combination of both – called a **trap**). There, more and more of its folk (more hydrocarbons) follow it sheepishly and join in getting trapped as well.

All of them – the initial water (**formation water**), the **oil** and the **gas** sort themselves out in the trap by their respective densities, with the water at the base, followed by the oil, and then topped by the gas. There, they all remain entombed for millions of years, until *homo sapiens* (we humans), appear on earth much, much later, get wise, and develop adequate technology to find and extract the oil from the deep recesses of the earth (**exploration** and **production**).

Meanwhile we have also developed an insatiable taste for luxury goods and lifestyle powered by energy-gulping slave machines (manufacturing plants and machines, cars, aeroplanes, factories, industry, house-hold goods and machines, etc) and within barely a hundred and fifty years have almost completely plundered what it took mother Earth over 600 million years to put together (when photosynthesizing life, albeit primitive, first appeared and began to capture the sun's energy to form fossil fuels). In the process, we have given back to mother Earth, despite her benevolence, damaging green-house gases (GHG) and other pollutants which have disrupted the earth's ecosystems. Even worse, wars have been, and are still being, fought to secure the petroleum energy resource, populations have been oppressed, the Earth itself has been badly shaken, climate has changed – perhaps irreversibly – and petroleum, being non-renewable, will one day be used up and come to an end.

This, in a nutshell, is the synoptic overview of the story of petroleum on Planet Earth. At some point in the future we will have no choice but to develop other sources of sustainable and renewable energy (solar, wind, tidal, nuclear, geothermal, etc.), or go back to wood (if trees will still be growing on a ravished Earth), or simply go back to where we originally started – animals and human slaves!

Now, why do some areas (countries, communities, localities) have this resource buried under their land whereas others do not have it? With its broad industrial application as a versatile raw material, and particularly as the primary source of energy for an energy-hungry world (and currently sold at over $95 US dollars for a barrel in November 2007 at the time of completing the writing of this lecture) its commercial value is certainly not in question; in deed it seems so valuable that countries are fighting wars over it and people are killing others and getting killed over it.

However, before we begin to answer the question of the geological controls over its occurrence and distribution in space and time let us first of all remind ourselves with exactly what this resource is in the first place. The word Petroleum is derived from the Latin words *petrus* (rock) and *oleum* (oil). We are therefore dealing with rock oil, a naturally occurring hydrocarbon compound found in subsurface rocks, but which might sometimes seep out to the earth's surface. There are various varieties or forms in which it may occur, and these include crude oil *sensu stricto*, natural gas, bitumen, tar sands, oil shales, etc

Chemistry

Petroleum is a mixture of hydrocarbons (saturated and aromatic), with minor amounts of nitrogen, sulfur and oxygen compounds (NSO compounds), as well as minor contents of organometallic compounds (commonly of vanadium and nickel), and traces of several other elements. Petroleum may be composed of these compounds in the gaseous, liquid or solid state, depending on the nature of these compounds and the prevailing conditions of temperature and pressure.

Hydrocarbons are molecules of hydrogen (H) and carbon (C) bonded together. One carbon atom can bond with a maximum of four hydrogen atoms, resulting in the simplest hydrocarbon called methane, CH_4, which exists as a gas. Other simple hydrocarbons are ethane (C_2H_6) and propane (C_3H_8), both of them gases as well under normal temperature and pressure conditions. Their structure is said to be saturated as there are no spare bonds, and is therefore relatively stable; a change in chemistry can only come about by replacing one or more of the hydrogen atoms. Where spare bonds are available the hydrocarbon is said to be unsaturated, and is less stable. The saturated hydrocarbons include structures with simple straight carbon chains (the normal paraffins or normal alkanes), branched chains (the isoalkanes) and rings (cyclohydrocarbons).

Aromatic hydrocarbons are unsaturated, have cyclic structures, and include many biomarker compounds used in correlating oils to their source rocks – an important exploration technique used by petroleum geoscientists.

Mandatory Prerequisites for Petroleum to Occur at a Specific Location in the Subsurface

For oil and gas to occur at a particular location the following conditions must be met, and *all of them together*, without exception. For the petroleum geologist, these would seem to be his six 'geological commandments':

1. There must exist a **geological basin,** also called a **sedimentary basin** or basin, for short, (a structural depression or 'sink', in the earth crust, formed by Plate Tectonics, in which sediments will be received and accumulate over geologically long periods of time, usually in the order of millions of years). As a general rule, basins with about 3km or more thick sediments and the normal geothermal temperature gradient of 3 °C/100m have good prospects for oil and gas (all things being equal), although there are exceptions eg. in rift basins where abnormal high geothermal gradients of 5-6 °C/100m or more permit sedimentary fill of 1.5 -1.8 km thickness to bear hydrocarbons (Hiller 1986).

2. There must be present in the basin a so-called **source rock** (sediments – usually mudrocks/shales and carbonates) which are rich in organic matter, at least 0.5% to about 4% or more of total organic carbon, TOC). The source rock should undergo sufficient thermal (heat-driven) maturation deep in the subsurface as they subside or get buried into the so-called 'oil generative window' or geological underground 'kitchen' where the organic matter is 'cooked' into oil or gas, or both, over several million years. Kerogen (insoluble organic matter) and bitumen (organic which is soluble in organic solvents) are the initial products of the transformation of organic matter buried with sediment in anoxic conditions. There are three types of kerogen; some are gas-prone while others are oil-prone, or both. Ideal temperature for peak generation of oil is between 80 – 150 °C; at higher temperatures the oil gets cracked to yield gas. After having generated the hydrocarbons, the source rock should be able to expel it, causing it to migrate to where it can accumulate. The whole gamut of generation, expulsion and migration to a reservoir is called 'petroleum charge'.

3. There must exist within the same basin a so-called **reservoir rock** (generally carbonate rocks and sandstones) which should be porous enough to store the oil and gas in its pores, and permeable enough (ie. the pores should be inter-connected) to let the oil and gas to flow through it in order to be commercially exploited.

4. There shall also be a **caprock** or **topseal rock** (an impervious rock, usually shale or evaporite salt rocks) to confine it and prevent its loss to the surface through buoyancy or seepage.

5. There must be a **trap** configuration in which the petroleum, by virtue of the geometrical relationships of the confining and surrounding rocks, is imprisoned, without the possibility of escape over millions of years, until found and drilled into by geologists and engineers. Traps can be structural (geometrical contraption such as folds, faults, etc.), or stratigraphic (changes in the composition of surrounding rocks), or a combination of both.

6. Finally, the **timing** of generation, migration and entrapment, must follow in the 'proper' sequence, such that for example, the geological trap must be in existence *prior* to the generation and migration of the petroleum, failing which there will be no accumulation.

This seems like a tall order, but that is precisely what it takes, without exception, if a community or country is to have oil and gas deposits under their land. If as much as just one of these parameters or factors is not fulfilled, there will be no petroleum resources at that particular location at that stratigraphic level in the subsurface.
The mandatory and unconditional fulfillment of *all* of these factors *together* underscore the fact that petroleum exploration is indeed a very risky business.

Although, all the above prerequisites are important, the by far most important and overriding prerequisite is the presence of a source rock with enough thermal maturity to generate and expel the petroleum in the first place. Without its generation and expulsion, all the other prerequisites even if fulfilled will not lead to accumulation of petroleum.
A crude analogy: If you play lottery you *may* or *may not* win; but if you don't play you *cannot* win. Playing is like generating. No play, no win; no generating, no accumulation.

Indeed, geologists call the combination and interplay of these prerequisites a 'Petroleum Play'. A play is said to be *proven* if these factors have successfully led to the accumulation of petroleum in the particular area under consideration called the 'Play Fairway' (like in the game of golf). In such successful scenarios, the play is said to be 'working'. Geologists sure have their fair share of jargon.

Now, let us examine each of these parameters a little more closely in order to assess our situation locally within Nigeria to see the pattern of occurrence and distribution of petroleum and why it is so distributed. In other words, let us attempt to explain why some communities have the deposits under their land whereas others do not.

But first, we will take a cursory look at the global distribution of the world's major petroleum basins, and see the place of Nigeria in the scheme of things (Fig. 12).

With relatively 'easy' oil and gas deposits having been found and exploited in the world's onshore basins, focus is now shifting to the shallow shelves and deep offshore realms (Oti and Beka, 1995). Even the polar regions, under heavy glacial cover, are not spared.

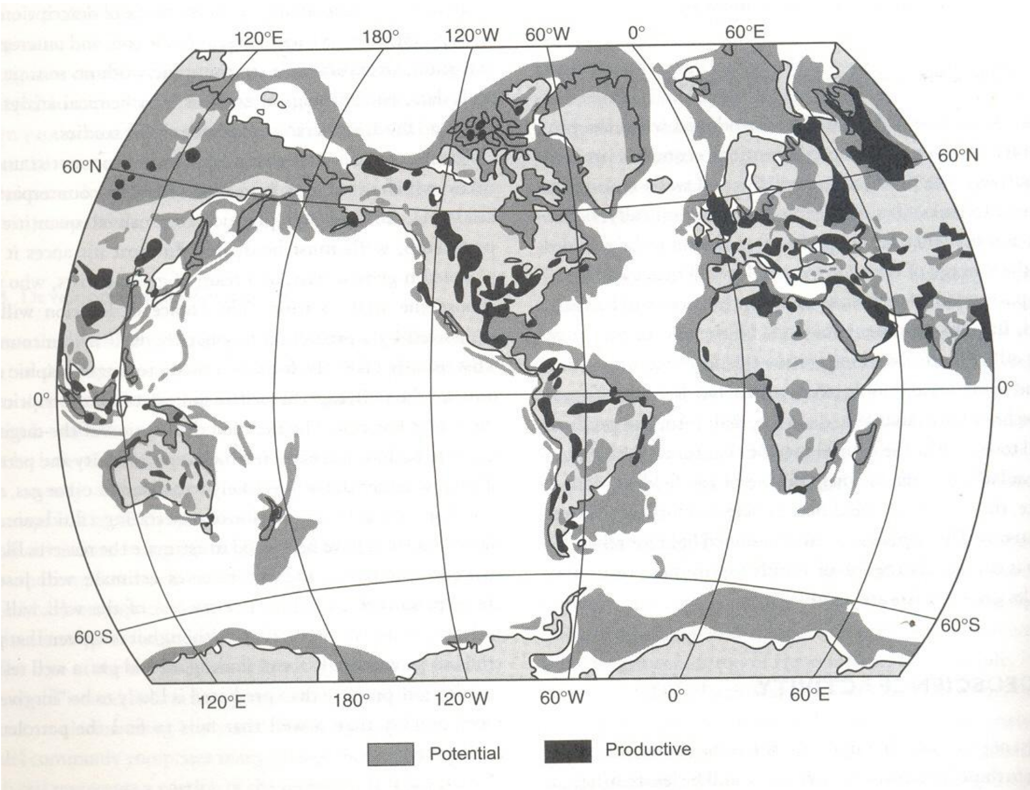


Figure 12. Global distribution of the World's major Petroleum Basins (After Halbouty, 1986)

Nigeria's Geological Basins

Let us take a cursory look at a simplified sketch geological map of Nigeria to see exactly where Nigeria's geological basins are located (Fig. 13), because, as a rule, it is only in basins that oil and gas can form, stored and be found and exploited (Klemme, 1980; Koch, 1987; Hiller, 1988). The implication is that, at least in theory, it is not ruled out to find oil & gas in those basin areas. But in practice many of those areas have tested negative, for some of the reasons outlined above.

The non-basin areas are the so-called Basement Complex areas which are made up, not of sedimentary rocks, but of igneous and metamorphic rocks (Odigi & Oti, 1990; Ukaegbu and Oti, 2004; Ukaegbu and Oti, 2005) which are neither petroleum source rocks nor petroleum reservoir rocks. Therefore, oil and gas cannot be found in them (except in the extremely rare circumstances where petroleum from close-by basins can migrate into them if they are suitably fractured enough). Following our 'six petroleum geological commandments' these non-basin areas are ruled out, *ab initio*, as far as the occurrence of petroleum is concerned, although like South Africa, these non-petroliferous basement-rock areas are blessed with various solid minerals which could on the long term be more economically valuable and sustainable than petroleum. These igneous and metamorphic rocks occupy much of central northern Nigeria and most of western Nigeria, as well as much of the eastern border areas of the country adjoining the Cameroons.

The basins are:
Sokoto Basin (actually, Nigerian sector of the larger Iullemmedden Basin)
Chad – Borno Basin
Benue Trough Basin (Upper, Middle and Lower)
Nupe Basin
Anambra Basin
Dahomey Basin
Niger Delta Basin

(There are smaller sub-basins such as the Gongola Sub-Basin, the Yola Sub-Basin, the Afikpo Sub-Basin, as well 'subs' of these sub-basins called 'flanks', eg. the Calabar Flank and the Benin Flank, but for our present purposes we will ignore them as they can be subsumed within the main basins).

Some of these basins, notably the Niger delta basin, the Anambra basin, the Benue Trough basin and the Borno (Chad) basin have adequate sedimentary volumes and thicknesses, as well as the right range of geothermal gradients (heat flow) to have good prospects for oil and gas deposits. However, the Benue Trough basin and parts of the Anambra basin may have suffered somewhat too high geothermal heat flow due to tectonism and magmatism which may have adversely affected the otherwise good prospects.

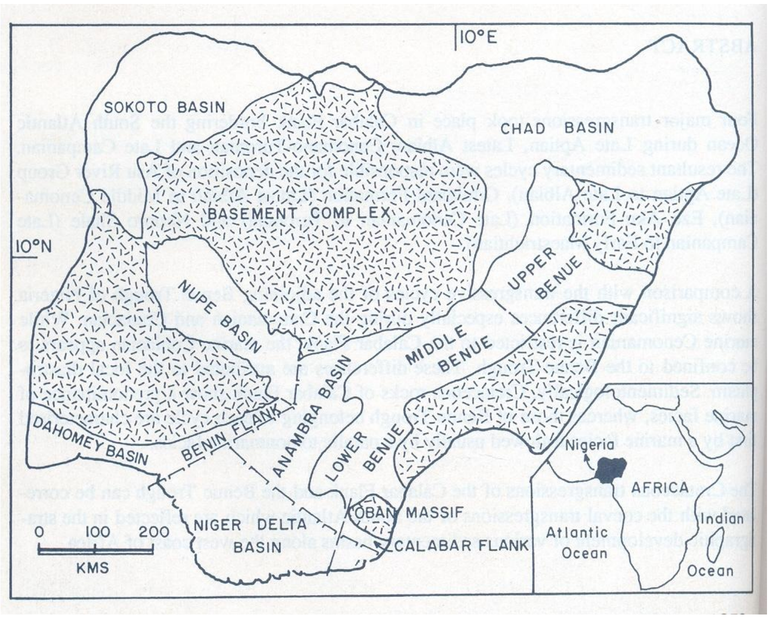


Figure 13. Sketch geological map of Nigeria showing the main sedimentary basins (plain), and the crystalline basement complex (stippled). Note: oil and gas can only occur in the basins filled with sedimentary rocks, not the basement complex areas comprising igneous and metamorphic rocks.

Availability of Petroleum Source Rocks, Reservoir Rocks & Traps in Nigeria's Geological Basins

Following the criteria set out above for a good source rock under Mandatory Prerequisites (above), it is pertinent to ask: do we have petroleum source rocks in Nigeria, and if so, where? Do we have petroleum reservoir rocks that will store the oil & gas once they have been generated and expelled by the source rocks? What about the trapping mechanisms – are they available to ensure they are held captive? Concerning the all important source rock requirement, again the Niger delta basin, the Dahomey (Benin) basin, the Anambra basin, the Benue Trough basin and the Borno (Chad) basins all do fulfill this requirement, but to varying extents.

In the **Chad (Borno) Basin** the shales (hardened mudstones) of the Gongila and Fika formations deposited during Upper Cretaceous times some 70-80 million years ago, as well as similarly aged shales interbedded with the Bima formation, have good source rock potential having reached thermal maturation at depths of 2500 to 5000m oil generative window (Dike 2002). Across the border into Chad and Niger, similar shales have been responsible for the favourable petroleum plays in those neighbouring countries, hence the great expectations here in Nigeria. Furthermore, our Bima and Gongila formations have well developed potential reservoir sandstones and carbonate rocks (Petters and Ekweozor, 1982; Oti, 1990c). However, structural traps may have been compromised unduly by tectonism, unfavourably affecting seal integrity, a situation further adversely complicated by magmatism and volcanism leading to thermal cracking of any generated petroleum into gas. Consequently, with probably no effective seal during the critical phase of petroleum migration, the generated gas may have dissipated to the surface, accounting for disappointing results from over 23 wells drilled by NNPC which tested only minor gas shows in only three of the wells (Dike, 2002). Further detailed studies appear necessary to fully understand the petroleum play of this basin which is thought to have better prospects.

During the 1990s, the **Upper Benue Trough basin** (especially its geologically highly attractive Gongola sub-basin) witnessed active exploration efforts for petroleum. A major multinational oil company, for instance, acting on behalf of herself and her JV partners undertook bold and aggressive exploration operations on OPL 803, 806 and 809. It acquired substantial seismic data over the basin in order to fully understand the basin architectecture and configuration. After extensive geological and geophysical appraisals it was established that only about 50% of the Gongola sub-basin is prospective, the other 50% being unprospective shallow basement. More interestingly, the companies were able to generate the Kolmani River-1 prospect close to the Bauchi/Gombe border (Hoffman, 2002), in which petroleum plays were firmly established. Finally in 1999, with high expectations the company drilled a well to a total depth (TD) of 9138 ft at substantial costs, penetrating the Kerri Kerri, Gombe, Pindiga, Yolde and Bima formations, but unfortunately struck only insignificant amount of gas in the top of the Yolde Formation. Consequently, the unsuccessful prospect was abandoned. According to Hoffman (2002) some, if not all, of the predicted oil may have been cracked into gas due to the relatively high geothermal gradient associated with the rift basin environment. However, Nwachukwu (2007) argued that apart from thermal cracking of generated oil, the Benue Trough basin as whole, on account of abundant and dominant terrestrial organic matter, ought to be essentially gas-prone in the first place, not oil-prone. Clearly, further in-depth studies are required to fully appraise the basin's prospectivity.

To date, the **Middle & Lower Benue Trough basins together with the contiguous Anambra basin** which constitute about two-thirds of the entire Trough length have not fared better in terms of finds of commercial amounts of petroleum deposits, although this should probably not be so in view of the fact that analogous rift basins worldwide (eg. Gulf of Suez Graben in Egypt, North Sea Viking Graben, North Sea Central Graben, Rhein Graben in Germany, Gulf of Bohai Basin in East China, etc) are petroliferous (Hiller, 1988; Klemme, 1980). But why is the case different for the Benue Trough, at least so far?

Sedimentary rock volumes are more than adequate, reaching depths of over 6 kilometers especially at the flanks of the central linear axis of uplifted horst block of the trough, and over 9 km in the Anambra basin. Mature source rocks (the Asu River Group Shales, the Eze-Aku Shales, the Awgu Shale and the Nkporo Shale) are also available in the basin and are known to have generated and expelled hydrocarbons, having entered and exited the oil window. Furthermore, excellent reservoir rocks (porous and permeable sandstones and carbonates) are also present in the basins (Oti, 1983, 1985, 1988, 1989, 1990b, 1990c, 1990d; Oti & Koch, 1990; Amajor, 1990; Petters, 1995; Dike, 2002). To a large extent, feasible petroleum plays are established. However, despite this and the fact that gas and oil shows have been found in the Anambra basin (Avbovbo and Ayoola, 1981), commercial hydrocarbon pools are yet to be discovered and produced in these basins. Nonetheless, the petroleum plays established for the Anambra basin are highly promising and attractive, hence further exploration efforts are encouraged, although widespread seeps would appear to give rise to concerns regarding trap integrity. The middle and lower sections of the Benue Trough, although encouraging as well, appear to have suffered thermal cracking of generated oil into gas owing to high geothermal gradients associated with the rift environment, as well as uplift of horst block by tectonics which exposed deeply buried petroleum plays to shallower depths where they may have been eroded and lost.

The Nigerian sector of the **Dahomey (Benin) basin** is significant as it is associated with the bitumen deposits in parts of the coastal states of Western Nigeria, particularly Ondo State. These highly viscous to solid hydrocarbons extend in a belt oriented east-west across these states and have been estimated by Adegoke and others (1991) to be equivalent to about 30-40 billion barrels of heavy oil. Ekweozor and Nwachukwu (1989) were able to show that these solid hydrocarbon tar sands which can be mined like normal solid minerals were sourced from Lower Cretaceous shales offshore the Benin Basin. Furthermore, the authors showed that the bitumen originated as conventional oil which migrated updip from the offshore shales into sandstone reservoirs but became degraded by microbial action when they encountered near-surface meteoric waters.

Niger Delta Hydrocarbon Province

In 1908, the German Nigerian Bitumen Company drilled the first wells in search of oil in the region, but it was only in 1958 did Shell-BP bring the first productive oil well on stream at 5,100 barrels per day (Tuttle and others, 1999). From then till date, only this basin - the **Niger delta basin** - has been the source of Nigeria's commercial oil & gas production. With proven reserves now hitting the 35 billion barrel mark for crude oil, Nigeria - thanks to the region - now boasts some 6,000 oil wells, nearly 13,000 kilometers of pipelines onshore and offshore, about 112 flow stations, six FPSOs and three FSOs; furthermore the country now has an installed capacity to produce about 3 million barrels of crude oil per day, according to Funso Kupolokun, former Group Managing Director of the Nigerian National Petroleum Corporation (NNPC), as reported in The Guardian of 19 August 2007. The province is also richly endowed with gas. Natural gas reserves as reported by Reijers and others (1997) stands at some 260 tcfg, which translates to 46.3 bboe (or billion barrels of oil equivalent). With these impressive credentials it is no surprise that Nigeria is the world's seventh largest exporter of crude oil.

It is also no surprise that this basin of deltaic sediments, like many similar buried deltas worldwide, are habitats of huge oil and gas deposits. This is because of geologic controls which ensure that the requirements for petroleum plays are met in deltaic basins. Many experts believe that a substantial percentage of the world's yet undiscovered petroleum reserves will be located in ancient buried deltas across the globe (Oti & Postma, 1995).

Evolution and Geological Structure of the Niger Delta Basin

As a prolific hydrocarbon province, the geological evolution of the Niger Delta is well known (Short and Stauble, 1967; Weber and Daukoru, 1976; Evamy et al., 1978; Ejedawe, 1981; Whiteman, 1982; Stacher, 1995; Tuttle et al. 1999). Following the rifting in Late Jurassic times some 200 million years ago which eventually led to the separation of South America from Africa and the opening of the South Atlantic Ocean, the proto-Niger delta started to evolve in Early Tertiary times about 54 million years ago. As sediments borne by the Niger-Benue drainage systems continued to debauch into the then newly formed Gulf of Guinea, the delta started growing into the Atlantic Ocean by what geologists call progradation – similar to what happened to the Mississippi delta of the US which grew and continues to grow into the Gulf of Mexico, another hydrocarbon province. Examples of other deltas around the globe include Egypt's Nile delta, Venezuela's Orinoco delta, France's Rhône delta, Romania's Danube delta, Indonesia's Mahakam delta, Bangladesh's Ganges-Brahmaputra delta, etc, etc.

As time went on and more sediments were injected into the basin, the Niger delta continued its gradual growth into the Gulf of Guinea, and from then till now has covered a distance of about 250 kilometers to the present shoreline (Evamy et al. 1978, Doust 1989, Stacher, 1995). Even under the sea, the sediments have advanced several kilometers into the deep offshore, hence the exploration and production of oil and gas offshore as well. So, the Niger delta is not just the visible part which we can see on the surface. It is one of the largest deltas in the world, covering an area of about 140,000 km^2 with a sedimentary pile some 12.5 km thick in its deepest parts, and still growing (Weber and Daukoru, 1976; Doust and Omatsola, 1990). With more sediment input, the weight of the overburden continues to increase, thus increasing the load pressure on the oceanic crust which continues to subside (depress), thus creating more space for more sediment to be accommodated.

A simplified geological cross-section of the Niger delta basin shows a tripartite subdivision of the sedimentary rock succession into a 6km-thick basal unit (Akata Formation) made up of mudstones, a middle 4.5km-thick unit (Agbada Formation) made up of alternating sandstone and mudstone layers, and a top 2km-thick unit (the Benin Formation) made up of mostly loose sands.

Because of rapid sedimentation rates and growth, deep gashes called growth faults cut across these rock units causing horizontal displacements and arching of the rock layers and these form excellent trapping geometrical configurations for oil and gas, known as structural traps. In some cases, the traps are purely stratigraphic (such as a buried former river channel) or a combination of both structural and stratigraphic. Figure 14 shows some of the common petroleum traps in the Niger delta.
With abundant terrestrial organic matter brought into the basin by the rivers, as well as the indigenous marine organic matter present in the ocean, combined with adequate depth of burial and temperature regime, source rock requirement is fulfilled by the mudstones of the upper Akata and lower Agbada formations. Further requirements of availability of reservoir rocks is met by the presence of porous and permeable sandstones which are interbedded in the Agbada formation. In summary, there is viable and proven petroleum play in the Niger delta basin.

Exploration and production started from the onshore parts of the basin, moved progressively into the shallow shelf and is currently now in the deep offshore, where giant fields are steadily being discovered with new and advanced geological and geophysical technologies. Because of its geological characteristics, the deep, distal offshore parts of the Niger delta is particularly promising in delivering more giant oilfields and growing Nigeria's hydrocarbon reserves (Beka and Oti, 1995).

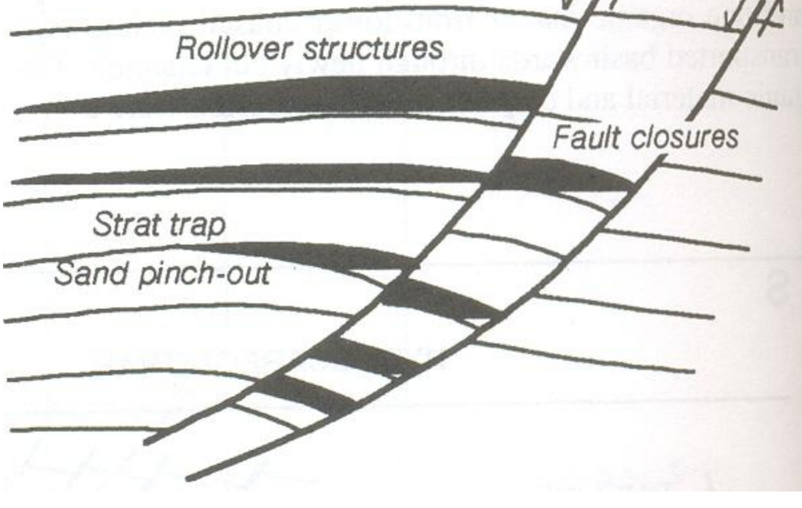


Figure 14. Typical types of petroleum traps in the Niger Delta. Note: Black = petroleum accumulations. (From Stacher, 1995, modified after Weber and Daukoru, 1976)

Location of Oil 'Pools'

The word 'pool' is perhaps misleading when we are discussing petroleum occurrence in the subsurface (underground). There is no 'lake' as such of accumulated oil in the underground. Instead the oil occurs in the minute spaces, called pores, between individual sand grains if the sand is not too cemented by other minerals in the process of becoming a sandstone (Fig. 15). Or in the case of carbonate reservoirs the oil is in the tiny spaces between the carbonate crystals, carbonate grains or in solution vugs. Commonly, three phases are present in the pore system: oil, gas and water, but in order to be produced the oil has first to separate itself from this mixture and be concentrated somewhere. Where the geological conditions are favourable, as in a simple case of an anticlinal fold trap, differences in density of the fluids ensures their separation. In the anticlinal fold the lightest of the three i.e. the associated gas migrates to the top of the anticline where its further movement upwards is stopped by an impervious rock layer. Then the oil floats upward through the water and sandwiches itself between the gas and the water, and all three remain there until drilled into (Fig. 16). When a well is drilled into the reservoir the pressure exerted by the gas cap forces the oil to the well head and it gushes out forcefully on its own. When the natural pressure diminishes to very low levels pumping is then applied to lift up the oil from the great depths in the ground to the surface. Eventually, the oil stops to flow despite the pumping – and some residual oil, often more than half will remain behind and will need secondary and tertiary interventions by petroleum engineers to flush the residual oil towards the well head again for production to continue (Ikoku, 2000; Ajienka, 2005).

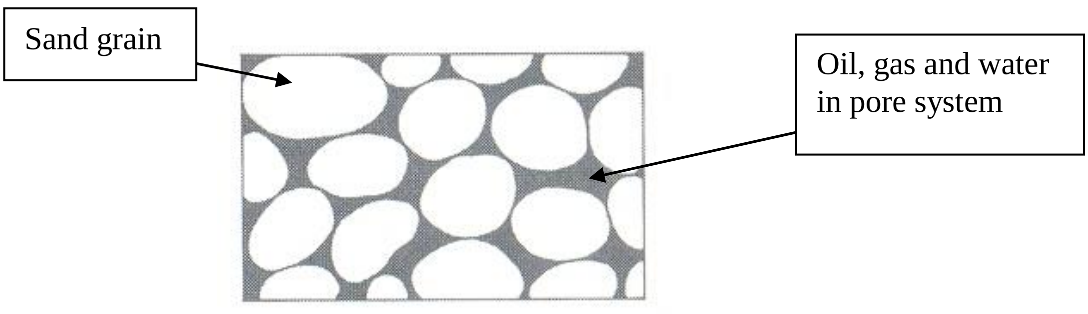


Figure 15. Oil and gas do not occur in 'pools' underground, but in the tiny pore spaces between rock particles

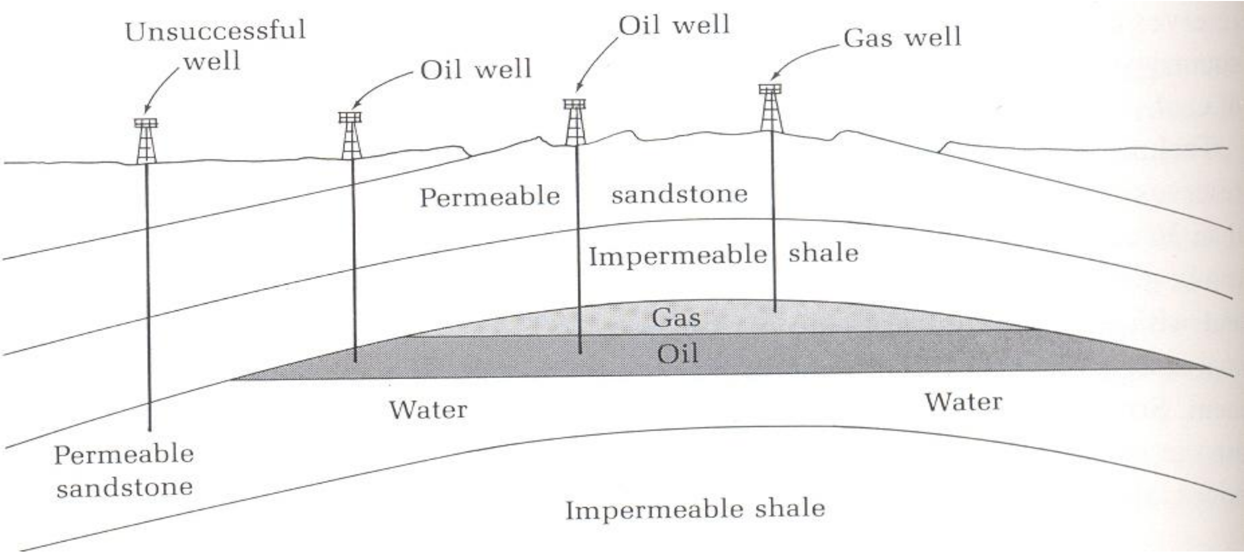


Figure 16. Gas, Oil and Water separated into vertical layers by their respective densities in a simple anticlinal fold trap. Wells drilled in the area may strike gas only, oil only, water only, or nothing at all depending on the surface location and depth of penetration. (From Menard, 1974).

Lifetimes of Petroleum and Mineral Resources

Accuse not Nature, she hath done her part;
Do thou but thine

Milton, Paradise Lost

For non-renewable resources such as petroleum and minerals it is crucial to know how long they will last before they are exhausted, if we want to be able to plan effectively for many social and economic purposes. The lifetime is the interval of time when it is first exploited and when it is all gone.

There are many ways to try to estimate how long a non-renewable resource will last. One of such ways is simply to assume that the lifetime is equal to the total original amount of the resource divided by the average rate of consumption, *provided* the original total amount is known accurately and the rate of consumption is constant.

In the words of Menard (1974):

"In the language of childhood, if you have 15 oranges and eat one per day, they will last 15 days. … If you didn't know whether you had 15 or 31 oranges, it would be difficult to plan. However, everything we know about fuel and energy consumption indicates that they are each increasing by a constant proportion each year. This changes the arithmetic dramatically. Suppose you eat one orange the first day, two the second, four the third, and so on. On the fourth day, you consume 8, and all 15 oranges are gone. If you actually had 31 oranges, it would make little difference in the lifetime of the resource. On the fifth day, you would eat 16 oranges, and all 31 would be gone. The life of the resource would be only one more day – in other words, one more doubling period."

It is therefore clear that uncertainties inherent in estimates of geological resources such as petroleum and minerals in the subsurface matter little if the rates of consumption continues it present exponential growth.

The inescapable conclusion is that mankind cannot continue with its present rate of consumption of fossil fuel resources, since their quantities are finite. At some point, mankind will have no option but to develop other sources of energy.

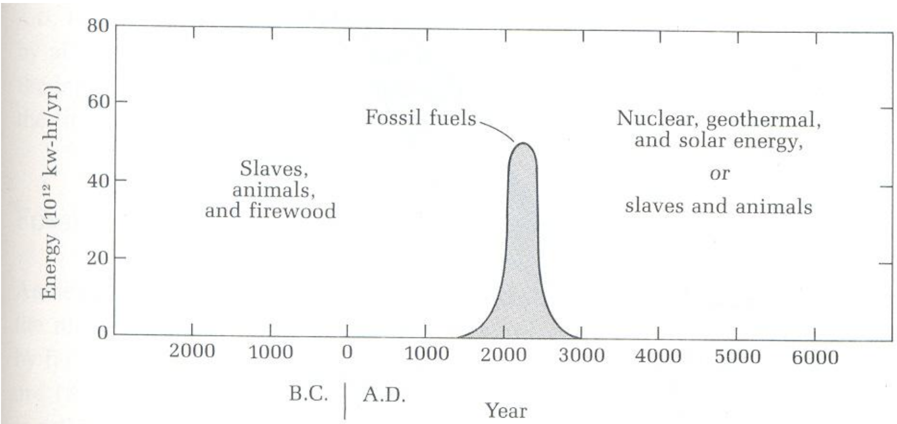


Figure 17. The energy sources of mankind, illustrating the brief duration of the fossil-fuel epoch (From Menard, 1974, after Hubbert, 1971)

Figure 18. Exploration in medieval times: water-witch (wizard) or dowser of the 16th century in search of ground water. Essentially a witch doctor or voodoo practitioner, he explores for groundwater using a forked stick held horizontally as he walks over an area until a so-called '*irresistible force*' pulls the stick to point downward when it is over a pool of ground water. (From Gilluly et al. 1968).

The world has since come a long way: today geologists, geophysicists and petroleum engineers deploy an array of modern technological tools (satellite imagery or remote sensing, gravity and magnetic methods, seismic methods, electrical methods, geochemical methods, wireline logging methods, etc. in the search for oil and gas).

Figure 19. Cartoon depicting the return of the geologist/miner from field work (from Seibold, 2002). Seems this is not the easiest of callings.

Petroleum & Mineral Resources: Impact on International Relations

Tables 1 and 2 show statistics of the proven reserves, production and consumption of oil and gas resources for the different geopolitical regions of the world. If we look at the global figures for oil alone for these three parameters, for example, we see that over 60% of the world's proven reserves are located in the Middle East alone, whereas the combined proven reserves figures for North America, Europe & Eurasia, and Asia Pacific adds up to only about 20%. Compare this with the consumption figures of both parties and the picture is stark and revealing. A meagre 6.7% and a staggering 84.1%, respectively! Clearly, the appetite of the strong and mighty consumers is being satisfied with the disproportionately large reserves of the weak and small. This scenario sets the stage for potential asymmetrical conflict.

Because the availability and use of energy resources directly correlates with the desirable indices of higher and better quality of life, better levels of education, healthier population and a generally enhanced well-being of a society, the large consumers must have these resources at any cost, including war, to ensure a 'security of supply'. A lack of use of energy resources, on the other hand, directly correlates with the key elements of poverty, low levels of education and health, and the restriction of opportunities to achieve self-reliance and development. Hence, Africa's abysmally low level of consumption of only 3.3% is worrisome, and reflects some of the main reasons why Africa is seen by many as the dark and backward continent where poverty, disease, superstition, ignorance and fratricidal wars continue to take their toll.

Particularly noteworthy are figures for the rate of consumption from 1988 through 2004. Whereas rates have marginally decreased for Europe & Eurasia, and has only modestly increased for North America by 20%, it had hit some 100% for Asia Pacific by 2004! Thanks to the end of the Cold War since the late eighties that has led to its economic boom and its emergence as a formidable economic power bloc, China alone is expected to gulp, apart from its substantial domestic output, an additional 3m-5m barrels of imported crude per day in 2010, from its 1999 figure of 1.4m b/d, to fuel its booming economy and newly-found luxury life-style (Jaffe, 2005). This hunger for additional oil explains China's proactive and high profile, some say aggressive, oil diplomacy in Africa and other parts of the developing world, giving rise to further concerns in the capitals of the major consuming nations as to whether the increasing competition from the new kid in town would hamper their own access to adequate supplies – or even worse, lure these developing nations to forge closer political and economic ties with the new emerging international power.
According to Jaffe (2005), it is explosive economic growth in Asia (China, South Korea, Japan, India, and the so-called 'Asian Tiger' countries – but especially China) that will lead to astronomical rise in oil consumption rates, and consequently shift geopolitical trends in international relations.

With concerns in the western hemisphere over 'security of supply' from the Middle East, combined with Latin America's (particularly Venezuela's) apparently uncooperative posture towards its North American neighbour, the US is increasingly looking towards friendly Africa, especially countries in the Gulf of Guinea –

particularly Nigeria – to meet a sizable portion of its oil import needs in the long term. This could confer new political clout and advantages on Nigeria.

World gas reserves, on the other hand are heavily weighted in favour of Eurasia, particularly Russia which – thanks to its huge Siberian reserves - accounts for about 40% of global figures; and North America with just under 30%. Many countries of the European Union depend on gas supplies from Russia, and Russia regularly exploits these countries' dependency on Russia's gas to apply political pressure and win some advantages.

Nigeria, on its part, has relatively huge gas reserves – in fact much more than oil. When the West African Gas Pipeline Project is completed, Nigeria could harness increased political leverage over countries in the sub-region, and beyond.

Clearly, therefore, Nigeria seems poised to reap huge political and economic benefits from her petroleum and mineral resources. In doing so, however, it would do well to carry along everyone, particularly those areas of the country from where these benefits are derived. These areas should not only be adequately protected from environmental degradation associated with the extraction of these resources (Akpokodje, 1998; Ajienka, 2005), but should also derive adequate benefits from the exploitation of the resources. This would ensure peace and stability, two crucial requirements for sustainable development.

Concluding Remarks

Mr Vice-Chancellor, Sir, Ladies and Gentlemen, I would like to conclude this inaugural lecture with a verse from Shakespeare's *Anthony and Cleopatra*, modified slightly. The slight modification which I am taking the liberty to make, with due respect to the great master of letters, is only to interchange the word "I" in the original verse with the word "Geology".
Shakespeare's verse should then read:

In Nature's infinite book of secrecy
A little Geology can read

Yes, geology – in deed science – can figure out so many things that are not readily discernable. It has shown us that the occurrence and distribution of mineral and petroleum resources is not an arbitrary affair; if anything, with modern geological and geophysical methods we can predict their origin and location. The science of geology, among other accomplishments, has also shown us that geological processes account for ***how*** these resources form and ***how come*** they are located exactly where they are.

But the far deeper philosophical question may be asked as to ***why*** these geological processes are operating in the first place. The answer is outside the scope of science. We should perhaps seek the answer elsewhere – perhaps in philosophy itself, or in religion, mankind's last succour when we do not comprehend; I do not know.

Ladies and Gentlemen, I thank you for your attention.
Professor Dr.rer.nat. Michael N. Oti

Tables 1 & 2. World Total Oil and Gas Statistics. (From: Fundamentals of the Global Oil and Gas Industry, 2005. Petroleum Economist, 2005, p.143)

Oil

Proved reserves

bn barrels	1988	1992	1996	2000	2004	% share of total
North America	100.0	92.7	89.3	75.6	61.0	5.1
S and C America	69.3	78.8	90.7	97.7	101.2	8.5
Europe and Eurasia	77.2	81.4	82.6	115.5	139.2	11.7
Middle East	651.1	659.7	672.2	691.0	733.9	61.7
Africa	59.0	61.1	74.9	93.4	112.2	9.4
Asia-Pacific	39.7	37.5	39.1	42.6	41.1	3.5
World total	996.2	1,011.2	1,048.8	1,115.8	1,188.6	100.0

Production

million b/d	1988	1992	1996	2000	2004	% share of total
North America	14.6	14.1	14.1	13.9	14.2	17.3
S and C America	4.1	4.8	6.2	6.9	6.8	8.8
Europe and Eurasia	17.1	14.2	14.0	14.9	17.6	22.0
Middle East	15.2	18.7	20.7	23.4	24.6	30.7
Africa	5.8	7.0	7.4	7.9	9.3	11.4
Asia-Pacific	6.3	6.9	7.6	8.0	7.9	9.8
World total	63.2	65.8	69.9	75.0	80.3	100.0

Consumption

million b/d	1988	1992	1996	2000	2004	% share of total
North America	20.3	20.3	21.8	23.5	24.6	29.8
S and C America	3.5	3.7	4.3	4.7	4.7	5.9
Europe and Eurasia	23.0	22.0	19.4	19.5	20.0	25.4
Middle East	3.0	3.6	4.3	4.6	5.3	6.7
Africa	1.8	2.0	2.2	2.5	2.6	3.3
Asia-Pacific	12.1	15.3	18.8	21.1	23.4	28.9
World total	63.8	67.0	70.9	75.8	80.8	100.0

Figure 1: World total oil reserves

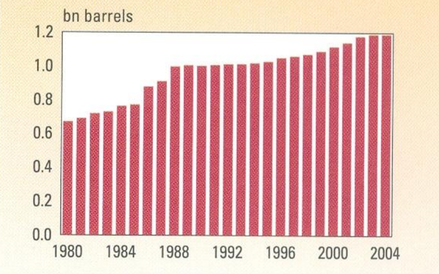


Figure 2: World total oil production

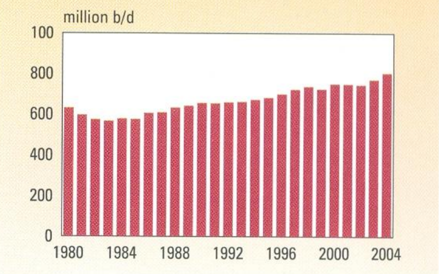


Table 2.

Natural Gas

Proved reserves

trillion cm	1988	1992	1996	2000	2004	% share of total
North America	9.5	9.3	8.4	7.5	7.3	4.1
S and C America	4.9	5.5	6.1	7.0	7.1	4.0
Europe and Eurasia	47.8	62.1	62.5	61.7	64.0	35.7
Middle East	34.3	44.0	49.3	59.8	72.8	40.6
Africa	7.7	9.9	10.2	12.5	14.1	7.8
Asia-Pacific	8.9	9.4	10.4	12.3	14.2	7.9
World total	113.0	140.1	146.9	160.8	179.5	100.0

Production

bn cm	1988	1992	1996	2000	2004	% share of total
North America	618.3	668.5	733.3	769.6	762.8	28.3
S and C America	54.5	61.0	81.4	97.9	129.1	4.8
Europe and Eurasia	933.5	952.4	945.4	959.5	1,051.5	39.1
Middle East	93.3	114.0	158.0	206.8	279.9	10.4
Africa	58.5	75.3	88.9	126.6	145.1	5.4
Asia-Pacific	133.4	174.4	228.4	272.9	323.2	12.0
World total	1,891.4	2,045.5	2,235.5	2,433.2	2,691.6	100.0

Consumption

bn cm	1988	1992	1996	2000	2004	% share of total
North America	608.4	684.0	763.4	791.2	784.3	29.2
S and C America	54.5	61.0	81.4	94.0	117.9	4.4
Europe and Eurasia	935.6	965.9	977.5	1,012.9	1,108.5	41.2
Middle East	90.5	110.6	150.7	185.4	242.2	9.0
Africa	35.6	40.3	47.2	55.2	68.6	2.6
Asia-Pacific	134.7	180.1	239.6	299.7	367.7	13.7
World total	1,859.3	2,042.0	2,259.9	2,438.3	2,689.3	100.0

Figure 3: World total gas reserves

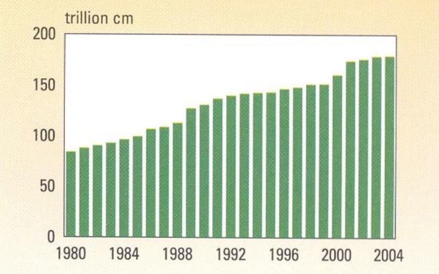
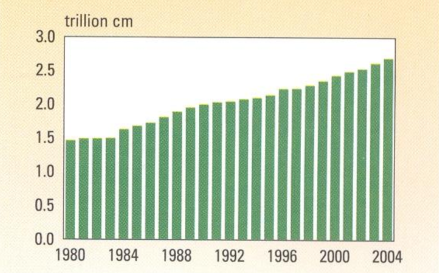


Figure 4: World total gas production



Source: BP Statistical Review of World total Energy, Cedigaz

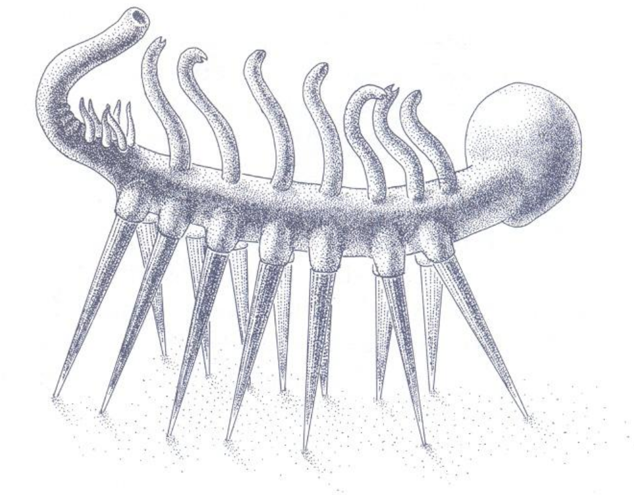


Figure 20. *Hallucigenia*, a bizarre, weird, one-inch long creature that roamed the sea floor 530 million years ago, but discovered and recovered in 1910 from a limestone quarry (the Burgess Shale), 8000 feet above sea level in the Canadian Rockies, British Columbia, Canada. Despite its apparent and suggestive shape, it is not certain which end of the creature is the anterior (head and mouth) and which is the posterior (tail and anal opening). (From Gould, 1989).
Science fiction writers need not go any further to have better inspiration of what shapes monsters, big or small, ought to look like!

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