

GOLD EXPLORATION IN TROPICAL AND SUB-TROPICAL TERRAINS

WITH SPECIAL EMPHASIS ON CENTRAL AND WESTERN AFRICA

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This dissertation is submitted in partial fulfilment of the requirements for the degree of Master of Science (Mineral Exploration) at Rhodes University, Grahamstown and was prepared in accordance with specifications laid down by the University.

ABSTRACT

The aim of this dissertation is an attempt to provide a general guide for future gold exploration in tropical and sub-tropical terrains. The dissertation includes a brief discussion of the various exploration techniques used in regional and local exploration. This provide the necessary background knowledge to discriminate between the constraints and applications and to be able to select the techniques which are more suitable for gold exploration in tropical and sub-tropical terrains.

Weathering, gold geochemistry and soil formation, fields often neglected, are emphasized to illustrate the importance of the mobility and dispersion of gold in the weathering of the lateritic soil profile. A sound knowledge and experience in regolith mapping is to the advantage of the explorationist.

Case studies with special emphasis on Central- and Western Africa are included to illustrate the effectiveness of some of the gold exploration techniques in tropical and sub-tropical terrains.

Gold exploration is a highly complex and demanding science and to be successful involves the full intergration of all geological, geochemical and geophysical information available. An intergrated exploration method and strategy would enhance the possibility of making viable discoveries in this highly competative environment where our mineral resources become more depleted every day.

Where applicable, the reader is refered to various recommended literature sources to provide the necessary background knowledge which form an integral part of gold exploration.

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1.0 INTRODUCTION

The sharp increases in production costs of the ultra deep gold mines in South Africa restrict new exploration programmes and development of such deep gold mines. Together with other problems such as temperature gradient, safety, health and labour, entrepreneurs have been forced investors to invest in exploration for more attractive gold occurrences elsewhere.

The growing interest of South African mining and exploration companies to explore and invest in Central and West African countries initiated the need for an exploration guide for gold in tropical and sub-tropical terrains. The more politically stable countries with good infrastructure and which are underlain by Proterozoic and Archean rocks, are currently attracting the most attention. Another attraction are the alluvial gold occurrences, traditionally mined by local artisans. The sources of these alluvial deposits are mostly unknown and offer potential target areas. A rapid increase in exploration activities has taken place in Ghana, Mali, Ivory Coast, Burkina Faso, Guinea, Senegal, Niger, Gabon and Tanzania since 1990.

2.0 ASPECTS OF EXPLORATION METHODS FOR GOLD

2.1 EXPLORATION TECHNIQUES

2.1.1 Geological Mapping

Geological mapping is generally regarded as the most important fundamental stage to mineral exploration. Walking an area enhances the chances of finding mineralised outcrops. It also improves the geological understanding of the region which furthermore provides the necessary framework within which the exploration programme can be conducted. Understanding of the geological environment is paramount to the proper assessment of potentially mineralised terrains. Previous mapping and reports are useful, but should be carefully assessed i.e. the geologist must apply his own working hypotheses, not influenced by previous work.

This type of information gathering must also be viewed in context. Different types of mineralisation tend to occur in definite geological environments and features such as particular lithologies, structure and recognition of alteration patterns may all have important bearings on the style of mineralisation. The recognition of such features in the field at the reconnaissance stage may assist in defining target areas for detailed investigation by more costly methods (Peters, 1987).

As much of the above pertains to mapping on a relatively local scale it is emphasised that this sort of exercise must focus in on areas. This means either interpreting existing maps or compiling a regional map from scratch. This overview, even if mineralisation is located in one or two small areas, gives added data to the conceptual model, and brings the mineralised occurrence into context. It also aids later adjustments and reassessments of data when looking for extensions to ore bodies or for blind ore bodies. This regional overview concept cannot be over emphasised, as the practise of some exploration companies of selecting target areas for detailed mapping and exploration methods prior to having a regional picture is considered by the author to be very short-sighted, and although appearing cost-effective, eventually leads to a poorly integrated and unsystematic exploration policy. An appreciation of regional geological features provides a far more controlled and systematic appraisal of all possibilities of target selection in a given region (Mosely, 1981).

The foundation of any serious exploration programme must revolve around geological mapping to support a sound geological base. It is also important to integrate all regional surveys during mapping exercises - e.g. soil or stream geochemistry, lithogeochemistry and regional geophysical surveys. The ultimate outcome is a series of maps from regional to local scale, which allow a constructive assessment of the geological picture, and allows scope for rejections, revisions, and modifications of the exploration model. A further point of emphasis, directly related to this aspect, is a constructive and systematic application of orientation surveys during regional appraisals (Mosely, 1981).

Geological maps are also vital for the compilation and interpretation of cross-sections, and portray an immense amount of data if properly compiled.

Fundamental to this aspect is the identification of rock types, generally on a regional level, and more specifically at the outcrop level. Rocks must be identified before they can be mapped. Integrated petrographic studies during mapping, initially of regional suites, and then of more detailed sampling is a valuable exploration tool. The microscope is a seriously underused instrument in exploration, and should be as fundamental to a geologist as using a handlens and rock hammer in the field. Alteration patterns are often missed during the initial field reconnaissance and mapping. Petrographic examinations will always elucidate and substantiate field observations. The exploration geologist should undertake his own description of a given sample or thin section, as once more it places the petrographic and lithological properties of the rock in context. Furthermore this type of exercise should be maintained through reconnaissance to detailed stages, as an integrated facet of the programme, not a rushed sideline investigation. Geochemical analyses should be closely integrated to petrographic studies, as they further enhance the data base on which to make further appraisals and decisions (Peters, 1987).

The scope of geological mapping in tropical terrains is often constrained by poor exposure, and usually highly variable geomorphological features. Reconnaissance mapping should note all outcrops in areas traversed. In areas of poor exposure, careful and detailed float mapping may be instrumental in finding mineralisation. Obviously there are many different surface expression of orebodies, often only what the trained eye can perceive, or else what may be picked up by the integration of other methods (e.g. geochemistry, geophysics). The careful assessment of gossans has proved a valuable tool in evaluation of many massive sulphide deposits.

Present day computerised Geographic Information Systems (GIS), such as ARCINFO, together with CAD draughting applications provide a basis through which to generate maps and overlays at various scales, without the tedious delays of hand draughting each set. Furthermore the digitised data file can be easily updated. Although initial capital costs are fairly high, the payback in efficiencies in time is very quick, and frees the geologist to undertake the full scope of analytical work that he is trained to do.

Digital data is only as good as the input, combined with the interaction between geologist and draughtsperson (Peters, 1987).

2.1.2 Geochemical Exploration

In a geochemical survey, regardless of the method and utilisation in reconnaissance or detailed exploration work, investigations can follow a systematic sequence (Zeegers and Leduc, 1993):-

1.) Selection of pathfinder elements, sensitivity and precision required, sampling patterns are made on the basis of cost, known or suspected geologic conditions, the results of laboratory work on similar material, and, most importantly an orientation survey or equivalent experience in similar terrain and with orebodies similar to those sought. A geochemical orientation survey should be carried out in the following manner :-

- * Firstly establish the conditions under which the main survey is to be carried out.
- * Examine a vertical profile of a similar mineral deposit, if possible.
- * Determine as best possible, the nature of the mineralisation, the nature of dispersion, and compare an anomalous situation with that of background. This may be attained by using 1 or 2 pits, examination of the soil profile, the optimum sampling depths and the optimum mesh sizes for chemical analysis.
- * Inspection of the drainage pattern.
- * Experiment with sample density; for example stream sediments should be representative of the catchment area. If water samples are to be taken, what volume and where; stream sediments - how many, what mesh size, or panned concentrates, mesh size and for which elements the samples should be analyzed.
- * Soil sampling traverses can be made across the mineral prospect.

- * If there is no known anomaly or mineralisation zone one must establish background, threshold, and anomaly levels for each different geological area in soils, stream sediments, and rock, plus the optimum sampling interval and the analytical error should be established.
- 2.) Many of the above facets are included in continued sequential exploration. A preliminary, or first coverage field sampling program, should include check samples and depth (profile) samples to establish a level of reliability and to evaluate "noise" factors.
- 3.) Sample preparation in the field (where possible) before submission to the laboratory with regular check analyses.
- 4.) Statistical treatment and geologic evaluation of the data, always in connection with available geological and geophysical data.
- 5.) Confirmation of apparent anomalies, follow-up sampling, and analysis and evaluation in smaller areas, using closer sampling intervals and additional geochemical methods.
- 6.) Target investigation with a provision for resampling and for additional analysis of stored samples.

The last point is important, because geochemistry relates anomalies to a conceptual model of an orebody, and early drill holes may change this model, be it due to intersection of a different type of mineralisation or elemental association, or even a displaced surface anomaly (e.g. tropical and sub-tropical terrains) with thick over burden that may obscure geophysical methods.

Exploration geochemistry is a broad tool, which when integrated properly with geological and geophysical parameters, can provide much data and insight into the exploration model. A systematic approach is allways favoured as then the criteria for making fundamental decisions on given anomalies in a region are consistent, which in the long run will benefit the exploration in detailing and evaluation of target areas.

2.1.3 Geophysical Exploration

Geophysical information is interpreted in relation to patterns in geology, and the patterns are evaluated with respect to known or supposed relationships between rock types, structure, stratigraphic sequence and ore mineralisation.

As such it is a powerful and integral tool of exploration, invariably used in reconnaissance and follow-up work. The geologist should have a working knowledge of the many applications and uses of geophysics. The processing of data should be left to people with expertise (i.e. geophysicists) but the interpretation thereof is regarded as a task for the geologist.

The applicability of any given method in a given situation is quantified by the signal (information) to noise (extraneous effects) ratio. Within any geophysical message there may be anomalies, significant departures from the normal pattern of values. These anomalies must be explained in terms of geological conditions, including the possibility of mineralisation, and all alternative conditions should be considered. Usage of more than one technique reduces the number of possible alternatives. The use of geophysics begins in the reconnaissance stage, with airborne methods (e.g. magnetic) serving to outline broad geologic features, and continues into the most detailed stages, where ground methods, drill-hole (downhole) methods, and even underground geophysics can be directed toward finding orebodies. Reconnaissance methods are invariably undertaken in conjunction with geological mapping (Rose et al., 1991).

The essential requisite of any geophysical method is to have a contrast in some measurable physical property between ore and the adjacent rock. In gravity work the property is rock density, in electrical and electromagnetic work, it is conductivity. The contrast is essential, but may be affected by the shape and attitude of the ore body and the ratio of size to depth of burial. Methods such as gravity, magnetics, resistivity and induced polarisation depend on the volume of the body, whereas electromagnetic signals depend on the area of the body normal to the applied field - thus a flat lying disc can give the same electromagnetic anomaly as a sphere or a thick lens of the same radius.

In general, airborne geophysical methods are used in reconnaissance exploration, and ground geophysical methods are used in more detailed investigations, although in many cases combinations and sequences can be combined. Airborne surveys are fast, relatively inexpensive per unit area, can obtain several kinds of surveys at once, and provide a more objective coverage than ground surveys in many kinds of terrain. The survey patterns are reasonably uniform and complete because they do not have the access and traverse problems of ground surveys in swamps, dense bush and rugged topography.

Ground methods, especially electrical methods, are utilised in detailed exploration for ore bodies, as well as aiding geological mapping. Ground Electromagnetic (EM) and Induced Polarisation (IP) methods are used where massive and disseminated sulphide deposits are sought. Ground radiometric surveys are used in searching for uranium orebodies. Gravity and seismic surveys may aid geological mapping, and determine configuration of bedrock in alluvium covered areas. A recent development called ground penetrating radar appears to have good applications to alluvial prospecting (bedrock profile) as well as shallow ($\pm 20\text{m}$) penetration of hangingwall/footwall rocks in underground development (Rose et al., 1991).

The co-ordination of a geophysical survey to an exploration programme is largely the responsibility of the geologist.

The geophysicist chooses field methods and traverses based on interpreted geology, and the geologist (and/or geophysicist) uses the information in making an interpretation (Parasnis, 1986).

The geologist and geophysicist should discuss and design a programme incorporating allowances for geological conditions, sources of noise, access, facilities and logistics, when (which season), what sort of delays are expected, a facility for extended surveys, implementation of an orientation survey, the nature of survey control, what subsurface information is available. During the programme co-ordination should include sorting of apparent anomalies, drilling and trenching for more subsurface information, provision for supplementary geophysical investigations, and extended coverage. Finally, on completion of the programme, a decision on follow up work must be made.

2.1.4 Photo-geology and Remote Sensing

Remote Sensing, in its broadest definition, includes geophysical exploration, instrumental chemical analysis, and all the various techniques that use energy from the electromagnetic spectrum.

The more common usage of the term, refers to imaging methods that derive data from areas on the earth's surface rather than from depth. The spectral frequencies of remote sensing range from 3×10^8 to 1×10^{15} Hz, the range of microwave sensing, radar thermal scanning, photography and ultraviolet scanning (Fig 1).

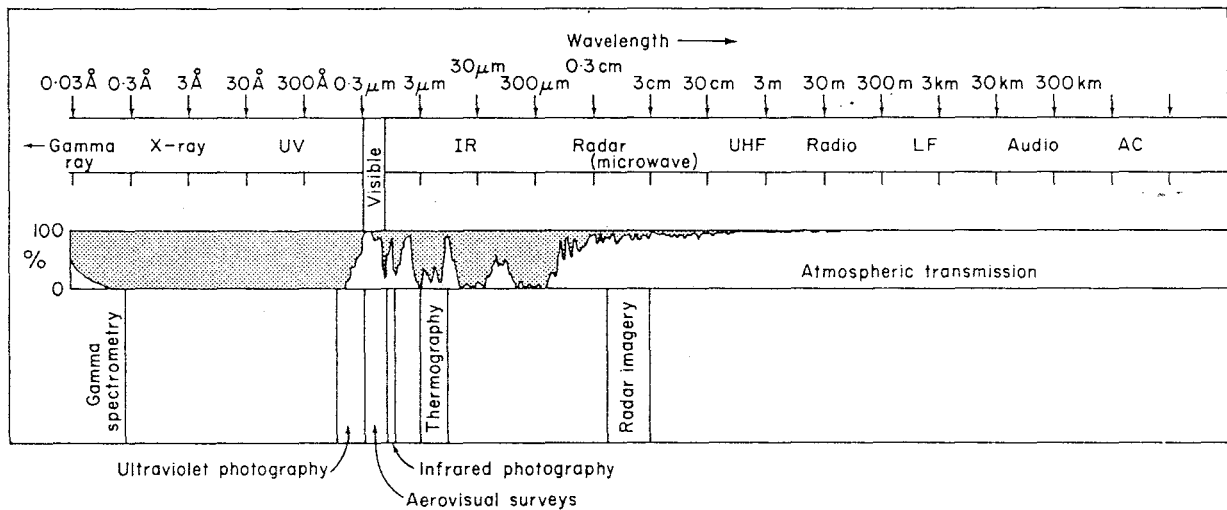


Fig. 1 The electromagnetic spectrum and their significance in remote sensing (after Rose et al., 1993).

Most remote sensing techniques use Passive systems that only collect incoming radiation e.g. the electromagnetic energy of the sun, reflected energy from the surface of the earth and emitted energy (heat) from the surface of the earth. A few systems are active, e.g. pulsed laser, side-looking airborne radar (SLAR) in which signals are sent as well as received. Nearly all remote sensing methods are important, or potentially important, in a specific way to exploration, although the most widely used are spacecraft imagery and aerial photography in the visible and near-visible wavelengths. Applications are mostly during reconnaissance stages, because that is when a synoptic view is required - i.e. small-scale photographs and time-scanning imagery from spacecraft.

2.1.5 Exploration Drilling

Subsurface drilling is of paramount importance to mineral exploration and is an integral tool in regional, and the progressively more detailed appraisal of potentially mineralized terrains. Drill-hole information can be related to the following stages in exploration (Heinz, 1985) :-

- 1.) Orientation - usage of past core and results
- 2.) Reconnaissance - for stratigraphic or lithologic information, especially where stratabound orebodies are sought
- 3.) Target area investigation - information on key structure, stratigraphy and zoning, reference points in geophysical interpretation
- 4.) Target testing - Presence or absence of mineralisation.
- 5.) Evaluation - outlining of mineralisation, sampling to determine size, grade of potential ore-body
- 6.) Preproduction - Further delimitation of ore body, ore reserve assessment, geotechnical (down-hole, rock mechanics) and metallurgical investigations. mine development guidelines
- 7.) Mining - Continued evaluation, blocking out ore and providing information for mine planning. There are many methods of drilling, and it is also important to have a flexible, but systematic method of logging core, so as to attain the maximum information (Heinz, 1985).

Careful consideration is given to drill hole patterns, inclinations, utilising all available information (geologic, geophysical, geochemical and photogeology). Surface exploration drilling may involve percussion and/or diamond drilling. Pilot boreholes are often percussion drilled to save cost.

Details of diamond drilling will not be expanded on here, suffice to say that in weathered ground better recoveries are gained using as large a diameter core-barrel as possible. Conventional wire line drilling (utilising a double tube) generally gives reasonable recoveries. However in fractured and/or weathered ground, triple-tube drilling is very effective.

Auger drilling can be the most efficient method of soil sampling where cemented horizons are present or if composite samples of whole soil profiles 1 - 2 m deep are required (Heinz, 1965). Although superjacent anomalies have been recorded in soils developed from transported overburden, such anomalies cannot be relied upon, so drilling to sample buried residuum (nodular laterite, saprolite) is recommended.

Deep drilling may be used as a direct follow up to relatively widely spaced (200 x 50 m) soil sampling or after more detailed surveys are used. Auger and rotary air blast drilling methods are suitable above the water-table. Vertical drilling is suitable for following-up anomalies in the ferruginous horizons or evaluating lateritic deposits. However, in environments where there is little secondary dispersion in the saprolite, it is commonly essential to drill overlapping angle holes to ensure that supergene mineralization is intersected.

A final point is that diamond drilling is a costly business. Core should be well labelled with run depths clearly marked, and preferably stored under a roof in a metal core tray (which does not rot with time or get eaten by ants). The scope to reassess core is vital, especially as the exploration model and/or commodity sought could change with time.

3.0 PROCESSES IN THE SURFICIAL ENVIRONMENT

3.1 SURFACE WEATHERING AND PROCESSES

The economic importance of gold deposits in deeply weathered terrain has dictated a need for the understanding of weathering processes that have contributed to the development of these terrains (Gleeson, 1994). An understanding of the geochemical environment is essential for the efficient application of geochemical surveys, whether at regional or local scales.

Levinson (1980) stated that geochemical exploration methods are largely based on a systematic study of dispersion of chemical elements in natural materials surrounding, or associated with, ore bodies. Dispersion is a process of distribution or re-distribution of elements by physical, chemical and biological activities (Rose et al., 1991).

Physical processes include all those that cause rock disintegration without chemical or mineralogical changes. This disintegration increases the reactive surface area and thus facilitates the decomposition of rocks by chemical reaction with the abundant water, oxygen, and carbon dioxide of the surface environment. Biological activity contributes either directly or indirectly to both physical and chemical weathering. These processes usually take place side by side, though their importance varies according to environmental conditions. Thus, in extremes of arid deserts and arctic conditions, and in many areas of mountainous relief, physical disintegration is usually the dominant mechanism of rock decay. Under most other climates, chemical attack is by far the dominant factor in controlling the nature of the weathering products at all depths within the zone of weathering. By contrast, the principal domain of biological activity is restricted to the near-surface zone of soil formation (Rose et al., 1991). The application of geochemistry to mineral exploration has progressed markedly since the 1950's. Geochemical prospecting and geobotanical prospecting are based on the knowledge that an envelope of primary mineralisation is likely to occur around a mineral deposit and a secondary dispersion pattern of chemical elements is often created during weathering and erosion of the deposit (Lawrance, 1995).

Geochemical methods are utilised to detect primary and secondary dispersion haloes, which invariably constitute a bigger target than the ore body itself. Geochemical environments related to dispersion have been subdivided by Levinson (1980) in :-

1. **Primary environments** - embraces those areas extending downward from the lower levels of circulating meteoric water to those of the deep-seated processes of igneous differentiation and metamorphism.
2. **Secondary environment** - comprises the surficial processes of weathering, soil formation and sedimentation at the surface of the earth.

The primary environment is generally one of relatively high temperature and pressure with little free oxygen, and limited movement of fluids. The secondary environment, on the other hand, is characterized by lower temperatures and pressures, abundant free oxygen and other gases, and the relatively free flow of fluids (Levinson, 1980).

Movements of materials between the primary and secondary environments may be presented graphically in the form of a simplified close system known as a geochemical cycle (Fig. 2). The secondary environment represents that part of the sampling media where most of geochemical sampling (soil, stream, rock, water, etc.) is carried out (Rose et al., 1991).

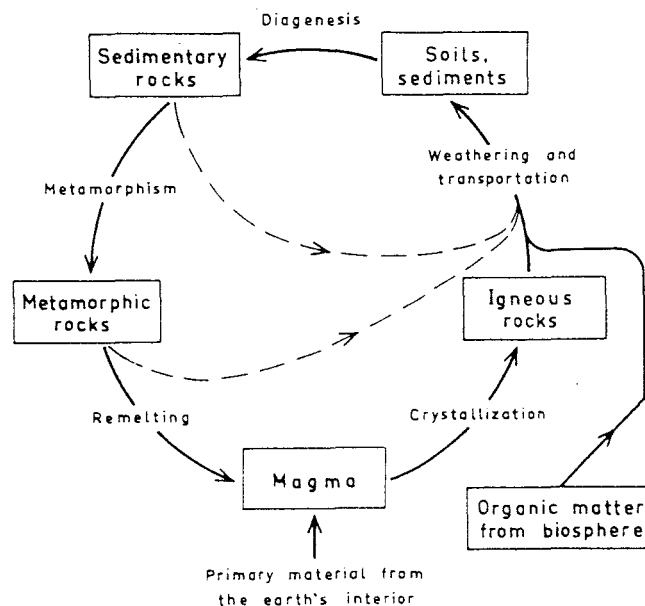


Fig. 2 The geochemical cycle (from Levinson, 1980)

3.1.1 Primary dispersion

In exploration geochemistry primary dispersion is synonymous with the distribution of elements in unweathered rocks and minerals, whatever their origin. Knowledge of primary dispersion in a region assists interpretation of secondary dispersion data i.e. stream sediment and soil sampling surveys (Freyssinet, 1993).

It is directly related to lithogeochemical sampling, and aids definition and distinction of anomalies due to possible mineralisation and those due to high background unmineralised rocks. On a regional scale lithogeochemical sampling is used to define metallogenic provinces, and on a more local scale to locate blind ore bodies extending from known deposits by delineating the primary dispersion haloes that may be associated with mineralisation (Levinson, 1980). This type of survey is also synonymous with petrographic studies mentioned in Section 2.1, and is best applied to areas of good outcrop or else if there is drill core available. A direct application of lithogeochemistry on a local scale is the detection of minor/or major changes in element concentration in primary haloes e.g. K_2O/Na_2O and Rb/Sr ratios and As, Hg, Sb in Au veins and hydrothermal deposits are a couple of typical examples.

3.1.2 Secondary dispersion

During weathering rocks break down by physical and chemical processes which disperse the various elements contained in the original rocks into soils, stream sediments, ground waters, river waters, the sea, air, plants and animals (Freyssinet, 1993).

The degree of this dispersion is related to a given element's mobility. Elements with low mobility (e.g. Be, Au, Sn, Si, Ti,) occur in or as stable minerals which are very resistant to the effects of normal chemical weathering, and are generally dispersed as clastic fragments by slow mechanical weathering into soils and stream sediments. Highly mobile elements (Na, K, Mg) readily enter water soluble phases and are widely dispersed by surface and ground waters.

Secondary dispersion is, thus, very important in exploration geochemistry, as it results in the various elements present in an ore body being dispersed over a much wider target area, enabling the presence of mineralisation to be detected as an anomalous metal content in soils, stream sediments, plants and surface and ground waters. Soil and stream sediments are the most commonly used methods in regional and local geochemical surveys (Freyssinet, 1993).

An understanding of secondary dispersion in a given terrain is influenced by climatic and geomorphic conditions. Two parameters (pH and Eh) are critical to the mobility of any given element, as they control the chemical conditions within the weathering environment. The pH is a measure, in broad terms, of the alkalinity or acidity of a given solution. Eh (the redox potential) is a measure of the reducing or oxidising potential of an environment.

In natural environments redox potentials are largely dependant on the amount of oxygen available and the amount of organic matter present.

High oxidation potentials are found in areas that are hot and well-drained to which atmospheric oxygen has had access, whereas waterlogged environments with a high organic content are strongly reducing, thus becoming acidic with low pH e.g. peat bogs. Waterlogged, organic-free environments are only oxidising where they are in free contact with the atmosphere. Confined waters rapidly lose their oxygen and by hydrolysis of silicates become alkaline so that below the water table environments tend to be alkaline and reducing. The consequences of Eh-pH conditions are very important in determining the mobility of most elements of interest in exploration geochemistry - thus it is often a good move during reconnaissance and/or orientation surveys (see later) to test the nature of waters, as the dispersion patterns of ore-related minerals (e.g. Mo-Cu) are often quite different (Freyssinet, 1993). Weathering is regarded as the total effect of all subaerial processes that co-operate in bringing about the decay and disintegration of rocks (Holmes, 1965). Temperature variations are not considered to be directly involved in the granular disintegration of rocks but the main role is an indirect one governing the moisture and also the solubility of gases or salts in rock pores. Moreover, the rates of chemical reactions are increased with increasing temperature (Rose et. al, 1991).

Certain mineral species are more resistant to chemical weathering than others, the general sequence of resistance being :-

oxides -> silicates -> carbonates -> sulphides.

Chemical reactions related to geochemical weathering consists essentially of four processes :-

1. Hydration - Hydration (absorption of water) and hydrolysis (chemical reaction to produce or consume H^+ or OH^- ions) are commonly regarded as the most important chemical reactions involved in rock decomposition. Hydration implies absorption of water molecules into the crystal structure of a mineral.

2. Hydrolysis - Mafic minerals generally alter much more rapidly than felsic minerals and this sequence follows closely the order of crystallization in Bowen's reaction series. The weathering of silicates is primarily a process of hydrolysis, whereby the ionic species H^+ and OH^- become incorporated into the structure of minerals; more specifically, there is a reaction between water and the ion of a weak acid or a weak base.

3. Oxidation - Oxidation is the dominant weathering process of interest in exploration geochemistry. This is because oxidation produces gossans, iron and manganese oxides, and secondary dispersion haloes from sulphide minerals.

4. Simple Solution - The simple solution of many minerals in the abundant water of the surface environment can be an extremely important factor under some conditions. The most spectacular example of solution is the formation of limestone caves by the solution of calcite in CO_2 -bearing waters to form soluble calcium bicarbonate.

Clays, organic matter and hydrous oxides of Fe and Mn all have the ability to adsorb metallic ions, and thus have a marked effect on the mobility of many elements in the secondary dispersion environments.

Cd, Cu, Ni and Zn are strongly scavenged by Mn oxides, As is strongly scavenged by Fe, whilst Cu, Mo and Pb are only weakly scavenged (Freyssinet, 1993). Geochemical surveys may utilise these principles, with the collection and analysis of Mn-Fe oxide concretions and coatings, plus "gels" for their trace element content - which may reveal better anomaly - background contrast than that obtained from conventional sediment surveys.

Dispersion processes, in brief include :-

- 1.) mechanical processes, whereby clastic fragments derived by the weathering of rocks are dispersed by agencies such as gravity, water, wind, ice and animals.
- 2.) Solution processes, where constituents of original rocks and minerals pass into solution, and are carried away by surface and ground waters to be eventually precipitated or redeposited because of adsorption or changes in pH, Eh and chemical environment. This results in broad dispersion patterns of some elements, whereas stable minerals such as gold, cassiterite and monazite are usually present in discrete clastic mineral grains. Sampling of stream sediments, depending on the elements to be analysed for, should include routine sediment sampling as well as heavy mineral concentrates.
- 3.) Biogenic processes include plants which take up numerous trace elements together with their normal nutrients from the soil. The elements may be reconcentrated upon decay of the plant, and by bacteriogenic processes.

The direct application of geochemistry to gold exploration is often through the usage of pathfinder elements, which are elements associated with that element or commodity sort, indicated below (after Levinson, 1980 and Rose et al., 1991) :-

PATHFINDER ELEMENTS	TYPE OF DEPOSIT
As, Au	Au, Ag; vein deposits
As, Sb, Hg, Te, Se, S, U	Epithermal Au-Ag deposits
Sb	Au-As rich Fe formations
As, Au	Au-Ag-Cu-Co-Zn; complex sulphides

Geochemical data has to be interpreted using quantitative control with no bias in order to maximise the significance of anomalies. Statistical and graphical means are used to determine background, threshold and anomalous levels. Data, such as analytical results, must be cross-checked for contamination and should be ratioed, or manipulated by moving averages to generate patterns that may enhance zones of mineralisation.

Methods such as factor analysis, discriminant analysis and multivariate spectral analysis may be applied. The key is to evaluate data in a simplistic, unbiased manner, that is practical to quick application and integration with existing data from other surveys/programmes. Computer applications definitely aid the integration of various databases. More often bulk geochemical assays are undertaken on stream, soil and sometimes rock samples.

An important facet in this stage of geochemical surveys is the interrelation between the geologist and the geochemist. In fact prior to implementing any geochemical survey the geologist should systematically plan the elements to be assayed for and by which method i.e. what is a desirable detection limit, what are the most cost effective methods.

3.2 GOLD GEOCHEMISTRY

3.2.1 Gold Dispersion

In lateritic profiles overlying gold deposits, migration of gold in the supergene fluids has been inferred from surface dispersion patterns (Lecomte, 1988; Freyssinet et al., 1989) and by the presence of high purity supergene gold grains (Lecomte and Colin, 1989 and Howell, 1992). The mobility of gold in laterite profiles in semi-arid and humid climates and the gold dispersion patterns are interpreted in terms of evolution of the landscape and a succession of different climates.

Gold appears most mobile in the dry climatic period when dissolved salt content in the ground waters is highest with gold dissolution by chloride and/or thiosulfate (Freyssinet, 1993).

A tropical rain forest environment is characterized by high rainfall (1250 mm/yr in the Ashanti area), alternating wet and dry seasons, and high daily temperatures (20° -30°C in the Ashanti area), such that chemical weathering occurs at rapid rates (Freyssinet, 1993).

Beneath a deep soil cover lies a saprolitic zone of leached rock extending down to the unweathered bedrock. Regolith is a general term for the entire mantle of weathered material whether residual, introduced or transported. Saprolite is defined by soft, weathered products which retain many of the structures and textures of their parental rock. Weathering of the bedrock occurs at the water-rock interface and involves the leaching of mobile components from primary mineral assemblages and the formation of stable secondary assemblages. The saprolite can be subdivided into lower and upper units with increasing oxidation up the profile.

Continued fluid interaction and leaching of elements results in the progressive loss of material which is greatest in the upper portions of the saprolite where textures are more porous. Eventually microsubsidence occurs, resulting in the loss of the primary fabric to produce the soil horizons. The soil profile (Fig. 3) is composed of a massive clay (B) horizon which is separated from the underlying saprolite (C) horizon by a transitional unit (B/C horizon). Capping the soil profile is the surface (A) horizon which is composed of resistant primary minerals, secondary iron oxides-hydroxides, and organic matter in a fine argillaceous matrix (Bowell et al., 1993).

Gold deposits occur in tropical rain forest terrains throughout Central and West Africa, South and Central America, and Southeast Asia. Where gold mineralization is exposed at the surface, the gold-bearing veins will undergo oxidation. Where these deep soil profiles are characterized by stonelines (a line of angular to sub-angular fragments which parallels a sloping, weathered topographic surface at depth) overlain by loose clay horizons, geochemical redistribution of elements occurs both laterally and vertically. This results in a mushroom-shaped anomaly of gold (Fig. 4), providing a wide but weak target for exploration (Zeegers and Lecomte, 1992).

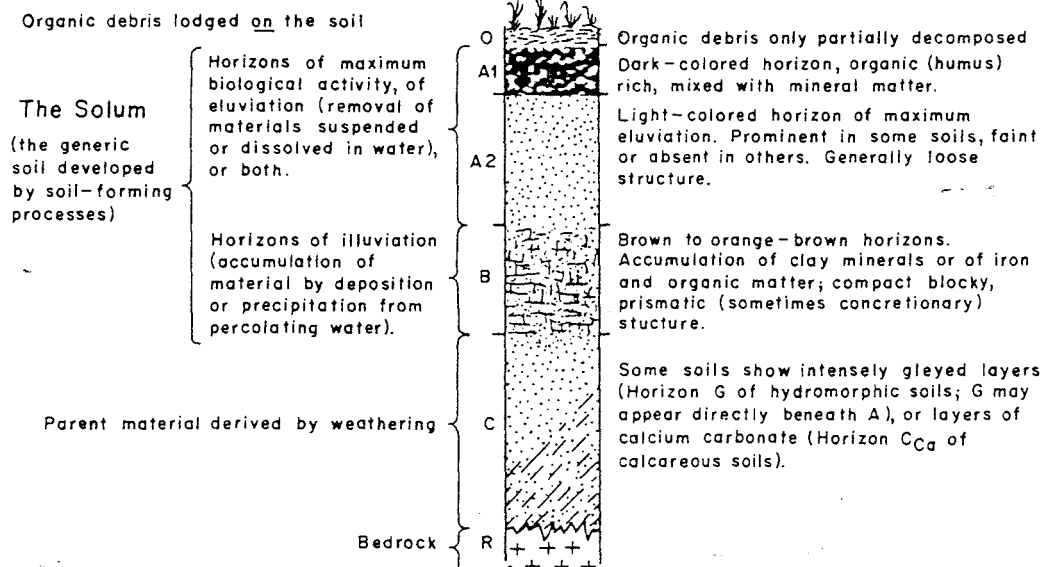


Fig. 3 A simplified soil profile (after Rose et al., 1991).

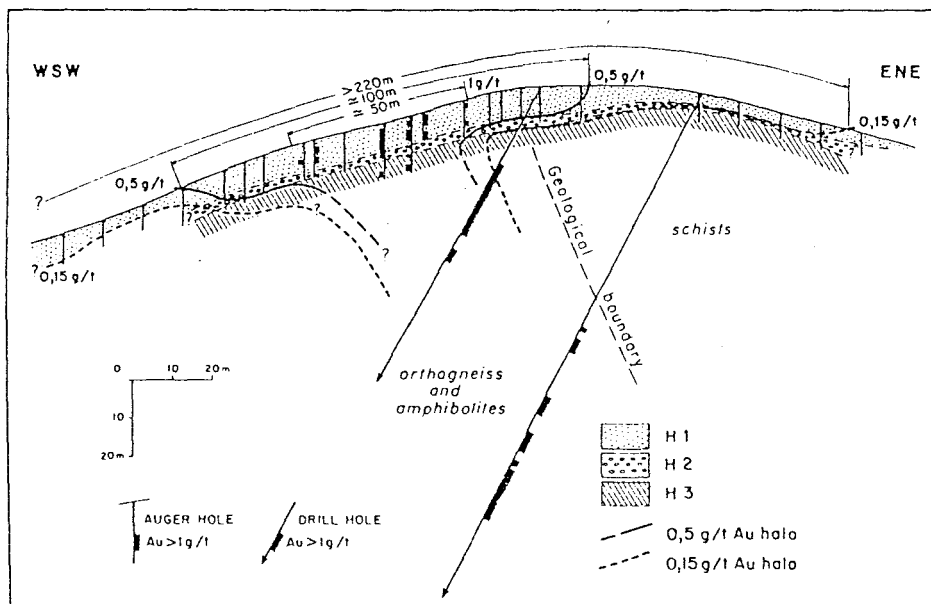


Fig. 4 A mushroom-shaped anomaly at Dondo Mobi, Gabob (after Zeegers and Lecomte, 1992).

At the Dondo Mobi prospect in Gabon, the dispersion of gold in the weathering profile above bedrock gold mineralization was investigated by Lecomte and Colin (1989). From a study of gold grain morphology they demonstrated that part of the primary gold was dissolved, but no evidence was found to indicate reprecipitation of secondary gold in the supergene environment, suggesting that the gold dispersion pattern had an important residual component. Thus, stoneline environments are indicative of conditions leading to a surficial gold dispersion largely by mechanical processes. In high-relief terrains, any preexisting profile has generally been removed by erosion, and allochthonous material is common on the slopes. Locally, stripping may remove the entire soil profile exposing fresh rock. The mechanical component of geochemical dispersion is important, and it can be difficult to precisely locate the origin of geochemical anomalies obtained in these residual soils (Freyssinet, 1989).

Chemical processes of dispersion of gold can also be active in tropical rain forest terrains (Webster and Mann, 1984). In the Morobe gold fields of Papua New Guinea, primary native gold occurs in gold-quartz-rhodochrosite-sulphide veins. In the weathering zone, the Mn carbonates are replaced by oxides, and mobilization of gold and silver may be achieved through thiosulphate ligands formed by the weathering of sulphides, the pH being controlled by the dissolution of carbonate minerals. The secondary dispersion of gold and silver, however, is limited with a narrow enrichment halo of a few meters in the soil around the shear zone. The supergene mobilization of gold occurs as a mixed Au-Ag thiosulphate complex, leading to the formation of supergene gold containing 16 weight percent Ag (Webster and Mann, 1984).

Consequently it is unlikely that biogeochemical recycling of gold has had a large effect on gold mobility in the soils and this is demonstrated by the low concentration of gold (<1.2 ppm) in ashed samples of bark, stems, and vegetation from the rain forest in the Sansu prospect (Lecomte and Colin, 1989). Geochemical distribution patterns for Au in the soils of the Mborguene lateritic profile in Cameroun show a wide dispersion halo of over 200 m in diameter centered around a silicified gold-bearing breccia which is approximately 3 to 5 m wide (Freyssinet et al., 1989).

Such a wide distribution halo is attributed to extensive supergene lateral distribution of gold in ground waters and is characteristic of equatorial tropical weathering regimes. The result is a mushroom-shaped anomaly representing a wide but weak gold anomaly around the weathering shear zone. In less extreme weathering regimes the supergene fluids do not have the ability to mobilize gold over large distances (10 - 100 m, as seen at Dondo Mobi), and consequently, gold has a limited dispersion in the soils around the shear zone, although significant dispersion can occur as at the water table. Despite the fact that gold is actively dissolved in the soil waters, mobility appears to be very limited (up to a meter) such that dissolution of the gold and reprecipitation occurs essentially in situ. This limited gold mobilization and reprecipitation may be due to variations in Eh-pH over a relatively short distance in the soils, and the fact that the gold complexes which form are only transiently stable either thermodynamically (and dissociate due to changes in Eh, pH, or activity of components) or kinetically (so react to form more stable species).

The in situ dissolution and reprecipitation of gold in the soils explains the occurrence of secondary and residual gold in the same heavy mineral concentrates. It also explains the preservation of hypogene gold dispersion patterns with a pipelike morphology and limited redistribution of gold in the soils immediately over auriferous shear zones (Freysinet, 1993).

From the mineralogy and geochemistry of the weathering profiles at Ashanti, it is possible to assess the potential of various ligands to form stable gold complexes. The behavior of gold in the supergene environment is dominated by the chemistry of gold complexes. The unassociated ions Au^+ and Au^{3+} cannot exist in natural waters due to the high oxidation potential required for their formation and this is shown by the high free energy and low stability constants of the simple gold ions in water (Table 3.4). Ligands act to reduce the oxidation potential required to dissolve the gold, but they themselves do not oxidize the gold. The solubility behavior of gold therefore lies in the stability of the gold complex produced and the ability of the environment to oxidize gold. Under the oxidizing acidic to neutral (pH range of 4.2-6.8) conditions in the Ashanti soils, chloride, thiosulfate, cyanide, thiocyanate, ammonia, and fulvic acid can be considered as potential ligands together with gold hydroxide complexes.

3.2.2 Gold Mobility

Various lines of evidence support the concept that Au is mobile as dissolved or colloidal complexes in surficial environments. Several studies have found elevated dissolved Au concentrations in the vicinity of Au mineralization.

In arid and semiarid regions dissolution of elemental Au by oxic, acidic, chloride-rich waters has been proposed as a mobilization mechanism (Table 1). The chloride-complexed Au (AuCl_4^- , AuCl_2^-) can then migrate to the water table or more reduced zones in the profile where reduction to elemental Au can occur in the presence of Fe^{2+} or Mn^{2+} , or because of dilution and subsequent disproportionation. This mechanism can also account for the increased fineness often observed for lateritic Au over bedrock sources since dissolved Ag-Cl complexes are less prone to reduction and hence can migrate away from zones of Au reduction (Andrade, 1991).

Further evidence of Au mobility in surficial environments comes from recent studies in lateritic terrains where Au particles are observed to decrease in size from bedrock to the surface.

In addition, Au grains show increased fineness and become corroded and rounded toward the top of the profile. Secondary Au as crystals enclosing lateritic minerals is also sometimes observed. Gold enrichments have been observed in peat and other organic-rich horizons. Such enrichments may result from the interaction of elemental or dissolved Au species with humic and fulvic acids or other organic fractions (Mann and Webster, 1990).

The extent to which Au is transported and dispersed in surficial environments will depend on the mineralogy of the profile through which transport takes place as well as the forms of Au present. Adsorption or other scavenging processes are likely to be important in this regard. Fe and Al oxides (dominant components of lateritic profiles) adsorb Au species such as AuCl_4^- and $\text{Au}(\text{S}^{2-}\text{O}_3)^{3-}_2$ (Table 1).

Table 1 Summary of chemical environments suitable for gold mobilization by ligands commonly found in weathering profiles (After Coope, 1992).

Ligand	Chemical Environment for Dissolution	Dissolution Reactions
Organic complexes	oxidizing neutral-acid biological activity	$\text{Au (electrum)} + \text{Organic Acid}^a + \text{O}_2 + \text{H}^+ \Rightarrow \text{Au(Organic)}^{n+} + \text{H}_2\text{O}$
Thiosulphate complexes	oxidizing mildly acid- mildly alkaline low-moderate carbonate	$\text{Au (electrum)} + 2\text{S}_2\text{O}_3^{2-} \Rightarrow \text{Au(S}_2\text{O}_3)_2^{3-}$
Chloride complexes	oxidizing acid high Cl^- concentration	$4\text{Au (electrum)} + 8\text{Cl}^- + \text{O}_2 + 4\text{H}^+ \Rightarrow 4\text{AuCl}_2^-^b + 2\text{H}_2\text{O}$

Au accumulates in vegetation. Little attention has been given to the possible importance of vegetation as a mobilizing agent for Au. The role of vegetation may be especially significant in tropical regions where stable, vegetated surfaces have existed for long periods of time (Lawrance, 1995).

The cycling of Au through vegetation may be one of the more significant mechanisms for Au mobilization and dispersion in lateritic terrains provided a stable vegetated surface has existed over mineralized zones for long time periods (10^6 - 10^7 years).

1. Gold in the Exogenic Environment.

Mann and Webster (1990) stated that during lateritic weathering gold is complexed in oxidising fluids related to those observed from the oxidation of pyrite and arsenopyrite at the weathering front that occurs by the acid forming reactions.

Where gold remobilisation occurs from a quartz vein or stockwork system, secondary gold distribution is essentially lateral, at or near the palaeowater table, and has a characteristic "T" shape (Mann and Webster, 1990). The near surface anomaly, often located in the lower part of the mottled zone, may extend up to tens of metres either side of the host vein or lode system.

In some cases deflation and erosion result in a mechanical enrichment of the near surface lens. Where chemical remobilisation is the sole contributor to the process, the grade of the near surface zone is often less than that of the hosting vein or lode (Mann and Webster, 1990).

2. Geochemistry of precious metals in laterite

The ratio of mechanical dispersion to hydromorphic dispersion is a key parameter with regards to understanding the type and size of geochemical dispersion haloes in laterites (Zeegers and Lecomte, 1992).

In seasonally humid climates the preexisting laterite profiles, particularly the Fe-rich "cuirasse", may be several metres thick, representing a very specific geochemical environment with regard to Au and other elements. Some leaching of Au occurs in the cuirasse, but some secondary Au is present while primary Au grains may also survive. Quite contrasted geochemical haloes (100 - 1000 ppb Au) may help in locating underlying primary Au mineralization.

Pathfinder elements, such as As, also display highly contrasting anomalies in the upper ferruginous horizons of the profile. In the saprolite, leaching of Au is less important, and the grades obtained are close to those in the primary mineralization, with, of course, a less developed halo of dispersion (Mann and Webster, 1990).

Based on the current understanding, the potentially most important aqueous gold species in the natural environment are tabulated in table 2 (Coope, 1994).

Table 2 Gold mobilization in soil and groundwaters (After Coope, 1992).

SPECIES	POSSIBLE ORIGIN	SOLUBILITY CONDITIONS	PRODUCT
$\text{AuCl}_2^-/\text{AuCl}_4^-$	Oxidative dissolution of gold under acid saline conditions. $\text{Au} + 2\text{Cl}^- \xrightarrow{[\text{O}][\text{H}^+]} \text{AuCl}_2^-$	Oxidized/saline/acidic; pH < 4.0, Cl > 35000 mg/L	High fineness gold
AuI_2^-	Dissolution of gold under moderately oxidative conditions $\text{Au} + 2\text{I}^- \xrightarrow{[\text{O}][\text{H}^+]} \text{AuI}_2^-$	Enhanced where I ⁻ is released by decomposition of organic matter	High fineness gold
$\text{Au}(\text{HS})_2^-$	Dissolution of gold by reduced waters during early supergene alteration, or by biologically generated reducing solutions $\text{Au} + 2\text{SH}^- \xrightarrow{[\text{O}]} \text{Au}(\text{SH})_2^-$	Reduced/neutral	Medium-high fineness gold
$\text{Au}(\text{S}_2\text{O}_3)_2^{3-}$	Weathering of gold/pyrite in neutral to alkaline solution $\text{Au} + 2\text{S}_2\text{O}_3^{2-} \xrightarrow{[\text{O}]} \text{Au}(\text{S}_2\text{O}_3)_2^{3-}$	Alkaline to weakly acid (meta-stable)	Medium fineness gold
$\text{Au}(\text{CN})_2^-$	Interaction of cyanide with gold $\text{Au} + 2\text{CN}^- \xrightarrow{[\text{O}]} \text{Au}(\text{CN})_2^-$	Cyanide present	Low fineness gold
$\text{Au}(\text{CNS})_2^-$	Oxidizing; Interaction of $(\text{CNS})^-$ with gold $\text{Au} + 2(\text{CNS})^- \xrightarrow{[\text{O}]} \text{Au}(\text{CNS})_2^-$	Mildly acid to alkaline pH	Low fineness gold (?)
Au-organic matter	Interaction of organic matter with gold under oxidizing conditions. $\text{Au} + \text{FA}^{2-} \xrightarrow{[\text{O}]} \text{AuFA}^-$	Dependent on source of material. Fulvate complex stable over wide pH range.	High fineness gold fine grained
Colloidal gold	May be formed during reduction of gold by organic matter $\text{Au}^+ + \text{OM}^- \rightarrow \text{Au}^0$	Not confirmed for natural waters	High fineness gold fine grained

As emphasized by *Bowell et al. (1993)*, these ligands act to reduce the oxidation potential required to dissolve the gold but do not themselves oxidize the gold. The solubility behaviour of gold therefore lies in the stability of the gold complex produced and the ability of the environment to oxidize the gold.

3.3 SOILS AND SOIL FORMATION

3.3.1 Soil Profile

Soils are a complex mixture of inorganic mineral matter and decomposed organic residues. They are formed from disintegrated or decayed rock which is a product of weathering. From a human point of view the formation of soil is by far the most important result of weathering. Soils differ greatly from area to area, not only in quantity but in quality and capacity to support the growth of plants. The same processes of weathering which produce the mantle-rock are continually at work breaking it up into finer and finer particles into a more complete decay. Soil proper is the thin upper portion of this mantle which is decomposed and altered sufficiently to support plant life (*Levinson, 1980*).

Levinson's (1980) concern of how little most geologists know about soils, emphasizes the importance of a sound knowledge of soils and their formation. Soils are an important sampling medium, and the dispersion of metals in soils forms the basis of many exploration programs.

One of the characteristic features of soils is the layering evident in vertical sections. The sequential layers are called horizons. Each horizon differs in composition, colour, texture, and/or structure, and the boundaries between them are often very sharp. From the surface downwards the horizons are designated as A, B, C and D. and they often have defineable sub-horizons such as A₀ or B₁. A succession (complete or incomplete with some missing horizons) is referred to as a soil profile, regardless of the thickness of each layer (Fig 4). Soil profiles may develop on parent material which can either be residual, or transported.

The A and B horizons constitute the solum, or true soil above the parent material, and consist of organic matter, a leached layer, and a layer of deposition. The profile grades downward into the weathered and then the fresh parent material referred to as the C and D horizons respectively. The C horizon of residual soils consists of variously weathered fragments of parent material, with any anomalous metal values similar to those in the parent bedrock.

A Horizon

The uppermost layer of the A horizon consists of organic debris lodged on the soil and is the zone of maximum biological activity. A_0 is the designation for the partially decomposed, or matted organic debris commonly called humus and the A_1 horizon is characterized by humus mixed with some mineral matter.

The A_0 horizon closely reflects the chemistry of the vegetation from which it is derived and analysis of material from this horizon is the basis of biogeochemical prospecting.

As water filters through the decomposed organic matter, carbonic and various organic acids are formed, with the result that the pH may be 4 or less. Although the acids are weak, they are continually being replenished by the decomposition of humus.

They move downward to lower levels where they react with other mineral matter and the soluble products released by weathering processes are also continually moved downward in solution. This depletion is characteristic of the entire A horizon, and is called eluviation (leaching). Where leaching is intense an A_2 zone will be found. This horizon is devoid of most of the organic matter, trace elements and much of the clays, and as a result, is light in colour, as opposed to the dark colours characteristic of higher horizons. The A horizon is a very poor sampling medium for geochemical purposes because of the intense leaching.

B Horizon

Whereas the A horizon is one of eluviation, the B horizon is one of illuviation (accumulation), and part of the leached material from the A horizon is deposited here.

The most soluble elements (e.g., the alkalis and alkaline earths as well as some metals) may be carried further downward, enter the groundwater system, and possibly be removed from the area. Where removal is complete as in a well-drained soil in a humid area, the profile is referred to as an "open" chemical system and soils in this environment are likely to be acid soils. Alkaline soils are characteristically found in dry or semi-arid regions, where water is insufficient to drain completely through to the water table - hence a closed chemical system.

The lack of water in such areas results in the precipitation of a calcium carbonate layer, called calcrete or caliche. It is found at the general level of the B horizon. Because the B horizon is one of accumulation of elements, and because the clay minerals and iron and manganese oxides which are found there have the capacity to adsorb metals to varying degrees, this zone is the one normally sampled during geochemical exploration soil surveys. It is generally easy to identify by virtue of its brownish colour and clayey texture.

C Horizon

The upper part of the C horizon consists of the bulk of the soil, and it grades downwards into unaltered parent material. The C horizon is only sampled in a limited number of situations such as where the A and B horizons are missing, or where anomalous values are expected to be found there (e.g., in some laterites).

The soil horizons are commonly more complex than has been described above. Multiple sub-horizons may exist, parts of the profile may be missing because of erosion or very poorly developed, and complexities may be introduced by multiple and vastly different cycles of weathering. The thicknesses of the individual soil horizons vary considerably. As a generalization, the A horizon varies from a few centimetres to 1 metre, and the B horizon from a few centimetres to about 2 metres. The C horizon is generally thicker than the other horizons, and in well-leached tropical soils in which weathering has been an uninterrupted process it may extend to 100 m or more.

Clay Minerals

Clay minerals are the insoluble products of chemical weathering of silicates, and they are often concentrated in the B soil horizon. There are five common groups of clay minerals, and a sixth, the mixed-layer clay minerals, that includes more than one type. The most common types of clay minerals are listed in table 4 together with their cation exchange capacity (base exchange capacity), which is a measure of their ability to adsorb cations (expressed in milliequivalents of the adsorbed cation per 100 grams of the clay).

The cation exchange capacity of clay minerals arises from the fact that between the plates and along the exposed edges of their plate-like structures, they contain unsatisfied bonds, and the overall charge of the plate is negative (Andrade, 1991). The cation exchange capacity increases with pH and thus at low pH values little adsorbed metal will be found on clay minerals. Particle size, surface area, amount of soil moisture, degree of crystallinity, and other factors all affect the ability of clay minerals to adsorb metals.

Table 3 Clay minerals and their cation exchange capacity (after Levinson, 1980).

<i>Group</i>	<i>Minerals</i>	<i>Cation Exchange Capacity (meq/100gm)</i>
kaolinite (kandite)	(halloysite, dickite, etc.)	3 - 15
mica	(illite, glauconite, etc.)	10 - 40
montmorillonite (smectite)	(beidellite, montmorillonite, etc.)	80 - 150
chlorite	(vermiculite, etc.)	10 - 150
fibrous clays	(palygorskite, sepiolite, etc.)	low
mixed-layer	(montmorillonite-illite, etc.)	variable

The general order of adsorption of some cations on clay minerals in decreasing order is (Boyle, 1979 and Levinson, 1980) :-



The common metals are also adsorbed to some degree. However, it is manganese and iron oxides commonly found in soils and sediments, which are the controlling factors in the fixation of the important heavy metals (Zn, Cu, Ni, Co) rather than the clay minerals. Clays (argillaceous rocks) generally have low permeability, which affects the ability of metal-containing fluids, or vapors, to penetrate them and can effectively mask an expression of buried mineralization (Mann and Webster, 1990).

3.3.2 Classification of Soils

The explorationist is concerned with classification of soils because of his need to recognize different types of dispersion during soil-forming processes, and to correlate these dispersion processes from one region to another.

Soils can be classified in many ways. In general, three categories of soils may be distinguished, azonal, zonal and intrazonal (Rose et al., 1991). In azonal soils, the nature of the soil is determined mainly by the parent material and represent immature soils. In zonal soils, a mature soil profile has developed, and the general characteristics of the soil are determined by climate and vegetation. In the intrazonal soils, a local condition, such as drainage, is the dominant influence on the characteristics of the soil. Figure 6 illustrates the close relationship of the distribution between zonal soils and climate. Rose et al. (1991), Levenson (1980) and Fitzpatrick (1971) are recommended for a more comprehensive description on the classification of soils.

3.3.3 Factors Affecting Soil Formation

There are five major factors affecting the formation of soil (Levinson, 1980 and Rose et al., 1991), briefly described below.

1.) Climate:

Climate is the most influential factor in chemical weathering and in the development of most soils. The distribution of the morphoclimatic zones in the world are illustrated in figure 5.

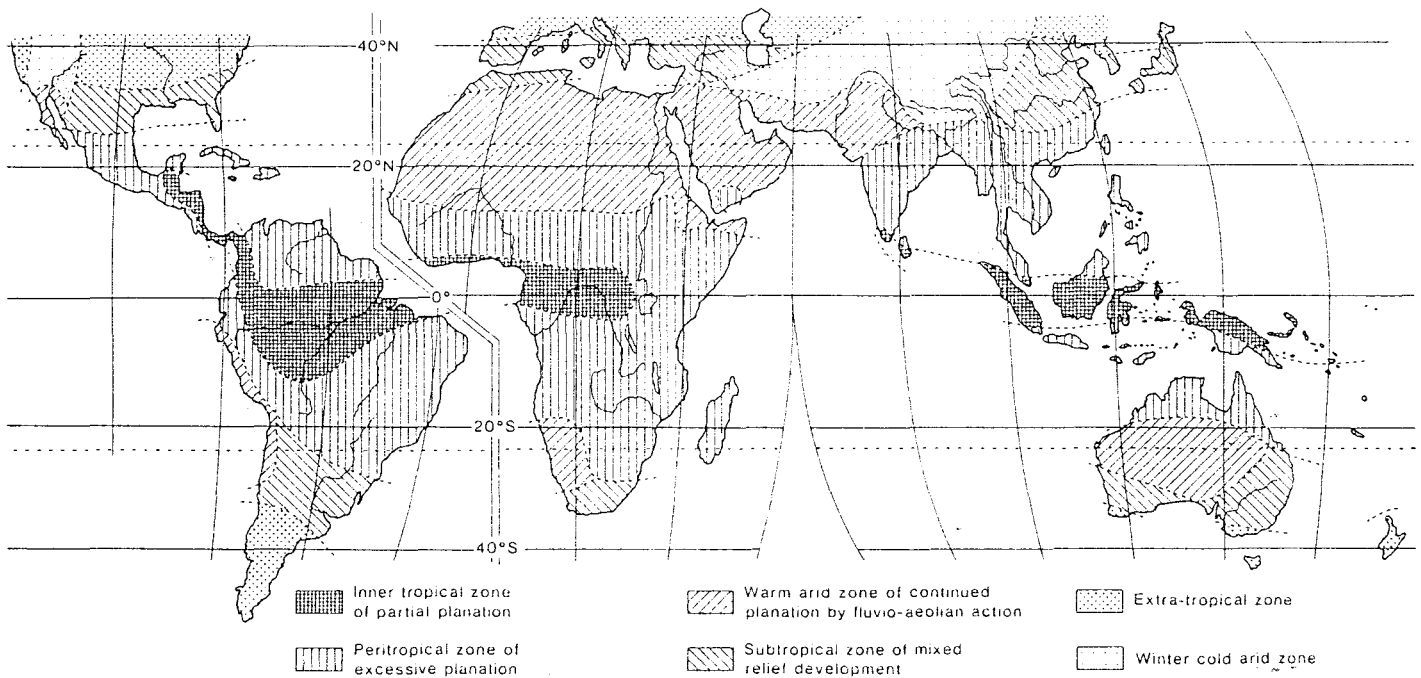


Fig. 5 World distribution of the morphoclimatic zones (after Rose et al., 1991).

Temperature and precipitation strongly influence the amount and type of vegetation, the rate of decay of this vegetation, the rate of weathering and leaching, the type of soil formed, and the position of calcium carbonate accumulations. Climate also exerts an influence on the type and abundance of living organisms such as bacteria which assist in soil formation processes. It is also a major factor in determining the type and abundance of humus in soil horizons and this in turn affects the pH. Humus generates acid conditions which increase the rate of mineral decomposition and the migration of elements to lower horizons.

2.) Biological Activity:

Vegetation is the main biologic factor in soil formation, although microorganisms do influence weathering and soil processes. Plants supply most of the organic material to the soil. With decomposition, vegetation is converted to carbon dioxide, water and various organic acids, and elements in the rock are then mobilized. Some of these elements will come directly from weathered rock, whereas others will be released from the decaying vegetation. The accumulation of humus is largely controlled by climatic conditions.

3.) Parent Material:

In the simplest case, a clean quartz sandstone can yield only silica upon disintegration, whereas in the same environment a granite with feldspars, mica and quartz, may release many elements upon weathering and probably will develop a different profile.

In the case of a limestone in a humid area, the soils developed on it will have a tendency to be alkaline, thereby counteracting the acidity of decaying organic matter. A porous, permeable parent rock assists leaching and the movement of fluids, and increases the rate of soil development. On an overall basis, the effect of parent material is mainly that of influencing the rate of weathering and soil formation.

4.) Topography Relief :

Topographic relief influence soil formation through its relationships with ground-water levels, drainage, and erosion. The A and B horizons are most strongly differentiated in regions of moderate to high rainfall where there is free drainage and effective leaching. Such profiles develop most readily, therefore, on the interfluvies in undulating country. In low-lying areas, the terrain may be saturated with water, almost to the surface. In such circumstances, a very different profile may develop. This profile consists of an organic-rich surface layer, overlying a pallid or mottled subsoil, in which reducing conditions prevail and leaching is at a minimum.

If water stands at the surface, peat may form. Changes from one drainage condition to another are usually transitional and give rise to a related sequence of profile types. The angle of slope affects drainage and erosion. In general, there is more rapid erosion, a greater volume of surface runoff, and less percolation on steep slopes than on gentle ones. Consequently, soils on steep slopes tend to be shallower, and show less distinct horizon development and a higher content of stoney material than those on more gentle slopes. In areas of very high relief, the elevation determines the local climate, with the result that soil types characteristics of different climates occur in topographically controlled patterns.

5.) Time:

Time is an important factor in soil development in tropical terrains, where weathering mantles have been evolving since the Tertiary or earlier. Soil formation has operated over very long time intervals, and any changes in the factors involved will influence the nature of the product (Butt and Zeegers, 1992).

The evolution of the soil cover can itself induce changes in the internal factors of soil formation. Landscape evolution due to pedogenesis may alter the conditions of groundwater movement. The development of horizons with different fabrics involves changes in permeability and in the rates at which minerals dissolve and are formed (Butt and Zeegers, 1992).

Soils are classified as juvenile or mature according to their state of development with respect to the present-day surface. Where erosion is active, soils will necessarily remain in a juvenile condition irrespective of time. If the time factor is adequate, and erosion proceeds no faster than soil formation, a mature profile will eventually result.

Partially indurated shales and sandstones are easily changed by weathering into soils, whereas the formation of soils from igneous and metamorphic rocks requires long units of time (Mann and Webster, 1990).

3.4 DURICRUSTS

3.4.1 Classification of Duricrusts

Duricrusts are a striking feature of the tropical and sub-tropical landscapes forming extensive, resistant horizons which form a surface or near surface caprock, best seen in incised landscapes, Goudie (1973), Butt and Zeegers (1992) subdivided duricrusts into three principal types :-

- 1) **Calcrete** - superficial gravels cemented by CaCO_3 formed by the deposition from solutions of calcium bicarbonate.
- 2) **Silcrete** - a conglomerate consisting of surficial sand and gravel cemented into a hard mass by silica or by the silicification of calcrete.
- 3) **Ferricrete (laterites)** - residual deposits formed under special conditions in tropical and sub-tropical terrains and consists essentially of hydrated Fe/Al oxides with silica as the most common impurity (Fe - laterite and Al - bauxite).

A more detailed discussion will be confined to ferricrete (laterite) and their chemistry in relation to gold exploration in tropical and sub-tropical terrains with only a brief description of the other major duricrust types.

The reader are referred to Goudie (1973) Kuzvart and Bömer (1978), and Grey et al. (1992) for a more detail study on duricrusts.

The principal types of duricrust frequently show a close relationship with present day climate. However, duricrusts commonly relate more closer to palaeoclimates, as old as Cambrian in certain cases. Rainfall is generally more important than than temperature in controlling duricrust distribution, but silica solubility, as free quartz, is closely related to temperature and solution pH.

Moderate to high temperatures in the tropics and sub-tropics are an important factor and alternating conditions of wetting and drying are essential for sesquioxide precipitation. Areas with peaked summer rainfall lose carbonate through leaching, resulting in a tendency to ferricrete formation.

Worldwide, duricrusts cannot be uniquely identified solely with a particular climatic regime, geographic location, age or single formation process (Fig. 6). Rather they form in response to a variable combination of physico-chemical conditions, the most important of which are climatic control and a favourable regime of groundwater fluctuation (Rose et al., 1990).



Fig. 6 World distribution of lateritic soils (after Lawrance, 1995).

3.4.2 Ferricrete (laterites)

Laterites (Fe-oxides) and bauxites (Al-oxides) are surficial accumulations of the products of rigorous chemical selection, developing where conditions favour, greater mobility of alkalies, alkali earths and Si than of Fe and Al (McFarlane, 1976). Enrichment of Fe and/or Al is a characteristic of laterite residua. In practice recognition of laterite is based on physical properties, the development of which do not coincide with a particular chemical assemblage.

The world distribution of laterites are illustrated in figure 6 and the close resemblance with the distribution of zonal soils and climate in figure 5 are remarkable.

The term bauxite is by convention reserved for alumina-rich laterite from which Al may be economically extracted. It describes a subgroup of materials within a larger genetic group of alumina enriched laterites.

The proportion of Al and Fe found in laterites has been variously attributed to Al, Fe and quartz content of the parent rocks (Gray et al., 1992). During the process of lateritization the primary minerals in the parent rock are broken down, leached of some of their components and secondary minerals form from the residua (Gray et al., 1992). These in turn are broken down and suffer the loss of some of their components such that the residua re-group to form more stable secondary minerals in a continuing process. The routes by which primary minerals yield place to the secondary minerals occurring in laterites and bauxites are varied. Feldspars may weather directly to kaolinite, or this stage may be preceded by halloysite and/or montmorillonite. Kaolinite formation is commonly the point at which the bulk of the Fe becomes available for retention or mobilization, but goethite may be directly produced by weathering of other primary minerals, for example biotite and hornblende (McFarlane, 1976). In some laterite profiles goethite gives way to haematite progressively upwards in the profile and goethite crystallinity improves in that direction. In other laterite profiles haematite is a relatively early weathering product. In some laterites there is an apparent inversion with relatively early weathering products reappearing in greater abundance in the top of the profile. This is due to the ability of pisoliths to protect from weathering the minerals they enclose.

The survival of the toughest of the early formed pisoliths and their accumulation as a surficial residuum can be compared with the survival and residual accumulation of very resistant primary minerals. Consequently the early weathering products which the pisoliths encapsulate can survive into the surface horizons. Laterite structures range from those in which the iron forms discrete segregations (commonly pisolithic structures) to those in which the iron occurs as a continuous skeleton (commonly vermiform or vermicular structures). Between these extremes lies a range in which both types of segregation co-exist, with varying predominance.

3.4.3 The Lateritic Profile

Laterite profiles vary enormously in scale. The laterite may be a few centimetres to tens of metres thick. Below this the saprolite, leached or unleached of Fe can vary from a few millimeters to over 100 metres. Figure 7 represents a schematic diagram of a complete lateritic weathering profile (Lawrance, 1995).

The accumulation of a chemical residuum requires that relief be sufficiently low to allow the products of chemical selection to accumulate more rapidly than they are removed by mechanical erosion. The slope at which lateritization may begin will vary with the permeability of the materials and also with the vegetation cover which affects the proportion of infiltration and the degree of protection from erosion afforded to the residuum. In a tectonically stable area lateritization can be placed within the late stages of landsurface reduction.

Laterite blankets can be subdivided into areas where either relative or absolute accumulation predominates, relative accumulations owing their concentration to the removal of more mobile components and absolute accumulations owing their concentration to the physical addition of materials. Fe escaping retention in topographically higher positions moves in solution downprofile and downslope and tends to be precipitated in slope-bottom situations where the water-table approaches the landsurface. There is also downslope mechanical movement of residua from higher topographic positions.

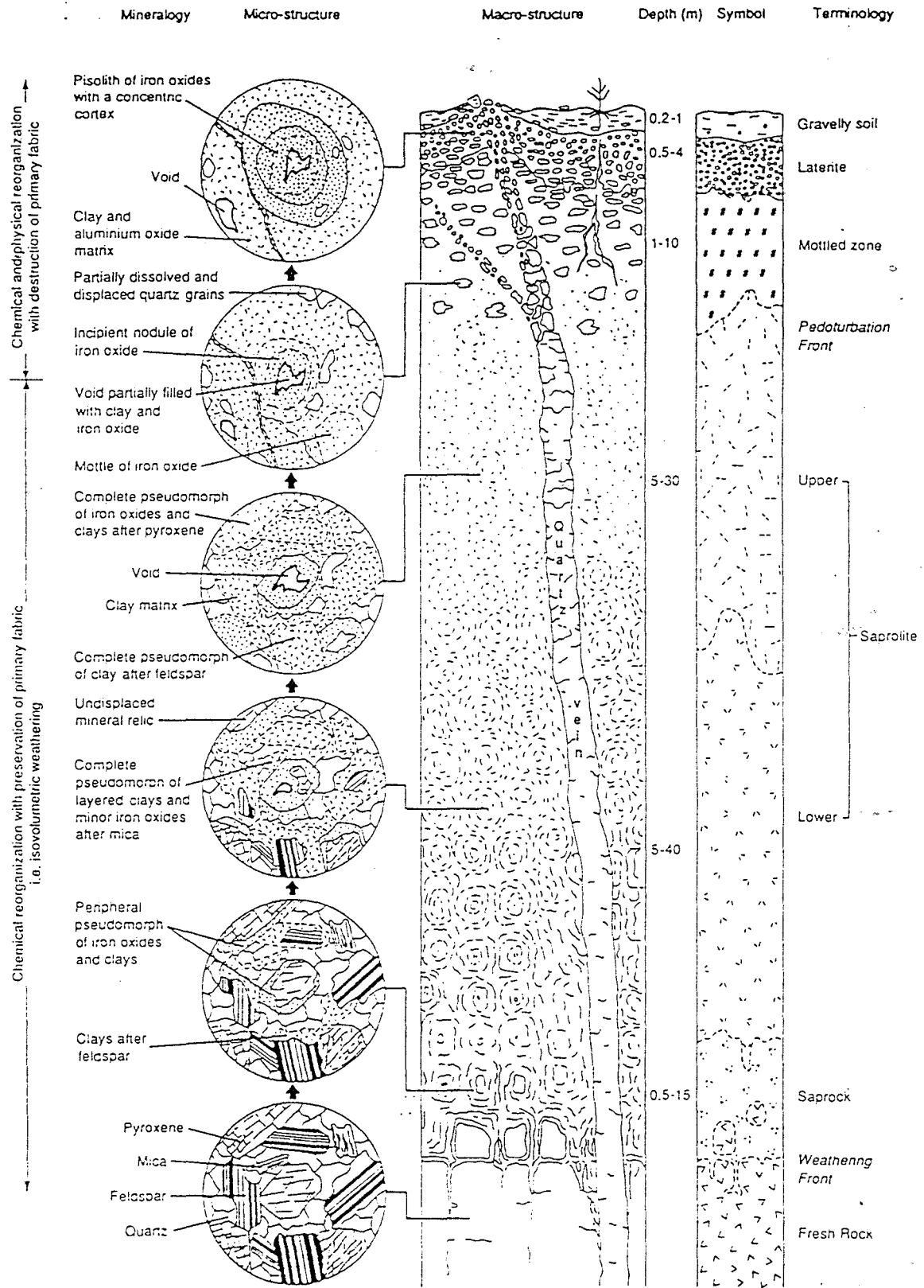


Fig. 7 Schematic representation of a complete lateritic weathering profile (after Lawrance, 1995).

In the early stages of lateritization, when slopes are comparatively steep, slope bottom situations are usually the first to show accumulation. Laterites are essentially residual accumulations of chemically resistant materials. The developing profile shows, from the base upwards, the stages of formation, their synchronous occurrence indicating that the process must have begun earlier at the top than the bottom. The products of each stage of weathering provide parent material for the succeeding stage. Much is known about the factors affecting the formation of metallic oxides and hydroxides in the weathering profile.

Selective removal or retention depends in large part on pH and Eh, organic complexing and rates of reactions. Weathering products from each horizon may survive into higher-lying horizons where more advanced chemical selection and its products predominate. This results in a structural and mineralogical assemblage which is not in a state of equilibrium at any particular horizon.

The association of laterites with stable or near stable landsurfaces carries with it the implication that the mineral assemblages in the profile are in a state of equilibrium. This could not be further from the truth. Responses to changes in conditions are so slow that in effect they never catch up with the changing conditions. It is important that the contents of laterites should be seen and be studied as the products of a history of conditions, not of a single set of conditions.

Lateritization is a supergene enrichment process, intimately associated with the movement of the land surface interface. Incision of a laterite surface terminates neither chemical selection nor prevents further movement of the laterite-bearing interface where it survives. For this reason it may be useful to distinguish between and to consider separately two periods in the life of a laterite :-

1. the early formation period, during the late stages of land-surface reduction, when the nature of the landsurface evolution most influences the development of the residuum and

2. the later post-incision period when, on the surviving now elevated parts of the original lowland, the nature of the laterite most influences the form and movement of the landsurface interface, the period when the supergene enrichment effects are most pronounced.

Some soil profiles are characterized by a stone line overlain by a brown-yellow loose-clay horizon (Fig. 8). Concordant with topographic surface, such stone lines may be traced continuously over considerable distances (Lecomte, 1988). These pedological profiles overlay a thick in situ weathered bedrock, called saprolite and have been considered unsuitable for the application of geochemical exploration techniques, mainly because of the thickness and the presumably allochthonous character of the weathering profiles.

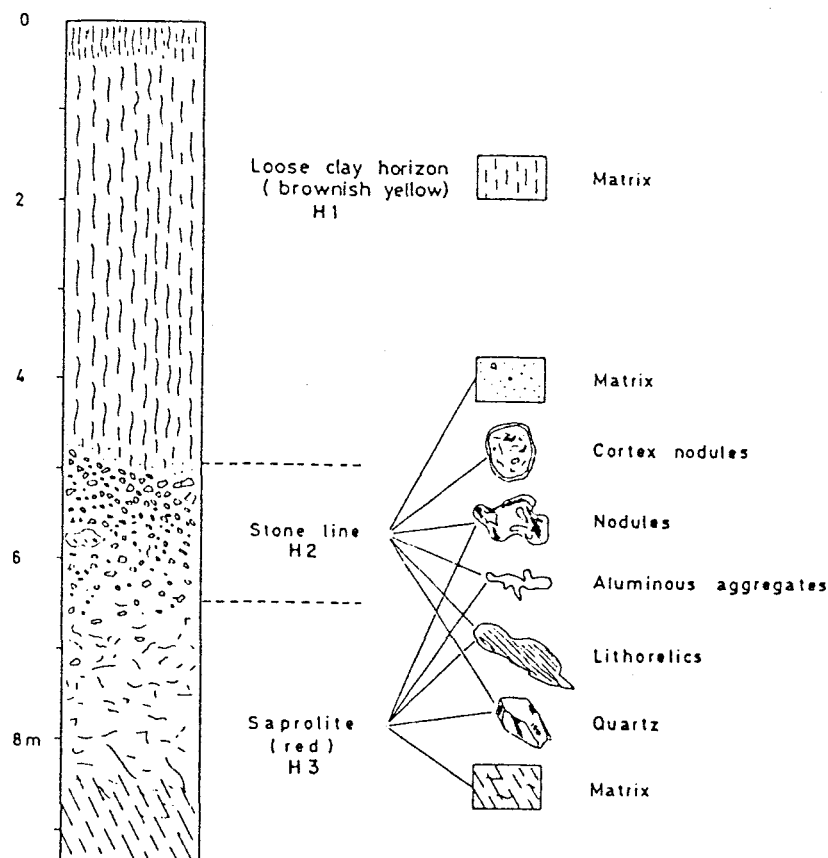


Fig. 8 A schematic diagram of a stone line profile (after Lecomte, 1988).

4.0 GEOCHEMICAL APPLICATIONS FOR GOLD IN TROPICAL AND SUB-TROPICAL TERRAINS

4.1 ORIENTATION SURVEYS

An orientation survey is a preliminary investigation designed to obtain technical information for planning an optimum routine survey (Rose et. al., 1991). The intent is to develop procedures that maximize the contrast of significant anomalies and minimize the number of false anomalies. Orientation surveys are absolutely essential in terrain where there has been little or no prior experience with geochemical exploration methods. In terrain where considerable previous geochemical work has already been done and effective routines have been established, elaborate orientation surveys are not so vital. An orientation survey normally consists of a series of preliminary experiments aimed at determining the existence and characteristics of anomalies associated with mineralization of the type to be sought. This information may then be used in selecting adequate prospecting techniques and in determining the factors and criteria that have a bearing on the interpretation of the geochemical data.

Although the orientation study will provide the necessary technical information upon which to base operational procedures, the final choice of methods to be used must also take into account other factors, such as cost of the operation and availability of personnel. If possible, these preliminary experiments should be undertaken in the vicinity of known deposits that have not been disturbed or contaminated by human activity, so that the natural geochemical pattern can be observed. It is important, however, that orientation should be conducted in areas where the geological and geomorphological characteristics are representative of those likely to be encountered during prospecting.

Determination of the distribution of gold values in unmineralized terrain is of equal importance. Background studies must be carried out well away from the possible influence of known mineralization. They should also cover the full range of environmental conditions that exist in the exploration area (Levinson, 1980).

The nature of the overburden, whether it is of glacial, alluvial, or wind-borne origin, is the first question that must be answered by the orientation survey. Sometimes it is surprisingly difficult to discriminate between residual and transported soil. The safest method, therefore, is to make critical and careful examinations of complete sections of the overburden at the start of every new field survey. If road-cut exposures are not available, the soil profile should be examined by pitting or augering.

4.2 STREAM SEDIMENT SAMPLING

Stream sediments, specifically silts and clays, are the basis of most drainage basin surveys, and as such sediments are considered to be representative of the catchment area, collection of the correct material is essential (Levinson, 1974). Stream sediments are a natural composite of all the material upstream from a sample site. They obtain metals by erosion of soil and rock and from inflows of groundwater. The metals may be contained in grains of minerals, but they are more commonly held in soil particles or precipitated coatings on rock and mineral fragments.

An anomalous drainage train may decay rapidly downstream or it may extend large distances (Rose et. al, 1991). Because many trains are persistent, stream-sediment sampling is effective in reconnaissance work where a single sample may represent a very large catchment area. In some areas, one stream-sediment sample is taken for each 100 km² of terrain; more commonly a sample represents only a few square kilometers of terrain, with two to three samples sites per kilometer along a main stream and at points on tributaries just above their junction. In detailed stream-sediment surveys, samples may be taken every 50 to 100m along the stream; in this work, metal values should increase upstream toward the source and then decline abruptly. The principle is clear-cut, but, as might be expected, complicating factors such as changes in grain size and grain mineralogy during downstream dispersal can provide a geologist with false anomalies (Peters, 1987). Stream sediment samples are generally easier to collect and easier to process than are soil samples. However, cultural noise is a particularly irritating problem because so much of humans trash ends up in streams and so much of the work of civilization is sited along streams.

Approximately 50 to 100g of minus 80 mesh material are taken from locations in low order streams, generally from the active stream bed, from pools, or from accumulation of fine material beneath boulders. Organic material likely to contain erratic metal concentrations should be avoided. Stream banks are not sampled in reconnaissance, but they are often sampled in the follow-up stage to locate the source of an anomaly.

4.3 SOIL (LOAM) SAMPLING

Soil sampling differs in several very important respects from stream-sediment sampling. It is generally employed in follow-up surveys where a drainage basin reconnaissance survey has isolated an anomaly, or narrowed an anomaly down to a particular watershed, or where geophysical, radiometric and other methods have indicated the possibility of mineralization. However, soil surveys have also been successfully used as a reconnaissance technique in flat areas where other methods are not applicable.

Soil surveys are almost always conducted on a grid system, preferable square but usually rectangular, with sample locations between 50 and 200m apart for the follow-up survey (Levinson, 1980). The line and sample spacings, especially for the follow-up survey, must be selected so that they will cross the strike of an ore body, and outline it. Therefore, the probable size and shape of the body will be a factor in determining the grid system, but is obvious that the more detailed the sampling, the more confidence one can place in interpretation.

In the initial phase of soil sampling, the grid should be selected so that at least two adjacent lines will intersect any ore body. Sample points along these lines should be spaced at intervals such that at least two points fall on each line within the anomaly. In places where the veins are discontinuous, and the ore body not homogeneous, a closer sampling interval will be necessary. Base maps should be prepared, indicating such information as geology, soil types and topography, so that the analytical data can be properly interpreted. Very accurate locations of the samples sites is only necessary in the more detailed stages of exploration. Initially, pace and compass traverses are usually sufficient (Zeegers and Leduc, 1991).

4.4 ALTERNATIVE SAMPLING TECHNIQUES

1. Lithogeochemistry

Lithogeochemistry techniques applied to gold exploration are not really specific, compared to application in the search for other types of ore deposits. Most of the published data are issued from orientation surveys undertaken in known mineralized environments. The presence of enhanced gold contents in some lithologies, thus suggesting a potential for mineralization, is mentioned in a general way by Boyle (1979), who also described extensive primary haloes around hydrothermal gold deposits. Lode-type deposits are generally characterized by gold haloes (Boyle, 1979).

2. Heavy-mineral concentrate geochemistry

Exploration programmes commonly make use of alternative sampling techniques involving the separation of fractions of surface material (soil, alluvium) according to specific gravity or magnetic susceptibility. In gold exploration, different approaches are possible using heavy-mineral concentrates obtained by panning or by heavy liquid separation (Zeegers and Leduc, 1991) :-

- 1.) optical determination and estimation of the content of visible gold and identification of possible pathfinder minerals; i.e. grain counts.
- 2.) chemical analysis with determination of gold content of the non-magnetic, heavy-mineral fraction.

To summarize, heavy concentrate surveys for gold exploration seem to be most useful for regional exploration. Optimum responses can be expected where physical processes of dispersion are most active. It should be kept in mind that some styles of gold mineralization (in which gold occurs in the crystal lattice of sulphides, or free but very fine grained) can be missed by heavy-concentrate techniques.

3. Biogeochemistry, Hydrogeochemistry and Atmogeochimistry.

Biogeochemical, hydrogeochemical and atmogeochemical prospecting for gold has been largely ignored. Only a limited amount of work has been done in the western world to assess the effectiveness of the technique and the results are somewhat diverse depending on the scale of the surveys.

5.0 GEOPHYSICAL APPLICATIONS

5.1 GENERAL

The objective of geophysical surveys in mineral exploration has traditionally been to detect subsurface geological features. This may reflect the presence of mineralization in depth and, if possible, to measure the dimensions the ore body. Geophysical methods may also be used to locate extensions to known mineralization and for determining the size, depth and internal characteristics of an orebody. Marked improvements in geological concepts of ore genesis have led to a better appreciation, amongst geologists, of mineralized environments, and this has had an effect on the use of geophysics in recent years. One of the main applications of geophysics lies in areas where the orebodies and associated structures are not exposed.

In designing a geophysical survey it is desirable to develop a sound geological model because the results of geophysical investigation will ultimately have to be interpreted in terms of subsurface geology. In order to effectively screen the geophysical anomalies, it is therefore imperative that the geoscientist should be thoroughly familiar with both the geology of the area and the geophysical properties of the rocks in the region. The most effective use of geophysics in mineral exploration necessitates the translation of a conceptual geological model into physical values at the outset of a geophysical programme as this will dictate the choice of the most suitable geophysical method. The reliability of the geological picture which ultimately develops will be in large part dependant on the geologist's ability to interpret the geophysical data in terms of the local geology.

The choice of a geophysical method will depend on the characteristics of the mineral sought, including the deposits anticipated size, shape and depth extent. For gold exploration in tropical and sub-tropical terrains, the nature of the host rock, the immediate ore environment together with depth of weathering, gold mobility, duricrust formation, ect. are very important considerations. Figure 9 shows some of the principal geophysical methods used in mineral exploration. Table 3 summarizes the factors that adversely effect the sensitivity of the main geophysical methods. Most of the methods are integrated with on-site microcomputers for plotting analog and digital records, for filtering the data, and for relating the data to geophysical response models.

Method	Parameter, characteristic physical property	Main causes of anomalies	Applications: direct indirect investigation		Method	Parameter, characteristic physical property	Main causes of anomalies	Applications: direct indirect investigation	
GRAVITY ground, marine	gravity, milligal (1 gal = 1 cm/s ²), density	deposits of heavy ores, differences in the distribu- tion of densities	iron ore, chromite, pyrite, chalcopryite	geological structural mapping, placer configuration	SELF-POTENTIAL ground, logging	natural potential field, mV, conductivity, oxidability	massive con- ductive ores, graphite, filtration	sulphides pyrite, pyrrhotite, chalcopryite, galena, pentlandite	associated minerals, tin, cobalt, gold, silver
MAGNETIC ground, airborne, marine, logging	earth magnetic field: total intensity, vertical gradient, $I_y = 10^{-5}$ gauss, magnetic susceptibility	magnetic content of the material, contrast of magnetization	magnetite, pyrrhotite, titano- magnetite	iron ore, chromite, copper ore, kimberlites, geological structural mapping	ELECTROMAGNETIC ground, airborne, marine, logging	electromagnetic field induced by energizing coil or wire, natural electromagnetic field, standard VLF transmissions, pulse EM field, electrical conductivity	conductive mineralization, surficial con- ductors, shear zones	conductive sulphides, oxides, graphite, magnetite	ground follow-up, associated minerals, shear zones, weathered zones, kimberlites
RESISTIVITY ground, marine, logging	apparent resistivity, Ωm , resistivity, conductivity	conductive vein, ore body, sedi- mentary layer, resistive layer, limestone, volcanic intru- sion, shear zone, fault, weathering	massive sulphides, quartz, calcite, special clays, rock salt	detailed tectonics, base metals, phosphates, uranium, potash, coal	RADIOACTIVITY ground, airborne, logging	gamma radiations, μ Roentgen, radioactivity	radioactive elements uranium, thorium, potassium	radioactive minerals, coal, phosphates, monazite	ground follow-up, geological structural mapping, differentiation in granites
INDUCED POLARIZATION ground, logging	time domain, chargeability, ms, polarizability, %, frequency domain, frequency effect, %, metal factor, ionic-electronic, over voltage	conductive mineralization, disseminated or massive	conductive sulphides, oxides	associated minerals, zinc, tin, gold, silver	SEISMIC ground	refraction, reflection, travelling time of elastic waves, m/s, elastic wave velocity, dynamic modulus	contrast of velocity, marker at variable depth, fissured rocks	buried channels, faults, general tectonics, sand, gravel deposits, heavy minerals	tin, heavy minerals placers, coal, uranium

Fig. 9 A diagrammatic summary of the main geophysical methods (after Kuzvart and Bömer, 1978).

Table 3. A summary of factors that adversely effect the sensitivity of the geophysical methods (after Ward and Rodgers, 1967).

Method	Geologic noise	Topographic noise	Location and orientation errors
gravity	—local density inhomogeneities — regional gradients — bedrock relief	incomplete topographic correction due to lack of detailed knowledge of subsurface density distribution	elevation errors, latitude correction errors
magnetics	—local susceptibility inhomogeneities —regional gradients —bedrock relief —remanence inhomogeneities	topographic correction extremely difficult to make with any assurance due to irregular magnetization of irregular shapes	usually are insignificant except irregular terrain clearance in airborne surveys
resistivity	—local conductivity inhomogeneities —regional gradients —bedrock relief —buried contacts —broad shear zones —graphite horizons —masking effect of highly conductive or highly resistive overburden	topographic correction extremely difficult to make with any assurance due to irregular distribution of subsurface conductivities	usually are insignificant but see under induced polarization
electromagnetics	— local conductivity inhomogeneities —faults, shears —graphite horizons —masking effect of highly conductive overburden	usually are insignificant in inductive methods but same as for resistivity with conductive methods	erroneous orientation of transmitting coil relative to receiving coil
induced polarization	—minor magnetite in country rock or overburden —graphite horizons —clay minerals in overburden or country rock —masking effect of highly conductive or highly resistive overburden	usually insignificant but all our theory assumes electrodes on flat earth. Gullies can and do give resistivity and induced polarization anomalies.	usually insignificant but all our theory assumes electrodes placed on flat earth. Must correct for irregular surface if theory to be strictly applicable.

5.2 AIRBORNE GEOPHYSICS

In general, airborne geophysical methods are used in reconnaissance and ground geophysical methods are used in more detailed investigations. There are, however many instances in which either airborne or ground methods could be used. In a extended exploration programme, combinations and sequences of methods may be appropriate, and there is often a need to weigh their individual advantages (Parasnis, 1986).

Airborne surveys have some impressive characteristics. They are fast, they are relatively inexpensive per unit area, several kinds of surveys can be obtained at once, and they can provide a more objective coverage than ground surveys, especially in tropical and sub-tropical terrains because they are reasonably uniform and complete and they do not have the access and traverse problems of ground surveys (swamps, dense brush, rugged topography etc.).

Airborne surveys have considerable flexibility, but they have some specific weather and terrain limitations as well. Because many surveys must be flown with a terrain clearance of less than 150 m in order to obtain a suitable signal, days or weeks may be lost because of low clouds. Flight-track recovery, the relating of the finished survey to ground features, is often done by selecting points in a narrow strip of ground photographed during the survey; for this, too, weather must permit some recognizable features to be visible (Peters, 1987).

An airborne survey will give more accuracy than a ground survey in some areas, but it will seldom provide such detail or such sharp signals as a ground survey. A ground survey can be made with more closely spaced lines, and it can be done with a wider choice of methods and equipment. However, navigation along pre-planned flight lines using preset GPS are currently widely and frequently used (Rose et al., 1991).

A choice must sometimes be made between helicopter and fixed-wing aircraft for an airborne electromagnetic or radiometric survey. Helicopters have an advantage in being able to maintain a more constant ground clearance above rugged terrain. Also, helicopters have a slow-flying capability that allows for greater accuracy and they can land for a ground check in critical areas. Helicopter geophysical surveys can therefore be used in detailed work as well as in reconnaissance. Still, there are disadvantages. Helicopters are much more expensive to operate than are fixed-wing aircraft, they can cover only a third as many line-kilometers per day at best, they have a relatively short range of operation, and they require more maintenance work per flying hour.

The decision to use a helicopter in a geophysical survey is generally based on the assumption that the helicopter will permit an essential level of accuracy or detail that could not be matched in a fixed-wing survey (Peters, 1987).

5.2.1 Aeromagnetism Surveys

Aeromagnetic surveys are well-established ways of finding indications of lithologic contrast, faults, folds, and concentrations of ore. Total intensity contour (isogram) maps show distortion of the earth's magnetic field by patterns in crustal rocks. When the regional magnetic field, which is represented by the more uniform background trend, is subtracted, magnetic anomalies remain. Aeromagnetic anomalies so slight that they rise to only a few gammas above the regional background may be significant in a mapping program (Parasnis, 1986).

Rock magnetism is a function of magnetic susceptibility, the ease with which the constituent minerals may be magnetized. A strong aeromagnetic anomaly may therefore be associated with a variety of rock conditions. Metamorphic derivatives of ferruginous sedimentary rocks cause some of the strongest magnetic responses. Precambrian banded iron formations have a particularly high magnetic susceptibility (Peters, 1987).

The aeromagnetic map with total intensity magnetic contours, is interpreted directly or it may be processed further to obtain a filtered map. There are various types of filtered maps, many of which simply assist in discriminating between shallow and deep anomalies. Interpretation is done by referring to geophysical models and by matching whatever geology is known with the more complete aeromagnetic pattern. A fault zone may be recognized as an anomaly by comparing the aeromagnetic pattern with models of dipping slabs or it may be recognized by the displacement or truncation of other anomalies.

The aeromagnetic signature of a certain lithologic sequence will have characteristics that relate to the magnetite content in its members, and the signature may be traced across the map from places where parts of the sequence are known on the ground. Obviously, the most effective interpretation of aeromagnetic maps, or of any geophysical data for that matter, is done by geologists and geophysicists working together (Peters, 1987).

5.2.2 Airborne Radiometric Surveys

The principal methods in airborne radiometric surveying are gamma-ray spectrometry and total-radiation radiometrics. Both methods employ the same basic ideas and detectors. Gamma-ray spectrometry is generally more versatile than total-radiation radiometrics.

The detecting unit consists of one or more crystals of thallium-activated sodium iodide, a material that emits a flash of light, a scintillation, when struck by a gamma ray. The intensity of the scintillation is directly proportional to the energy of the gamma ray, which is in turn a measurable function of the uranium, thorium, or potassium source (Peters, 1987).

The scintillation is converted to a voltage by a photomultiplier tube, and the pulse height is compared with that of a reference source. Voltage pulses and gamma-ray count rate data are recorded in multiple channels and processed by an on-board microcomputer. Results are obtained with reference to diagnostic spectral windows, as equivalent values for uranium, thorium, and potassium, as ratios between the elements, and as total count (Peters, 1987).

Interpretation of airborne radiometric data is best done with as much prior knowledge of overburden conditions, rock types, and terrain as can be obtained. Photogeology is therefore usually done just ahead of radiometric work and is regarded as a reconnaissance programme. On the basis of a reconnaissance map, a radiometric anomaly may be explained entirely by the position of a granite knob surrounded by alluvium or by a high hilltop or it may have a spatial connection with known or suspected pegmatite dykes.

5.2.3 Airborne Electromagnetic Surveys

Airborne electromagnetic methods provide a means of mapping the electrical conductivity of the uppermost rocks in the earth's crust. There are several methods, all of which have a common principle.

An alternating current from a transmitting coil (active system) or from a larger and more remote source, such as atmospheric electricity or radio stations (passive system), generates an electromagnetic field in the earth's crust. Where the field encroaches on an anomalously conductive body, eddy currents are induced. The eddy currents generate a secondary electromagnetic field that can be picked up by detector coils and recorded. There is a problem in identifying the conductive body, because graphite zones, conductive overburden, and some clay beds as well as metallic mineralization can cause anomalous signals. The problem is met, but only in part, by multifrequency (multichannel) systems in which the response from conductive overburden can be identified and taken into account (Peters, 1987). Airborne electromagnetic surveys have been very successful in locating anomalies from orebodies, especially from the electrically interconnected mineralization of gold deposits in temperate areas with little surficial oxidation (Rose et al., 1991).

5.3 GROUND GEOPHYSICS

One of the principal advantages of ground electrical surveys is their capability of making direct contact with the earth. For this reason, electrical methods are widely used in detailed exploration for orebodies. Ground magnetic methods, like aeromagnetic methods, are used as aids to geologic mapping as well as in searching for orebodies. Ground electromagnetic methods are in general use where massive sulfide deposits are sought. Ground radiometric surveys are not as often applied to geologic mapping as are airborne radiometric surveys. Gravity methods most often have a follow-up function in the interpretation of other geophysical anomalies, and they are used in subsurface geologic mapping (Rose et. al, 1991). Gravity surveys are hampered by terrain effects, especially in mountainous country, but they are less affected when made in deeper underground mine workings (Peters, 1987).

5.3.1 Ground Electrical Surveys

An electrical method, induced polarization (IP), is the most popular ground geophysical method used in mineral exploration.

Although originally designed for work with disseminated sulfide bodies, induced polarization was soon found to give more diagnostic anomalies above vein deposits than had been obtained by the longer established electrical resistivity methods. Electrical self-potential and equipotential methods of prospecting are less popular than in past years. Resistivity is a measure of the difficulty in sending an electrical current through a substance (Peters, 1987).

Induced-polarization methods use the two modes of electrical conduction that occur in mineralized rocks, ionic (in pore fluids) and electronic (in metallic minerals). When a current is applied to a medium containing both types of conductors, an exchange of electrons takes place at the surfaces of the metallic minerals causing (inducing) a polarization and forming an electrochemical barrier. This barrier provides two useful electrical phenomena. First, an extra voltage, an overvoltage, is needed to send the current across the barrier. When the current is cut off, the overvoltage does not drop to zero immediately; instead, it decays, allowing a current to flow for a short time. Second, the resistivity of a mineralized rock having the electrochemical barrier has diagnostic characteristics, including phase displacements and differences related to the frequency of the applied current. In unmineralized rocks, the applied current is carried only by the ionic solutions in pore spaces and the resistivity is independent of the frequency of the current. Induced-polarization surveys are made by the time-domain method, using the decay phenomenon, and by the frequency-domain method, using the resistivity contrast phenomenon.

All common sulfide minerals except sphalerite are electric conductors; so are most other minerals with a metallic luster, including graphite and some kinds of coal. Thus minerals other than ore minerals will give an induced-polarization response. A response, geologic noise, is also obtained from some clay minerals that are not electronic conductors but have an unbalanced surface charge.

4.3.2 Ground Magnetic Surveys

Ground magnetic surveys have become increasingly popular with field geologists because of the availability of small, easily operated magnetometers. Often the magnetic survey will be run by the geologist as a part of a mapping programme. The most common instruments currently in use are proton precession and fluxgate magnetometers.

5.4.3 Ground Electromagnetic Surveys

Ground electromagnetic systems generally operate in the frequency domain, but there are also time-domain (TDEM) transient methods, and there are methods that combine the two. There is a wide variety of techniques and instruments involving vertical coil systems and horizontal coil systems of transmitters and receivers, and there is the Turam system with a long fixed cable as the energizing source. Audio-frequency magnetotellurics (AMT) is a system that combines the measurement of electric and magnetic fields from natural and applied sources over a wide range of frequencies. In VLF-EM ground systems, easily portable equipment provides a means of making quick subsurface investigations while mapping or doing reconnaissance work.

5.3.4 Ground Radiometric Surveys

Hand-held radiometric instruments have two types of detectors, Geiger-Miller tubes and scintillators. The Geiger counter, an instrument that became a standard item of equipment for geologists and prospectors during the 1950s, has been replaced by more sensitive scintillation detectors for reconnaissance surveys. Geiger counters have a relatively weak response to gamma radiation, but they are mechanically robust and have greater electronic stability than do scintillation detectors. Geiger counters are therefore preferred for making accurate measurements in areas of strong radioactivity, in uranium mines, and in orebody boreholes. Scintillometers are used for detecting total gamma radiation, and gammaray spectrometers are used for differentiating between radiation from uranium, thorium, and potassium sources.

5.3.5 Seismic Surveys

The seismic methods of geophysical exploration utilize the fact that elastic waves travel with different velocities in different rocks. The principle is to initiate such waves at a point and determine at a number of other points the time and arrival of the energy that is refracted or reflected by the discontinuities between different rock formations. This then enables the position of the discontinuities to be deduced. The elastic waves could be set off by explosives placed in a shallow hole or by vibrators which is usually mounted on large trucks. The importance of the seismic methods lies above all in fact that their data, if properly handled, yield an almost unique and sound interpretation (Parasnis, 1986).

Stratigraphic interpretations from seismic data depend on the data being sufficiently free of noise so that the seismic response is predominantly that of the rock formation. Thus, good recording and processing are essential. Given a reasonably noise-free response, seismic wavelength limits the detail which can be seen in two dimensions: vertical, or the thickness of stratigraphic units; and horizontal, or the areas size of features (Ward, 1977).

5.4 SATELLITE IMAGERY AND AERIAL PHOTOGRAPHY

5.4.1 Satellite Imagery

Various satellites (Landsat-1, -2, -3) have been placed in orbit, capable of transmitting multispectral scanner (MSS) data on 4 spectral wavebands, 2 of which (bands 4 & 5) correspond to the green and red portions of the visible spectrum, and the other 2 (bands 6 & 7) which correspond to near-infra red portions of the spectrum just beyond the visible zone. With the advent of Thermal Infra red scanning a far greater spectrum is now available.

Landsat produces computer-compatible tapes as well as derived photographic images. Geological reconnaissance commonly uses black and white prints (bands 5 and/or 7) and "false colour" composites of several bands (4,5, & 7).

In a false colour composite vegetation appears in shades of orange and red, water in black, and soil and rocks in shades of green, gray, red, orange and brown. Imagery can be processed in various ways so that the colour ratios can be made to enhance certain spectral differences. Geologic features can also be enhanced by selecting imagery from certain times of the year, e.g. when partial snow or vegetation bring out subtle differences in structure or lithology, Present Landsat imagery affords good resolution and broader MSS data, however it has limited use on a global scale because not many countries have the necessary receiving equipment.

One of the drawbacks of Landsat imagery is the time factor - it is incapable of transferring images from space, so they have to be digitised. Aerial photography therefore is quicker, although Landsat (and Remote Sensing methods generally) have the advantage of picking up non-visible information.

The principal advantage of satellite imagery in comparison to aerial photography is its better synoptic view of large areas, hence the application during early stages of reconnaissance. It should be used in conjunction with aerial photography (for the synoptic view), whilst aerial photography, especially colour, has the benefits of higher resolution, and stereoscopic image (Wade, 1993).

5.4.2 Photo-geology and Aerial Photography

Aerial photography and their geological interpretation are integral tools in all reconnaissance and follow-up work. The initial aerial photographic interpretations to create a base map and to obtain synoptic views at almost any scale provides valuable information for the explorationist. Photogeological interpretations are critical for the overview, they give the possibility of a variable perspective, an appreciation of landforms and the interaction of many geological features. It also give vital clues in the study of structural features and their inter-relationship with the lithological units.

Structural analysis is never complete unless one undertakes a thorough photogeological interpretation.

Interpretation of photographs largely revolves around interpretations of tonal contrast, texture and geomorphic features. Land forms are distinct, and relief displacement permits stereoscopic vision, which emphasises even the most subtle variations in terrain (Peters, 1987).

Photography should be planned for the various seasons, depending on the vegetation pattern. Evergreen vegetation may be too dense in all seasons for an effective look at the ground. Topographic relief may be so great that the photographs are badly distorted unless taken at extremely high altitude (therefore at a small scale). Radar imagery has poorer resolution than photography, but it cuts through cloud cover and even light vegetation (Coggan, 1984). For a more advanced and better overall coverage on geophysical exploration, a textbook by Parasnis (1986) is recommended.

6.0 CASE STUDIES

6.1 INTRODUCTION

Central- and West African case studies included in this guide for gold exploration in tropical and sub-tropical terrains are more relevant and beneficial to the South African geologist. The growing interest of major South African mining and exploration companies to explore and invest in Africa supports the concept to develop a sound geological knowledge by utilising case studies. The case studies illustrate the effectiveness and constraints of some of the exploration techniques used in tropical and sub-tropical terrains and could eventually ensure a greater success rate in gold discoveries. The reader are referred to the reference list for other case studies.

6.2 GENERALISED GEOLOGY OF CENTRAL- AND WEST AFRICA

A brief introduction to the tectonism and regional setting of Central- and West Africa are necessary to understand the African geology. The similarities between the large massifs, mainly Proterozoic age, of the Guyana Shield and West African Craton before the Gondwanaland break-up are illustrated in figure 10.

The Precambrian W. African - S. American Link (East Gondwanaland)

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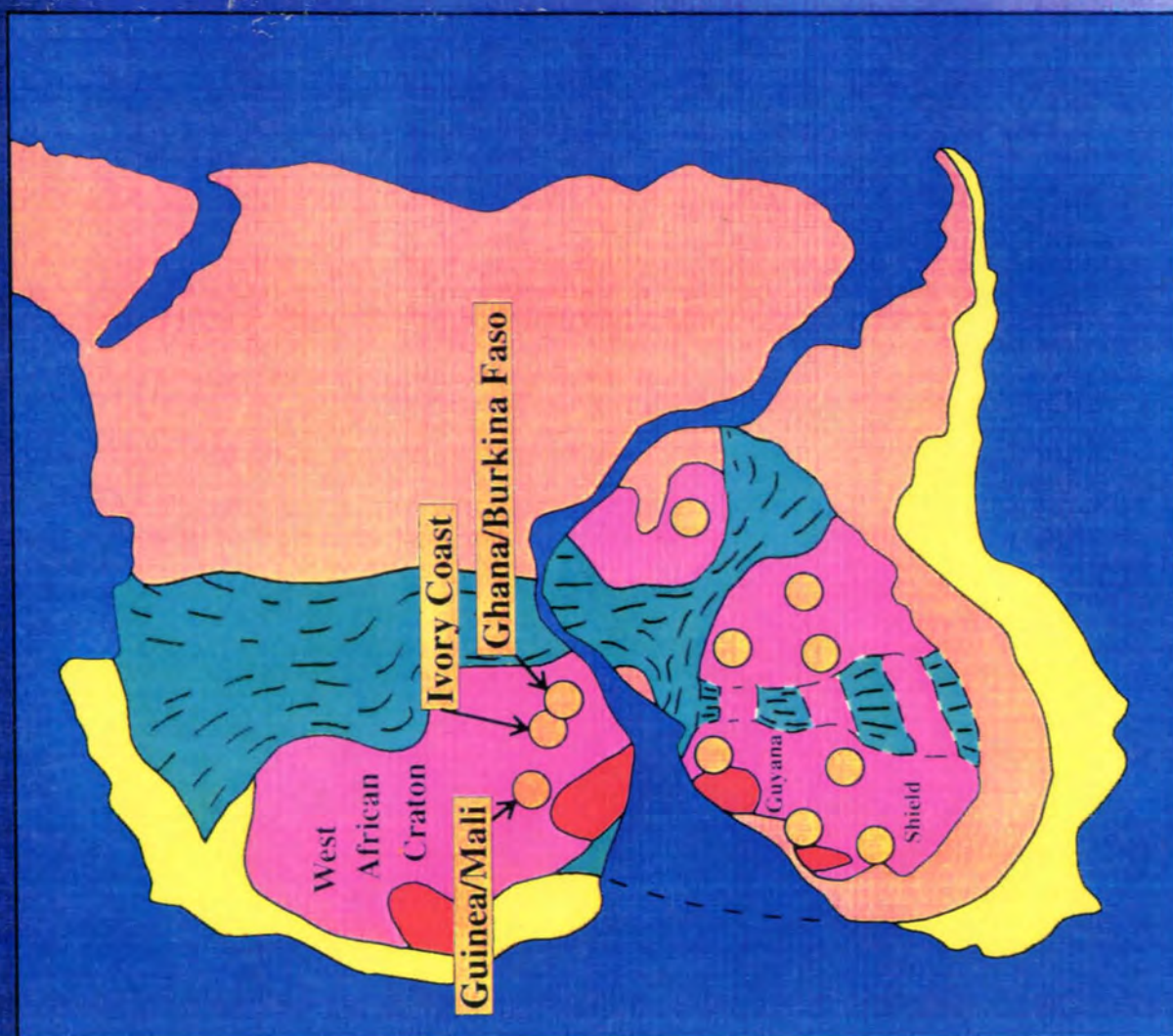


Fig. 10 The Precambrium linked of th Guyana Shield and West African Craton
(adopted from Golden Shamrock Mine's internal report, unpublished).

Orogeny events which began about 2000 Ma and lasted over 200 Ma resulted in extensive metamorphism of existing rocks, prolonged igneous activity and the deposition of various sedimentary rocks. The multistage metamorphic history has resulted in both regional and contact metamorphism, ranging from very low- to medium-grade. The pronounced west-northwest elongation of late-stage deformation influenced both greenstone and granitoid rocks (Fig. 10). Faulting and the emplacement of dykes re-activated many of these deformation zones which acted as the main source for the hydrothermal gold deposits.

The West African Shield, which on the basis of age, lithology and regional tectonics can be divided into an older, Archaean terrain, and a younger, early Proterozoic (2000 my) domain (Fig. 10 and 12). A generalised stratigraphic succession for Central and West Africa are presented in the table below :-

PHANEROZOIC	CENOZOIC MESOZOIC PALEOZOIC	
PROTEROZOIC	UPPER PROTEROZOIC MIDDLE PROTEROZOIC	
	LOWER PROTEROZOIC	Tarkwaian Eburnean Birimian
ARCHAEAN		Liberian
		Archaean

Table 5 Correlation of the birimian Supergroup and the Eburnean events (after Petters, 1991).

	Ghana	Côte d'Ivoire	Liptako, NE Haute Volta, and W Niger
2.03 Ga	TARKWAIAN { - Huni formation (quartzites and phyllites) - Tarkwa formation (phyllites) - Banket formation (quartzites and conglomerates) - Kewese formation (conglomerates)	Windéné granite and Bondoukou type granites Kinkéné series	Epizonal sediments of the Amarasinde and Bellekoiné formations — the Liptakoian
2.13 Ga	~~~~~	Eburnian II ~~~~~	? ~~~~~
UPPER BIRIMIAN	{ - Syntectonic and intrusive granitoids - Basic volcanic formation - Acid volcanic formation - Volcanic arenaceous formation	Baoule type granites Volcano-clastic formation de Louga = Série de Inahiri	Granitoids Mesozonal metamorphites of the Dibirshi and Tambao formations
2.27 Ga	~~~~~	Eburnian I ~~~~~	~~~~~
LOWER BIRIMIAN	{ - Upper arenaceous formation (sandy flysch) - Upper argillaceous formation (pelitic flysch) - Middle arenaceous formation (sandy-pelitic flysch) - Lower argillaceous formation - Lower arenaceous formation	Orthogneissified granitoid Flyschoids Kounoukou and Doulayeko paragneiss	
2.6 Ga	?	~~~~~	? ~~~~~
		N'iega - Pauli Plage gneissified granite Monogaga paragneiss	Pre-Birimian crystalline basement

Petters (1991) tabulated the correlation of the Birrimian Supergroup and the Eburnean events in table 5. The difficulty in correlating the various rocks and events across countries emphasized by various authors can be ascribed to a general lack of continuous outcrops in tropical and sub-tropical terrains. A better understanding of the regional geology and tectonic events are fields that need more attention.

Figure 11 illustrates the distribution of Lower Proterozoic rocks throughout the African continent which are successfully implemented to delineate exploration targets in African countries with known gold deposits and areas of possible gold discoveries.

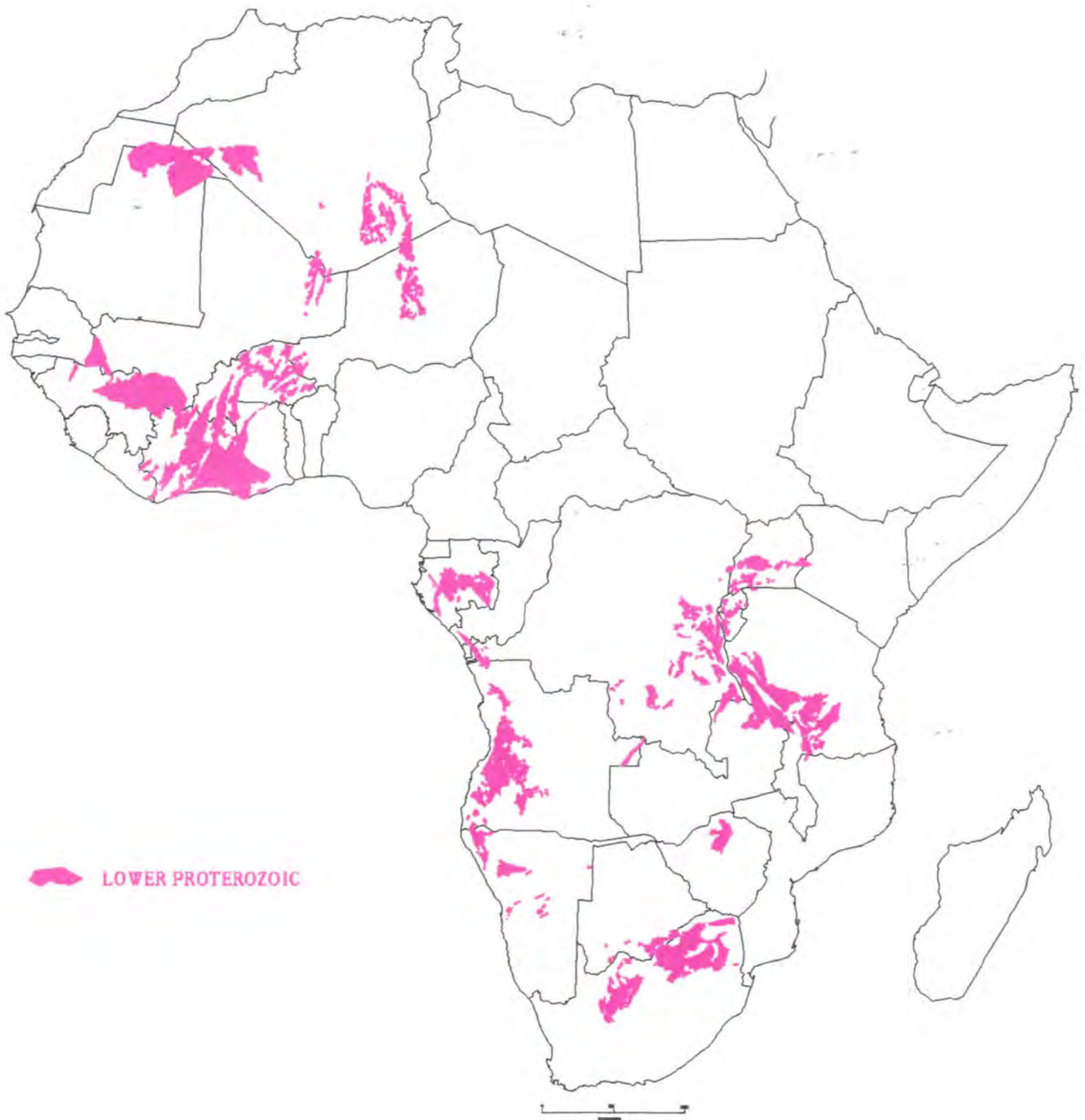


Fig. 11 The distribution of Lower Proterozoic rocks in Africa (adapted from Rangold's internal report, unpublished).

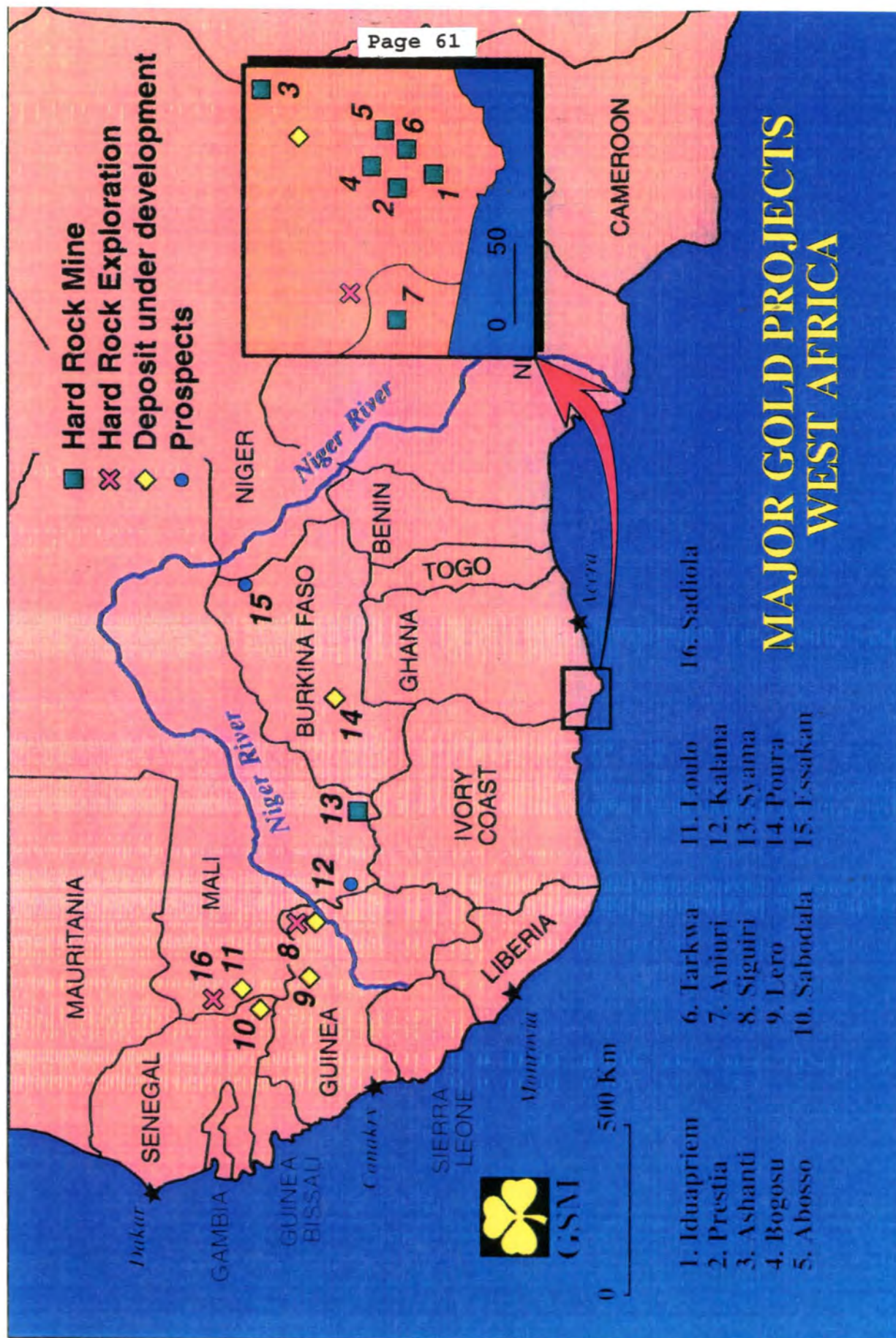


Fig. 12 The regional geology of West Africa (adopted from Golden Shamrock Mine's internal report, unpublished).

6.3 CASE STUDIES

A general classification of the major gold mineralization types, based on criteria such as the type of host rock, type of host structure, and the geometry of the orebody and its parageneses allow us to distinguish between the following types (Milési et al., 1989) :-

1. mineralization enclosed in tourmalinized turbidites (Loulo in Mali).
2. mineralization with disseminated sulphides enclosed in volcanic or plutonic rocks (Yaouré in Côte d'Ivoire, Syama in Mali).
3. gold-bearing conglomerates (Tarkwa district in Ghana).
4. lode mineralization with gold-bearing arsenopyrite (Ashanti in Ghana).
5. gold and polymetallic sulphides (Poura in Burkina Faso, Kalana in Mali).
6. alluvial and eluvial placers.
7. lateritic orebodies (Ity in Côte d'Ivoire).

Figure 13 show the localities of the better known gold deposits, prospects and occurrences in West Africa.

6.3.1 Pouna, Gabon

The Pouna case study as described by Colin et al. (1993) originated as part of a mineral inventory, requested by the Government of Gabon and was carried out from 1981 to 1990. The area surveyed is covered by primary rain forest and has a humid equatorial climate with a mean annual rainfall of 2000 mm and very difficult to access. Their main goals were :-

1. Define and evaluate anomalous areas with a high probability for discovering mineralization.
2. Carry out geological mapping in order to assess the regional and local geology.

The regional exploration approach used aerial geophysics and remote sensing methods in conjunction with systematic geochemical and mineralogical surveys.

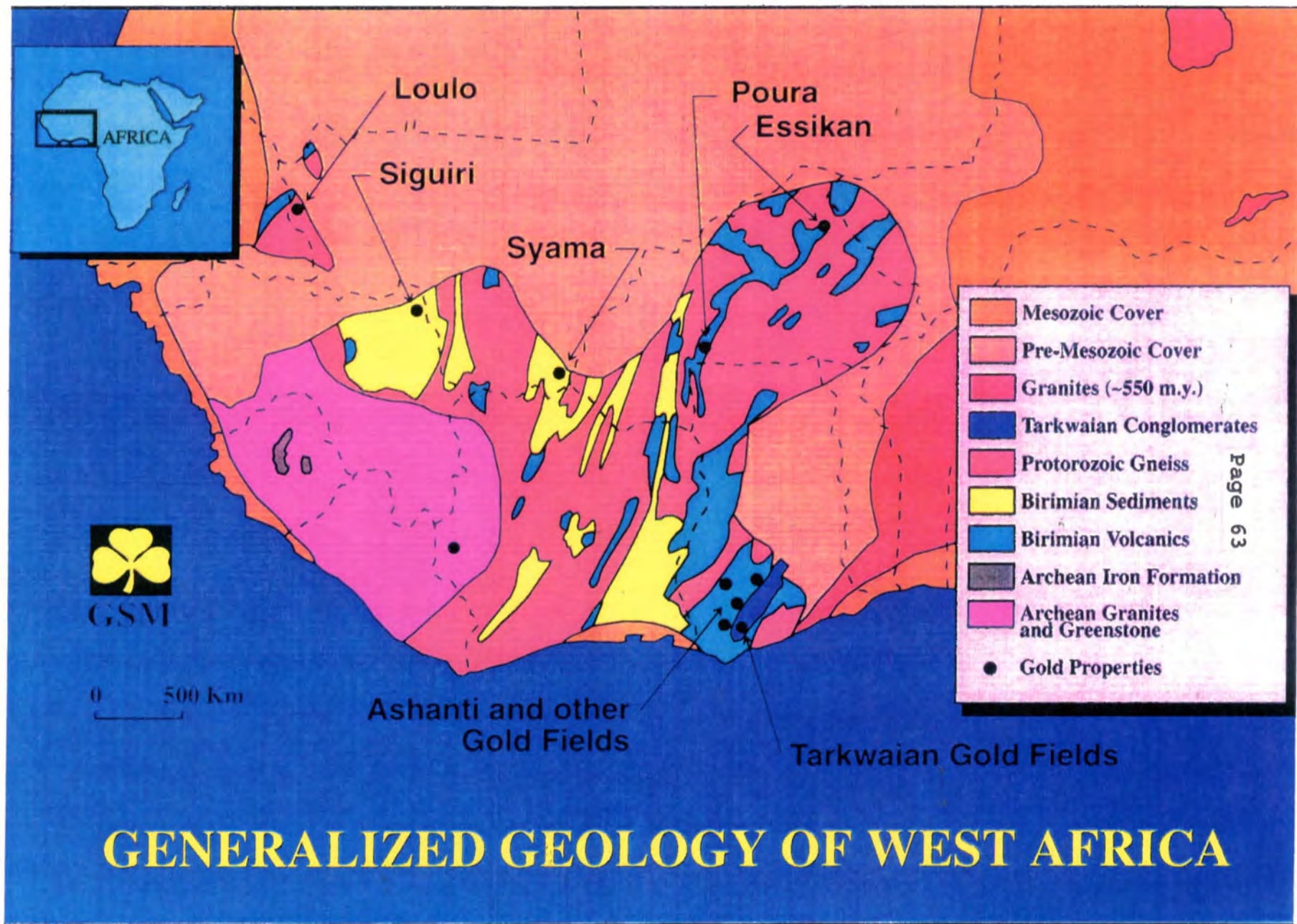


Fig. 13 Localities of the better known gold deposits, projects and mineral occurrences in West Africa (adopted from Golden Shamrock Mine's internal report, unpublished).

The regional exploration approach used aerial geophysics and remote sensing methods in conjunction with systematic geochemical and mineralogical surveys. Concurrently with the regional surveys, detailed studies were carried out on some typical sites in order to determine the physical and chemical processes involved in the supergene gold dispersion that takes place during weathering of primary ore within the surficial environment (Colin and Lecomte, 1988; Lecomte and Colin, 1989; Colin et al., 1992; Colin et al., 1992; Edou Minko et al., 1992 and Lecomte and Zeegers, 1993). Thus, the economic priority of gold exploration indirectly accelerated research into the behaviour of gold within the lateritic regolith under equatorial conditions.

The study is based on the Eteke gold district of South Gabon (Fig. 14), using the Pouna case history as a specific example and relating this to the results obtained at Dondo Mobi and in the Congo watershed.

The flow-sheet in figure 15 summarizes the strategy developed for gold exploration that was used by the bureau de recherches géologiques et minières (BRGM) during the Gabon mineral inventory (Lecomte, 1986). The objective is to progressively focus on targets, commencing with a systematic regional survey and thereafter progressively, eliminating unattractive areas at each stage of the investigation.

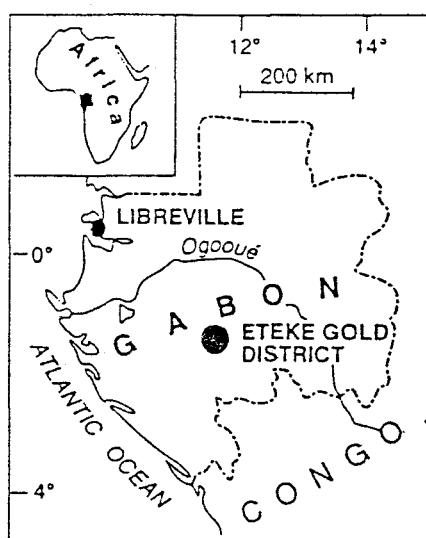


Fig. 14 Locality of the Eteke gold district (After Colin et al., 1993)

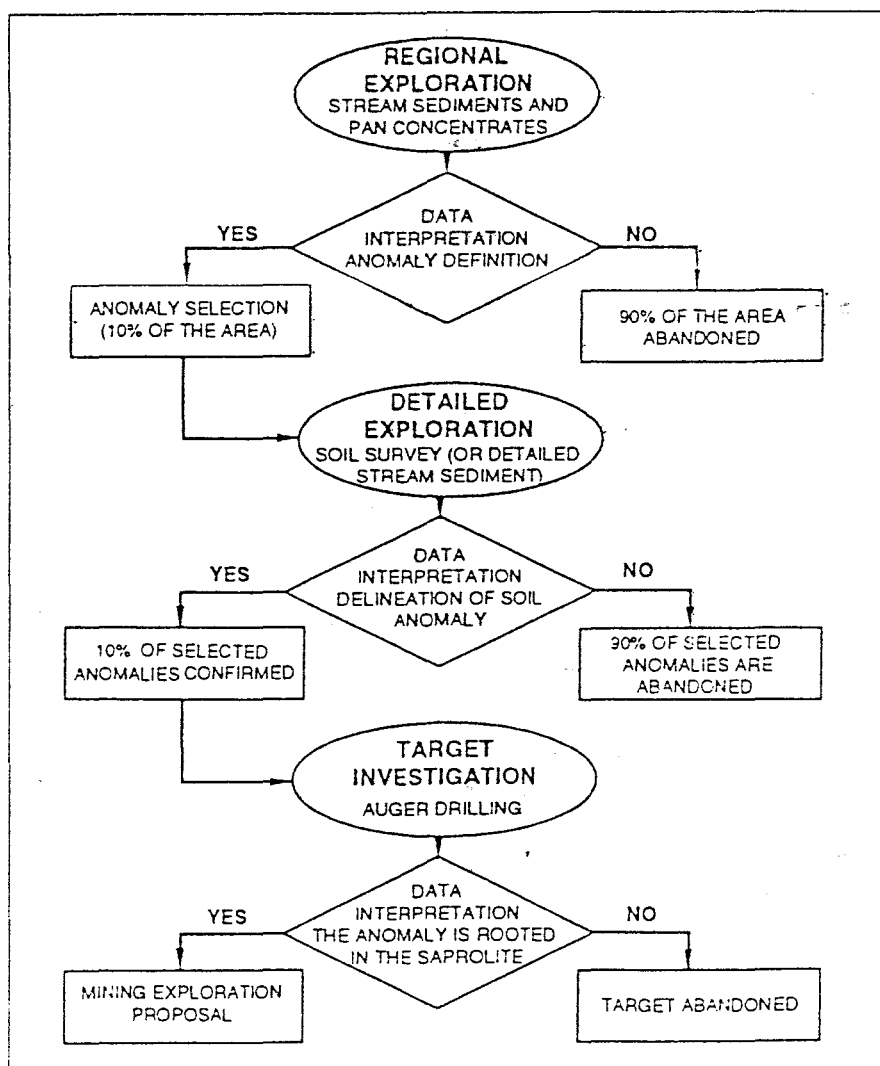


Fig. 15 A flow-sheet diagram showing the procedures during exploration (after Lecomte, 1986)

The sampling media can be different for each exploration stage, illustrated in figure 15, with respect to the drainage and regolith systems. The regional exploration stage concerns the drainage system (Fig. 16), from which two types of sample are collected systematically and regularly, stream sediments and alluvial gravel concentrates. Under an equatorial climate, the morphology typically develops as mamillary hills separated by a dendritic drainage system with flat valley floors and a sharp break between the alluvial sediments and the slope soil (Fig. 16). At a specific sample locality, the stream sediments integrate the influence of the drainage basin for about 100 m upstream (Lecomte, 1986). The $-125\ \mu\text{m}$ stream-sediment grain size fraction is analyzed for gold.

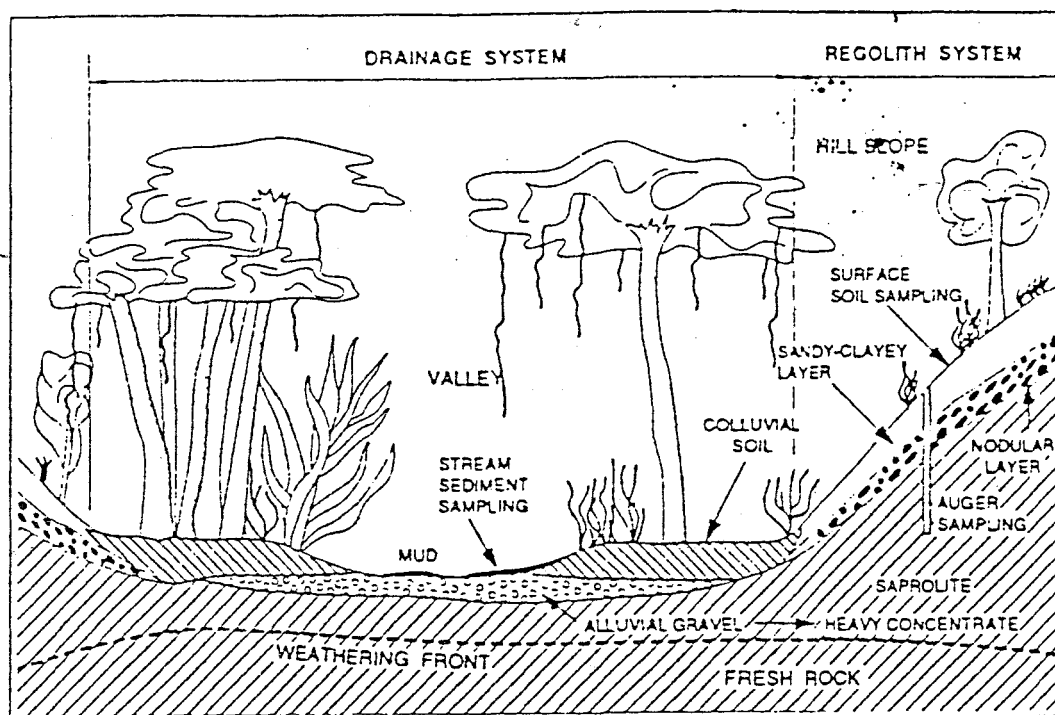


Fig. 16 Schematic cross-section of the drainage and regolith systems showing sampling media (after Collin et al., 1993).

The alluvial gravel samples are taken from the stream bed and panned in situ, after being dried, the pan concentrates are examined through a binocular microscope and the gold particles are sorted and weighed.

The objective of the regional exploration stage is to define significant Au anomalies in relation to the regional and local backgrounds and the geological context. On the completion of this stage, about 90% of the area surveyed will be abandoned and the remaining 10% will be investigated during the defined exploration stage (Fig. 15).

The detailed exploration stage involves more detailed stream-sediment and pan-concentrate sampling at a greater density. If the target is sufficiently well defined, however, exploration may proceed directly to a soil survey.

Only about 10% of the area covered by the detailed exploration stage will be of further interest. These target areas are then investigated by an even more detailed soil survey and/or by auger drilling.

The auger holes sample the regolith, which consists of three principal layers (Fig. 16) :-

1. A friable homogeneous yellow sandy clay layer, usually 1-5 m thick.
2. A nodular layer, 2-3 m thick, that is a relict of an older lateritic crust
3. Saprolite up to 100 m thick.

The holes are drilled to depths of 5-15 m through the sandy-clay and nodular layers into the saprolite, which is sampled at 1 m intervals.

Regional Geology and Mining History

The Pounga area covers 100 km² in the southwestern part of the Eteke gold district of South Gabon and is underlain by the orthogneissic Archaean basement comprising tonalite and granite, and preserved by synclinal lenses of Lower Proterozoic schist and gneiss, amphibolite, greenschist and talc schist. Both Archaean and Proterozoic rocks have been affected by intense pre- and post deformational hydrothermal alteration and the formations are strongly folded and faulted, with the result that the geological history is very difficult to interpret (Prian et al., 1988). Between 1940 and 1960, extensive alluvial mining yielded 3.5 tonnes of gold from the river system. The mean gold content in the gravel ranges from 1 to 10 g/m³ (Legras, 1960).

Regional exploration

Regional exploration of the Pounga area was carried out in 1986 with the collection of 392 stream-sediment samples and 50 pan concentrates (Labbé et al., 1987).

The regional gold distribution and the areas of greatest interest were then determined from the sample analysis results and the sites of the old alluvial workings.

In general, the pan-concentrate data (Fig. 17a) defined large homogeneous areas of significant anomalous values within which it is difficult to isolate specific groups of interesting samples. More than 50 of the 135 panned concentrates contained at least 0.1 g/m³ Au, with about 15 values greater than 0.5 g/m³ Au. These are mostly, related to previously worked gravel dumps.

Conversely, significant anomalies from the stream sediments are widespread (Fig. 17b). These are either due to contamination from old alluvial mine workings, or correspond to no known alluvial gold occurrences and constitute new areas for detailed follow-up exploration. About 100 of the 392 stream sediment samples contained over 50 ppb Au, and 23 contained over 200 ppb Au (maximum of 615 ppb Au). Twelve targets were defined in the area.

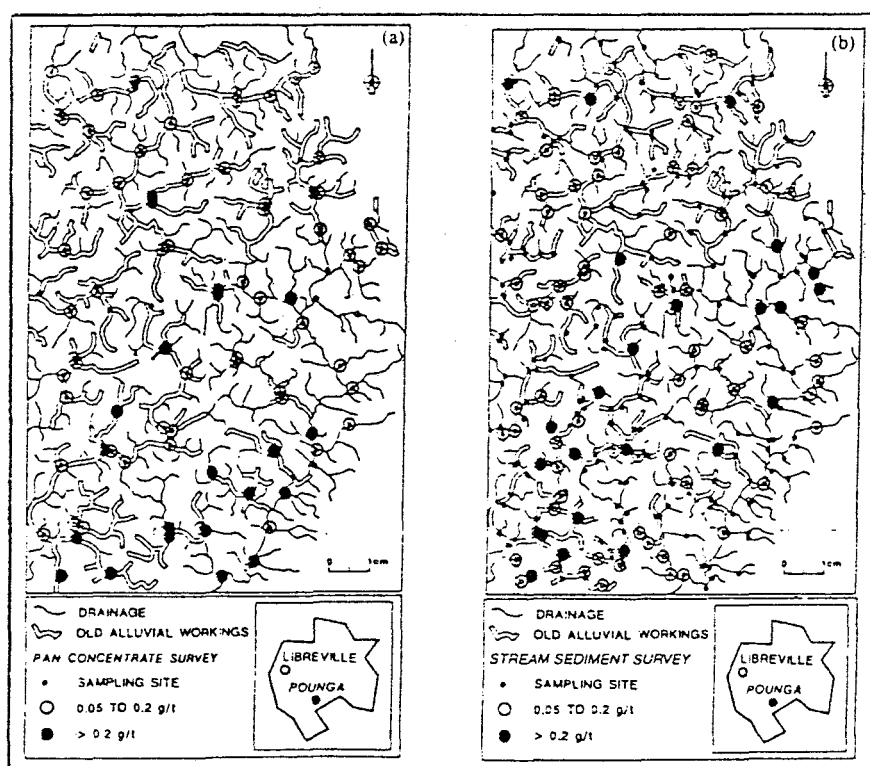


Fig. 17 Regional exploration in the Pounga area : a) gold distribution shown by panned concentrates b) gold distribution shown by stream sediments (after Colin et al., 1993).

Detailed exploration: soil and auger sampling

From the initial 100 km² of the regional survey, about 45 km² were chosen for the detailed soil survey following interpretation of the results. Out of the 2907 soil samples collected on 50 x 200 m or 100 x 200 m grids, more than 200 samples contained over 100 ppb Au, and about 50 over 200 ppb Au.

The spatial distribution of the analysis (Fig. 18) reveals :-

- 1.) two anomalous patterns, 3 and 1 km long, trending N 030° in the west of the area;
- 2.) several anomalous patterns that outline a circular anomaly, about 1 km wide, around a specific geological structure in the central and eastern part of the area. This anomaly, which is open to the north, is associated with N 030° or N 160° trending lenses of metavolcanic and metasedimentary Proterozoic rocks within the Archaean granitic basement, and is expressed in the soil by centripetally decreasing concentrations of W, Cr, Fe, B, Cu and Au.

Four of the soil anomalies (Fig. 18) were drilled to the saprolite by power auger. This phase comprised 347 holes at 10 m intervals drilled to depths of up to 14 m. At each site, the gold contents of the saprolite commonly reach 0.5 g/t, with local maxima of 1.0 to 1.5 g/t. the highest concentrations define areas up to 50 m wide that correspond to lenses of concealed Proterozoic rocks.

Outcropping muscovite schist gives maximum concentrations of 0.5 to 1.8 g/t Au and appears to represent the primary gold source. The schist is also characterized by a hydrothermal chemical signature (K₂O, Ba, W).

Panned concentrates of the soil yield grades of up to 4 g/m³ Au which is in close agreement with the total Au content of the rocks and suggests that the primary gold is rather coarse grained.

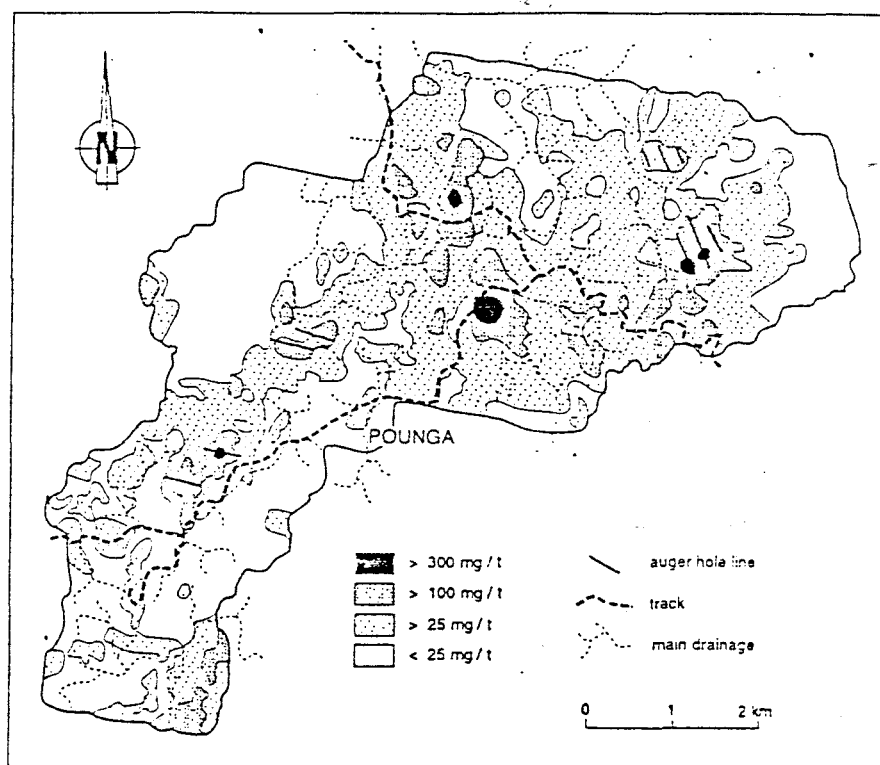


Fig. 18 Gold distribution shown by detailed soil sampling in the Pounga area (after Colin et al., 1993).

Colin and his colleagues believed that the gold is to be transported in rivers by the same chloride and organic ligands that complex gold in the regolith. However, the gold flux reaching the ocean represents only about 4% of the total gold released by weathering, the remainder precipitating rapidly, probably by photo-chemical redox reactions. Consequently a proportion of the gold leached from the regolith is redeposited in the drainage system. This process partly explains the increased gold content in the downstream alluvial gravel and in the stream sediment compared to the soil. The gold content of the gravel is also supplemented by the detrital accumulation of placer gold inherited from the gold-rich regolith, and the total abundance may exceed that in the saprolite layer and the primary mineralization. This can explain the statistical increase in gold content at Pounga from regolith systems to drainage systems (Colin et al., 1993).

Collin and colleagues suggests that the statistical decrease of gold content from fresh rock to saprolite and soil found at Pouna results from a super imposition of :- (1) increased leaching of gold during in situ weathering of the mineralized rocks and (2) surficial translocation of gold, which decreases as a function of increasing distance from the gold-rich soil source.

Equatorial rain forest conditions favour such chemical and physical processes and enhance the dispersion haloes within surficial soils and drainage systems, thus increasing the probability of finding gold anomalies.

6.3.2 Kangaba case study, Mali

The intense gold exploration of the past several years has been particularly focussed on thick lateritic covers, such as in Western Australia and Western Africa, because of the low production costs involved in mining and processing gold deposits in lateritic profiles. This development in exploration has led to extensive research into the behaviour of gold under supergene conditions with the aim of enhancing geochemical exploration techniques in tropical environments. Recent research (Butt, 1989; Freyssinet, 1993; Butt and Zeegers, 1989; Freyssinet, 1993 and Lawrance, 1995) shows that gold behaviour in weathering profiles is strongly dependent on the geomorphological environment and, in particular, on the paleoclimatic history.

1. Morphological and climatic conditions of the Kangaba area

The Kangaba area is located in the south-western part of Mali, between the Niger River and the Guinean border. The climate is tropical with two contrasted seasons; a rainy season of five months and a dry season. The annual rainfall is about 1200 mm. The region is one of undulating plateaux of 360 to 440 m altitude with a 60 to 80 m thick lateritic cover dissected by lateral erosion proceeding from the stream drainage. A fairly large portion of the landscape is capped by a ferricrete (Freyssinet, 1993).

2. Regional geology

South Mali is underlain mainly by the Precambrian volcano-sedimentary Birimian Series (2300 - 1950 Ma) which forms elongated belts (Fig. 12) separated by granitized or migmatized pre- or post-Birimian rocks (Milési et al, 1989). In the Kangaba area, the Birimian series is composed mainly of metagreywacke, arkose and tuff (Cottard et al., 1981).

3. Sampling and analysis

A study was made of gold mineralization and its dispersion halo on a lateritic plateau (Freyssinet, 1993).

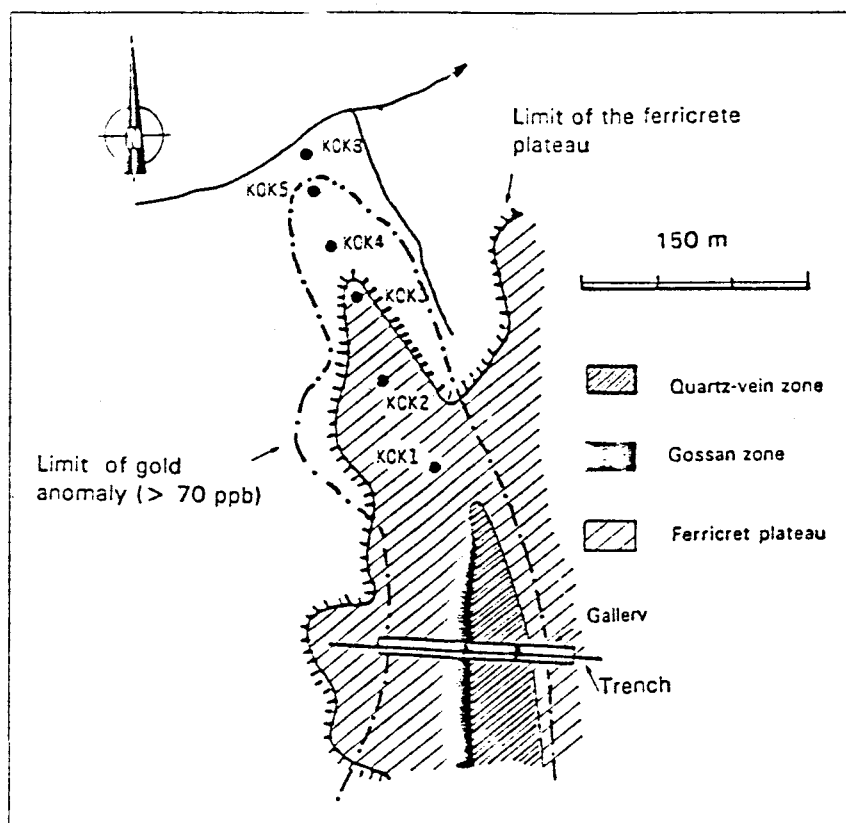


Fig. 19 The locality of the pits, trench and gallery on the ferricrete plateau in the Kangaba area (after Freyssinet, 1993)

Channel samples were collected from a line of pits along the longitudinal axis of the soil anomaly, and also from a gallery dug in the saprolite at 6 to 8 m depth and from a trench dug in the outcropping ferricrete along the transverse axis (Fig. 19). Sample intervals were each 50 cm in the pits and each metre in the gallery and the trench.

4. Profile of the weathering facies

The weathering profile in Kangaba area (Fig. 20) is a typical old and well-preserved lateritic profile that contains the four main horizons (Freyssinet, 1993) :-

- 1. Parent rock.**
- 2. Saprolite.**
- 3. Mottled zone.**
- 4. Ferricrete, comprising :-**
 - a. soft massive ferricrete (carapace);**
 - b. massive ferricrete;**
 - c. sub-pisolitic ferricrete;**
 - d. pisolitic ferricrete.**

A grey silty soil with ferricrete nodules frequently overlies the ferricrete. This vertical sequence of weathering facies results from the progressive development of each horizon corresponding to a progressive lowering of the weathering profile (Freyssinet, 1993).

Saprolite

The saprolite horizon, in which primary textures are preserved, is 50 - 70 m thick and partly saturated by groundwater. Most of the primary minerals have been altered to secondary minerals such as kaolinite, hematite and goethite; only quartz, sericite and resistant minerals are preserved. The saprolite has a fine-grained, slightly porous texture, and is composed mostly of a grey kaolinitic matrix surrounding primary minerals (Freyssinet, 1993).

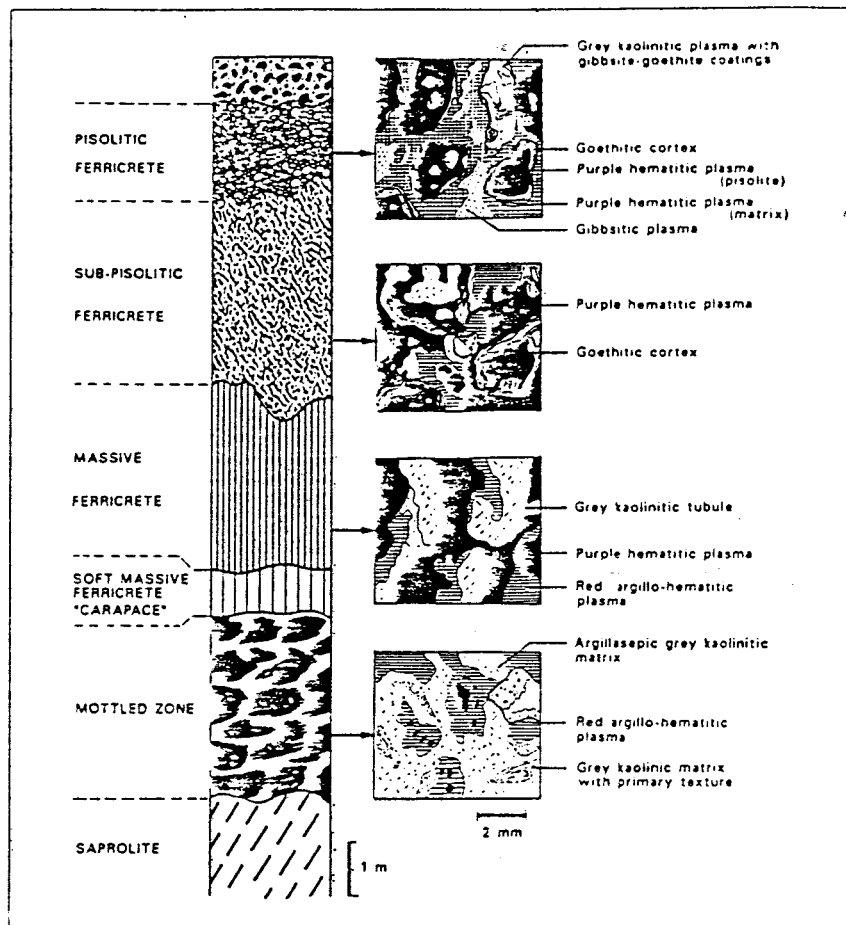


Fig. 20 The weathering profile in Kangaba area (after Freyssinet, 1993).

Mottled zone

Freyssinet (1993) described the mottled zone to be 1 - 2 m thick, overlies the saprolite in the unsaturated zone. The preserved macro-texture of the rock is progressively destroyed, predominantly through the dissolution of sericite and its replacement by uniform kaolinitic matrix.

This horizon is marked by the formation of ferruginous spots, mostly hematitic, which increase in size upwards until they coalesce to form a red argillo-hematitic matrix (Fig. 20) which partly replaces the grey kaolinitic matrix.

Iron concretions become concentrated at the top of the mottled zone, forming hard millimetre size nodules within the red argillo-hematitic matrix; these nodules are composed of a purple hematitic matrix where kaolinite has almost entirely disappeared.

Ferricrete

The ferricrete overlying the mottled zone develops where purple hematitic matrix prevails and is characterized by two major factors (Freyssinet, 1993) :-

- 1. Intense leaching of kaolinite, and**
- 2. a high absolute accumulation of hematite.**

This horizon is generally 3 - 5 m thick and is made up of several facies. At the base of the ferricrete horizon, soft massive ferricrete comprises predominant purple hematitic plasma associated, with red argillo-hematitic matrix; the grey kaolinitic matrix is present only as residual tubules through which water percolates (Fig. 2). The hematitic areas appear relatively uniform and impart a massive aspect to this facies.

The soft massive ferricrete is transformed upwards into massive ferricrete, which retains the same structure but is more indurated and is characterized by an intense accumulation of hematite at the expense of kaolinite.

The massive ferricrete is overlain by sub-pisolitic ferricrete, characterized by the formation of aluminous goethite coatings along cracks within the purple hematitic matrix. The goethite develops in a concentric manner to form cortexes progressively isolating areas of purple hematitic matrix (Fig. 20). This process increases upwards in the profile, leading to the formation of the pisolitic facies.

The pisolitic ferricrete is marked by the dissolution of quartz, kaolinite and hematite. Goethite and gibbsite are the minerals which mostly develop, generally at the expense respectively of hematite and kaolinite.

The iron pisoliths coalesce and become cemented by a purple hematitic matrix. Gibbsite, which is the last phase to precipitate, fills pores in the ferruginous matrix (Freyssinet, 1993).

4. Primary mineralization

Freyssinet (1993) indicated that the primary mineralization in the study area is contained in a lode, about 50 m wide, related to a major north-south shear zone. Hydrothermal alteration is marked by a sericite-chlorite assemblage and by the presence of pyrite and arsenopyrite; the oxidation front of the mineralization is located at 120 m depth. Mineralization structures, studied from the gallery in the saprolite horizon, reveal two main contiguous mineralized zones (Fig. 19) :-

1. A quartz-vein zone, 42 m thick in the gallery which constitutes the main mineralized facies. It is composed of quartz tension gashes a few centimetres wide, with a saccharoidal texture.
2. A gossan zone, 16 m thick in the gallery, composed of a fine stockwork of millimetre-thick quartz veinlets crossing a massive gossan body derived from the oxidation of pyrite and arsenopyrite.

Mineralized structures remain unaffected in the saprolite but progressively disaggregate in the mottled zone and mainly the ferricrete. A coarse sandy horizon at the base of the ferricrete corresponds to the residue of vein or stockwork quartz, as other components are intensively leached (Freyssinet, 1993).

5. Secondary gold particles

The remobilization of primary gold in the profile enables neogenesis of secondary gold particles in the different horizons. Freyssinet (1993) identified two generations of secondary gold particles which can be distinguished by their shape, their habitus and their chemical composition.

The first phase of reprecipitated gold is seen mainly in the saprolite horizon of the gossan zone where it forms a discontinuous cortex of secondary gold. The secondary gold fills angular cavities at the contact between the primary particle and the oxidized gangue. The chemical composition of the cortex generally shows 0.5 to 1.5% Ag, whereas the primary grain contains 7 - 9% Ag. This type of gold is relatively enriched in traces of sulphur (up to 1%) compared to the primary core.

The second phase of reprecipitated gold is not directly associated with the mineralized zones and is seen in the different alteration facies of the mottled zone and the ferricrete.

This neogenic gold generally occurs as spherules or microcrystallites of $< 1 \mu\text{m}$. The spherules seem to develop preferentially at the surface of the hematite matrix. In the mottled zone, gold is clearly associated with the argillo-hematitic domain, where it appears as very fine flaky particles filling the porosity of the hematitic matrix. Electron microprobe analysis of the larger particles has shown this neogenic gold to be extremely pure with no silver.

6. Gold remobilization processes in the ferricrete profile

The results obtained from Freyssinet's study provide a better understanding of gold mobility in lateritic profiles. It has been possible to determine the vertical and lateral evolution of gold in relation to the pedogenic development of the ferricrete. With this type of weathering, the primary gold is little affected during the development of the saprolite, and the only remobilization observed is related to oxidation of the sulphides of the primary gold. The secondary gold is confined to cavities in the oxide gangue; this first stage of remobilization is limited and most probably occurs at the sulphide oxidation front at the base of the profile, as has been shown by Webster and Mann (1984).

The second stage of gold remobilization occurs during the development of the ferricrete, where the rate of gold leaching is related to the increase of ferruginization.

The mechanism of gold dissolution involves a process of atmospheric corrosion characteristic of a non-saturated environment: the dissolution of gold begins in a specific micro-environment where water forms thin membranes lining the pore walls.

This type of environment is favourable for the formation of the ferricrete, whose development intensifies with advancing dehydration of the soil. Thus the top of the ferricrete profile is subjected to variations in air humidity and can become extremely dehydrated during the dry season. In such conditions, micro-environments are formed with very specific chemical and physico-chemical conditions that are responsible notably for the mobility of the iron. The combination of these effects related to the dehydrating conditions at the top of the profile can explain the intense leaching of gold in the ferricrete (Freyssinet, 1993).

Gold migration in the ferricrete profile

The specific distribution of gold in the weathering horizons results from the pedogenic evolution of the ferricrete profile. Since the acid is intimately associated with certain new formed domains as is demonstrated by the gold distribution in the different facies. The dissolved gold partly reprecipitates in the ferricrete and the mottled zone, generally as micron-size spherules included in or coating the zones of hematitic matrix (Fig. 21).

The model involving vertical lowering of the profile with its sequence of weathering horizons (MacFarlane, 1983) provides a conceptual framework where processes of acid migration can be associated with the ferricrete formation (Fig. 21). The dehydrating conditions at the top of the profile during the dry season allow dissolution of the primary gold, as described earlier. The remobilized gold then migrates and partly reprecipitates within the macro porosity. Most of the gold reprecipitation occurs in the mottled zone at the ferruginization front where the percolating solutions are slowed down because of an abrupt decent in permeability at the transition between the mottled zone and the saprolite (Freyssinet, 1993).

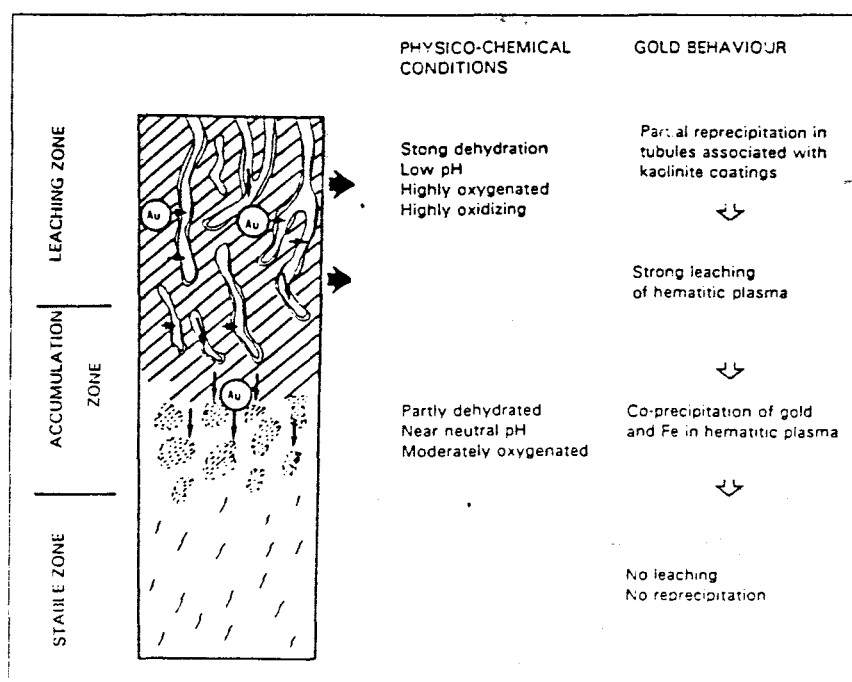


Fig. 21 Model of gold remobilization and migration related to ferricrete formation (after Freyssinet, 1993).

As this horizon can be partly saturated at the beginning of the rainy season, the average activity of the water is significantly higher in the mottled zone (Freyssinet, 1993).

Lateritic dispersion of gold

The structure of the dispersion halo indicates two dispersion modes involving both mechanical and chemical processes. The coarse primary gold is dispersed over some 70 m downslope of the mineralization, which clearly effects the lateral mechanical effects, but this process is limited to the top of the ferricrete. The chemical dispersion is separated from the mechanical dispersion which is related to the iron mobilization and therefore intimately associated with the formation of the ferricrete (Freyssinet, 1993).

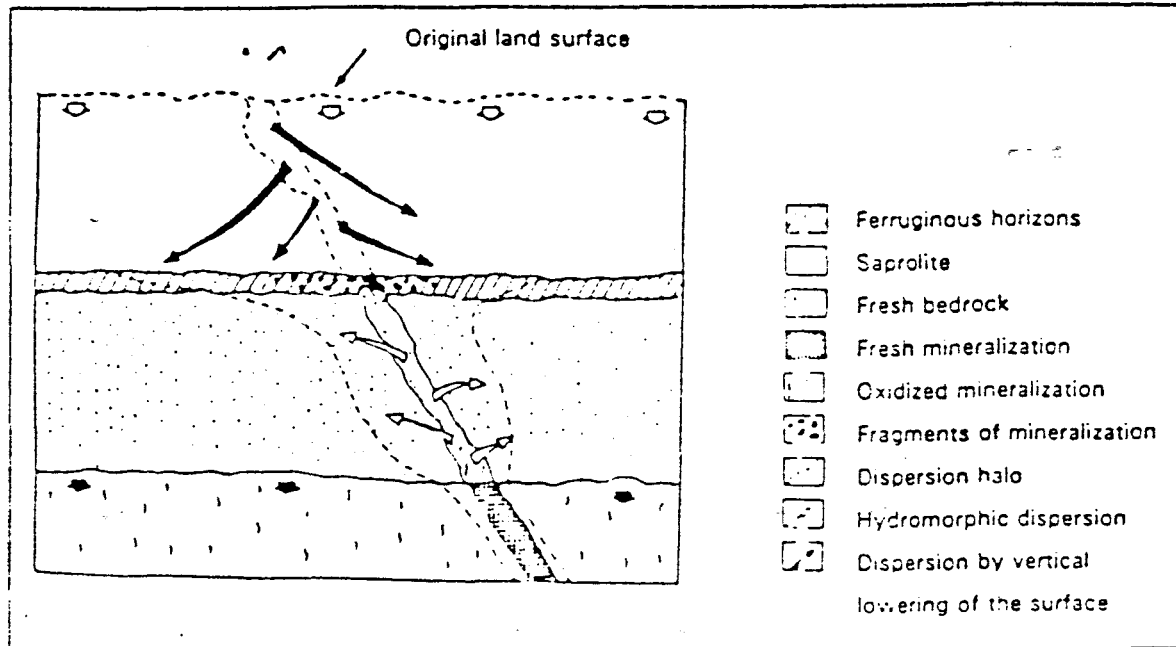


Fig. 22 Lateral dispersion model by land surface lowering during the ferricrete formation (after Freyssinet, 1993).

In a downward vertical weathering model (MacFarlane, 1983), the surficial gold halo comes from the mineralization dissolved during the lowering of the profile (Fig. 22). The chemical dispersion is separated from the mechanical dispersion which is related to the iron mobilization and therefore intimately associated with the formation of the ferricrete (Freyssinet, 1993). In a downward vertical weathering model (MacFarlane, 1983), the surficial gold halo comes from the mineralization dissolved during the lowering of the profile (Fig. 22).

The mechanical and chemical dispersion spreads in relation to the degradation of the mineralized structures and the advance of the ferruginization front, which is why the dispersion halos in the lateritic environment remain mostly located in the ferruginous zone (Freyssinet, 1993) with only limited hydromorphic dispersion in the saprolite.

Paleoclimatic influence on the gold signal

The ferricrete profile described in this study corresponds to a well preserved lateritic profile developed over a long period of time under tropical climates shifting between wet and more seasonally contrasted regimes (Tardy et al., 1992). The evolution of the gold in this profile can be considered as characteristic of an old and very evolved ferricrete formation.

The dispersion of the gold is thus highly dependent on local conditions of subsurface drainage and surface enrichment can therefore result in economic grades (Webster and Mann, 1986).

Freyssinet stated in his conclusions that gold in lateritic profiles follows complex behaviour patterns that are highly dependent on the pedogenic evolution of the weathering profile. Gold behaviour is therefore controlled by redox reactions at profile scale. Its high mobility in the non-saturated zone implies an intense leaching and partial reprecipitation at the ferruginization front. The formation of lateral dispersion halos is also a complex process related to the ferricrete formation and combining mechanical movements at the top of the ferricrete and chemical transfers at its base.

The model of gold evolution in the ferricrete profile has a direct implication for exploration methodology, the interpretation of the geochemical gold signal and the selection of surface anomalies. A knowledge of the degree of weathering is essential considering the strong reduction in the gold concentration from the saprolite to the top of the ferricrete (Freyssinet, 1993).

6.3.3 Ilesha, Nigeria

Regional geology

The Ilesha case study described by Elueze and Olade (1985) covers an area approximately 250 km² in southwest Nigeria. It is underlain by a north-south trending belt of Proterozoic rocks that forms part of the greenstone belts of the Nigerian basement complex (Fig. 23).

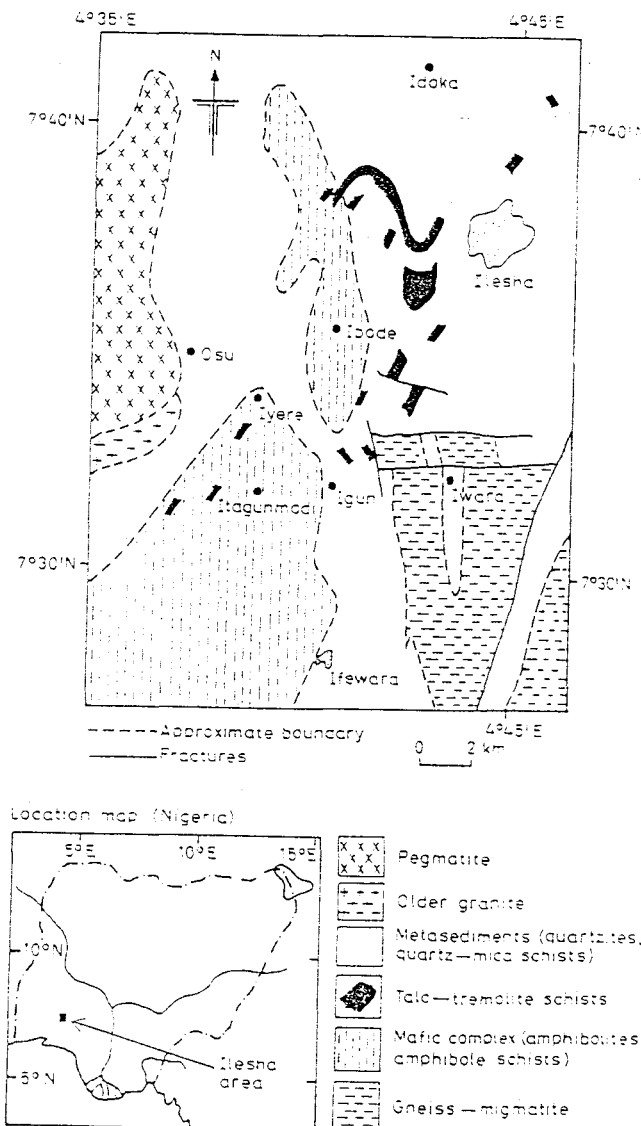


Fig. 23 General geology and locality map of Ilesha area (after Elueze and Olade, 1985).

As part of an extensive regional exploration programme initiated by the Nigerian Mining Corporation, a reconnaissance stream sediment survey was undertaken in the Ilesha district, the main objective being to delineate areas with potential for gold mineralization.

The area of interest was delineated by geological mapping, the chief consideration being the well-known association of mafic rocks with gold mineralization. The dominant rocks are metamorphosed mafic volcanics and volcanoclastics which include amphibolites, talc-tremolite schists, chlorite and mica schists and are intruded by granite gneisses. Economic interest focussed principally on the alluvial gold deposits, which are believed to have been derived from auriferous quartz veins and stringers and disseminations within the amphibolites and associated mafic schists.

The topography of the Ilesha area is for the most part undulating, with an average elevation of 400 m above sea level, except in the southwest, where an inselberg landscape is quite well developed. The area is drained by a few main streams, but these possess numerous tributaries. The alluvial sediments in the upper parts of the drainage system are composed mainly of sandy silt, but downstream often comprise clays rich in organic matter.

The area has a humid tropical climate with an annual rainfall of 1500 mm. Although the area lies in a zone tropical rain forest, the vegetation now consists of secondary growth on account of intensive cultivation and deforestation. Chemical weathering is generally intense, penetrating to depths in excess of 20 m, particularly in areas that are underlain by greenstone rocks.

More than 300 stream-sediment samples were collected from carefully selected sites which represents a sample density of about one sample per km². From previous orientation surveys, the -100 mesh fraction regarded to be the most suitable, are selected for analysis. Statistical treatment of the analytical data and the construction of frequency distribution and probability plots assists in obtaining thresholds for the anomalous values.

To facilitate assesment of the geochemical patterns maps are presented that show the distribution of elements of economic or exploration significance (Fig. 24 and 25).

Elueze and Olade (1995) revealed that the only elements with distrbution patterns that are related to known mineralization are As, Au and Ni.

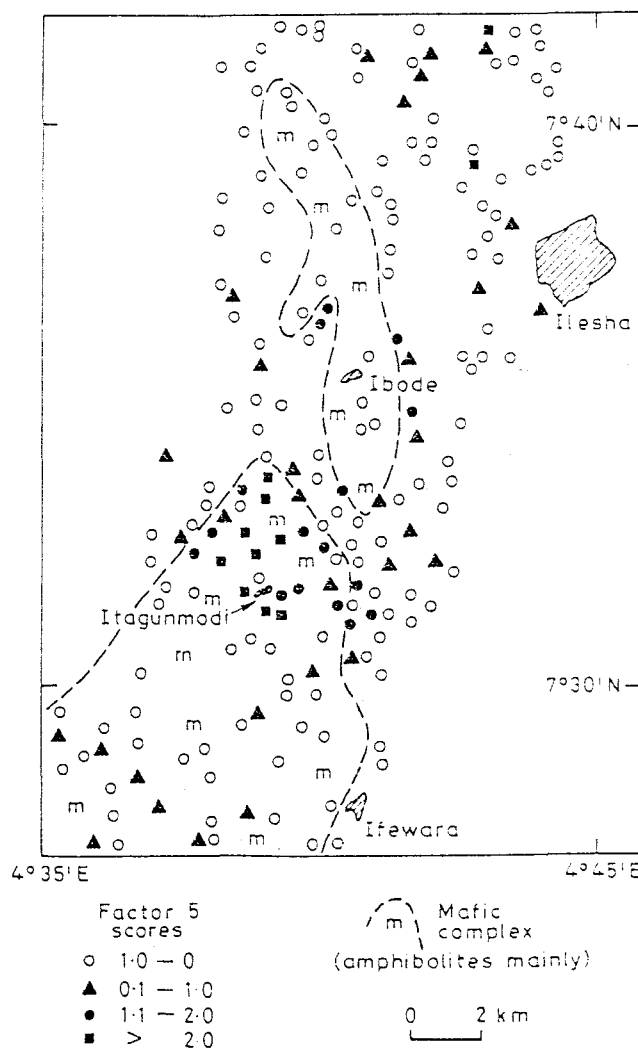


Fig. 24 Distribution of As in stream-sediments in the Ilesha area (after Elueze and Olade, 1985)

Arsenic values range from less than 10 to 97 ppm, those in excess of the regional threshold of 21 ppm being confined to areas around Itagunmodi and 3 km north, near Iyere (Fig. 24). In these areas the occurrence of sulphide-bearing auriferous quartz stringers and disseminations in amphibolite has been reported and the enhanced arsenic values may be related to these features.

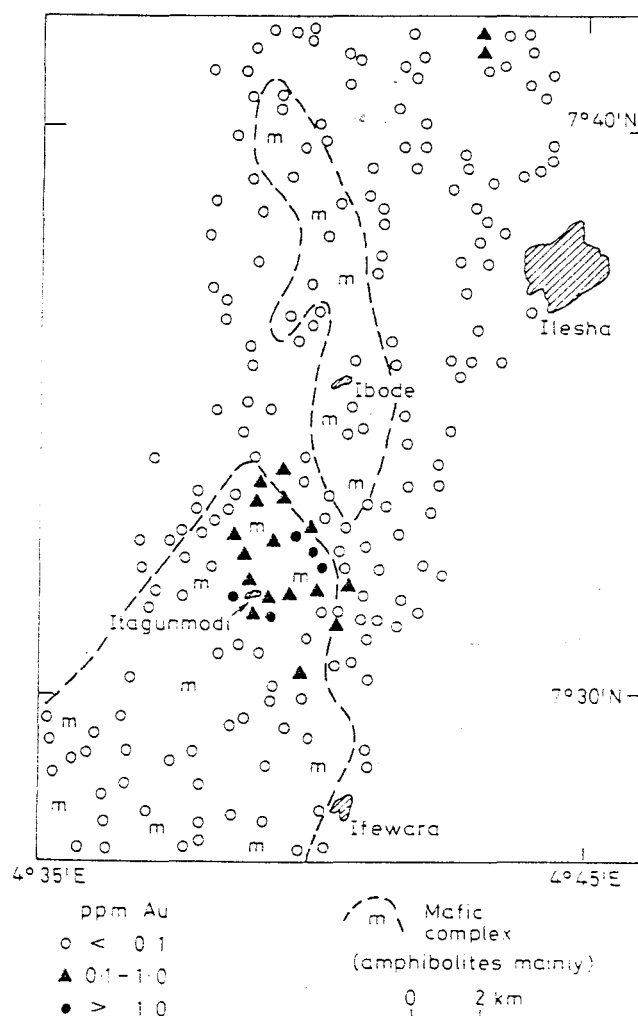


Fig. 25 Distribution of Au in stream-sediments in the Ilesha area (after Elueze and Olade, 1985)

Gold values in active stream sediments are generally low and erratic, only a few values exceeding 1 ppm (Fig. 25). The area around Itagunmodi, however, which contains the highest density of old gold workings, is characterized by Au values that generally exceed 0.1 ppm.

Elueze and Olade (1985) concluded that the interpretation of stream-sediment reconnaissance geochemical data from the greenstone belt of the Ilesha area showed that the areal distribution of trace elements is subject to strong lithological and environmental controls.

The high background concentrations and the viability in abundance of the chalcophile elements can be attributed easily to the mafic-ultramafic bedrock and to the compositional variations within it, which would make the detection of subtle but significant anomalies related to mineralization a very difficult and subjective exercise. Arsenic, which is widely used as a pathfinder for gold in other greenstone belts, shows no clear-cut relation to any of the known mineralization in the Ilesha district. This may also be attributed to the masking effect of the compositional variation in the bedrock. Although slightly enhanced gold values are associated with streams that drain known alluvial workings, gold cannot be regarded as a reliable indicator element in itself because of its erratic distribution and the possibly widespread distribution of natural background values by alluvial mining.

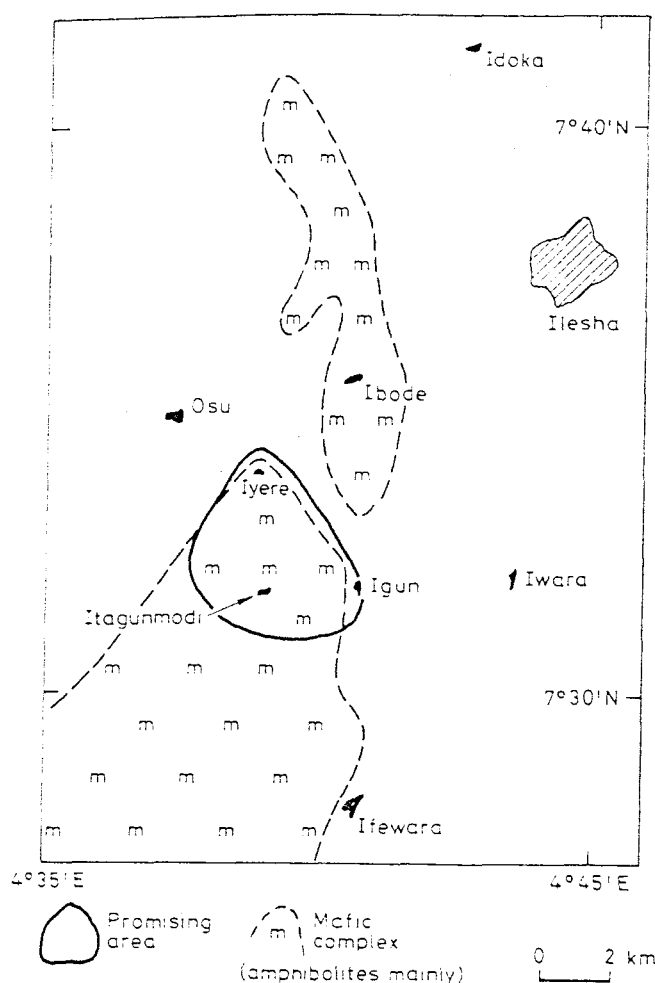


Fig. 26 Outline of map showing favourable areas for follow-up exploration (after Elueze and Olade, 1985)

Although the exact nature of the primary gold mineralization in the area is not well understood, it is known that the rich gold ore shoots are closely associated with abundant arsenopyrite veins (Eluze and Olade, 1985).

Eluze and Olade (1985) regarded the most promising area for follow-up exploration to be the area around Itagunmodi and extending northwards to Iyere (Fig. 25). This could be investigated further by a combination of detailed stream-sediment and soil survey.

7.0 EXPLORATION STRATEGY AND THE INTEGRATED GOLD EXPLORATION PROGRAMME

7.1 EXPLORATION STRATEGY

A major consideration in the evolution of a strategy for exploration of any particular region is the availability of resources of men and materials. This consideration often leads to the use of conventional exploration methods.

However, all modern programmes for the integrated development of natural resources, including exploration for minerals, have to take cost benefit aspects into consideration. The simple profit-and-loss approach may not be in keeping with the responsibility of development. As protection of the environment and the maintenance of ecological balance would call for extra investment in formulating the strategy of exploitation, these matters must receive due consideration at this early stage of exploration.

In tropical and sub-tropical terrains, rapid appraisal of the exploration situation may be difficult because of poor accessibility, so remote sensing data is of great value. A sound knowledge and understanding of the geology is necessary, however, and this can only be obtained by ground field work in certain areas. This must be integrated with all other geoscientific data in a concurrent synthesis. Selection of target areas for follow-up work must be made in the light of the interpretation of these data.

The exploration strategy in rain forest areas should take into consideration the development of the soil, its depth, size fractions, pH, concentrations of K, N and P, clay mineralogy, etc. Geochemical anomalies have to be viewed in the light of these characteristics so that they may be interpreted either as direct indicators of potential targets or as pathfinders.

The prime objective of the initial reconnaissance exploration programme should be to confirm the presence of gold in stream gravels and soils.

However, it is important to note that if exploration geologists do not comprehend the processes that have gone into the formation of the soil profile at any particular place, they could be destined "to spend a lifetime chasing phantom ore deposits or, worse still, stepping blindly over hidden treasures" (Moore, 1994). Therefore, an understanding of the complex factors that have gone into the development of tropical and sub-tropical landscapes is an essential prerequisite for exploration geologists who are using the surface materials as guides to the discovery of buried mineral deposits. When large numbers of samples have to be processed, it is important to have rapid instrumental analysis and ultimate success will depend on an effective feed-back of results.

There is, however, no escape from conventional foot-slogging geological mapping if full results are to be achieved; but these efforts can be helped by having base-lines and traverse lines cut along and across strike trends of the formations, with numbered pegs placed at suitable intervals. This will, of course, be necessary for geophysical and geochemical surveys but will facilitate the geological work primarily.

Once the areas have been mapped geologically, the remote sensing, geophysical and geochemical data interpreted and synthesized, all the messages communicated by these different modes could be brought into tune with the geological setting. Areas for further search, by surface or subsurface exploration, should be dealt with sequentially. While drilling might be adequate to evaluate bedded mineral deposits, for vein-type deposits such as base metals it may be necessary to undertake exploratory mining for their proper assessment and delineation of the behaviour of the ore bodies.

In conclusion it may be said that though the methodology and techniques of mineral exploration to be adopted in the tropical rain forest areas may not differ basically from those developed in other geographical and climatic areas, the methods should reckon with the special features resulting from the physical and biological processes operating in the rain forest areas.

7.2 THE INTEGRATED EXPLORATION PROGRAMME

Gold Mineral exploration is a highly complex and demanding science and to be successful, it generally involves the full integration of the geological, geophysical and geochemical sciences. In the past, mineral exploration had been relatively easy and many discoveries have been made by routine prospecting. The marked increase in demand for gold over the past thirty years provided the necessary stimulus for the development of improved geophysical and geochemical techniques. These methods have contributed significantly in locating a number of new ore occurrences. Many of the orebodies discovered in the past were recognised because they represented amongst the most prominent physical and/or chemical features located in the survey area. As the majority of the obvious near surface deposits have already been located, it can be concluded that an increasingly large proportion of the future discoveries will be reflected as more subtle geophysical and/or geochemical anomalies. Sound geological perception is necessary in order to recognise the significance of the subdued responses and a wide range of methods is available to assist in the environmental reconstruction.

Geophysics forms but a part of an exploration sequence which may involve field geological studies, photogeological interpretation, trace element geochemistry, trenching, drilling or underground development.

In designing an effective exploration programme, geologists must utilize the most appropriate aids available in ore search in an efficient and balanced sequence.

Economics will normally dictate the preferred exploration strategy but the final choice will be modified by considerations of the local environment, availability of personnel, accessibility, timing aspects and numerous other factors. The relatively low cost of geological investigations compared with geochemical and geophysical methods normally ensures that geology will (or should) form the primary exploration tool in most environments, particularly in areas of abundant outcrop.

Geological investigations form an important interpretative base for geochemical and geophysical surveys consequently geological surveys inevitably form an integral part of most exploration programmes. If the basic geological model applied in the exploration of a region is badly conceived, excessive expenditures are inevitable during the subsequent exploration phases and the probability of locating an economic and viable ore deposit will be significantly diminished.

Conversely, if the geological characteristics of a deposit and its environment are thoroughly understood before exploration is initiated, greater economy will be effected in the execution of a programme, and the likelihood of success will be considerably enhanced. This is a basic and undisputable fact of mineral exploration which has direct implications on the design of geophysical surveys.

Geochemical methods are cheaper than the majority of geophysical techniques and they are of direct value in locating positive indications of mineralization.

Geochemical surveys can also be conducted concurrently with geological investigations and consequently geochemical surveys are commonly employed prior to the commencement of ground geophysical surveys. Trace-element geochemical studies may be used to screen areas that have been defined as priority areas on the basis of airborne geophysical investigations. A typical example would be in following up magnetic anomalies which could reflect magnetite quartzites, skarns or ultrabasic bodies, all of which may hold base metal potential given the right geological setting. Geochemistry is particularly effective in regions largely covered by shallow residual soils and ground magnetic surveys may be employed to augment geological mapping in these areas.

Geological mapping and geochemical surveying is severely limited in areas overlain by thick transported overburden or deep tropical soils and exploration in these regions may be geophysically orientated.

In order to screen geophysical anomalies it is commonly necessary to use a number of geophysical methods and this can lead to the successive elimination of extraneous anomalies. Ward (1966) indicates how the successive use of electromagnetic, magnetic and gravity surveys may be employed to eliminate a number of anomalies detected during the search for massive, nickeliferous sulfides.

Barren pyrrhotite, magnetic carbonaceous sediments and magnetite-bearing massive pyrite bodies will, however, remain a problem, which could only be resolved through the application of geochemical and/or geological methods.

A hypothetical example of a typical exploration sequence that may be considered in exploring for gold in tropical and sub-tropical terrains, is tabulated below and clearly illustrates the important role that each discipline can play in integrated exploration programmes.

The integration of the different exploration techniques will become increasingly important in future surveys. This will place increased demands on the explorationist whose geological perceptions of the environment will provide the necessary basis for interpreting geophysical and geochemical data. The geologist's ability to perceive, in three dimensions, the geological environment in which he is working, is potentially the most effective remote sensing technique available in mineral exploration. An awareness of the character of geophysical and geochemical responses that can be anticipated over a blind orebody, is another necessary requirement of a true explorationist.

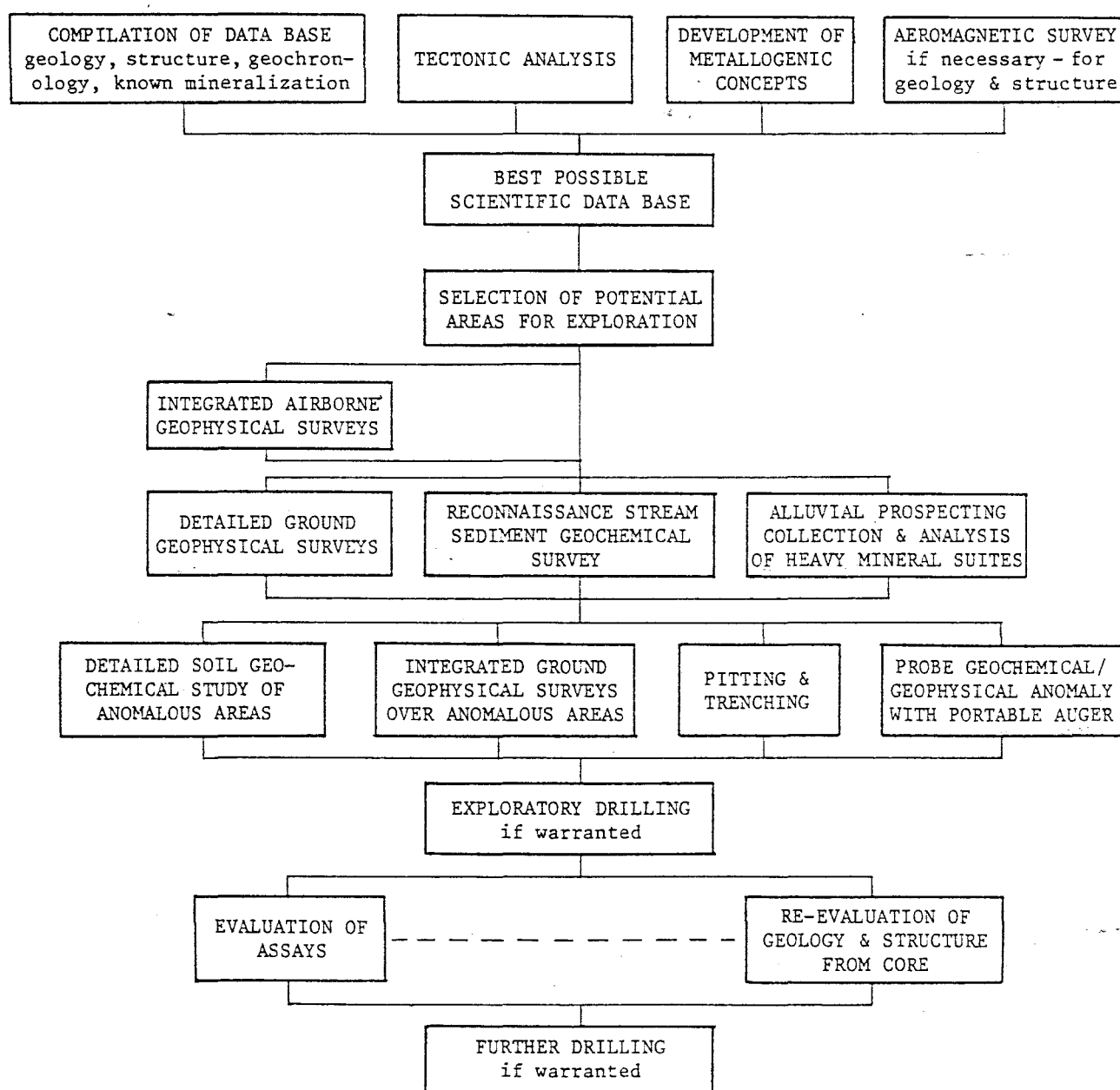


Fig. 27 Exploration techniques and stages during an integrated exploration programme (after Singh, 1977).

The integration of the different exploration techniques will become increasingly important in future surveys. This will place increased demands on the explorationist whose geological perceptions of the environment will provide the necessary basis for interpreting geophysical and geochemical data. The geologist's ability to perceive, in three dimensions, the geological environment in which he is working, is potentially the most effective remote sensing technique available in mineral exploration.

An awareness of the character of geophysical and geochemical responses that can be anticipated over a blind orebody, is another necessary requirement of a true explorationist.

8. CONCLUSIONS

The original intention of this review was to cover the entire field of gold exploration in tropical and sub-tropical terrains in as much detail as space and time permitted. However, it soon became apparent to the author that this is a considerably large field than was initially appreciated. As a result, most of the different disciplines described could be expanded to the extent of forming a dissertation or review, in their own right. This review are therefore an attempt to provide a guide for gold exploration in tropical and sub-tropical terrains and where applicable, further infill reading are recommended.

The importance of a sound geological knowledge of the various disciplines related to gold exploration in tropical and sub-tropical terrains are emphasized. The various disciplines ie. Soil forming processes and gold geochemistry are fields often being neglected during the initial planning stages of an exploration programme. The well illustrated case studies of Central- and West Africa succeed in providing valuable information of successful exploration techniques.

The secret behind any future successful mineral discovery lies in a well structured and managed integrated exploration programme where all available information and exploration techniques are incorporated to ensure success in this highly competitive environment where our mineral resources become more and more depleted every day. The author sincerely hoped that the reader has benefitted by gaining a better insight into the guide for gold exploration in tropical and sub-tropical terrains and the potential value of an integrated mineral exploration programme for future mineral discoveries.

9.0 RECOMMENDED INFILL READING

The author wish to recommend the following references as infill reading material to provide the necessary comprehensive background knowledge to ensure a successfull, future exploration geologist :-

Weathering - Levinson (1980), Rose et. al (1991) and Lawrance (1995)

Gold Geochemistry - Levinson (1980), Rose et. al (1991), Freyssinet (1993) and Lawrance (1995)

Duricrust - Goudie (1973), McFarlane (1983), Butt and Zeegers (1994)

Soil Formation and Processes - Fitzpatric (1971), Levinson (1980),

Geochemical Exploration - Levinson (1980), Zeegers and Leduc (1991)

Geophysical Exploration - Parasnis (1986), Wade (1993) and Paterson (1985)

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