UNIVERSITY OF PORT HARCOURT

THE OTHER FIVE PERCENT: AN EXERCISE IN THE GORILLA PSYCHOLOGY

By

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PROGRAMME

1. **GUESTS ARE SEATED**

2. **INTRODUCTION**

3. **THE VICE-CHANCELLOR'S OPENING REMARKS**

4. **CITATION**

5. **THE VALEDICTORY LECTURE**

The lecturer shall remain standing during the citation. He shall step on the rostrum, and deliver his Valedictory Lecture. After the lecture, he shall step towards the Vice-Chancellor, and deliver a copy of the Valedictory Lecture and return to his seat. The Vice-Chancellor shall present the document to the Registrar.

6. **CLOSING REMARKS BY THE VICE-CHANCELLOR**

7. **VOTE OF THANKS**

8. **DEPARTURE**

DEDICATION

Dedicated to my parents, Late Mr. Isaiah Ukaigwe Olekanma and Late Madam Evelyn Nwaibari Olekanma.

ACKNOWLEDGEMENT

A great many people have contributed to my development in life. My parents, Late Mr. Isaiah Ukaigwe Olekanma and Late Madam Evelyn Nwaibari Olekanma who inspite of my refusing to go to school insisted and sent me to school in 1953.

I am indebted to my children Anene, Ogechi, Ugochukwu, Chinelo, Agbonma and Obiozor.

Every person has his own map of the world; some peoples' maps are small, while other peoples' maps are medium or large. It is within this map that they place themselves and relate to one another. Barr. Lucius Ezekamadu Nwosu (SAN) and H/E Chief Achike Udenwa. I thank you for making my map larger than University of Port Harcourt.

Not everything that counts that can be counted and not everything that can be counted counts. Prof. B.I.C. Ijeomah (Agidigbo), thanks for making me to count and be counted.

To my colleagues in the Department, Faculty and the University, I am grateful for meeting you in my life's journey. Every person you meet in life has been destined by God Almighty; you have something to teach him/her and they have something to teach you. We are products of this grand design. Prof. Charles Ofoegbu for identifying me and recommending me to the University of Port Harcourt for employment.

Last but assuredly not the least, I express my gratitude to the entire students of the Department of Geology, particularly the post graduate students who have gone through the conversion program to become geophysicists and they have insisted that I give this lecture, I mention also my secretary, Miss Ifeoma G. Chukwuka who painfully typed the manuscript.

My academic training at The University of Adelaide, South Australia would not have been possible without the Commonwealth Scholarship and Fellowship Plan Programme. I am indebted to them and to my supervisor, Prof. David M. Body.

I thank God Almighty who made everything possible.

THE OTHER FIVE PERCENT: AN EXERCISE IN THE GORILLA PSYCHOLOGY

1.0. Introduction

One of the most important practical applications of geophysics is in the search for accumulations of oil and gas. This is largely a matter of looking for suitable rock structures that might have trapped the accumulations. Typically, useful reserves of oil and gas are found at depths of several thousand metres below the Earth's surface. It is only at such depth that the conditions of pressure and temperature are right to cook the organic remains in a source rock, leading to the formation of oil and gas. These petroleum products are expelled into the surrounding rocks, displacing the water which is otherwise present in the pore spaces. Being less dense than the water, the oil and gas tend to rise up through the porous rock until they cannot pass. Thus, a petroleum accumulation will tend to form at the top of a "buried hill" (anticline) of porous rock, which is capped by an impermeable layer. Therefore, petroleum exploration is largely a matter of looking for such buried structures.

Sometimes, it is fairly easy to guess the structure at the depth of several thousand metres by extrapolating the structures visible at the surface. In such a case, the hypothesis that deep structures are geometrically similar to the shallow ones can be easily tested by drilling a few wells. However, such easy cases have usually been drilled long ago. If we want to look for new oil-fields today, we must search for deeply buried structures that have no expression at all at the surface. In principle, this search could be carried out by drilling a large number of exploration wells. However, wells are expensive to drill and in many cases, especially offshore, trying to find fields by more-or-less blind drilling would be hopelessly uneconomic.

It is at this point that the geophysicist can offer a great deal of help. Geophysical methods permit us to build up a picture of the sub-surface structure to depths of several thousand metres. With this knowledge, a small number of wells can be precisely situated so as to test the most prospective structures, furthermore, the geological information gained from the well, which in itself tells us only about a zone within a few feet of the borehole, can be extrapolated laterally with some confidence, perhaps for many kilometers in favourable cases. Various geophysical methods (gravity, magnetic, seismic refraction) can be used to delineate sub-surface structure, but they mostly have very poor vertical and horizontal resolution, giving us a very generalized picture of the sub-surface. One method, however, can give us rather precise knowledge of sub-surface, with a resolution down to a few tens of metres in many cases. This is the seismic reflection technique, which in the very last fifty years has become a basic tool of petroleum exploration.

In petroleum exploration, approximately 95 percent of the dollar expenditures are devoted to the seismic method, and only about 5 percent to gravity, magnetic, and the occasional other methods that have made their appearance in the field for a short time and usually have not lasted very long.

From its beginning in the early 1920’s, geophysical prospecting used three different physical principles in the determination of underground geology. These are (1) the propagation of elastic waves through the earth which is the basis for the reflection and refraction seismic methods, (2) the measurement of small variations in the intensity of the gravitational field, and (3) the measurement of small variations in the magnetic field. In the nearly 100 years since these three principles were first applied, there have been many advances in instrumentation, in field techniques and in interpretation, but petroleum exploration still is based almost entirely on these same three physical principles. Many attempts have been made to use other measurements, such as electrical, chemical, and radiation, as well as witch sticks and black boxes, and many of these have had extensive trials in the field in the search for petroleum. In spite of the fact that very great rewards would accrue to any person or company which could devise any successful alternative method indicating oil or conditions favourable for oil accumulation, none of these other schemes has lasted very long in the field, and we still depend, in oil exploration, on the three basic physical principles.

Therefore, it seems unlikely that there is to be any great new breakthrough in petroleum exploration and that the advances in the future probably will be along the line of better use of the methods which we now have, especially in interpretations which coordinate the different geophysical indications with each other and with geology.

Let us consider why the seismic method dominates the exploration industry to the extent that it takes 95 percent of the petroleum geophysical expenditures. To a great many people, the mention of “geophysics” has come to mean “seismologists” or the “reflection seismograph”.

In the first place, the seismic method is very effective; also, it is very much more expensive than either of the two methods. In terms of cost per unit area covered, subject, of course, to many wide individual variations, the relative costs of seismic, gravity, and magnetic surveys are approximately in the ratio of a dollar, a dime, and a penny. There may be reasons other than high cost and greater effectiveness which account for the high proportion of expenditures for the seismic method. The basic principles of the method are simple. An explosion produces a disturbance or noise of some kind which travels downward in the earth to a discontinuity. Reflections from that discontinuity come back to the surface and are detected by suitable instruments, and the time of travel is measured. If one knows the speed of propagation, it is simple matter to determine the depth at which this reflection occurs. These principles are so simple that, if I may be pardoned for saying so, they can be understood even by a geologist. Furthermore, the immediate result of the reflection seismic operation is a map which is essentially geological in nature. The map is readily understood by geologists because it is similar to the familiar subsurface maps they make from well information.

Gravity and magnetic field operations yield maps which are not obviously geological in nature. Another step is required before these maps can be directly related to geology. This step is an interpretative one which often is not readily understood and to some extent has carried an aura of mystery. Geologists often are too much inclined to consider gravity and magnetic maps as directly indicative of structure. This tendency was recognized many years ago by DeGolyer (1928) in a paper entitled "*The Seductive Influence of the Closed Contour*." This little two-page paper points out that geologists, who have been trained to look for closed contours as indicative of closed structures favourable for the accumulation of oil, are too much inclined to consider that closed contours on gravity and magnetic maps may be directly indicative of closed structure. This is only occasionally true on gravity maps and almost never true on magnetic maps. The much more subtle relations to geology, which are commonly deeply hidden in gravity and magnetic maps, must be brought out by removing regionals, calculating derivatives, or other analytical processes which are not readily understood. Therefore, geologists or management may be inclined to turn to the more easily understood reflection seismic method more often than they should and to neglect the very substantial exploration help which can be provided by these other two methods.

With these introductory remarks, we will now proceed to a discussion of the fundamental principles with samples of application of, first, the magnetic and, then, the gravity method. The discussion is concerned almost entirely with basic principles and with certain aspects of interpretation and not at all with the instrumentation and field operations.

1.1. Magnetic Method

In figure 1, the shaded area represents any sort of a magnetic body, meaning simply that it is a volume of material that is more magnetic than its surroundings. Being more magnetic, the lines of magnetic force tend to pass through it more easily and, therefore, to be squeezed together within and next above the area of the body. This squeezing together of the lines of magnetic force is equivalent to an increase in the intensity of the magnetic field.

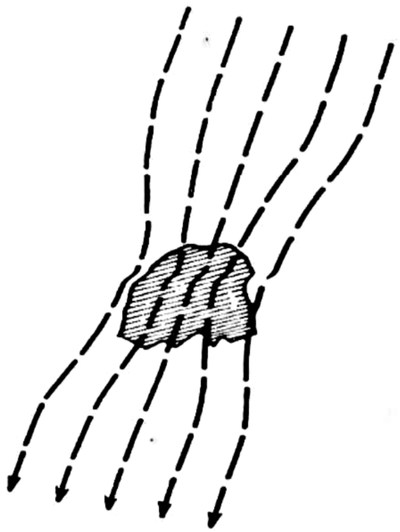


Fig.1 *Magnetic body and distortation of magnetic field (after Nettleton 1961)*

In figure 2, we put the same diagram in the geological environment. The more magnetic area now may represent an intrusive body of basic igneous rock with a relatively large content of magnetic materials, largely magnetite. The adjacent area may represent granitic basement rocks with a moderate magnetic content. Overlying both of these is a section of sedimentary rocks with practically no magnetite. Above, and measuring the variations in the intensity of the magnetic field, is an airborne magnetometer.

The variations in the magnetic field measured by the magnetometer are almost entirely due to variations in the concentration of magnetite in the rocks.

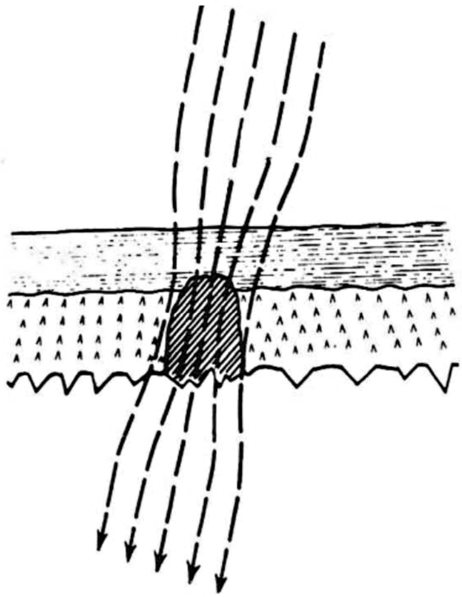


Fig. 2 *magnetic body in geological environment (after Nettleton 1961)*

The magnetic minerals, magnetite, pyrrhotite and ilmenite are widely distributed throughout the Earth's crust. Magnetite forms both major and minor constituents of many different rock types and when occurring in large concentrations forms massive magnetic iron ore deposits. The magnetic minerals pyrrhotite and ilmenite are considerably less abundant than magnetite but nevertheless form important constituents of certain economic mineral deposits.

Many geological formations by virtue of their content of magnetic minerals, will behave like large buried magnets (fig.3) and will then have associated with them a magnetic field. This very local magnetic field will be superimposed on the normal magnetic field of the earth.

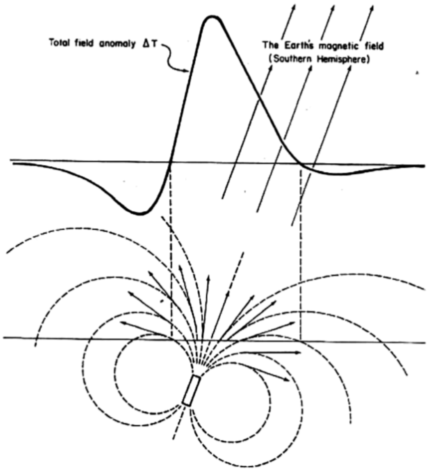


Fig. 3. *Am magnetic body beneath the surface acts like a bar magnet buried parallel to the earth's magnetic field. It has its own lines of magnetic field (dashed curves), the vectors of which (arrows shown at the surface) add to or subtract from the earth's field depending on their direction. As a result there is an anomalous magnetic field over the buried body shown as the profile above.*

Measurements of the magnetic field taken in the locality of such geological formations will show departures from the undisturbed Earth's magnetic field in the vicinity of these formations. These changes or anomalies as they are called could be large or small and could be either an increase or a decrease of the Earth's field and will depend on the depth of burial, degree and direction of magnetization and the attitude of the formation in relation to the direction of Earth's field at that locality.

Magnetometers are the instruments used for measuring the magnetic field and by virtue of their sensitivity and range are able to measure not only the changes of field between two rock types with only small differences in magnetic content, but also the prominent anomaly of a dolerite dyke or the extremely large anomaly over a magnetic iron ore deposit.

The basement rocks nearly everywhere have so much more magnetite in them, and, therefore are as much more magnetic than the sediments that, for practical purposes, we can usually consider that the features measured by the airborne instrument have their origin at or below the surface of the basement or the base of the sedimentary section and that measurements would be practically the same if the sediments were not present at all. This is a very important feature because, by understanding the nature of the anomalies caused by irregularities in the magnetization of the basement, we can determine the depth of their source and, thereby, the depth to the basement surface and the thickness of the sedimentary section. Also, we can determine major structural features on the basement surface.

In order to make such interpretations, we must understand the general nature of the anomalies. Figure 4 shows examples of the total intensity anomaly as measured by the airborne magnetometer for the same body in different magnetic situations. The body is a sphere, polarized in the direction of the Earth's magnetic field. The upper left-hand diagram shows the anomaly when this body is near the magnetic pole where the magnetizing field is vertical. In this case, the anomaly is a simple maximum with a very weak negative zone on each side, so weak that it hardly shows in this diagram. If we move further south where the magnetic latitude is $67^1/_2°$, we see the beginning of the development of a negative anomaly on the north flank and a shift of the maximum south from the point over the center of the disturbing body. At 45° inclination, the negative anomaly is more strongly developed, and the shift is also greater. At $22^1/_2°$ inclination, the negative and positive anomalies are of almost the same magnitude with the negative part somewhat sharper. Finally, at the magnetic equator where the polarization is horizontal, the principal part of the anomaly is the minimum centered over the body so that what began at high latitudes as a simple positive anomaly has turned inside out to become a negative anomaly at low magnetic latitudes. (The series would be repeated with a left-to-right change if the diagram were continued to the south magnetic pole.)

Figure 4b shows on the right side a magnetic map in a situation corresponding approximately with $22\frac{1}{2}^{\circ}$ inclination as shown on figure 4a.

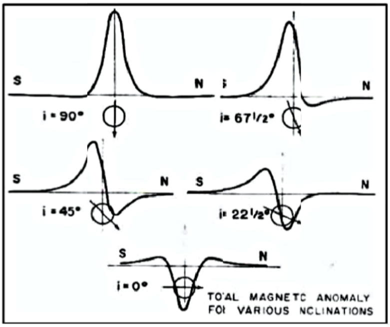


Fig.4a. *Variation in form of anomaly in total magnetic intensity with change in magnetic latitude.*

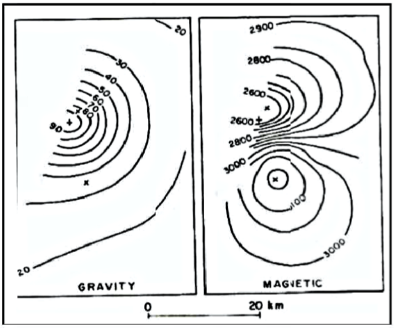


Fig.4b. *comparison of gravity and magnetic maps in same area.*

1.2. Gravity Method

The analysis of gravity surveys is quite different from that of magnetic surveys. The theoretical background is considerably simpler. A body with a specific density contrast will produce the same gravity anomaly no matter where it is on the Earth’s surface and, therefore, is not subject to variation in its expression with latitude or orientation as a magnetic anomaly. On the other hand, the gravity interpretation lacks the great geological simplicity which the magnetic method has because of the definite contrast at the surface of the basement. The basement surface may or may not be a surface of density contrast at which gravity anomalies have their origin.

The origin of gravity anomalies may be anywhere from the grassroots down. There may be density contrast anywhere within the sedimentary section, and, there may or may not be density contrasts at surface of the basement. Density contrasts may extend into the basement rocks much more deeply than the magnetic contrasts. In the magnetic case, there is a limit to the depth at which the magnetic contrasts can occur because, with the universal increase in temperature with depth, magnetite loses its magnetization where the temperature reaches the Curie point.

The exact depth of this loss of magnetization is not known but is probably in the range of 15 to 20 miles. There is no such limit on density contrasts and gravity anomalies may have their origin at any depth in the basement extending down at least to the Moho discontinuity. Therefore, unlike magnetic maps, gravity maps can and usually do contain anomalies having their sources over a wide range of depths from near-surface to very deep within the basement rocks. This means that before any quantitative analysis of gravity anomalies and accurate relation of such anomalies to geological disturbances can be carried out, it is first necessary to isolate or separate out the anomaly itself from its background.

2.0. Gravity and Magnetics in Oil Exploration: A Historical Perspective

The first U.S. oil discovery using any geophysical method came in 1924 at Nash Dome, Texas, as a result of survey with the Eotvos torsion balance. This gravity-measuring device was invented in 1888, and first was used for hydrocarbon exploration in Czechoslovakia in 1915 – 1916. It was very slow to operate and was sensitive to near-surface irregularities, and these problems provided the impetus for developing a sensitive pendulum apparatus.

Wyckoff and Eckhardt tested a practical pendulum instrument in Kansas and Oklahoma in 1925-26. After joining Gulf in 1928, they refined and developed the tool and it was field-tested in Michigan in April 1930. Gulf and other companies tried other pendulum methods, but by July 1932 the Gulf (Wyckoff) pendulum was in regular operation. Cleaveland Oil Field (Texas) was found by Gulf with this pendulum; Conroe Dome, which was visible in torsion-balance data, also was defined. The pendulum was a great improvement, but still did not have the sensitivity and speed of operation required for efficient exploration. At their peak, pendulum crews could observe a maximum of about 250 stations per month. The next step was the gravimeter.

Apparently, Humble Oil tested the first gravity meter in the United States, in 1930, but never placed it in regular use. Gulf developed a gravimeter in 1932-35 which began routine operation in May 1935. This instrument was the first field gravimeter, with an accuracy of better than 0.1 milligal, and it was very fast to operate. The Gulf (Hoyt) gravimeter received general industry acceptance, and thousands of stations were observed by Gulf crews from 1935 to 1955. An all-time Gulf high was reached in March 1938, when 7300 stations were obtained; the overall total for Gulf crews alone was more than 750,000 stations. Industrywide, torsion-balance crews went from forty-plus crews in 1935 to zero in 1940., while gravimeter crews increased from one in 1935 (Gulf's) to forty-plus in 1940 (sixteen were Gulf crews). Improvements over the Gulf meter by Worden and Lacoste and Romberg increased the use of the gravity method even more. The latter instruments are those in most common use today.

Gulf had developed a practical water-bottom gravity meter by 1940. This instrument was simply an encased Gulf gravimeter mounted on a tripodal stabilizing arrangement. It could be converted to a land-based meter with a few mechanical adjustments. The water-bottom meter was used successfully to find salt domes in the Gulf of Mexico before good seismic coverage was available. The data also were used (and still are used) to help plan detailed seismic surveys.

A by-product of seismic and gravity exploration in the swampy coastal areas of the Gulf of Mexico saw the invention in about 1950 of the marsh buggy, which was used to transport geophysical crews and equipment.

The pendulum apparatus first was used in a moving vehicle (a submarine) in 1930. Not until 1958 did gravimeters come into use on surface ships. After the LaCoste and Romberg established platform gravitymeter was introduced in 1965, shipborne gravity surveys became common, usually in conjunction with seismic and magnetic acquisition as well. This is the type of shipborne meter in greatest use today. It virtually has supplanted more expensive and cumbersome water-bottom operations.

Significant advances in gravity methods took place in the mid-to late 1970s, with development of borehole and airborne gravimetry. Airborne gravity refers to data acquired from a moving helicopter, in comparision with helicopter-supported surveys, in which the helicopter lands for a datum reading. After considerable controversy and development, airborne gravity has found application in several exploration situations, such as remote, unexplored jungle and desert areas, rugged topography, and the land-ocean interface.

Among the most recent advances in gravity exploration is renewed use of high resolution gravity gradiometry.

2.1 Satellite Gravity

Gravity derived by observing orbital variations of satellites as they are perturbed by the Earth's gravity field provides valuable information about the deep internal structure of the Earth. The coverage is global, encompassing both land and oceans. These data are used in studies of plate tectonics, subduction zones, core-mantle and mantle-crust anomalies, and isostatic compensation beneath mountain ranges.

Gravity derived from satellite altimetry measurements and analysis of satellite orbits is an inexpensive way to obtain good spatial coverage over large areas of ocean. It has been used to map fracture zones, seamounts, hot-spot chains, mid- oceanic ridges, subduction zones, and many previously undiscovered features. In offshore areas where reliable bathyrnetry is available, the effects of sea-bottom topography can be removed to produce gravity maps suitable for mapping continental-margin structure and detecting sedimentary basins. The long-wavelength components of satellite gravity maps can be used to tie and level smaller marine gravity surveys, providing a common mesh in which local high-resolution surveys are imbedded. In frontier areas, satellite gravity can be processed with bathymetry data to detect submarine basins.

2.2 Magnetic Survey Instruments

Ground magnetometers were in common use in the 1920s and 1930s. A 1926 Gulf Oil discovery in Garza County, Texas, was based on the interpretation of a magnetic survey. As a reconnaissance tool, however, ground magnetometry was slow and cumbersome. In an attempt to eliminate these drawbacks, the first experimental airborne magnometer was tested in the USSR in 1936. This instrument used rotating induction coil and had a sensitivity of 1000 grammas, which was inadequate for oil-exploration work.

The Gulf airborne fluxgate magnetometer was developed by Victor Vacquier and others in 1939 – 1941. Its 1-gamma sensitivity would make the meter valuable in exploration, but it was realized immediately that this device also could detect submerged metallic objects such as submarines. After successful “detection and disposal” of an enemy submarine in a test flight in December 1942, the Gulf magnetometer was used throughout World War II. In April 1945, test flying for hydrocarbon exploration began in Western Pennsylvania. The Gulf airborne magnetometer, the second to be invented but the first practical instrument, became the industry standard.

The Gulf instrument was supplanted in about 1955 by the proton-precession magnetometer, and in the 1960s by optically pumped alkali-vapor magnetometers. The 0.01gamma sensitivity of the latter provided the ability to measure tiny vertical gradients in the Earth’s magnetic field. The Gulf magnetometer still is used frequently as a ground monitor, and in the 1970s, new fluxgate surveys began appearing on the market as a low-cost alternative to surveys flown with the higher- sensitivity instruments.

Unlike seismic data, gravity and magnetic data go out of date very slowly, if ever. In spite of refinements in acquisition and processing, old data can still provide a wealth of information to the interpreter. Few oil companies today acquire their own gravity or magnetic data. Specialized contractors perform an admirable job both in acquisition and processing. Many oil companies do, however, prefer to do their own interpretations, integrating proprietary information into the study. Many companies also have their own processing, refinement, and modeling programs, although these also are becoming inexpensive and varied on the commercial market. Powerful personal-computer-based software packages are available for everything from modeling to automated depth estimation.

Most analysis of the state of the art in potential fields focus on advances in computer-based processing techniques, many of which are merely improved (and very useful) ways of displaying data and processed data. Improved resolution in terms of acquisition, processing and most importantly, geologic information content are making both gravity and magnetics useful tools for modern exploration programs.

3.0. Integration of Gravity and Magnetic Methods in Exploration Decision Process

The geologic integration of gravity and magnetic data can be used to reduce risk at two key stages of the exploration process. The first stage, often referred to as basin reconnaissance, is the role automatically relegated by most explores to gravity and magnetic methods. Contrary to this widespread notion, however, gravity and magnetic methods are equally effective for reducing risk at the more local scale typified by the prospect itself. In cases in which the application of gravity and magnetic analysis negatively impacts a prospects viability, valuable exploration resources can be directed at finding different and, it is hoped, more economic prospects.

3.1 **Basin Reconnaissance Stage**

Exploration risk parameters evaluated through the geologic integration of gravity and magnetic data during the basin reconnaissance (or new venture opportunity) stage include:

1) Regional hydrocarbon trapping structures
2) Regional hydrocarbon fetch areas
3) Regional hydrocarbon source-thickness estimation
4) Regional hydrocarbon migration pathways
5) Thermal maturity; and
6) Optimization of seismic survey placement

The basin reconnaissance stage marks the time of a company's initial interest in an area.

This stage is characterized by a massive effort to capture existing available data so that the area's potential for commercial prospects can be evaluated best using the precious resources available.

During this stage, the integration of gravity and magnetic data is used, among other things, to delineate basin and sub-basin boundaries as well as regional structures proximal to the basinal areas. The location of regional trapping structures is of course, one of the classic exploration uses of the gravity and magnetic methods. In case the basement is both dense and magnetic, basement structure and depth can be delineated and mapped using gravity and magnetic data. Basement structure is of interest, of course, because it is often related to structure in the sedimentary section. Additional confirmation of regional sedimentary structure is made through the use of gravity data which unlike magnetic data are also sensitive to structures in the sedimentary section (although modern, high quality, and high sensitivity aeromagnetic data are being used to map some sedimentary structures for which sufficiently large magnetization contrasts exists).

3.1.2 Definition of the various basin and sub-basin geometrics

This enables the areal extent of the possible hydrocarbon fetch areas to be evaluated. This is, again, a classic exploration application of the gravity and magnetic prospecting methods. The position of the fetch areas relative to each other and to the regional trapping structures is a useful interpretative result of the gravity and magnetic analysis. This result facilitates the high grading of prospects in case multiple ones are identified.

3.1.3 Calculations of sedimentary thickness

These are made, later to be related to possible sources thickness (or lack thereof). These two estimates ultimately are linked to the volume of hydrocarbons generated. In the ideal situation (i.e., local geology cooperating), magnetic basement mapping and modeling are used to define the depth (and thus, thickness of sediments) and configuration of the basin, and gravity modeling is used to confirm the thickness and possible constitution (e.g., clastics as opposed to carbonates, etc.) of the expected sedimentary section.

3.1.4 The location of regional trapping structures relative to the fetch areas

This sets the stage for an analysis of the possible hydrocarbon migration pathways, and the focusing of those hydrocarbons by regional structure.

The one area of basin reconnaissance in which gravity and magnetic data are not apparently well exploited is that of thermal maturing modeling. The inference of present and past distributions of heat within the sedimentary column is influenced in part by the thermal properties (thermal conductivities, for instance) of the crustal rocks. The base of the crust (or Moho) is definable with regional gravity data, the basement depth and configuration with magnetic data, and the presence of anomalous conductors (such as salt) often can be determined with gravity data. Hydrocarbon thermal maturity modeling currently does not take good advantage of model parameters estimated using gravity and magnetic data, namely, the interpreted geometry, depth and lithology (and thus thermal conductivity) of the different crustal units.

3.1.5 Optimization of Seismic Survey Placement

Unfortunately, it is often the case that gravity and magnetic analysis is undertaken after a seismic program has been designed and shot. It makes more sense, both technically and economically, to optimize the seismic program layout (i.e., seismic line orientation, spacing and length) by using information from the interpreted gravity and magnetic data. Such an approach helps ensure that seismic moneys are spent more effectively.

3.1.6 Gravity and Magnetic Analyses Can Address Various Petroleum Issues

Gravity and magnetic data can be used in many ways to solve different exploration problems, depending on the geologic setting and rock parameters. Although most think of gravity and magnetic as tools to map structure, these data can be analyzed to provide insights to other elements of petroleum exploration and production. Table I describes some of the techniques that can be applied to address a wide variety of issues. The impact of-all these techniques increases if the gravity and magnetic analysis is integrated with other data and studies.

Table 1:

Issue	Gravity and magnetic tasks	Integrated with
Source Rock Deposition • Where were the source rocks deposited? • How deep are the source rocks?	Depth to magnetic basement Regional basin enhancements	Seismic data Regional geology
Source Maturation • Where are the "cooking pots" and fetch areas? • What is the present-day heat influx into the basin and how much does it vary? • What is the thickness of the crust? • What is the overburden?	Depth to magnetic basement Isostatic residuals Sediment thickness Depth versus density modeling Regional structural modeling Curie point (regional heat flow) Delineation of volcanics	Seismic data Well data Density and velocity data Heat-flow data
Hydrocarbon Migration • How much relief is there on the basement? • What are the 'shapes" of the 'cooking pots"? • Are major vertical conduits near source areas? • Are major lineations present and how do they relate with more recent geologic features?	Magnetic inversion Depth to magnetic basement Vertical fault identification Gradient analysis Regional depocenter and sediment path enhancements	Well and outcrop data Topography Remote sensing Seismic data Sequence stratigraphic analysis Seismicity
Reservoir Prediction • Where are the thickest sediments? • Where is the highest sand probability? • Where was the source of sedimentation? • What is the influence of tectonics on deposition? • Have the sediment depocenters shifted over time? • What is the compaction history of the sediments? • Do the sands have lateral continuity and connectivity?	Depocenter and sediment path enhancements Integrated basin modeling Density inversion Provenance(magnetic lithology) determination Sedimentary magnetic analysis Paleomagnetic analysis Integrated velocity analysis (2-D and 3-D)	Seismic data Lithologic data (outcrop and well) Sequence stratigraphic analysis Biostratigraphic data
Trap • Where are the major structures?	Residuals and enhancements 2-D/3-D structural/stratigraphic	Seismic data Outcrop information

• What is the structural grain? • Are faults in the sedimentary section? • Are lateral porosity changes present?	modeling Fault identification—gradient analysis Structural inversion Density inversion	Topography Remote sensing Seismicity
Vertical Seal • Where are salt overhangs? • How, thick is tabular salt? • How thick are volcanics?	Residuals and enhancements Layer stripping Integrated 2-D/3-D modeling Sedimentary magnetic analysis	Seismic data Sequence stratigraphic analysis
Timing • What are the ages of sedimentary features? • How do all the petroleum system elements fit together and what is the timing?	Integrated 2.5-D structural/ stratigraphic modeling Layer stripping and enhancements Tectonostratigraphic analysis Paleomagnetic analysis	Density and velocity data Seismic data Biostratigraphic data Back-stripping Palinspastic reconstructions

After Johnson A.E., 1989

3.3.6 Gravity and Magnetic Data as a Resource Evaluation Progresses

Many times, explorationists believe that once they have a gravity/magnetic survey, they don’t need any more. Does that hold for seismic data as well? of course not. Today, increasing seismic resolution is becoming the norm. Similarly, higher resolution gravity and magnetic data should be acquired as a play concept advances from reconnaissance to delineation. Even 4-D applications can be utilized in some situations. Table 2 describes the gravity and magnetic techniques that can be used as a resource evaluation program progresses. Each type of application requires different data resolution, Survey instruments and software tools are available to meet all these specifications, but the cost can vary substantially. Use can be made of this table to help plan or license the data and technology that fit ones need.

Table 2:

	Play identification	Prospect capture	Prospect evaluation	Resource appraisal	Reservoir management
Tactics	Regional reconnaissance Petroleum system analysis Play analysis Establishing exploration focus and G&G expenditure	Prospect identification and risk assessment Lease and G&G acquisition Tectonostratigraphic framework Basin modeling	Prospect risk reduction Drill-site decision (less complex prospects)	Asset delineation and development Drill-site decision (complex imaging)	Reservoir performance monitoring Enhanced recovery
Gravity utilization	Isostatic residual Regional tectonic analysis Basin and depocenter enhancements Regional modeling Digital data integration (with remote sensing. etc.)	Semiregional structural stratigraphic modeling Target-specific enhancements Layer stripping for improved delineation of exploration targets Sensitivity studies tied to density and lithology	Detailed, integrated 2-D/3-D modeling (with seismic horizons, density, and velocity information) Porosity/pressure prediction Salt edge/base determination Enhanced velocity analysis	Integrated 3-D rock properties and velocity modeling Integrated depth migration (pre- or post stack) Borehole gravity—remote porosity detection Detection of shallow hazards	Time-lapsed precision gravity Integrated reservoir characterization Borehole gravity
Gravity Resolution Required	1-5 mGal 2-20-km wavelength Continental grids, satellite gravity, airborne gravity	0.2-1 mGal 1-5-km wavelength Conventional marine and land surveys	0.1- 0.5 mGal 0.5-2-km wavelength High-resolution land and marine surveys	0.1-0.5 mGal 0.2-1-km, wavelength .01-005mGal (borehole) High-resolution land, marine, and gradiometer surveys	.02-1 mGal 1-5 years
Magnetic Utilization	Regional depth to magnetic -basement Regional tectonic analysis Euler deconvolution Curie point analysis -	Detailed basement interpretation Detailed fault and lineament analysis Delineation of volcanics, salt, and shale	Detailed, Integrated 2-D/3-D Modeling-faulting, base ment structure, volcanics, salt edges, and sediment timing "Depth slicing" and lineament analysis Sedimentary magnetic analysis	Detailed 2-D/3-D modeling, inversion Integrated migration (pre- or tack) Magnetostrati hy	None published

Magnetic Resolution Required'	20-km spacing 5-8-km grid 1-5 nT Continental grids, older surveys	2-5-km spacing 1-2-km grid 0.5-2 nT Modern digital surveys, marine surveys, digitized older analog surveys	0.5-1-km spacing 0.1-0.5 nT High-resolution, low altitude surveys	0.25-0,5-km spacing 0.1-0.5 nT High-resolution, low-altitude surveys Borehole magnetometer	
* Typical-required resolution; needs to be tailored to source depth and signal strength					

After Johnson A.E., 1989

3.2 Gravity's Role in a Modern Exploration Program

Much has been written about integrated exploration programs that incorporate all geologic and geophysical data available, but in practice, most prospects presented to management or to prospective investors consist only of subsurface geologic information and seismic data. Many prospect generators do not realize the existence of, or take the time and effort to use, gravity data already in their files or readily available for purchase. Most prospects can be enhanced and better defined by including information derived from a gravity survey.

Most geologic features in the sedimentary section associated with the accumulation of oil and gas are related directly to horizontal density changes of magnitudes large enough to be mapped by an accurate gravity survey. A partial list of such features includes anticlines, synclines, reefs, faults, and horizontal changes in the thickness of salt beds, which, of course. include salt domes, pillows, and ridges.

The map resulting from a gravity survey is a Bouguer map. A Bouguer gravity map consists of gravity values (the vertical component of the Earth's gravity) which have been corrected for latitude, elevation, and terrain. The Bouguer map is the response of all the horizontal changes in density over the mapped area, from the surface to the center of the Earth. To derive the maximum information from these data, they must be "processed" and interpreted.

The first step in this procedure is to derive a residual map. The residual maps used in petroleum exploration normally consist of gravity responses from horizontal changes in density within the sedimentary section. These maps can be used in several ways by an explorationist.

3.2.1 The Anatomy of a Good Gravity Survey

The following steps must be taken to design and implement a gravity survey that will produce an accurate Bouguer gravity map:

1. Determine the shortest wavelength anomaly (smallest diameter) that will be encountered in the area to be surveyed. This must include both the desired sedimentary anomalies and the unwanted “noise” anomalies. This wavelength will, govern the station spacing of the entire survey. At least two samples per wavelength are needed to prevent aliasing and adequately define an anomaly. Once the station spacing has been determined, the entire survey should be metered on a square grid of this spacing.
2. The accuracy of the survey is dependent on three primary factors: the proper location of the station, the measurement of the elevation of the station, and the accuracy of the gravity meter. If we assume a case where the accuracy of the gravity meter is ±.025 mGal (.25 gravity units), the elevation accuracy must be less than ± 6 inches because an error of one foot of elevation will create an erroneous elevation correction of .5 to .8 units. To maintain this degree of accuracy, the error in location of the station must be held to less than 15.25 m (50 ft).

3.2.2 Three-Dimensional Modeling

The most powerful tool available to the gravity interpreter is a 3-D gravity modeling program designed around an accurate and versatile calculation algorithm such as the Talwani and Ewing (1960). A gravity interpreter, using constraints from subsurface and seismic data and sedimentary density data from density logs, can construct detailed models of salt domes. Employing these models, one can detect the presence of and can map unusual shapes and overhang of a dome. The modeling program can he used not only to model single structures but also many structures over an extended area of deep-seated salt pillows and ridges, including both the top and base of the salt. Reefs, faults, anticlines, synclines, and igneous plugs also can be modeled by similar techniques.

The following is a method of using 3-D gravity modeling to obtain an accurate map of the salt.

1. A contour map of the top and base of the salt over the mapped area is drawn, using all constraints from seismic and geologic data.
2. Each contour of the salt structure map is digitized.
3. The gravity contrast between the sediments and salt obtained from density logs is used to calculate the gravity response of the salt at each contour level.
4. The gravity response from all contour levels is integrated over the entire modeled structure and a calculated gravity map is produced which has grid points identical to the grid points of the residual map.
5. The calculated map is subtracted from the residual map, producing a difference map which shows the location and amplitude of the misfit between the gravity response of the models and the gravity response of the structures.
6. The modeled structures are altered and recalculated to obtain a better fit between the calculated and the residual map.
7. This procedure is repeated through several iterations until the best fit is found, while remaining within the constraints of the seismic and subsurface data.

   This procedure results in a structural interpretation that is the best fit of the seismic, gravity, and subsurface geological data (c.f. Ukaigwe 1999).

3.2.3 Residual Maps-Their Construction, Use, and Limitations

A residual gravity map is computed by subtracting a regional map from the Bouguer map or by filtering the Bouguer map with a wavelength filter. The result is a map in which some of the original anomalies of the Bouguer map either have been removed or suppressed. One of the primary reasons for creating a residual map is to remove the anomalies originating in or below the basement and to preserve the sedimentary anomalies undistorted. Through the years, many techniques ‘have been developed with varying degrees of success. The following is a brief discussion of three residual methods.

3.2.3.1 Modeled Residuals

A model residual map is produced by creating a 3-D model of the basement anomalies, calculating the map of their responses, and subtracting this map from the Bouguer map. If the size, shape, depth, and density of all the basement anomalies were known, a map of their gravity responses could be calculated and subtracted from the Bouguer map, thus creating a residual map which contains all the sedimentary anomalies with no distortion.

3.2.3.2. Profile Residuals

Our profile residual map is produced by plotting profiles at equal intervals across the Bouguer map in north-south and east-west directions. A curve that matches the interpreted regional anomalies is fitted to each profile and all the curves from the intersecting profiles are fitted, adjusted, and combined to create a regional map. Values from the regional map then are subtracted at each gravity station from the Bouguer map to create the residual map. The pitfall of this method is in determining the exact shape of the regional anomalies.

3.2.3.3 Wavelength Filtering and Ring-residual Maps

Prior to the use of digital computers, gravity interpreters calculated residual maps by the ring-residual method. The process was slow and labor- intensive. The Bouguer map was gridded on a square grid and a value was recorded at each grid point. The interpreter then placed a template of rings around each grid point and read the gravity values around each ring. The values of each ring were averaged and the difference between this average value and the value at the center grid point was recorded as the residual value for the grid point. This method is sensitive to the dimensions of the circles used. For example, a poor choice of grid spacing will distort the residual map by either filtering out small anomalies or by smoothing several small anomalies into a single large anomaly.

With the advent of the computer, many gravity interpreters adopted the ring-residual method and renamed it wavelength filtering. Many times, grid points are created by computer gridding programs in areas where there are very few or no gravity stations. In some cases, the resulting residual maps are produced without the original gravity-station locations shown. Such maps contain false or badly distorted anomalies subject to misinterpretation.

By using several rings and weighing factors, interpreters can apply the ring-residual (wavelength-filter) method to more complex calculations such as second vertical derivative and upward continuation techniques. Swartz (1954) used 2-D Fourier transforms to study the filtering effect of ring-residual operators. He illustrated how this or any other wavelength filter which uses circular operators distorts the map by amplifying round anomalies and suppressing elongated ones. In other words, although these types of residual maps sort the anomalies according to wavelength, they distort the shape and amplitude of the anomalies according to shape. As a result, many explorationists have misinterpreted these ring-residual and wavelength-filtered maps and have become disenchanted with the use of gravity because the distorted anomalies do not relate properly to the geologic facts. We are concerned that this problem still exists for explorationists who use computer derived wavelength filtered maps of the type described above. For additional information of frequency analysis of potential-field data, see Dean (1958; Fuller 1969).

3.4 Gravity Data Define Basin Structure and Location of Major Oil and Gas Reserves.

All oil and gas accumulations are the result of lateral and vertical hydrocarbon migration from the generating depo-center into structural and/or stratigraphic traps. The position and direction of such main or preferred hydrocarbon migration pathways can be predicted: They are controlled by sediment permeability and by basin geometry (i.e., regional structure) at the level of main carrier beds.

Permeability cannot be predicted and is assumed in this approach to be omnipresent in fractured and porous rocks. Permeability restrictions will cause shortening of lateral hydrocarbon migration pathways; they will not alter regional migration directions. Basin geometry is obtained from regional structure maps. Ideally, regional seismic depth maps tied to reliable wells should be used. However, such maps are rarely available. In their place, regional Bouguer gravity maps are used successfully as regional deep-structure form-line maps if three main conditions are fulfilled:

1. An upper geologic sedimentary sequence in the basin should consist of low density rocks, overlying deeper high density rocks;
2. Topographic differentiations at the basin surface should be minor or absent, or the gravity database should be adjusted correctly for topographic surface effects; and
3. There should be no major influence from intrabasement density variations, or such variations must be corrected for using complementary magnetic data to map depth to basement.

Where these conditions are met, Bouguer gravity maps indicate:

a. Thickness of an upper (younger) low-density unit; and
b. Both regional and semiregional structure at the level of the lower (older) high-density unit.

Regional structure maps are used in the analysis of preferred hydrocarbon migration pathway position and directions, because (**Figure 5)**;

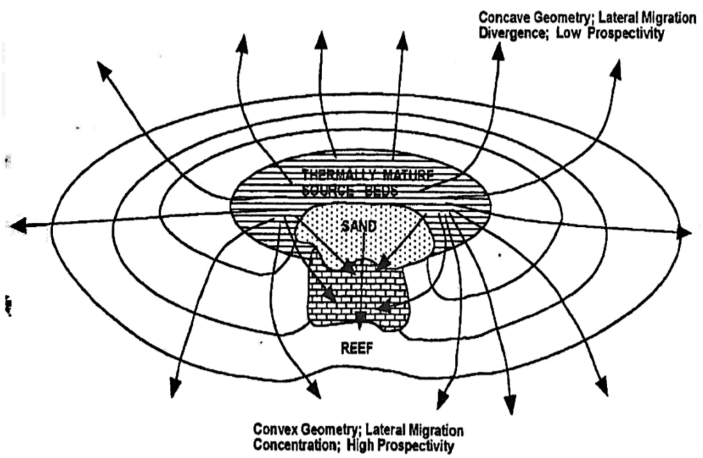


Fig.5. Basin geometry, preferred migration directions and prospectivity differences (from Pratsch, 1986)

i. Hydrocarbons migrate under the influence of subsurface pressures, and
ii. Subsurface isobars are parallel to regional structure, so that
iii. Hydrocarbon pathway directions tend to lie perpendicular to regional isobars, to regional structure contour lines, and to regional Bouguer gravity contours (Figure 5**)** (Pratsch, 1986)

Ideal are kidney-shaped depocenters (Figure 5); here, regional hydrocarbon migration pathways are focused toward positive structural anomalies plunging basinward. Such structurally positive areas also may offer preferred conditions for shallow-water reservoir development of both clastics and/or carbonates. It is here that the largest oil and gas fields in a basin will occur. The importance of these observations is well illustrated by the experience that in any producing basin in the world, 75% or more of its reserves are located on only 25% or less of its acreage (Pratsch, 1986).

There must be a critical minimum density of gravity stations or gravity- survey lines. A repeatable accuracies of about 5 mGal is required. This method, therefore, is well suited as interpretation of "old" surveys and for airborne surveys. Where the quantity/density of gravity stations permits the calculation of residual gravity anomalies, even local structures can be identified; this may become an important factor in preinvestment acreage evaluations.

3:4:1 Utility in Exploration of Continent-Scale Data Sets

Small-scale assemblies of gravity and magnetic data sets and their interpretation are valuable for hydrocarbon exploration. Since 1982 in the United States and 1988 worldwide, such data have become increasingly available and used in oil companies.

Applications

1) to provide a regional context for exploration strategy, concession and farm out evaluations, and medium to long-term planning
2) as a means of high-grading and refining geologic parameters that may have impact on exploration

3) to identify hitherto unknown (or little studied) features whose effects on the prospective section should be investigated further
4) as a means of defining the way geologic and tectonic features are expressed in gravity and magnetic data, and the mapping of such features in an academic sense (at least)
5) to suggest locations where the prospective section may be unexpectedly thick or may contain large structures (classical reconnaissance use of gravity and magnetics)
6) to identify locations where the discipline (gravity or magnetic) is good at or has difficulties in the resolution of geologic problems
7) in areas of good control, to interpret the data in detail in light of local geology and tectonics especially appropriate in frontier areas or areas where a company or individual has little experience or knowledge)
8) in areas of good control, to identify analogs to existing hydrocarbon production, and sometimes to derive and define new play concepts, even in mature basins
9) to permit the identification and interpretation of large features that cannot be "seen" in large-scale displays of data or in individual surveys, no matter how high the quality
10) to serve as a starting point for more detailed work
11) to provide a first-pass guide to planning seismic and other work
12) to serve as an index to data and data quality so that informed decisions can be made regarding further gravity- or magnetic-data acquisition
13) to provide a base of experience and interpretation that can be applied worldwide, whether by individuals or through use of in-house reports, a resource for first-pass, "quick-answer" interpretations.

In general, "comprehensive" interpretations of such data sets are preliminary; first pass efforts limited in terms of integrating other local information into the data set. By all means, such interpretation should be done in as much detail as feasible in a reasonable time frame. Interpretation of all or much of a data set will be more informative than piecemeal local interpretation that is not set into a regional context. Such work requires, at a minimum, enough geologic and tectonic knowledge in any area to constrain the interpretation of the gravity and magnetic data, especially in terms of structural style and orientation of inferred features such as faults.

Otherwise, literally any inference is possible. Such analysis is done best by a geologist who understands the limits and shortcomings of gravity and magnetic data in such displays, rather than a physics-oriented geophysicist who does not know enough geology. No interpretation of gravity or magnetic data is unique.

After a first-pass, interpretive context been established, others with more knowledge about specific areas should refine these regional interpretations in the light of other geologic, geochemical, or geophysical constraints. In many areas, these small-scale displays contain enough information to guide and constrain even very local work. However, such guiding only rarely can be provided through a cursory glance at the data without familiarity with the data set (its spacing, origin, etc.) and at least general knowledge of the geologic and tectonic meaning of the data at local levels (even though that knowledge may be interpretive rather than confirmed).

3.4.2. Pitfalls

i. Data and Grid Spacings

The single biggest problem in examining small scale data sets, which invariably are created from diverse original sources, is failure to be aware of the spacing of the original data or grids derived from them, or both. Digital compilations permit the redisplay of data at any scale, using various contouring packages. Such displays may be inappropriate to the original data set or the derived grid. Equally misleading are areas of broad spacing or no data at all. Today’s contouring programs can handle such situations.

ii. **Variations Among surveys**

In addition to the problems of data spacing, other survey parameters should be considered when examining maps that are amalgamations of diverse original surveys.

This problem is more common in assemblies of magnetic data. In particular, variations in aircraft flight altitude may make for spurious depth differences across survey boundaries. The argument could be made that such problems could be eliminated by upward or downward continuing of the assembled surveys to a single datum. This is true, but the amount of information lost by such processing negates the advantage.

iii. Bathymetry

A problem with gravity data offshore is the influence of ocean-bottom topography. Until recently, many offshore gravity data were free-air data, because inadequate knowledge of bathymetry precluded the preparation of Bouguer gravity maps. Free air gravity maps can mirror the contours of bathymetry. The intelligent way to resolve the problem is to interpret the data with bathymetry directly overlaid so the interpreter can take it into account. Increasingly, good regional bathymetric information provides a means of computing the Bouguer effect so "bathymetric anomalies" can be eliminated. Be aware that such computations are only as good as the bathymetric grid and some variability does exist in the quality of bathymetric data today. Bathymetric effects, essentially subsea-terrain effects, can produce error in the best Bouguer gravity map unless the bathymetry is well known enough that terrain corrections can be-made. An important specific feature in gravity data to be careful of, in interpretation is the continent-ocean transition anomaly, an intense linear high, found along many rifted margins. It is nearly coincident in places (but not everywhere) with the shelf break, so there is a bathymetric effect to consider.

iv. Geologic Pitfalls

One of the greatest difficulties in looking at a continent-scale gravity map is differentiating between a broad area of thick crust and a broad basin. In fact, without some constraints, it is not possible to make this distinction. Thick crust produces a broad gravity low because the relatively low-density crust sticks down into relatively high-density mantle. Precambrian shields and more local “pods” of crust can produce this effect, although variations in the upper mantle and asthenosphere, without thickening the crust, can do so as well. More important from the hydrocarbon-exploration point of view is the fact that a shallow, broad areas of low-density material (i.e., a basin) can create a similar gravity effect. One would expect narrower, near surface (versus lower crust) anomalies to be present that would indicate geologic variations within the basin, but if the data spacing is broad, such features may not be resolved. What remains is a broad gravity low. One might think surface geologic mapping of the world is good enough to make this distinction, but it is not. In many parts of Africa and some places in South America, it is impossible to tell if certain gravity lows are thick sediments or thick crust, and the existing geologic maps are either contradictory or uninformative.

In some places, intrabasement sutures create density contrasts that result in linear lows similar to elongate grabens filled with sedimentary rocks. This problem also exists in places where the surface may be mapped accurately as Quaternary or Tertiary deposits, leaving the subsurface interpretation unconstrained. In many, but not all, locations where this problem exists, magnetic data would permit the interpretation of shallow basement in a thick pod of crust versus nonmagnetic sediments and deep magnetic basement.

Exceptions exist, of course-sedimentary basins with abundant magnetic volcanics, and crystalline basement that is not magnetic. *It is a fact that some well- known basins coincide with gravity highs because they contain thick, dense material-typically inferred to be basalt*, especially if the basin is an extensional rift near a contemporary sea-floor spreading axis. Sometimes such gravity highs are interpreted more reasonably as mantle highs or bonafide structures (basement level or shallower) or even sedimentary variations (1000m of anhydrite, density 2.9 affect the gravity anomaly!). Let the tectonic setting be your guide.

A similar geologic problem with magnetic data is the differentiation of shallow basement from volcanics. Essentially, it cannot be done without at least some knowledge of geology and/or tectonics. However, a good clue lies in the fact that if shallow volcanics are found in an area of deep basement, two distinct magnetic horizons will exist, and this is often discernible in the magnetic data set, if the volcanics and basement are near each other vertically, this distinction becomes difficult or impossible without further processing and analysis.

The outline above lists some of the problems that are more or less specific to small-scale data sets. Other pitfalls of gravity and magnetic interpretation also apply, although some (e.g., cultural effects, shallow sources such as glacial drift, etc.) effectively are "filtered out" by the gridding and display scales typical of these compilations.

3.4.3 Gravity Maps of Africa

The project is proprietary compilations prepared by the University of Leeds, England, for consorita of oil companies. The maps are available for purchase. These compilations differ from government-published data in that they include confidential data provided to Leeds by their sponsoring oil companies. However, many of the data are published or held by major institutions such as the Defense Mapping Agency (now NIMA, National Imagery and Mapping Agency (USA), ORSTOM, and Bureau Gravimetrique Internationale (BGI) (France), and others, including published data for various countries, Leeds has done the immense job of carefully evaluating the data sets and rereducing them to consistent datums with the same correction factors. Effectively, this makes the data into two new data sets, to be thought of in their own rights. The problems discussed above still apply, but these assemblies are much better than some with more cursory corrections, or none at all. In spite of some large "holes" in the data sets, these maps are by far the best gravity maps of African. Leeds' display scale is 1:2,000.000 and 1:5,000.000 the 5 minute grids result in almost 1 million grid nodes for each area, based on about 500,000 original data on land and 1 to 2 million data points in offshore area.

3.4.4 The Isostatic Gravity Residual as a Regional Exploration Tool

The past fifteen years have been an exciting time for those involved in regional geophysical interpretation. This is primarily because of the introduction of large; continental-scale gravity and magnetic data sets, such as those compiled in North America by the DNAG committee (Geol. Soc. Am., 1987), and the numerous compilations by the University of Leeds (now GETECH), which includes South America, Africa, Europe, the former Soviet Union, and Asia (Fairhead, et al., unpubl.). These data sets offer a new synoptic view of continental areas for oil explorationists.

Continental-scale gravity data sets pose a special problem for regional interpretation. This is because of the well-known relationship between the Bouguer anomaly and elevation. In a regional sense, Bouguer gravity is more negative over higher elevations than at lower elevations. As an example, in South America, the regional gravity field ranges from a minimum of about -400mGal over the high Andes to near 0mGal at sea level. For almost 150 years, this has been understood to be the expression of the gravity effect at the crust-mantle interface (Pratt, 1855; Airy, 1855; Woollard, 1959; and Tsuboi, 1979). Dutton (1889) termed the concept of crust-mantle support for topography ***isostasy.***

Most oil explorationists are not concerned about these large, deep-seated effects. We are more interested in the shallower features. But isostatic gravity effects in continental-scale Bouguer gravity can confuse our ability to compare similar-appearing features which exist at different elevations.

For a synoptic view of a continental gravity data set, it is important that the regional isostatic field be removed in some intelligent fashion. Chapin (1996) provides details about a better method to remove the isostatic regional.

3.4.4.1 Significance of Isostatic Residuals

Both Heiskanen and Vening Meinesz (1958) and Simpson et al. (1986) discussed in detail the significance of Isostatic residuals. If our Earth model completely explains the gravity of the Earth, then there would be no residual. But since, as explorationists, we are searching for local unknown inhomogeneities in the crust (i.e., the next billion bbl structure), failure of our Earth model is quite important. Indeed, once the imperfect Earth model (which is considered the isostatic regional) is, removed, we have a better chance of identifying local anomalies.

There are three major causes for these isostatlc residual anomalies:

i. Failure of main assumptions in the isostatic and other Earth models used for computation. Some of this is minimized through a more rigorous approach towards the isostatic model (Chapin, 1996).
ii. Large-scale lithospheric loading and/or flexure. These are lateral effects which are manifested as “local” vertical imbalances. In other words, if the vertical column of rock were decoupled from the adjacent crust, it would tend to seek a different buoyant level.
iii. Isostatic imbalances. These are the anomalies of most interest for exploration purposes. There are three types:

a. the cause of the imbalance is still present. Examples: uplift of mountains, subsidence of basins.
b. the cause of the imbalance was recently present but is no longer present; therefore, the Earth still is readjusting. Example: giacial rebound in Canada and Fennoscandia.
c. the cause of the imbalance is gone, but rebound stresses do not exceed elastic limit of lithosphere. Example: many sedimentary basins and structures within these basins.

   If the explorationist needs to look at the regional geology over a wide variety of elevations, it becomes important to analyze isostatic gravity residuals. They can provide a wealth of information to the interpreter. One of the important benefits is the ability to compare similar structures in areas of different elevations. It can provide a more consistent view of an entire continent of gravity data for regional exploration.

3.4.4.2 One Person's Regional is Another Person's Residual

A "regional" is what you remove from the data to better image what you want to 'see" (residual). The best regional residual combination is achieved by applying geologic thought to the problem. What is the geologic target? If your goal is a better understanding of the asthenosphere, you may want to capture the very long wavelength "blue" anomaly (figure 6). The "red" anomaly may shed light on crustal thinning, while the "green" anomaly relates to basin depth. The short-wavelength "orange" anomaly may be caused by the hydrocarbon trapping structure.

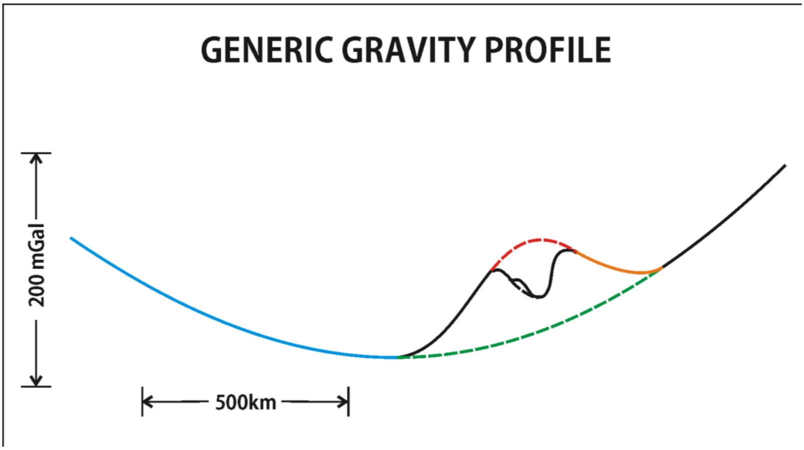


Fig. 6. Regional residual separation

3.5 The Compilation of Aeromagnetic Data for Hydrocarbon Exploration

Compilation of a single, uniform magnetic data set from a series of individual aeromagnetic surveys requires corrections and adjustments to account for differences between data sets collected at different times or under different conditions. For example, the measured values from an aeromagnetic survey collected at 305 m (1000 ft) above ground will be quite different from those collected at 3657 m (12,000 ft) above ground. Also, since the Earth's primary magnetic field changes with time, surveys measured ten or twenty years apart can differ significantly. Mathematical models can adjust these flight-level contrasts and correct for time variations.

Regional aeromagnetic data sets provide critical information on the tectonic framework of the upper crust. The patterns and amplitudes of anomalies reflect the depth and magnetic character of crystalline basement, the distribution and volume of intrusive and extrusive volcanic rocks, and the nature of boundaries between magnetic terranes. In addition, analysis of regional aeromagnetic data sets can yield estimates of the depth to bottom of magnetic sources, which puts constraints on the thermal structure of the upper crust (Blakely and Connard, 1989).

3.5.1 How Basement Lithology Changes Affect Magnetic Interpretation

Many people are intimidated by the magnetic method, but they are quite willing to attack gravity interpretation. This is usually a result of the inclination/declination issues with magnetics, and the fact that most people view a gravity map as a structural map. Magnetic maps are not structural maps; they are a contoured representation of magnetization changes in the geology. This is harder for people to "visualize in terms of real rocks and structure. Gravity interpretation seems easier because a gravity high usually correlates with a structural high (except in the case of salt), but simple criteria such as that can cause problems if the interpreter is not careful.

On the other hand, some aspects of the magnetic method are quite straight forward, one is the direct mathematical relationship between anomaly wavelength and source depth. Another important relationship is that basement lithology changes typically have amplitudes of hundreds of nanotesla (nT), but structural changes usually cause anomalies of only tens of nT (gammas).

It is also important to note that, depending on magnetic inclination, a fault and a lithology change can have distinctly different magnetic signatures. One might cause a symmetrical anomaly while the other causes an asymmetrical anomaly. This underscores the importance of preliminary model prior to undertaking any gravity or magnetic interpretation.

There is a common misconception about magnetics: If there are rock-type changes in basement, then magnetics cannot tell anything about basement structures. This statement is false.
Magnetic anomalies are a result of two things:
i. a lateral contrast in rock structure; or
ii. a lateral contrast in rock composition

If there is no lateral contrast, the magnetic field is flat.

Visual inspection of maps must be accompanied by some visual and quantitative analysis! Linear trends or breaks in trends will correlate either with lititology changes or structure (faults). After a few correlations with known (and expected) geology, the interpreter can make depth calculations. Anomalies of similar wavelength in an area give depth information for that area. If there are strong anomalies, probably related to basement lithology changes, and their areal distribution shows changes in wavelength, then the basement is changing in depth. This is quick analysis rather than a quick glance.

Sometimes, just having the data is not enough, and just looking at it is not enough, either. You also must analyze the data. How much analysis depends on the geologic problem, and the time available for interpretation.

The concept of continuation of magnetic anomalies (on profiles or maps) become broader longer wavelength) as the distance between the geologic source and the magnetometer increases. This concept of "continuation is key to the interpretation of magnetic data. As L.L. Nettleton puts it in his classic 1976 text: … *it is usually possible by simple inspection of a magnetic map over a broad area covering a wide range of depths to separate the map into areas shallow, intermediate, and large basement depth by noting the areas of sharp, intermediate, and broad magnetic anomalies….* The whole process of basement-depth determination depends on devising quantitative measurements of this relationship of sharpness to depth.

3.5.2 Basement Rocks

From Nettleton (1976 p369 – 370) actual basement rocks may be compared with a mildly stirred-up matrix of components with varying magnetite content. The condition may be generally likened to an old-fashioned marble cake with dark and light batter lightly stirred together and covered with frosting. The two colors of batter correspond to basement materials with relatively high and low magnetite concentrations and the frosting to the overlying sediments.

Such concepts would seem to make numerical calculations from geometric models not very relevant. This is not true, however apparently because at depths comparable with the horizontal dimensions of the units, effects from bodies with irregular boundaries are effectively simulated by models with simple geometric forms. Therefore calculated effects from simple models can be very useful in understanding the magnetic effects observed in nature.

Magnetic susceptibility is a measure of how susceptible the rock material is to being magnetized' by the Earth's magnetic field (induced magnetization). This is also a measure of the amount of magnetite (or other minor magnetic minerals) in the rocks. Susceptibility is a dimensionless unit, expressed in SI or cgs units. Journals prefer the more formal SI units, while practitioners and most software vendors use micro-cgs (cgs $\times 10^{-6}$) units for modeling. The following comments use micro-cgs units.

An "average" granite contains about 1% magnetite, which equates to about 2500 micro-cgs units. For comparison, the following table gives a simplistic rule -of thumb for rock susceptibilities:

Rock types	**Rock Susceptibilities** $(\boldsymbol{cgs \times 10^{-6}})$
Sedimentary rocks	0 – 600
Acidic basement rocks	600 – 5000
Volcanic mafic rocks	3000 – 10000
Pure magnetite	30,000

Real measurements from basement outcrop or cores are available for modeling purposes. It is impossible to use the actual measured susceptibilities to model structure. This is probably because outcrops are weathered and magnetite oxidizes fairly easily losing magnetization.

3.5.3 Magnetic Properties of Sedimentary Rocks

Although regarded as magnetically transparent by early practitioners of the magnetic method for oil exploration, sedimentary rocks have become the target of many modern surveys. Depending on the genesis of magnetization in sedimentary rocks, these modern surveys may yield detailed information about structure, fluid pathways, or geochemical reactions. Among the important geochemical reactions are those postulated to form certain species of iron oxides over oil fields (Donovan et al., 1979, 1984, 1986, 1988; McCabe and Sassen, 1986; McCabe et al., 1987; Elmore et al., 1987; Henderson et al., 1984). Reactions that produce magnetically important iron sulfide minerals and the geologic settings that favor such reactions are described by Reynolds et al. (1993) and by Goidhaber and Reynolds (1991).

Magnetization in sedimentary rocks may be divided into two main classes: primary or detrital (produced when particles of magnetic minerals are deposited with other sediment), and secondary (formed after deposition). In general, processes leading to detrital magnetization are understood better than the myriad possible reactions that can lead to secondary magnetization. Detrital magnetization is controlled by variations in the type and abundance of magnetic grains from the sediment source area and by the depositional environment itself. Secondary magnetizations may arise from many processes, but herein, we consider only magnetizations associated with chemical reactions that produce new magnetic minerals and/or that destroy, detrital magnetic particles.

Magnetic anomalies result from the total magnetization of the rock body, which is the vector sum of the induced and remanent magnetizations, induced magnetization arises from the interaction of magnetic minerals with the Earth's magnetic field; induced magnetization acts in the direction of the Earth's magnetic field and thus produces positive anomalies at high latitudes. The intensity of induced magnetization is the product of the effective magnetic susceptibility (k) and the local strength of the Earth's magnetic field (typical value 50000 nT). Susceptibilities for typical sedimentary rocks can vary from 36 to 3600 x 10^{-6} in SI units (3 to 300 x 10^{-6} cgs), with values as high as 20920 x 10^{-6} Sl (1665$\times 10^{-6}$) cgs) reported (all values from Carmichael, 1989).

Remanent magnetization exists independently of the present Earth's magnetic field. The intensity and orientation of remanent magnetization depend on the rock's magnetic mineralogy and orientation relative to the Earth's magnetic field at the time the magnetization was formed. If remanent magnetization is sufficiently strong and acts in a direction opposite to the present Earth's field, it can produce negative anomalies at high latitudes. The ratio of the strength of remanent magnetization to induced magnetization is called the Koenigsberger ratio. Koenigsberger ratios- greater than 1 indicate that remanent plays a greater role than induced magnetization and must be considered in anomaly analysis. Standard tables (Carmichael, 1989) list Koenigsberger ratios ranging from 0.02 to 10 for sedimentary rocks.

Relatively few case studies have been published that combine aeromagnetic interpretation with the detailed rock magnetic investigation required to establish unequivocally the source of anomalies in sedimentary rocks. In one such study, Reynolds et al. (1991) found different magnetic sources in their investigation of aeromagnetic anomalies over sedimentary regions of Oklahoma, Alaska, and Wyoming-Idaho-Utah. At Cement oil field (Oklahoma), they found evidence for secondary production of ferromagnetic pyrrhotite (Fe_7S_8) as a result of hydrocarbon seepage. Although the observed anomalies at Cement field (see Donovan et al., 1979) are caused by cultural features such as buried well casing and pipelines (Boardman, 1985), the amount of pyrrhotite there probably would be sufficient 'to generate very subtle anomalies in the absence of cultural interference (Reynolds et al., 1990). At Simpson oil field (Alaska), Reynolds et al. (1991) found that ferromagnetic magnetite (Fe_3S_4), some of which is related to hydrocarbon seepage, had sufficient natural remanent magnetization to contribute to magnetic anomalies. In the Wyoming- Idaho-Utah thrust belt, they found that detrital magnetite, commonly concentrated in heavy-mineral laminations in the Middle Jurassic Preuss Sandstone, was the source of the magnetic anomalies. In this and other studies, no direct evidence has been found of magnetic anomalies caused by secondary magnetite over oil fields.

3.5.4 Environmental Approach

Although gravity and magnetic surveys for hydrocarbon exploration typically are designed with relatively wide data spacings, to define relatively deep-seated features, environmental and mining projects are concerned with information from much nearer the surface. One of the biggest differences in these two kinds of surveys is, therefore, line or data spacing, which is much closer for shallow-target work. Ground magnetornetry commonly is used instead of airborne magnetics, so that the sensor can be closer to the small target anomalies.

Magnetic data still find their greatest application in mapping buried metallic objects such as waste drums, but excellent magnetic surveys have been used archaeologically to define tepee rings, hearths, and other structures. Similar approaches may contribute to understanding soil and channel distribution in aquifers and other environmentally interesting situations. An important use has been finding abandoned steel-cased well bores, which have serious impact on subsurface fluid flow. Gravity data can help locate buried void spaces and can assist in the delineation of subsurface features such as channels. A high-tech superconducting gravity meter can discern between a “filled” aquifer and a mostly empty one.

An excellent reference for geophysical work of all types in environmental applications is the SEG monograph Geotechnical and

Environmental Geophysics, 1990 (Investigations in Geophysics No.5, edited by Stanley H. Ward).

My own experience is primarily with precious-metal and copper exploration, tempered with training in economic geology of a wide variety of deposits and in a variety of geophysical exploration techniques. My research is focused primarily on use of potential fields for mineral exploration, but I highly recommend combining this information with Landsat, Induced polarization data, geochemistry etc., and with prior experience with remote sensing and a variety of electrical (and electromagnetic) techniques.

4.0 Geologic Interpretation of Magnetic and Gravity Data.

Geophysics is an indispensable tool for geologists looking for and developing oil and gas fields. Because it lets us “see” into the subsurface, geophysics allows petroleum geologists to build better images of the subsurface than is possible using only surface geology and information from well bores. In the past, geophysics was the domain of the geophysicists, and the geophysicists alone acquired, processed, and interpreted geophysical data. During the past two decades, however, the technology of geophysics has exploded; at the same time, the petroleum industry has been forced to look for more and more subtle traps in more and more difficult terrain. This placed a tremendous burden on geophysicists, and they naturally looked to their colleagues, the geologists, for relief. At first, geologists only helped with interpretation. Today, however, geologist are also involved in helping geophysicists make decisions regarding acquisition and processing of data.

Interpretation as we use the word involves determining the geologic significance of geophysical data (seismic, magnetic, gravity, etc.). This necessarily involves geologic terminology.

Indeed a number of decisions have to be made in data processing, acquisition, and even in the initial planning of a survey which prejudices the geologic conclusions and thus could be legitimately included as part of interpretation. Therefore, few books on the geologic interpretation of gravity and magnetic data exist. We cite Boyd (1967), Ukaigwe (1999 & 2004).

It is rare that the correctness or incorrectness of an interpretation can be ascertained because the actual geology is rarely ever known in adequate detail. The test of a good interpretation is consistency rather than correctness (Anstey, 1973). Not only must a good interpretation be consistent with magnetic and gravity data, it also must be consistent with all that is known about the area including electromagnetic data, borehole information and surface geology as well as geologic and physical concepts.

One can usually be consistent and still have choice of interpretations. Then more so when data is sparse, the interpreter should explore various possibilities, but usually only one interpretation is wanted, that which offers the greatest possibilities for significant profitable hydrocarbon or mineral accumulation. An interpreter must be optimistic, that is, he must find the good possibilities. The optimistic interpretation is usually preferable to the most probable, because the former will probably cause additional work to be done to test (and perhaps modify) the interpretation, whereas a non-optimistic interpretation may result in abandoning the area. Failing to recognize a possibility is an unforgiveable sin. It should be noted that “success” or “failure” that is finding or failing to find hydrocarbons in commercial quantity, is often a poor test of an interpretation because many factors critical to commercial accumulations cannot be predicated from geophysical data.

An ideal interpreter combines in one person training in both geophysics and geology. He is fully aware of the principles involved in the particular geophysical method. At the same time his geologic experience helps him assimilate the mass of data, much of its conflicting and arrive at most plausible geologic picture. Unfortunately, not all interpreters have the requisite knowledge and experience in both geology and geophysics, and often the next best alternative is to have a geophysicist-geology team working in close cooperation.

Deducing geologic significance from the aggregate of many minor observations not only tests the ingenuity of an interpreter, it also tests his in-depth understanding of physical principles.

Magnetic interpretation is somewhat complicated by the fact that the magnitude and shape of the magnetic mineral content, depth and attitude of the causative body but also to its altitude or orientation in relation to the direction of Earth's magnetic field. It may further be complicated by the presence of remanent magnetism often in a different direction to that of the magnetism induced by the present Earth's field.

The amplitude of the anomaly is determined by the depth, the magnetic susceptibility of the body, the magnitude of the Earth's field and to a lesser extent by the altitude of the body. Surprisingly, though it may seem amplitude is of least interest in interpretation. This is because of the large ranges of susceptibilities of apparently similar rock types.

The shape of an anomaly is of prime importance. From the shape we can determine the depth below the surface, the dip and get some idea of the dimension of the body.

Interpretation is probably for most of us the most interesting and challenging part of an airborne magnetic survey and the part on which I have spent most of my time and effort. The first two stages, the planning and conduct, call for competence and attention to detail; interpretation provides an opportunity for creative thinking and the satisfaction of discovering new relationships in geological facts and, in addition, the possibility of a spectacular major discovery such as: Abakaliki, Ilesha, the Benue trough, Chad Basin or the Niger Delta Oil Fields to mention but a few.

A number of general points are worth keeping in mind regarding interpretation:

1. The interpretation is part of a larger programme: the interpreter must not forget this.

2. Interpretation calls for the co-ordination of a great quantity of knowledge and varied information and is often a team operation to which geophysicists, mathematicians, geologists and geochemists contribute.
3. Interpretation is a continuing process which may extend over many years: data which at one stage may be incomprehensible can take a new significance with new ideas and new facts.
4. Insights and inspiration usually only come after much hard work.
5. Interpretation can be regarded as a process of question and answer: the aeromagnetic, geological and metalogenic maps can be regarded as rapid access data banks. The difficult part of interpretation is asking the right question: if you do this, the answer is (sometimes) easy.

Having noted these points we now turn to the interpretation procedure, which can be divided into a number of stages. (see Ukaigwe 1999; Chapters 8 & 9; Ukaigwe 2014, Chapter 5).

The interpretation procedure, the actual mechanics of which are discussed below is a cyclic process in which it is hoped that there is a refinement and improvement of the interpretation at the end of each cycle. The interpretation process should be marked by periodic reviews in which a dated map and a brief report indicate the progress. These periodic reviews should be carried out when geologists, geochemists and other people engaged in the project can listen to assessment. These informal reviews often produce additional information about unrecorded facts or unsubstantiated theories which can often be very helpful in developing the geophysical ideas. It also lets the geologists and others see how the interpretation is built up and they understand the results better this way. The actual process of interpretation is difficult to explain and the flow diagram figure 7 is an attempt at a general description. However, almost every interpretation takes on its own character and the interpreter has to develop some new approach to the interpretation, either minor variations in the techniques used, or a re-casting of the particular emphasis in the order of events.

As an interpretation progresses, earlier geophysical work should be re-examined as there may be unappreciated significant work which has been done earlier, and the features are only understood in the light of what is being discovered with the current interpretation.

At the completion of the interpretation when a final draft report has been written, a more formal discussion of the results should take place.

From my point of view, the aim of this discussion will be to discuss the results of the geophysical interpretation, but it would presumably be planned to do more than this. At this conference, the following matters should be discussed and clarified:

a. Are the geological facts used by geophysicists in the interpretation properly understood? It is important to make sure that no misunderstanding has occurred in using the geology.
b. Are there any so far, unrecorded geological observations?
c. Is there any information about lithological variations which may be responsible for changes in magnetic properties along and across strike?
d. Are there common features in ore bodies and prospects which have similar geophysical properties and associations?
e. Is there any unwritten speculation regarding geological relations within the area?
f. Can the geologist in the group follow the development of the geophysical ideas and are they getting all the help they should from the geophysicists in planning future work?

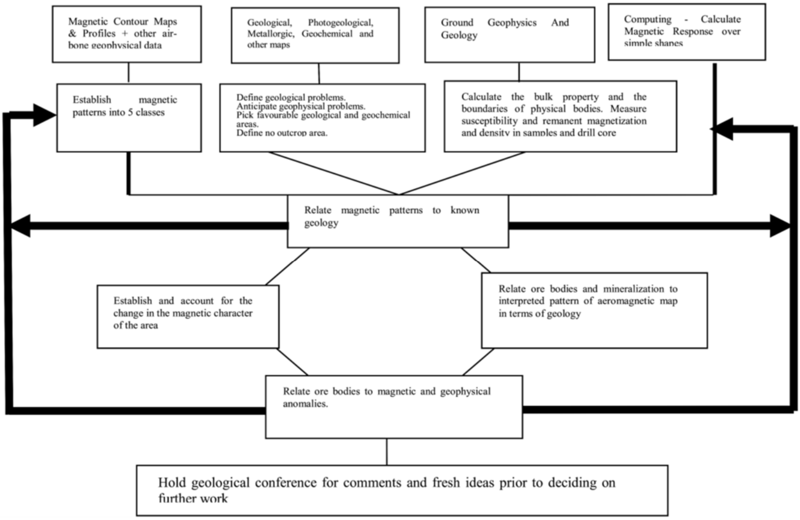


Fig. 7.1 *Flow chart for Aeromagnetic Interpretation*

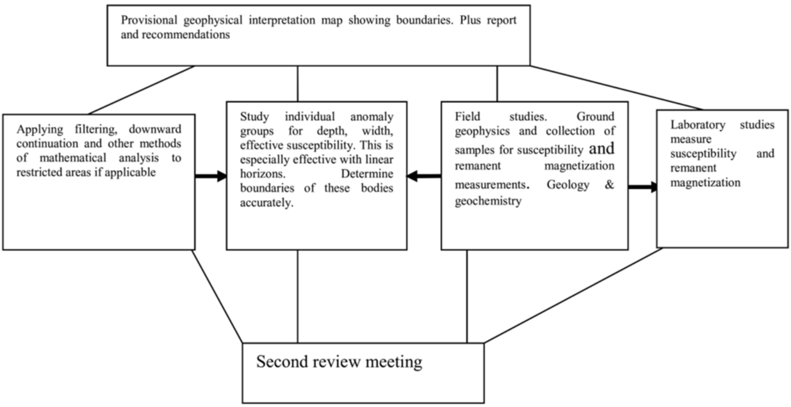


Fig. 7.2 *Flow diagram for formulation of geological ideas from geophysical interpretation*

Liaison between the geophysical interpreter and the rest of the group must be maintained because the geophysical maps should be carefully scrutinized and new facts recorded in the field. The geophysical interpretation should be tested regularly against these observations and modified. The geophysicists should be able to help the geologist formulate his new ideas by bringing in the geophysical checks. The relationship of activities is shown in figure 7.

4.1 The Interpretation of the Pattern of Anomalies on Magnetic Contour Map

The ideas on which the interpretation of magnetic contour maps and a more detailed discussion of some aspects of the work is provided in the "*The Contribution of aeromagnetic surveys to geological mapping*", Boyd (1970). *The importance of Aeromagnetic Evaluation of Structural Control of Mineralisation*: Domzalski *(1964)*, provides a very helpful account of this type of interpretation of aeromagnetic maps.

There are three parts of the interpretation:

1. A number of magnetic units are distinguished on the magnetic contour map. These units are distinguished usually by the character or the intensity of the anomalies.
2. Having done this the anomalies from the groups or units are analyzed to determine shape and the magnetic property of each body: this is done by studying the shape and amplitude of the magnetic profiles over the bodies.
3. These shapes must then be explained in geological terms and related to each other and to the known geology. This may be done by comparing the magnetic units with the outcrops shown on the geological map, or in areas where there is no outcrop to suggest from a consideration of the magnetic properties and shape of the body, the type of rock and structure which is likely to be responsible for the magnetic contour map into a number of units is done to simplify the handling of the thousands of individual anomalies of which the magnetic contour map is composed.

It will be found that most anomalies can be included within the following five groups. They are all better seen than described.

1. Equidimensional bodies (Figures 8 & 9) are generally approximately circular or oval and are often referred to as circular bodies. The boundaries of these bodies are usually fairly well defined and it is not difficult to establish the limits, although the precise position of the boundary may be confused if the body is remanently magnetized. These bodies are often intrusions of granitic or gabbroic type rocks and stand out because they are more or less magnetic than the surrounding background, but they may also be marked by a ring of small anomalies which is due to the alteration of the surrounding rocks. Occasionally, small basins of sediments have a similar appearance to non-magnetic granite and care must always be exercised in attributing any anomaly to a particular geological form if there is no confirmation from geological outcrop. Some of the equidimensional anomalies are the result of the thickening and concentration of magnetic materials within a structure such as a fold, closure or a thickened limb of a fold.

There are also a number of equidimensional anomalies which are not easily explained. Even in areas where the outcrop is good, there is no apparent relationship between a roughly equidimensional body and pattern as indicated by geological mapping.

2. ***Simple sheets*** (Figures 10 & 11) Simple sheets produce a single maximum and minimum and are usually, though not always, due to thin bodies. They are almost always more magnetic than the surrounding rock: they may be basic or ultra-basic dykes, bands of jaspillite and other sediments rich in magnetite. Magnetic bands sometimes in the young sediments produce small but persistent magnetic features on the maps. They are the easiest to interpret. They are usually caused by a single, uniform magnetic body which corresponds closely to the concept of the mathematical shape used in the calculations. Analysis of the shape of the anomaly will give information about the depth, dip and width of the body; if the width is less than the depth to the top of the body, it is very difficult to

distinguish it from a thin sheet. The simple sheet may, on occasions, pass into a more complex band of anomalies and this may lead to minor confusion in the interpretation. Narrow linear anomalies may also be produced by faults and along the edges of very wide magnetic bodies.

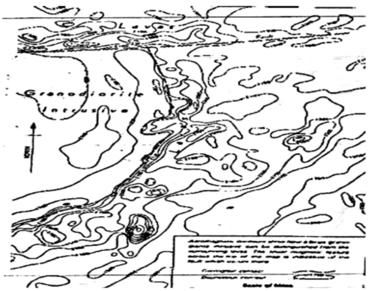


Fig 8. *Aeromagnetic contour show how large*

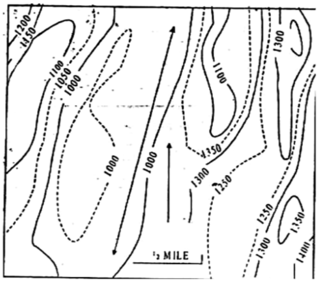


Fig.9. *Despite the low magnetic relief of the area, aeromagnetic contours parallel the trend of steeply folded and contorted gneisses. The average strike is seen as a glance, but many ground observations would be required in this case to yield equivalent results.*

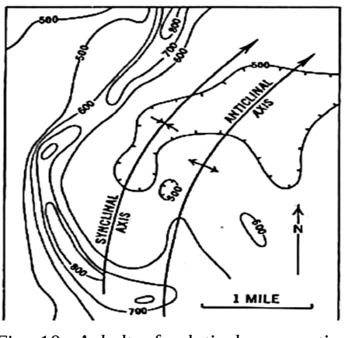


Fig. 10. *A belt of relatively magnetic volcanic rock is outlined by the aeromagnetic contours in the west hall of the map. The double curve toward the south is related to known folding, as indicated by the fold axes. Recorded at a flying height of 500 feet*

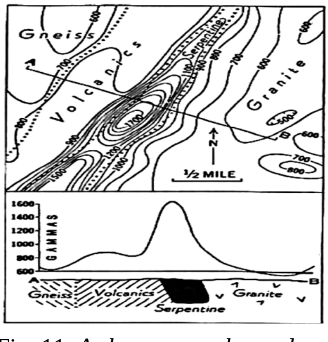


Fig. 11. *A sharp anomaly produced by a sill-like body of serpentinized peridotite. The shoulder on the northwest side of the anomaly is caused by a belt of volcanic strata. The asymmetry of the profile is related to the southeast dip of the serpentine.*

*3. **Complex zones*** (Figures 11 and 12). Wide areas of magnetic rocks which produce several anomaly peaks, are often due to greenstone belts, bands of schists, thick iron formations or intrusions of ultra-basic rocks. The grouping of anomalies into broad magnetic zones is a convenient way of dealing with many of the problem areas on the interpretation map at a first step. The boundary may be clear in places, but the other side or the continuation along strike may become less distinct so that the complex zone is usually open ended and often ill-defined. This unit, or the boundaries of the unit, which are often as useful as the unit itself serve to set aside the difficult areas which require more careful consideration at a later stage.

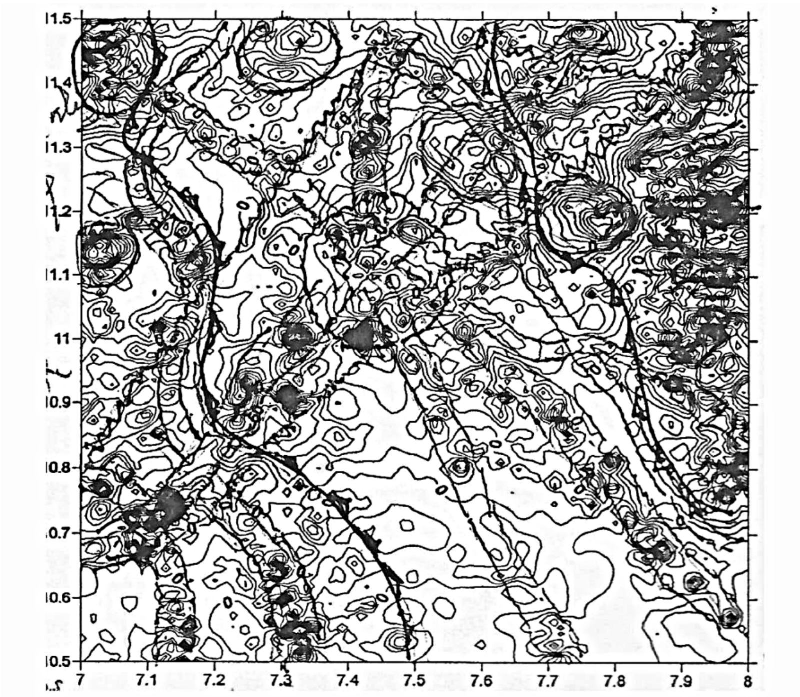


Fig.12 Aeromagnetic map of sheets 101 (Maska), 102 (Zaria), 123 (Kaduna) and 124 (Igabi); Northwest Region of Nigeria.

4. ***Dislocation*** (Figure 13). These indicate disturbances in the magnetic fabric of an area. Sometimes there is an observable displacement of magnetic horizons in which case the dislocation is probably a fault. On many occasions, the change is not clear. These dislocations may be marked by a change in the intensity or complete disappearance of magnetic anomalies along strike, or on occasions, it can be marked by the characteristic anomaly pattern of fault boundary. The term dislocation is preferred because the term fault has very clear implications to the geologists and they may be misled if the break which occurs in the pattern of magnetic anomalies is called a fault. The dislocation may take the form of an abrupt truncation of magnetic beds along the strike which may, in fact be due to a change in sedimentation, to an unconformity, to folding or to a fault. When there is a clear displacement of the horizon, the dislocation is probably a fault as the term used in geology, but even here, other interpretations are possible. There are a number of situations in which the movement along the dislocation may be due to the nature of a fault, but this movement does not necessarily take place within a limited volume as is normally the case with a fault. There may be a wide zone of the parallel joints, the zone itself perhaps being as much as or even 2 kilometers wide and movement of the order of a few centimeters may take place across each of several hundred of thousands.

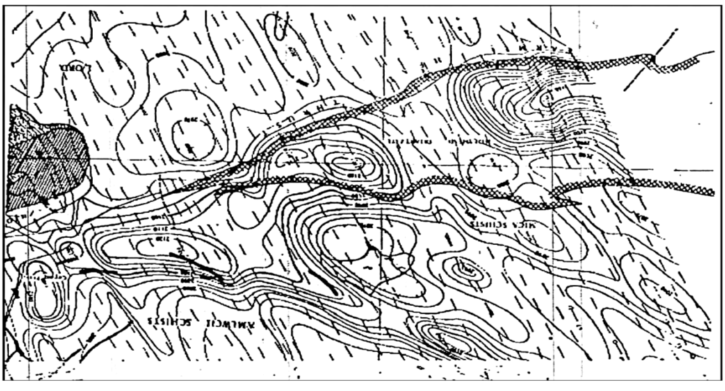


Fig.13. Dislocations on aeromagnetic maps

One feature seen on aeromagnetic maps is a regularity in the change of intensity of the anomalies along strike of magnetic horizons. There appears to be an alignment of the less magnetic sections of magnetic beds: this feature is included within the term “dislocation”. This reduction in amplitude of the anomaly may be due to reduction in the amount of magnetite in the rock or it may be due to a greater depth of weathering facilitated by the more jointed nature of the rocks.

Another feature of dislocations may be shown in the pattern of intrusive dykes. A dyke swarm may show a clear zig-zag pattern across the area, due to lines of weakness which are oblique to the main dyke trend, providing an easier path of intrusion.

These dislocations are often difficult to relate to the known geology. They often occur in areas where there is no outcrop; this may be significant. In some areas there may be a relationship between the zones of dislocation and the mineralization, though the relationship is not necessarily a simple one. In other areas too, higher yielding water wells occur in the dislocation zones. There is evidence of changes in the character of the sediments overlying large dislocations of this type which occur within the basement rocks. This may indicate that the faults were still moving during the period of deposition.

The surface cover may be in the form of a thin lens or a blanket of lava or sediment. The layer of lavas can present a serious noise problem which confuses the interpretation of the main source of the anomalies. This can be popularly confusing in areas where nothing is known about the geology and the anomalies are treated as part of the structure of the underlying rocks. Even when recognized, the lavas can be overcome in part by carrying out an upward continuation of data, but it is often not too difficult to allow for the effect of the volcanics.

The interpretation of results obtained over a sedimentary cover have already been mentioned above in detail in the use of aeromagnetic surveys in oil prospecting. The depth of the cover can be calculated from the shape of the anomalies and this information may be used to locate stream channels in a magnetic basement or to find areas on the edge of a sedimentary basin where the sediment cover is thin enough for it to be practical and economical to carry out mineral exploration.

In areas where the succession is not strongly magnetic, the magnetic contour map misses much important information; the contours in effect act as a filter rejecting the anomalies of small amplitude and short-wave length. A quick study of the original records may show anomalies 1, 2 or 3 gammas/nanotesla (nT). These minor anomalies can be plotted on the flight path maps and may add very substantially to our understanding of an area.

The possible interpretation of 1 gamma/nanotesla (nT) anomalies, shows how important it is to insist on a low noise level in the specification of the survey and how important it may be to use a high sensitivity magnetization with a noise level of about 1 gamma/nanotesla (nT).

4.1.1 Interpretation proper

The boundaries of the units recognized on the map should be marked on an overlay of tracing paper using coloured pens compared with the geological maps so that the source of the magnetic anomalies is established where this is possible. The process of division into units and comparison with the geological map would be repeated many times, so that the interpreter builds up over a period of many days or weeks, a map which reflects the many different units shown on the aeromagnetic map and at the same time establishes the magnetic character of the rock groups. The characteristics of the magnetic map in the mines and prospects should be examined carefully if the aim of the interpretation is the discovery of an ore body.

Several versions of the interpretation can be made: they should be dated to avoid confusion. A uniform colouring system helps to avoid confusion. The following code is suggested:

Simple sheets	blue
Boundary of complex zone	green

Dislocation	red
Mines and prospects	black
Geological information	pencil or crayon
Major geographical features	Indian ink

After this work has been going on for some time, it is often stimulating and salutary to write a short account of the conclusion drawn from this interpretation at this stage, as this often draws attention to some of the blanks and shortcomings and ambiguities in your work. This summary must be accompanied by a map drawn on tracing paper, on which all the boundaries are marked.

Once the initial sorting out of the anomaly groups has been done, the interpretation becomes selective and you try to solve specific problems often by analysis of the anomalies, such as:

a) The dip of boundaries;
b) The depth extent of bodies;
c) The change in width or susceptibility of simple sheets;
d) The thickness of the overlying soil, alluvium or sediments of special problems indicated by the aim of the interpretation.

After this, the magnetic groups must be related to the geology and the geological development of the area.

4.2 The Application of Aeromagnetic Interpretation to Mineral Exploration

The way in which aeromagnetic interpretation is used to aid mineral exploration varies greatly depending on the type of geology in the area, the degree of knowledge of the area and the stage to which the exploration programme is being carried out, and the type of supplementary geophysical information which may be available. Whenever radiometric or electromagnetic surveys are conducted at the same time as the magnetic survey, it is important that the interpretation of the magnetics should be closely coordinated as the successful outcome of the interpretation may in the end, depend on the interplay of information from both sources. (Confusion can arise if two interpreters working on different data begin to attach significance to their own work because it appeared to correlate with the other information).

In all exploration work, much of the application of interpretation is done by analogy with other areas. This can at times be misleading where a rule of thumb may not apply in the new area and as a result, anomalies are either given undue prominence or neglected because they do not fit into the pattern of another district. The normal sequence in using the magnetic survey for exploration is to establish the relationship of the magnetic map to the geology, before paying attention to selecting the less numerous anomalies which are caused by or some way related to the ore bodies.

The application of the magnetics in exploration may be made in a number of ways:

1. The simplest association occurs when the ore itself is magnetic. This is the case with bodies of magnetite and ilmenite which are valued on their own account, it occurs in gold and copper ores in western Canada which are associated with pyrrhotite; the tin veins in Bolivia contain magnetite; gold ore at Tennant Creek contains magnetite; some manganese ores also contain magnetite. In each case, the ore produces a magnetic anomaly and while there may be many other anomalies, due to other sources, the target itself may have a significant, magnetic response.

In such a situation, the interpretation may be simplified if it is known that the ore bodies occur within a certain host rock which has been mapped or where there is some other known control of mineralization. All anomalies within the zone of interest will be analysed to establish the size or width and the effective susceptibility of the bodies and those which are either wide or too low susceptibility or those whose physical characteristics most closely correspond to the ore body which is a target of the exploration.

If no geological control is known, it may be possible by establishing the magnetic patterns in the area, to recognize a correspondence between the position of known ore bodies and prospects and this magnetic pattern, and then at least to attach some priority to the study of anomalies from similar magnetic areas. In this way, the interpretation which may be a lengthy procedure of analyzing individual anomalies will be directed to what by analogy with the known ore bodies at the most promising areas. Otherwise it may be necessary to examine and analyse all anomalies.

2. Some mineral deposits are known to be associated with rocks which have a distinctive magnetic character. The numerous examples of deposits of this type include diamonds which are associated with kimberlites in Africa and USSR, nickel and gold in Western Australia, associated with ultramafic rocks, gold, asbestos and water, associated with dolerite dykes, tin, copper and gold, associated with granites, (Ukaigwe, 1985, 2004 a&b; Ukaigwe and Moutari 2004), platinum, iron, associated with norites and gabbros and niobium, phosphorous and rare earth elements associated with carbonatites in Africa, Canada and India.

In the normal exploration situation, something is already known about the geology of the minerals in the area and associations of this kind will have been established or at least suggested by geologists. However, the geophysicist can assist in this aspect of application of the method both by contributing his knowledge of associations of this type in other areas, and by observing correlation between deposits within the area of interest and magnetic units as established by interpretation, which may bring out fresh information from the geologists about the geological similarity of the groups of deposits.

3. In some cases mineral deposits are related to structures. Diamonds and tin are believed to be associated with major shear zones and much is made in many areas of the regional association between mineral fields and deep fault zones.

On a smaller scale, faults and small shear zones are associated with deposits of gold, lead-zinc, iron and copper and the geophysicist in his interpretation should be alert for indications of small structures which may act as host to ore deposits as discussed.

4. Some ore bodies, the sedimentary copper bodies of Central Africa and the uranium deposits in the Northern Territories, Australia lie close to major unconformities. Although unconformities may be difficult to distinguish from low or high angle faults in metamorphic terrain, the magnetic map does at times indicate such boundaries clearly and provides additional help in defining the areas where the more concentrated forms of exploration will be carried out.

5. Some structures and features of the geology may not be directly related to the ore body but may yet provide information which is helpful in establishing the extension of the ore body or in the understanding the regional geological setting in which the ore bodies occur.

For example, faults which post-date the mineralization, may displace part of the ore body and the recognition of the structure and the nature of its movement will assist in the development of discovery.

Magnetic horizons which occur within a sequence of syngenetic ore bodies may assist in the exploration by indicating folding and faulting of the horizon. This magnetic horizon may be composed of lavas, sills or magnetic sediments (Ukaigwe 1998).

The presence of magnetic sediments within a sequence which contains sedimentary ore bodies may itself be significant and contribute to understanding the development of sedimentation in the area and of the conditions which led to the formation of the mineralization of interest.

Knowledge of intrusive dykes or bodies of granites which may dislocate and terminate ore bodies may be derived from the interpretation of aeromagnetic data and so help in planning development of the ore body.

Dykes may form channel-ways for underground water and be important in hydrological studies of an area. There is often an enrichment of horizons of low grade iron mineralization close to intersection by dolerite dykes.

These applications of the aeromagnetic data are directed either in response to the geological problems in situations set up by the geologists who are advising the exploration manager or by analogy with geophysical applications of the method to similar problems elsewhere, either in Nigeria or overseas. In this second case, considerable care must be taken to make sure that the analogy is a reasonable one and the advice and opinion of the geologists should be sought on the reasonableness of the comparison.

Interpretation of gravity and magnetics data for mineral exploration is indeed very similar to petroleum exploration. The primary differences are due to the size of the final target, the depth that is economically of interest to the prospector and mining company, and the level of detail necessary for a final target before choosing drill sites that have a high probability of success or outlining an extension of an existing deposit. Regional surveys are of interest for choosing prospect areas or claim blocks, but successful drill sites should not be based on regional surveys alone.

I spent a fair bit of time on the mining end than getting involved in the petroleum business, the main differences that exist between mining and petroleum globalization is:
In the mining game, we tended to spend more time on the fabric of the magnetic data and less on detailed modeling 'of individual anomalies.

4.2.1 Depth to Magnetic Basement

Airborne magnetic surveys have been used for over twenty years by oil companies to establish the depth of magnetic basement in the search of large areas for sedimentary basins. In some cases this data is reinterpreted to provide further information about the regional character of the area when more detailed information has been obtained by means of seismic surveys and drilling. The main problem that the oil companies are concerned with is the thickness of the sediments and the shape of the basement are important factors in assessing the potential of the region for petroleum exploration. For their purposes, the interpretation consists of study of the shape of the magnetic anomalies which are analysed. From this information the position of faults, basement uplifts and buried hills have been recognized by interpreters using anomalies as described above, together with some of the minor features on the aeromagnetic records.

Volcanic rocks, if they are magnetic can be recognized within the layers of the sedimentary section and distinguished from the anomalies due to a deeper basement by the difference in wave length of the anomalies. The information about the presence of these volcanic rocks helps geologists to understand some variations within the sediments and provides the possibility of recognizing folding which affects the volcanic rocks. It shows geophysicists areas where they may have difficulty in using seismic reflection methods.

The use of the magnetic method to determine the depth of the magnetic rocks has not been widely used in mineral exploration where the main problem is concerned with the outcrop pattern. Any depth determinations made in mineral exploration usually concern specific depth determination on what is a potential drilling target and the method is not normally applied to regional depth studies. There are however a number of problems which will become more important in the future where this application of aeromagnetic surveys may be important.

Any method which will divide the area into those parts where the cover is thin and where exploration can be carried out effectively and economically, from those parts of the area where the sedimentary cover is too great at present to be explored and drilled, will open up extensive additional areas for mineral exploration. The techniques used in the evaluation of the aeromagnetic depth data by the oil companies is almost exactly the same as would be used for this purpose, the only difference being in the depths which will be measured. In the case of petroleum exploration, the depths are the order of hundreds and thousands of meters, for mineral exploration the depths are in the order of tens and hundreds of metres. This difference is important in terms of the accuracy which must be achieved in interpreting the data and while many of the areas have been covered by aeromagnetic surveys, the data available may not be ideal for this purpose. However, as this information is available for little more than the cost of copying the records held by the Nigerian Geological Survey Agency (NGSA) and the somewhat higher cost of an interpreter's time to analyse the records, this source of information should be neglected by companies who are concerned with prospects of exploration in the areas of basement which are at the present moment covered by thin layers of sediments.

Another use of the magnetic method may at times be applicable in exploration for alluvial mineral deposits, gold, uranium, diamonds or perhaps water, where the stream channels in which the deposit occurs have been cut in a magnetic basement rock. Obviously some of the deposits will not meet this particular criterion, but for any which do, some thought should be considered to producing a depth to magnetic basement rock of areas already covered by magnetic surveys, in order to work out where the stream channels of a particular area run. If no magnetic surveys are available, it may on occasions be worthwhile carrying one out to do just this. For example, the exploration of some of the off-shore areas in Nigeria, Angola and Cameroon might lend themselves to a magnetic study in which the unexposed geology beneath the alluvium and marine sediments is defined by the magnetic contour map and the presence of the stream channels will almost certainly be complicated in areas where there is deep weathering as the stream channels may not correspond with those areas in which magnetic basement is deepest. This, however, can only be found out by trying to apply the method. It is important to appreciate that if the magnetic method is being used for this purpose, that the actual depth determinations must be carried out very accurately and this may be difficult with data which has not been collected specifically for this purpose. If the digital recording is too infrequent, the errors in depth determination may be increased to such an extent that the method does not have adequate resolution to determine the position of the stream channels.

The method of downward continuation of the magnetic data may be particularly useful in solving this problem.

In the course of aeromagnetic surveys for oil prospecting, major shear zones which extend for great distances within the basement rocks which underline the sediments, have been recognized from the pattern of anomalies. These structures appear to influence the folding and faulting within the overlying sediments. An understanding of the basement structures from aeromagnetic surveys may therefore lead to an appreciation of the development of structures in the overlying sediments. In England, sedimentary basins of Upper Carboniferous age coincide with major dislocations in the regional magnetic map and it seems likely that these basins have developed along lines of weakness within the basement. In Cyprus and Benue trough (Ukaigwe and Indutime 2004) a similar phenomenon may be observed on a smaller scale where the overlying Cretaceous and Tertiary sediments are cut by minor folds and faults along a line which marks the extension of the major shear lines observed in the underlying volcanic rocks. Rivers which are flowing over these younger sediments are deflected when they cross a line which is an extension of these shear zones, although there is nothing to see in the geology which would suggest structures responsible for this deflection. It is possible that the deflections of the rivers may be due to more abundant jointing in sediments overlying these shear zones and that is what makes it easier for the river to establish itself in this particular direction.

This use of the aeromagnetic method to contribute to the regional appreciation of the geology of sediments which are overlaying an older magnetic basement should be borne in mind in the study of mineral deposits within these younger, non-magnetic sediments, as these underlying shear zones may mark lines of higher permeability for mineralizing fluids both in the Bonne Terra area of Missouri provides useful reading for this aspect of the relation of aeromagnetic methods to mineralization.

Bean and Am (1972), have developed methods specifically for the purpose of depth determination and these papers should be consulted for further information.

Two very simple methods can be used to estimate the depth of the magnetic basement very rapidly and simply. One is to measure the half-slope distance and the second to measure the distance from the maximum to the minimum of an anomaly. If these anomalies are due to narrow bodies and with experience the interpreter can often recognize characteristics of a narrow body, the depth can be found as a simple factor of the measured distance.

Less regular anomalies of the kind more often observed in mineral prospecting can also be used for depth determinations but uncertainties regarding the regularity of the body, its changes in magnetic properties along strike, and the limit that the strike extends, do make the process of analysis more difficult.

As mentioned above, downward continuation can be used to determine the depth of the magnetic basement of the rocks. The process of downward continuation is only valid when there is no magnetic material between the plain of observation and the plain to which the downward continuation is projected. If there is magnetic material the downward continuation calculations become unstable and this is shown by the erratic values obtained from the calculation. By carrying out downward continuation in stages, it should be possible to recognize those areas in which instability first occurs and so recognize the shallower areas of magnetic basement. This may be adequate for example to define the main stream channels in an area.

4.2.2 Application of Magnetic Methods

The results of both qualitative and quantitative interpretation of magnetic data often help to solve certain geological problems and finally to prepare a meaningful geological map of the area. For this purpose it is essential to establish the relation between magnetic anomalies and lithology, tectonics, mineral deposits etc. of the area.

However, the magnetic data is often handicapped due to ambiguity inherent for all potential fields. Further, the results of indirect interpretation are approximate since the actual geological bodies in nature do not correspond with the regular geometrical bodies assumed during interpretation. Another disadvantage is that during interpretation the knowledge of intensity of magnetization of the body is essential which is determined only approximately from the study of samples. Finally, the inhomogeneity, inclined magnetization of rocks, influence of the permanent magnetization of rocks, etc. will affect the accuracy of interpretation. In view of these uncertainties the data is interpreted by qualitative techniques and the quantitative parameters obtained if any are considered as approximate in evaluating depth and dimensions of the magnetized body.

For unique and accurate solution of a given geological problem magnetic prospecting is often coupled with gravity and either geophysical methods depending on the geological and geophysical peculiarities of the investigated region.

In general, the magnetic method is employed as one of the tools for solving the following geological problems:

a) Delineation of large structural forms favourable for the accumulation of oil and gas deposits.
b) Detection and demarcation of basic and ultra basic rocks, location and tracing of faults, contacts between formations having different magnetic properties, determination of depth to the basement, structures in the basement etc.
c) In the search and prospecting of strongly magnetic iron and titano-magnetic ores, and in favourable circumstances of weakly magnetic iron, chromite, manganese, bauxite etc.
d) In prospecting for copper, nickel sulphides, tin and polymetallic ores associated with magnetic minerals (magnetite, pyrrhotite etc.).

e) In locating non-magnetic ores surrounded by the magnetic host rock.

Owing to its inexpensive nature and easy operation, magnetic methods are now being widely used not only for the location of ore deposits and structures but also as an essential tool in all geophysical surveys.

5.0 Pattern Recognition

Oral story telling during the formative period of lives of children, shape their values, condition their moral sensibilities and help them to govern their emotions and appetites, as well as stimulating imaginative creativity among them. Max Luthi is right when he describes the strong hold the fairytale has on young and old especially before the diffuse on the printing poses. According to him:

"*The role fairytales play in the lives of adults in the prior to coming of the printing work, strengthens us in the belief that we are dealing with a peculiar form of literature, out of which concerns man directly"*
(Once upon a Time: On the nature of fairytale).

Fairytales correspondingly expands the boundaries of ones knowledge and broadens their cognitive potentiality, enhances mental, psychological and imaginative growth and stitches new experiences to those already available. It is, therefore a dynamic mode which aptly fits situations of expanding consciousness. Chinua Achebe, for his part, acknowledges the impact of oral story telling on his imaginative development in his autobiographical essay "*Named for Victoria, Queen of England*". Was it not Plato who said that "what is perceptible to the senses is the reflection of what is intelligible to the mind" or according to the remark of the Geothe: *"What is within is also without"*.

The fairytale I was told has conditioned my approach to understanding gravity and magnetic interpretation. It has been clear from the discussion in section 4 that the process of gravity and magnetic interpretation inspite of the complexities imposed by their contour representations is to impose an order from chaos. (Prigogine I. and Stengers I; 1984). The guiding principle in question comes from story told me in my early days about the "gorilla" and its "mindset". The story line runs like this: "In the event that you encounter a gorilla in the forest and it starts pursuing you one way of overcoming it is to leave an odd number of leaves on its way. As it approaches the leaves spread on the ground, it starts to match one against the other and when it fails to find a match for the odd number one, it starts to search around for the missing match and forgets the pursuit of its victim". This "psychology" of the gorilla is what in modern science is regarded as "pattern recognition".

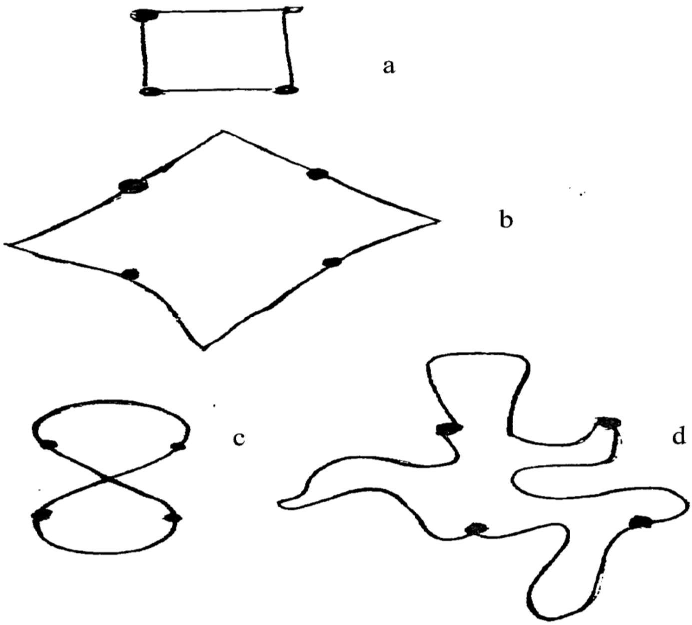
Human beings used pattern recognition to build amazing features on Earth.

Concepts of patterns recognized in skies (stars) led to the ancient peoples concept of gods. For example, the Egyptian pyramids face N – S, E – W. The stars lining up in the North gave rise to their idea of North. So it is for the South pointing stars. And the pyramids were aligned to these directions and the Egyptians also used pattern recognition of stars to construct the god "Cyrus" around 246 BC.

The "dogon tribe" of Northern Mali worshiped stars. Again ancient Polynesians navigators used patterns observed from the stars for navigations at sea. Today, patterns observed on stars are helping astronauts to navigate the moon. Apollo astronauts took the observed patterns of stars to navigate their way around the moon.

An arts teacher in the USA asked the children in her class to make four points on a sheet of paper and connect these points any way they liked (fig. 14). The children, all of whom were brought up in the Western culture, connected the points with straight lines leading to a rectangle shown in fig.14a. Hardly any child connected the points into the curvilinear forms shown in figs.14a – d.

This goes to show that the "eternal order of the psyche of the first group was *linear,* whereas the "eternal order of the second group is *curvilinear*, the former following a principle of minimal distance while the latter followed what I may call a principle of *plural distance* or if we wish a principle of *rhythm*. The latter agrees with the view which Fritjof Capra, a distinguished Chinese high-energy physicist stated in his book, "*The Tao of Physics*". In his words:



Figs. 14 a-d

> *"The natural world…is one of infinite varieties of complexities, a multidimensional world which contains no straight lines or completely regular shapes, where things do not happen in sequences but all together a world where as modern Physics tells us – even empty space is curved".*

We are now asking the same questions in a more sophisticated way. We use it energetically and emphatically as our ancestors did. Just as pattern recognition helped in the construction of the sextant. I have therefore tried to establish the following system of interpretation philosophy.

5.1 Philosophy of Interpretation

The transformations of the variations in complex magnetic field into meaningful geologic models should be organized into three stages of a *General Systems Theory*. This theory in all ramifications formalizes methods that have been employed by many workers in aeromagnetic interpretation of which among others are Boyd (1967, 1979) and Ukaigwe (1985).

In its implicit and primitive form, the systems approach can be detected in many traditional geological studies; beginning from the development of stratigraphic classification; the classifications of (1) tectonic elements in the sedimentary crust of the earth (2) zones of deep-faults (3) geological associations; and ending with structural problems of patterns of distribution of ore bodies. The systems mentioned above can be compared on the basis of various criteria, for instance, they can be compared on the basis of the properties of their constituent elements and their relationship with other isolated systems. To describe this property of systems, the concept of the state of systems should be employed, assuming that such a state can be measured in some way or at best can be roughly estimated. Such systems will be called "*static*". In analyzing static system, two stages are clearly distinguishable:

a) Set of elements whose relationships are to be discovered and hence studied. However, it is important to note that differentiation of these elements is always based on references or standards. In this connection the interpreter is both a "diagnostician" and an "instrument for pattern recognition"; and
b) Specification of those relations which are intended for use in uniting the elements of this set into an entity.

A necessary precondition for correct analysis of static systems is conformance to the principle of "specialization". This principle requires that the specificity of the tests used in such construct can be taken into account, and that the accepted rules for interpretation be used in covering from one set of tests to another related one. The above mentioned static system has formed the "philosophy" behind the interpretation of aeromagnetic data and indeed all geophysical information. (Section 4.0)

The second state of the system may vary continuously, sometimes so rapidly that it is almost impossible to distinguish the discrete elements of the system, or their discrete relationships or both. Such systems are defined in terms of certain processes which vary between times and are called "dynamic". Its study as shown above is important for the reconstruction of the past (Mclntyre 1980).

Finally, "*retrospective*" system is the name given to the analysis involving the reconstruction of the past. These are systems whose elements are linked by sequential (historical) systems, cause-and-effect (genetic systems) relationships. The peculiarity of such systems is known about static and dynamic systems. The procedure of achieving this is known as the principle of transference which, in essence, involves a series of hypothesis underlying conclusions about the processes that have occurred in the past. There is no doubt that the principle of transference does ensure a certain reliability of any conclusion, but it is difficult to estimate the degree of this reliability. Obviously, the accuracy of these conclusions decrease as one deals with ever more distant history of the earth.

Analysis as described above will no doubt result in geological and geophysical information being expressed in commensurable terms. Geologists and geophysicists deal with the same raw materials, but only measure them in different ways. Despite the advances, both in technology and recognition of the benefits of interaction between the two fields, there is still typically not enough communication, and when the two groups do not work together it causes inefficiency.

Further, information useful for exploration decision-making purposes as against geological form the academic point of view is then the next that is considered.

Elements defining the systems are catalogued in figure 7. These elements have recognizable descriptive characteristics within their various columns and these are recorded from magnetic zone to magnetic zone and synthesized to produce an interpretation.

These tasks are far from trivial, and it should be obvious for any interpretation that geological and geophysical information are expressed in commensurable term. The big question then is, how does one make an algebra of geological concepts and observations; is always important to be clear about the true purpose of an interpretation: the purpose of interpretation may be very varied. Information useful for exploration decision making purpose may be favoured or solutions of geological problems from the academic point of view. In this confused situation it is no wonder that many interpretations differ in emphasis and quality; for instance while Wright (1981) demands that geophysicists determine geometrical parameters and physical contrasts for the geologic interpretations. Body (1967, 1979) Emerson (1979) Ukaigwe (1985) prefer an intimate involvement in a complete interpretation, in fact, interpretations of this nature requires a greater rather than a fragmentary common dictionary or grammar should be established from these two disciplines that do not know each other’s language.

Geology is concerned with classifying systems in terms of their “behaviour” in time and geologists use relative systems concept not absolute to deal with isolated system. For instance, a mineral may be considered as a system composed of chemical elements. At the same time, this mineral is just an element in the structure of the system of a rock. Even the earth consists of various systems, each of which is part of another larger system.

The relationship among units in a geologic space are obviously not exhausted by ordinal ones. Other relationships may be envisaged among geologic bodies. The reason that geologists are so interested in systems governed by ordinal relationships become clear when one considers that it is these relationships which provided the basis for the reconstruction of the sequence of geologic history which is considered a problem of utmost importance. It therefore overshadows many, perhaps equally important relationships. Some of these are not yet apparent for geologists who now, of necessity, pursue only the class relationships of their primary interest. They search for that class in examining rock sections under the microscope, sequence of their crystallization from melt. They pursue the relationship in field mapping, where they compare sections and look for contacts between intrusions and their looking for relations among minerals which would indicate the sequence of their host rocks, or when they describe the relationships between ore bodies in a deposit. In all cases, they are after the same thing the sequence of events. In other words, in virtually all cases, the basic concern of the geologists is the solution of problems of historical geology.

6.0 Conclusion

It is hoped that from this discussion of magnetic and gravity methods, some better appreciation may be gained of their applicability to exploration, so that when geologists or others speak of "geophysics" they may remember that there is something to be considered besides reflection seismology. Perhaps in the future when the real possibilities of these more obscure and less well understood methods are realized, we may increase their proportion of the total exploration picture from their present five percent to perhaps ten percent. Also we may hope to open again the forgotten files of magnetic and gravity surveys for review and correlation with seismic data, subsurface geological and logging information as well as surface geology. Many new prospects may thus be found.

Nearly 95% of geophysical expenditure for oil exploration is for reflection seismology surveys. Most of the other 5% is for gravity and magnetic surveys.

To some extent the disproportionate large expenditure for seismic work probably are from a lack of understanding and appreciation of the usefulness of other methods. I have demonstrated the principles of gravity and magnetic method, pointing out their similarities and differences and give examples of their application. Methods of quantitative interpretation are demonstrated.

Pattern recognition is the basis of effective interpretation. One of the keys to accurate pattern recognition is to identify the characteristic signals. The pattern recognition of an anomaly signature is of vital importance to all interpretation sciences. The gravity and magnetic anomaly signature characteristics are results of one or more physical parameters such as configuration of anomalous zone, density, velocity and porosity contrasts, magnetic susceptibility contrasts and the depth to the anomalous body. It is important to note that the magnetic signal of a structure is highly dependent on its geographic location on the Earth.

Common grounds between geologists and geophysicists is that their basic objective is the identification of rock units, associations and structural relationships both of the each surface and in the subsurface. Their tasks differ only to the extent that Earth has special expertise in the collection and analysis of particular kinds of data. The important being that each kind of data gives access to a limited number of attributes of rock composition, structure and distribution. In particular, geophysics are measurements of physical properties of rocks. The purpose of any geophysical interpretation is to identify and explain differences in these physical properties in terms that further geological knowledge.

Whereas a geological map is an integration of a finite number of surface field observations, gravity and magnetic data maps are similarly composed of a set of semi-continuous physical measurements made along flightlines. The actual geophysical properties measured do not always show differences between petrographically distinct rock types. Magnetic contour maps are mapping the accessory magnetite content of both surface and buried rocks, so the boundaries of interpreted magnetic zone may not always be coincident with the geological boundaries. Hence “General Systems Theory” has been proposed for interpretation of these geophysical data.

Finally, this lecture and indeed every course I taught has been arranged on three levels: Concept, Content and Context. This follows from my definition of Geophysics i.e. Physics is the study of the physical phenomenon in nature. **Concept;** the application of physics to the study of Earth’s structure is Geophysics; **Content;** and the application of Geophysics to the study of the Earth’s structure so as to harness mineral deposits for the benefit of mankind; is Exploration Geophysics **Context**.

Epilogue

Although teaching was not my primary choice for I have never dreamed of becoming a teacher, yet I have not regretted my having been identified with this profession for almost 40 years. On the contrary, I feel proud to be counted among the thousands of mentors whose main concern is to teach our students not only in theory but more by example in the most important facts of life.

Education is the process of stimulating latent powers in an individual, of drawing out and developing the innate capacities for stimulating knowledge, of educing all the potentialities within the human personality. To educate is not only to sharpen the intellect and to enrich the emotion, but also to refine human sensibilities and powers. The letter of Abraham Lincoln to his child’s teacher furnished me with the defining factor in my educative process.

> “*He will have to learn, I know, that all men are not just, all men are not true. But teach him also that for every scoundrel there is a hero; that for every selfish politician, there is a dedicated leader. Teach him that for every enemy there is a friend.*

Teach him that a dollar earned is of more value than five found. Teach him to learn to lose and also to enjoy winning. Steer him away from envy if you can. Teach him the spirit of quiet laughter.

Teach him the wonder of books; but also give him the quiet time to ponder the eternal mystery of birds in the sky, bees in the sun, and flowers on a green hillside. In school teach him it is far more honourable to fail than to cheat.

Teach him to have faith in his own ideas, even if everyone tells him they are wrong. Teach him to be gentle with gentle people and tough with the tough. Try to give him the strength not to follow the crowd when everyone is getting on the band wagon.

Teach him to listen to all men, but teach him also to filter all he hears on a screen of truth and take only the good that comes through. Teach him how to laugh when he is sad. Teach him that there is no shame in tears. Teach him to close his ears to a howling mob; and to stand and fight if he thinks he is right.

Treat him gently but do not cuddle him, because only the test of fire makes fine steel. Let him have the courage to be impatient, let him have the patience to be brave. Teach him always to have sublime faith in his creator and faith in himself too, because then he will always have faith in mankind…

If we accept the truism that the ideal education is that which fully develops all the capacities of man, that is, his intellectual, aesthetic, moral and spiritual potentialities, then it is easy to perceive the role of this my compass in my teaching process. This is because a complete task of developing the whole man by taking care of his emotional and aesthetic powers and allow him the pleasure as scientist to lead in the discovery and realization of the truths which spurs the growth of his mental process.

Within the last three centuries, Rygard Kipling published a poem with the title “If”.

> *If you can keep your head when others are losing theirs*
> *and blaming it on you;*
> *If you can dream but do not make dream your master*
> *If you can move with Prince and Princesses but do not*
> *lose the common touch;*
> *If you can watch the truth you have spoken twisted by*
> *knaves to make a fool of you;*
> *If all men love you but none too much*
> *If all men lie about you but do not deal in lies;*
> *If you can afford to see all you have given your life lost*
> *in one pitch of toss and stoop to rebuild them with worn*
> *out tools;*
> *Yours is the world and what is more you will be a man*
> *my son..*

These are some of the lines that constitute a poem I learnt in class 2 from the “Approach to English Literature Book 2”. I like it so much and recited it so often to myself that it is a permanent possession. But the important thing is that this poem epitomizes for me the meaning, message and challenge of God’s gift of wonder. It has tremendously influenced my outlook, attitudes and habits at all times and in all places, especially during leisure and my encounter with my colleagues. It excited my curiosity and directed my attention to the external world of senses, filled with beauty of nature and of art and just waiting for the beholder to perceive, savor and enjoy. There is practically no limit to the knowledge, entertainment and enjoyment, that my focus only outwardly to the objective sphere, with its countless marvels of divine creation and human art, but also inwardly to the subjective realm of amazing imagery, fantasy and thought can bring as long as I am alive and conscious. I find it most effective in diverting my mind from unwholesome preoccupations, lightening its load, or dispelling the gloom cast by clouds of worry. Not only do I discover, learn and relax; I find no reason nor opportunity to get bored. I do not have the gift of beauty, but the world is full of wonder by which I can lose and forget myself in its contemplation and its enchantment.

I have had my full share of problems both in my hard or tough personal life and in my heavy demanding job like the assassination attempt of 3-3-2001 at my residence by 9:15pm. But with God's help and the full use of gifts of adjustment on which I have leaned so heavily all these years I have weathered their buffets and blows, managed to survive and emerged stronger and harder from the ordeal better prepared for later encounters.

From the circumstances, vicissitudes and ordeals that featured in my life I have acquired and developed some qualities important in adjustments and survival. These are acceptance of the inevitable, open mindedness, understanding, tolerance, flexibility, diversity of interests, moderation, contentment, and compassion. These have sufficed to prepare me to dealing with some of the adverse and negative aspects of my relationships with others – those that are irritating, disappointing, infuriating, painful, saddening – such as disloyalty, betrayal, ingratitude, insolence, arrogance, meanness, unkindness, disrespectful and snobbery. It had not been easy to cope with them but I have managed somehow.

In retrospect, looking back through the successive stages of my life, each with its own peaks and depths, aspirations and frustrations, hopes and despair, victories and defeats, joys and sorrows; I can honestly say that these closing years are my best. I am content with what I am, where I am and what I have. I hope to enjoy the peace, serenity and freedom of my retirement untrammeled by the rigid demand of a regular job schedule and the hectic rush and nervous tension of meeting deadlines. I am frankly and obviously old but still essentially whole in body and mind. My head is still up, my back straight, my limbs sturdy, my step firm, my senses intact.

There are still some challenges waiting around the corner – write more books in geophysics, visit places I have not reached before. But happily I am not bound to take up any of them. That is one of the pleasures of being retired. In the meantime I can take it easy and relax – enjoy all the many things that come my way, read as much as I like, dream as long as I care, see, admire, enjoy all the beautiful things around me, ignore little annoyances and irritants until:

> *Sunset and evening star*
> *And one clear call for me*
> *And may there be moaning at the bar*
> *When I put out to see…*

Thank you for listening…

References

1. Achebe Chinua, 1975; *Morning yet on creation Day*: "Essays" London Heinemann
2. Airy, G. B., 1855; *On the computation of the effect of the attraction of mountain-masses, as disturbing the apparent astronomical latitude of stations in geodetic surveys*: Trans. Royal. Soc. London, Vol.145, pp101-145
3. Airy, G.B., 1855; *Philosophical Transactions of Royal Society London* Vol. 145
4. Anstey, N.A., 1973; *How do we know we are right?* Geoph. Prospecting Vol. 21, pp407-411
5. Bader, J.W., and Bird, K.J., 1986; *Geologic map of the Demarcation Point*, Mt. Michelson, Flaxman Island, and Barter Island quadrangles, northeastern Alaska: U.S. Geol. Surv. Miscellaneous Investigations Series Map I-1791, Scale 1:250,000
6. Bean, R.J., 1966; *A rapid graphical solution for Aeromagnetic anomaly of two dimensional tabular body*: Geophysics Vol.31, pp963-970
7. Black, P.A., Green, C.M., Reford, M.S. and Summer, W. 1995; *A pragmatic approach to Continental magnetic compilation*; 65th Ann. Lat. Mtg. Geophy. Expanded Abstracts pp723-774
8. Blackely, R.J. and Connard, G.G., 1989; *Crustal studies using magnetic data*, in Pakiser, L.G. and Mooney, W.D. (Eds) *Geophysical Framework of Continental United States*, Geol. Surv. of Am. Memoir Vol. 172 pp45-60
9. Boyd, D., 1967; *The contributions of air borne magnetic surveys to geological mapping contributions* 26 – Geological survey of Canada 1967
10. Boyd, D., 1979; *Interpretation of Geomagnetic Surveys* – AMF Course Glenside South Australia
11. Carmichael, R.S., 1989; *Magnetic properties of rocks and minerals,* in Carmichael, R.S., (Ed.), *Handbook of Physical properties of rocks*: CRC Press, pp229-287
12. Chapin, D. A., 1996; *A deterministic approach toward Isostatic gravity residuals*: A case study from South America: Geophysics, Vol. 61, pp1022-1033
13. Copra F. 1979; *The Tao of Physics* (Suffolk: Fontana/Collins) 28p.

14. Dean, W., 1985; *Frequency analysis for gravity and magnetic interpretation*: Geophysics, Vol. 23, pp97-127
15. DeGoyler, E.L., 1928; *The seductive influence of the closed contour*. Econ.Geol.Vol.23 pp681-682
16. DeGolyer, E.L., 1947; *Notes on the Early History of Applied Geophysics in the Petroleum Industry Geophysical Papers*, Society of Exploration Geophysicists Tulsa Olka.
17. DNAG 1987; Decade of North American Geology and Magnetic Map of North America, 1.5,000,000. Geol. Surv. Am.
18. Domazalski W., 1966; *Importance of Aeromagnetics in the evaluation of Structural Control of Mineralisation*. Geophysical Prospecting Vol. 14, pp273-291
19. Donovan, T.J., Forgey R.L., and Roberts, A.A., and Elison, P.T., 1984; *Low altitude aeromagnetic reconnaissance for Petroleum in the Arctic National Wildlife Refuge*, Alaska: Geophysics, Vol. 49, pp1338-1353
20. Donovan, T.J., Hendricks, J.D., Roberts, A.A., Eliason, P.T., 1988; *Low-level aeromagnetic surveying for petroleum in arctic* Alaska, in Gryc, G., (Ed.), *Geology and exploration of the National Petroleum Reserve* in Alaska, 1974-1982; U.S. Geol. Surv. Professional Paper 1399, Vol. 1, pp623-632
21. Donovan, T.J., O'Brian, D.O., Bryan J.G., and Cunningham, K.I., 1986; *Near-surface magnetic indicators of buried hydrocarbons, aeromagnetic detection and separation of spurious signals*: Assn. of Petr. Geochem. Expl., Vol. 2, pp1-20
22. Dutton, C.E., 1889; On some of the greater problems of physical geology. Bull. Philos. Soc. Assoc. Vol.11 pp51-64
23. Eckhardt, E.A., 1940; *A brief History of Gravity Method of Prospecting* vol.5
24. Elmore, R.D., Engel, M.H., Crawford, L., Nick, K., Imbus, S., and Sofer, Z.,1987; *Evidence for a relationship between hydrocarbons and authigenic magnetitie*: Nature Vol. 325, pp428-430
25. Emerson, D.W., 1979; *Comments on Applied Magnetics in Minerals Exploration*. Bull. Aust. Soc. Expl. Geophysicists vol.10, pp3-5
26. Fairhead, J.D., 1986; *The Magnetic Map of Africa*, 1.5,000,000.
27. Fuller D.B, 1969, *Two-dimensional frequency analysis and design of grid operators*. SEG monograph (Ed.) by Stan Ward, pp658-708

[28] Goldhaber, M.B., and Reynolds, R.L., 1991, *Relations among hydrocarbon reservoirs, epigenetic sulfidization, and rock magnetization*: Examples from the South Texas Coastal Plain: Geophysics, Vol. 56, pp748-757

[29] Greene, E., and Bresnahan, C., 1987; *Three-dimensional gravity modeling of Gulf coast domes: Oil and Gas* Jour., October 12, pp64-69

[30] Harland, W.B., Armstrong, R.L., Cox, A.V., Craig L.E., Smith, A.G., and Smith, D.G., 1990; *A geologic time scale*: Cambridge Univ. Press

[31] Henderson, R., Miyazaki, Y., and Wold, R., 1984; *Direct indication of hydrocarbons from airborne magnetics*: Expl. Geophys. Vol. 15, pp213-219

[32] Jensen H., 1965; *Important Details and Application of a New Airborne Magnetometer*, Geophysics Vol.45 pp973-976

[33] Johnson, A.E., 1989; *Gravity and Magnetic Analysis can Address various Petroleum Issues* in Ukaigwe, N.F., 1999; *Principles of Magnetic Survey and Interpretation* pp395-401.

[34] Kelly, J.S., and Foland, R.L., 1987; *Structural style and framework geology of the coastal plain and adjacent Brooks Range*, in Bird, K., and Magoon, L., (Eds.), *Petroleum geology of the northern part of the Arctic National Wildlife Refuge*, northeastern Alaska: U.S. Geol. Surv. Bull. Vol. 1778, pp255-270

[35] Keller, G. R., 1988; *The development of gravity and magnetic studies*, emphasizing articles published in the GSA Bulletin: Geol. Soc. Am. Bull., Vol. 100, pp469-478

[36] LaCoste, Lucien, Clarkson H. and Hammilton G.,1967; LaCoste and Romberg stabilized platform shipborne gravimeter Geophysics vol.32, pp99-109

[37] LaCoste, L., 1967; *The measurement of Gravity at Sea and in the Air*. Rev. Geophy. Vol.5 pp477-524

[38] Lecture delivered on A.A.P.G. Distinguished Lecture Tour, Spring of 1961. Manuscript received, September 5, 1961.

[39] LeFehr, T.R., Nettleton, L.L., 1967; *Quantitative evaluation of a stabilized platform shipboard gravimeter*, Geophysics vol.32, pp110-119

[40] LeFehr, T.R., 1980; *Gravity method*. Geophysics vol. 45, pp1634

41. Luthi Max, 1990; *Once Upon a Time: On the Nature of fairytales New York*: Fredrick Ungar Publishing Co.

42. McCabe, C., and Sassen, R., 1986; *Magnetic anomalies and crude oil biodegradation*: Geol. Soc. Am. Abstracts with Program, Vol. 18, pp687

43. McCabe, C., Sassen, R., and Saffer, B., 1987; *Occurrence of secondary magnetite within biodegraded oil*: Geology, Vol.15, pp7-10

44. Mclntyre, J.I., 1980; *Geological significance of Magnetic Patterns Related to Magnetite in Sediments and Metasediments* – A Review Aust. Soc. Expl. Geophysicists June Vol. 1, No. 1/2 pp19-33

45. *Mining and groundwater geophysics* / 1967- Geophysical Survey of Canada, Economic Geology Report, No.26, 1970

46. Nettleton, L. L., October 1962; Bulletin of the American Association of Petroleum Geologists, *Gravity and Magnetics for Geologists and Seismologists*, Houston Texas Vol. 46, No.10, pp1815 - 1838, 25 figs.

47. Nettleton, L., 1971; *Elementary gravity and magnetics for geologist and geophysicists*: Soc. Expl. Geophys.

48. Paterson, N. L., and Reeves, C. V., 1985; *Application of gravity and magnetic surveys: The state of the art* in 1985: Geophysics 50, p2558

49. Pepper, T.B., 1941; *The Gulf Underwater Gravimeter*, Geophysics Vol.6, pp34-44

50. Peterson, N.R., and C.V., Reeves, 1985; *Application of Gravity and Magnetic Surveys. The state of the Art* in 1985 Geophysics Vol.50, pp2558-2594

51. Phillips, J.D., and Grauch, V.J.S., (Eds.), *Geophysical map interpretation on the PC*. U.S. Geol. Surv. Digital Data Series CD-ROM

52. Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993; *National geophysical data grids: Gamma-ray, gravity, magnetic, and topologic data for the conterminous United States*: U.S. Geol. Surv. Digital Data Series CD-ROM DDS-9

53. Pratt. J. H., 1855; *On the attraction of the Himalaya Mountains, and of the elevated regions beyond them upon the plumb-line in India*: Philos. Trans. R. Soc. London, 145, pp53-100

54. Pratsch, J.C., 1986; *The distribution of major oil and gas reserves in regional basin structures* – an example from Powder Basin, Wyoming, USA. Jour. of Petr. Geology Vol. 9, pp393-472

55. Pratsch, J.C., 1994; *The location of major oil fields*; example from Andean Foreland: Jour of Petro. Geol. Vol.17, pp327-338

56. Prigogine, I and Stenger I, 1984; *Order out of Chaos* (New York, Bantam 1984).

57. Rayner, J.M., 1967; The *Role of Geophysics in the Development of Mineral Resources* pp259-266 in Mining and Groundwater Geophysics 1967; Geol. Surv. Canada Econ Geol. Report 26, Ottawa 1970.

58. Reford, M. S., 1980; *Magnetic method*: Geophysics, Vol. 45, pp1640

59. Reid, A.B., 1980; *aeromagnetic survey design*: Geophysics, Vol. 45, pp973-976

60. Reynolds, R.L., Webring, M., Grauch, V.J.S., and Tuttle, M., 1990; *Magnetic forward models of Cement oil field*, Oklahoma, based on rock magnetic, geochemical, and petrologic constraints: Geophysics, Vol. 55, pp344-353

61. Reynolds, R.L., Fishman, N.S., Hudson, M.R., 1991; *Sources of aeromagnetic anomalies over Cement oil field* (Oklahoma), Simpson oil field (Alaska), and the *Wyoming-Idaho-Utah thrust belt*: Geophysics, Vol. 56, pp606-617

62. Reynolds, R.L., Fishman, N.S., Hudson, M.B., Tuttle, M.L., 1993; *Sulfidization and magnetization above hydrocarbon reservoirs*: *Applications of paleomagnetism to sedimentary geology, Society for Sedimentary Geology* Special Publication No. 49, pp167-179

63. Simpson, R. W., Jachens, R. C., Blakely, R. J., and Saltus, R. W., 1986; *A new isostatic residual gravity map of the conterminous United States* with a discussion on the significance of isostatic residual anomalies. J. Geophys. Res., Vol. 91, pp8348-8372

64. Stabler, C. L., 1990; *Andean hydrocarbon resources* – An overview in Ericksen, G. E., Canas Pinichet, M. T., and Reinemund, J. A., Eds., *Geology of the Andes and its relation to hydrocarbon and*

mineral resources: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, Vol. 11, pp431-438

65. Swartz, C., 1954; *Some geometrical properties of residual maps*: Geophysics, Vol. 19, pp46-70

66. Sweet, George, 1966; *The history of geophysical prospecting*: Science Pres, 3 vol.

67. Tachet des Combes, J., and Monday, J. F., 1995; *An evaluation of the uncertainties in the structural definition applied to the delineation of the Cusiana Field* (Columbia): Presented at the St. Petersburg ’95 International Geophysical Conference and Exposition.

68. Talwani, M., and Ewing, M., 1960; *Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape*. Geophysics, Vol. 25, pp303

69. Tsuboi, C., 1979; Gravity: George Allen & Unwin (Publishers) Ltd., 1983, English translation.

70. Ukaigwe N.F., 1985; *The interpretation of the aeromagnetic data of Olary Province South Australia and the development of Interpretation method* unpublished Ph. D Thesis, The University of Adelaide 108p

71. Ukaigwe, N.F., 1998; *Geological Interpretations from Aeromagnetic and Gravity Surveys over South Australia*. Indian Jour. of Geology. Vol. 23. No.2, pp88-98

72. Ukaigwe, N.F., 1998; *Aeromagnetic Lineament Study in the Olary Province, South Australia, Global Tectonics and Metallogeny*. Vol.4. pp175-188. With comments by O’Driscoll. ES. 1., 1995; Discussion. *Global Tectonics and Metallogeny*. Vol.: 4. No.4, pp189-193

73. Ukaigwe, N.F., 1999; *Principles of Magnetic Survey and Interpretation* Pearl Publishers 477p

74. Ukaigwe, N.F., and Moutari, S. 2003; *Induced Polarization Technique over Sirba Rivers Valley Area in Liptako Region of Niger Republic*. Jour of Scientific and Industrial Studies. Vol. 3. No.3, pp14-22.

75. Ukaigwe, N.F., and Indutimi, P., 2004; *A Regional Interpretation of Aeromagnetic maps of Upper Benue Trough*. Nigeria. Jour. of Applied Sciences Vol. 9. No.2, pp1-18.

76. Ukaigwe, N.F., and Moutari, S., 2004; Magnetic *Interpretation on the Liptako Retion*. Niger Republic. Jour. of Natural and Applied Sciences. Vol. 5. No.1, pp31-46.

77. Ukaigwe, N.F., 2004; *A Study of Aeromagnetic Profiles Across Olary Province South Australia*. African Jour. of Science. Vol. 7 No.1, pp1-15.

78. Ukaigwe, N.F., 2004; On *the Application of Aeromagnetic Data to the Indirect Exploration for copper Deposits in Olary Province*. South Australia. Jour. of Natural and Applied Sciences. Vol. 5 No. 1 pp77-95.

79. Ukaigwe, N.F., 2004; *An Analysis of Geology Curriculum in Tertiary Education in Nigeria*. Nigerian Jour. of Professional Studies in Education. Vol. 8. No. 5&6. pp80-92.

80. Ukaigwe, N.F., 2004; *Causes and Spatial Distribution of anomalous Magnetization in Grantitic Rocks*. Jour. of Science and Engineering Technology. Vol.13. No.2, pp1-15.

81. Ukaigwe, N.F., 2014; *A Guide to the Application of Gravimetric Method (Monograph) Exploration* Geophysics Monograph series Vol.1, 376p

82. Vacquier, V., Nelson, C., Steenland, Roland, G., Henderson and Isidore Zerte 1951; *Interpretation of Aeromagnetic maps*. Geol. Surv. Am. Mem.47

83. Vening Meinesz F.A., 1929; *Theory and Practice of Pendulum Observations at sea* Waltman Delft, The Netherlands.

84. Vening Meinesz F.A., 1929; *Gravity measurements at sea 1,2 and 3* publ. Netherland Geodesy Comm. Delft. 1932, 1934 and 1948.

85. Vening Meinesz F.A., 1941; *Theory and Practice of Pendulum*. Vol. 2 Observations at sea Waltman Delft. The Netherlands.

86. Wilson, C.R., Tsoflias, G., Bartelmann, M., and Phillips, J., 1997; *A high precision aeromagnetic survey near the Glen Hummel field in*

Texas: *Identification of cultural and sedimentary anomaly sources*: The Leading Edge, Vol. 16, pp37-42.

87. Wollard, G.P., 1959; *Crustal Structure from gravity and seismic measurements* Geophys. Res. Vol.64 pp1521-1544

88. Wright, J., 1981; 75th Anniversary Volume of the Sreiety of Exploration Geologists pp836-837

89. Wyckoff, R.D., 1941; The Gulf Gravimeter, Geophysics Vol.6, pp13-33

A CITATION ON
PROFESSOR NNAEMEKA FRANCIS UKAIGWE

My heart skipped a couple of beats when the 9th valedictorian, Professor Nnaemeka Francis Ukaigwe, a renowned scholar, author and thinker, asked me to write and present his citation to this august audience today, because Professor Ukaigwe remains one human being, I know that has never found it fanciful to talk or write about himself – his upbringing and profession or even his family. His argument has always been that he cannot see his face. However, one can see in Professor Ukaigwe, a man of several parts. It therefore becomes very difficult to decide on which side to start the narration. But I am aware that Professor Ukaigwe is a sound intellectual from Nkwerre in Imo State. I also know that he is a philosopher, an unrelenting champion of justice, equity, fair play and truth. He is a social crusader and a reformer in his own right. Again, I know that Professor Ukaigwe has a successful and flourishing marriage with only one wife, Dr (Mrs). P.C. Ukaigwe, and that their marriage is blessed with six children, all of who are very successful.

Professor Nnaemeka Francis Ukaigwe was born on February 4, 1947, into the modest family of Late Isaiah Ukaigwe Olekanma and

Late Madam Evelyn Nwaibari Olekanma (nee Ikpa), in a little known and obscure rural community of Omoba, in Isiala Ngwa South Local Government Area of Abia State. He grew up, like any other child from such rural setting, but not long after, his struggling parents noticed some distinctive features in his character, especially his expanding curious habits towards virtually everything around him. That set him up to start his early education first at St Georges (RCM) School and later at St Barnabas (NDP) School, Omoba. As was the fashion with bright children at that time, he was admitted into the famous Government Secondary School Owerri on 27th January, 1961. The civil war interrupted his academic pursuit but he was able to finish his Higher School Certificate (HSC) and Advanced Level GCE in 1970. In 1973, he was admitted into the University of Ibadan, where he obtained a B. Sc. Degree (Hons) Second Class Upper Division in Geology. He then proceeded to do the National Youth Service at the then Gongola State Water Board. After youth service, he joined the University of Ilorin as a Graduate Assistant in October, 1977. In June 1979 he proceeded to The University of Adelaide, South Australia on a postgraduate scholarship under the Commonwealth Scholarship and Fellowship Plan. He worked for and earned from that University a Ph.D degree in Exploration Geophysics in 1985. In October, 1986, he joined the Department of Geology, University of Port Harcourt.

Professor Ukaigwe has to his credit over 35 scientific articles in nationally and internationally reputed journals with high impact factors, 10 books and 4 book contributions, numerous reports and papers. He is a proud member of national and international professional bodies such as Nigerian Mining and Geosciences Society (NMGS), American Association of Petroleum Geologists (AAPG), Australian Society of Exploration Geophysicists (ASEG), Society of Exploration Geophysicists (SEG), among others. He is a Resource Person to the Nigerian Geological Survey Agency (NGSA). Professor Ukaigwe has served the University as Chairman and member of many panels and Coordinator, EEC/FGN Coastal Erosion Research Project and the National Secretary of that Research project. He has supervised several successful post-graduate students and directed several research projects financed within and outside Nigeria.

Mr Vice Chancellor sir, Professor Nnaemeka Francis Ukaigwe, has recorded tremendous academic achievements and acquitted himself as a distinguished scholar. Unaccustomed to loud life and feather bed, he rose through industry, commitment and excellence to the pinnacle of his academic career – Professor in Exploration Geophysics in 2006.

Professor Ukaigwe served as the Chairman of the Chapel of Annunciation, Catholic Chaplaincy 1991-1994, during which he was responsible for commissioning the architectural design of the church building standing today. He was a member of the Imo State University Governing Council, where he served in many statutory and ad-hoc committees, 2004-2007. He has served as the Secretary General of Orlu Zuru Mee, a socio-cultural organization of the 12 LGAs in Orlu Zone; Chairman, Njaba State Creation Movement and was the Special Assistant to the Federal Minister of Commerce and Industry, 2009-2010, where he supervised 17 Federal Parastatals and travelled widely.

Professor Ukaigwe’s friends regard him as liberal not only in his political views but also in his attitude to life. To some others he is a radical, and yet to some he is conservative. Professor Ukaigwe is all these depending on one’s perception of him. But we all share in this mixture of perception, though in varying degrees.

Mr. Vice Chancellor Sir, ladies and gentlemen, at this juncture, permit me to sound my flute for the man of the day, the man whose reach is always far beyond his grasp, the man with a past to be proud of and a chance for the future. I sound my flute for the man whose disposition symbolizes courage, excellence and uniqueness. I sound my flute for the man of ideas whose charm, restiveness and sharp intellect make him a rare breed. Above all, I sound my flute for this man whose marriage life has raised the bar on success.

Mr. Vice Chancellor Sir, distinguished ladies and gentlemen, I shall pause now, but permit me to sound my last flute once more, in honour of a man whose day is today. Let him brace up and do us a dance of his achievements. I present to you, sir, ladies and gentlemen, Professor Nnaemeka Francis Ukaigwe!

Professor Victor U. Ukaegbu
B.Sc. (Uniport), M.Sc. (Unijos), Ph.D. (Uniport)
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