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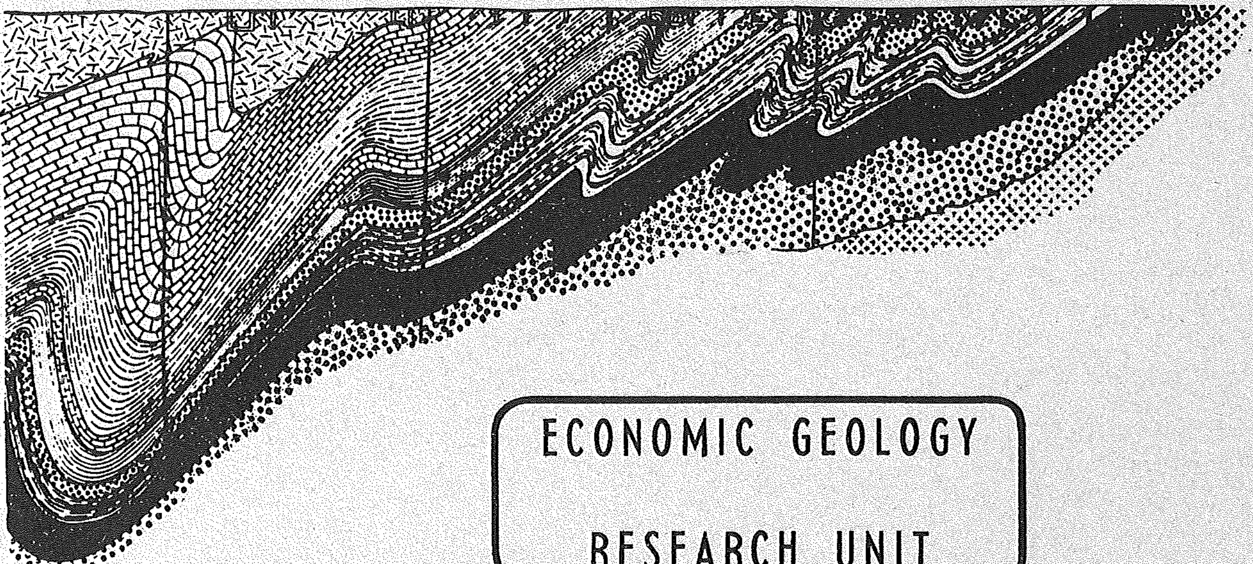

ECONOMIC GEOLOGY RESEARCH UNIT

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MINERAL EXPLORATION IN SOUTHERN AFRICA : PROBLEMS AND PROGNOSIS FOR THE NEXT TWENTY YEARS

D. A. PRETORIUS

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by

D. A. PRETORIUS

(Director, Economic Geology Research Unit)

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ABSTRACT

In a little more than 100 years, the mining industry in Southern Africa has attained a most impressive status, with the total value of South Africa's annual production alone reaching R1,300 million. It is held, by non-geologists essentially, that the acme of the mining industry will be experienced in the period between 1967 and 1972, and that, from the latter year onwards, only a decline can be anticipated in mining's contribution to the economy of the sub-continent.

This contention is examined in the light of growing knowledge of the fundamental components and controls of the distribution patterns of mineralization in space and time. No geological backing can be found in support of a pessimistic prognosis. It is believed that new ore-bodies will continue to be discovered at a rate which will counter the predicted deterioration in mineral production. Ten broad exploration targets are listed in which it is envisaged that many of the new findings will be made.

This confidence in future successes is conditional upon extensive changes, some revolutionary, being enforced on the overall approach to search procedure. The effectiveness of any exploration effort is stated to be a function of strategy, money, personnel, tactics, and evaluation. The most drastic changes are considered necessary in the strategy and evaluation aspects. The amount of money allocated to research in mineral exploration will have to be doubled if a better understanding of the processes and responses of mineralizing phenomena is to form one of the cornerstones of new strategy. Ten topics are presented in which it is thought that intensive research is called for in the immediate future. The highly subjective basis to strategy and evaluation in the past will have to be replaced, for the most part, by a systems approach with a powerful operations research component. An essentially quantitative environment will have to be established for optimal decision-making on all levels. The numbers and quality of exploration personnel will have to be improved through enhancing the status of the geologist in the mining industry and society and through a dynamic new attitude towards undergraduate and graduate education in at least one university in South Africa, responsive to the real needs of the mining industry. Present tactical procedure is believed to carry considerable potential for making new discoveries. Ten field and laboratory techniques are discussed in which significant new developments can be anticipated, to expand the range and efficiency of data-gathering processes. The most sobering fact which the mining industry will have to face in regard to exploration in the next twenty years is that, if the discovery rate is to be at the same level as that predicted for other major mineral-producing countries in the world, the amount spent on the search for ore will have to be increased seven-fold to of the order of R35 million per year. The exploration risks in the next twenty years will assume such proportions that boldness of the highest calibre will be the distinguishing characteristic of Southern Africa's mining entrepeneurs of the future.

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MINERAL EXPLORATION IN SOUTHERN AFRICA : PROBLEMS AND PROGNOSIS FOR THE NEXT TWENTY YEARS

THE NEED FOR EXPLORATION

When, at the end of 1967, South Africa declared the value of its total mineral production for the year as R1,287 million, exactly one hundred years had elapsed since Carl Mauch's discoveries in the Matabeleland-Tati area first attracted the serious attention of the world to the future great goldfields of Southern Africa. For the annual figure to have grown to this magnitude, there can be only one explanation : continuingly successful discovery and mining of gold, diamonds, platinum, base metals, non-metallics, and solid fuels. With a great past behind it, the mining industry is understandably questioning its future. In June, 1967, the then President of the Transvaal and Orange Free State Chamber of Mines, Mr. R. S. Cooke, said : *"The search for new gold-fields continues unabated, so far without avail. This does not mean that undiscovered gold-fields do not exist. What it does mean is that, at the present price of gold and constantly rising flotation pay limits for new gold mines, the chances of discovering payable deposits are becoming increasingly slender".* Since the value of gold recovered represents more than 60 per cent of that of the total mineral output, it follows that any serious decline in the rate of discovery and bringing into production of new gold mines must have very considerable consequences on the economy of South Africa.

It has been pointed out by Busschau (1968) that South Africa's gold production will probably level off at about 31 million ounces per year, between 1967 and 1972, and that it will drop by one-third by 1980 and by two-thirds by 1984. Twenty years from now, gold production will possibly be of the order of 9 million ounces per year, if no new discoveries are made. It cannot be anticipated that this serious decline in revenue will be offset entirely by increased production of other minerals. In the highly unlikely event of no further mines being established in any type of mineral deposit, and of all other factors remaining equal, a pessimist would have to estimate the total value of South Africa's annual mineral production, twenty years from now, at no more than about R400 million, approximately one-third of what it was in 1967.

The need for new discoveries of ore is obvious. Not only must the decline in production be countered, but the ever-increasing demands of an industrial society must be satisfied. Brant (1968) has indicated that the tonnage of ore requiring to be mined doubles itself every twelve years. Only sustained exploration can bring about the discoveries. If it was not so in the past, then exploration must, in the next twenty years, become the most fundamental operation in mining. Only it can keep the industry alive.

The challenge that lies ahead has been heavily underscored by Nel (1968) in his conclusion : *"The problems which confront the exploration geologist in the search for new gold mines within the confines of the presently-known Witwatersrand Basin, or, for that matter, in the search for other similar basins, are indeed formidable .....".* That it will be successfully met is indicated by Busschau's (1968) prognosis : *"If only on an estimate of probability, it seems to me quite wrong to assume that the gold mining industry will, from the early seventies onwards, be in an inevitable decline, nor that geologists will not be active in proving extensions to the existing fields. I would go further, and say that it would be a very bold man who would say that new gold-fields could not be discovered".*

THE NATURE OF EXPLORATION

The objective of exploration, as defined by Bailly (1968a), is *"to find and acquire a maximum number of new economic mineral deposits with a minimum cost and in a minimum time".* Such an operation is influenced by an indeterminable number of known and unknown variables, and must, at all times, be considered within the context of the vagaries of a gamble where the losers outnumber the winners by at least one hundred to one.

The effectiveness of an exploration effort can be measured by the extent to which the rate of discovery of new deposits is maintained or increased, or by the ratio of the gross value of the ore discovered to the total cost of exploration. This effectiveness *(E)* is a function of the main variables of the effort in accord with the following relationship :

$$E = f(s, m, p, t, e)$$

where s = *the strategy of the exploration program;*

m = *the money made available for implementation of the program;*

p = *the personnel involved in formulating strategy, executing tactics, and optimizing evaluation;*

t = *the tactics employed, within the strategical framework, to gather data for evaluation; and*

e = *the evaluation of the tactical results and of the program as a whole.*

The variables are listed in the order in which they normally enter an exploration effort. The relative positions of strategy and money might be reversed in some instances, where the latter is made available for exploration without a specific search proposal first having been submitted. Phased evaluation can be introduced at any point in the sequence of operations, permitting decisions to be made as soon as possible, and thus reducing unnecessary expenditure to a minimum.

The fact that the past discovery rate, which has culminated in the prestigious status of present mineral production, has not been maintained, particularly with respect to gold mining (Cooke, 1967), argues convincingly for changing the structure of current exploration procedure, possibly in all its aspects. To prevent the mining industry from going into the decline prophesied, course must be altered now, before 1972, while the full panorama of past, present, and future performances and projections can be viewed from the crest of economic security.

It is put forward that the most effective changes would involve strategy and evaluation components of the exploration system. Success in enhancing discovery rates is not believed possible without a revolutionary reviewing of these two aspects. Revision in the approach to problems of money, personnel, and tactics is also deemed essential, but possibly merit a lower order of priority.

STRATEGY

Strategy is concerned with problems of what to look for, where to find it, and how to search for it. It revolves about what Bailly (1968b) has described as *"the influence of genetic theories, ore deposit models, and target hypotheses on future ore discoveries"*. The end-products of strategy formulation are the definition of exploration targets and the design of search procedures.

The sequence of operations in defining and designing follows the path :

(1) seeking a better understanding of the definitive components of distribution patterns of ore deposits in time and space - (this is essentially an undertaking in analysing responses, in the form of known mineralization, and inducing processes which culminated in economically exploitable ore emplacement);

(2) generate, first, conceptual models and, then, probabilistic models of exploration targets, based on the outcome of the analysis and induction of responses and processes;

(3) specify, in as precise a manner as possible, the parameters of the target to be sought;

(4) develop a general philosophy of search procedure;

(5) plan the mode of attack on the target, the plan being dominated by a systems approach with a powerful operations research component; and

(6) evaluate, at the end of each phase of the subsequent tactical operations, the effectiveness of strategical planning, and modify, if necessary, model elements and target parameters.

It is questionable whether the full spectrum of operations has been incorporated in devising strategies which have guided the search for ore deposits in the past. Because of the undoubted increased difficulty which can be expected in making new discoveries in the next twenty years, it is believed that success will be forthcoming only if the whole process of formulating strategy, within the framework outlined above, is elevated to the rank of a first-order necessity in the exploration sequence.

(a) Defining Future Exploration Targets

(i) Responses and Processes

If a greater fundamental understanding can be obtained of the many factors which contribute to the localisation, in time and space, of economically significant mineralization, then it must follow that the discovery rate can be maintained, or improved, through what Cook (1968) has described as a *"better definition of objectives ..... and an increased emphasis on a concept-oriented approach in exploration"*. More precise knowledge must be sought, not only of the ore deposits themselves, but of the environments in which they formed. Understanding can be gained only through research, both basic and applied, and such research can best be carried out where there exists a *"dynamic fertilizing relation between education, industry, and state"* (King, 1968). A much closer working partnership between the mining industry in Southern Africa, existing universities in South Africa, Rhodesia, and overseas, and government-sponsored geological surveys and other research institutions in the territories that comprise the sub-continent is vital to future mineral production.

The broad geological features which are believed to have influenced the migration and concentration of elements of possible economic interest in the Earth's crust have been termed tectono-metallogenic units (Clifford, 1966) or metallotects (Guild, 1968). The importance of the time parameter in metallogenesis and the evolutionary change of style of mineralization in the metallotects have been discussed by, among many others, Pereira and Dixon (1965) and Pretorius (1965). Continuing decipherment of the chronological characteristics of the geological, geophysical, and geochemical controls of ore deposition will permit the isolation of optimum times for specific types of mineralization, and, through a study of the geometry of the evolution of the Earth's crust, such times can be correlated with optimum localities.

Geological space can be regarded as a function of structure and environment. The overall nature of mineralization might be better understood if the changes in its character are studied in the context of the sequential changes in the structure and environment of each rank of the spatial hierarchy : metallotect → metallogenic province → district → field → deposit → ore-body → pay-shoot. The importance of appreciating the relationship between the distribution of mineral deposits and structures of global and continental dimension has been stressed by Brock (1960). The need for research on down the scale has been indicated in Badgley's (1959) statement that *"systematic structural analysis of entire tectonic provinces, as an exploration tool, has been employed by relatively few geologists"*. Possibly even less thought has been given in Southern Africa to systematic variations in the igneous, sedimentary, and metamorphic environments in the provinces. That the locus of optimum mineralization is, more often than not, marked by the conjunction of a specific structural regime and an equally specific petrological environment has been too well established in the metallotects of the world for any doubt to remain that a more definitive knowledge of structure, environment, and time must be the foundation-stone of any new strategy of mineral exploration.

From such knowledge, an insight might be gained into the processes which give rise to the deposition of ore. With data on both process and response parameters, the task is considerably facilitated of integrating genetic theories and field observations into a target model. Greater understanding of processes is necessary to counter the adverse effects on exploration efforts produced by thinking which has been polarized by dogmatic adherence to a particular, sometimes obsolescent, genetic hypothesis. Perhaps, the most difficult problem in the path of inducing the processes which have led to the mineral deposits of Southern Africa is the relative absence of multi-disciplinary contacts between chemists, physicists, mathematicians, and research workers in the various branches of the earth sciences. It is in such contacts that the twilight fields are generated, which lead to so many of the scientific advances made today.

Research is needed to distinguish between primary and secondary causal factors leading to economically exploitable accumulations of metals and minerals; to appreciate all the stages in the transportation and concentration of detrital minerals by fluvial, lacustrine, and marine currents; to determine the extent, frequency, and intensity of the recycling processes necessary to convert protore to ore; to assess the influence exerted by Eh and pH on the migration of metals in solution; to establish the rôle played by biogenic substances in localizing mineralization; to understand the mechanisms of transference of elements from the mantle to the crust of the Earth; to learn the significance of the generation and emplacement of granites in ore formation; to interpret the contributions made by metamorphism and metasomatism to the movement of elements from one geochemical environment to another; to ascertain the relationships between volcanic activity and ore deposition; and, most important, to identify the sources of ore and protore.

When it is realised how many ore deposits are strata-bound in Precambrian sedimentary basins, it is not difficult to appreciate why so many geologists in Southern Africa are essentially syngeneticists. There is a predilection towards seeing the primary factor in ore deposition as the emplacement of lavas and sediments in those portions of the metallotects where mantle-tapping structures were preferentially developed and where environmental conditions permitted the maximum differentiation of the stratigraphic pile. Evidence is also increasing in support of the contention that the transgressive epigenetic deposits are secondary products of the stratiform mineralization, in accord with Boyle's (1968) conclusion : *"The metals, gangue elements, and volatiles in epigenetic deposits probably came from the country rocks that enclose, lie below, or lie lateral to the deposits. From their sites in the country rocks, the elements were mobilized during metamorphism or were collected by deep-seated circulating ground-waters or brines. Most elements probably migrate by diffusion and are concentrated by the action of dilatant structures or as a result of chemical reaction with favourable rocks such as limestones"*.

A cursory look at some recent observations and speculations on time, structure, environment, and mineralization in Southern Africa suggests conceptual foundations for some of the directions which future research into processes and responses might follow. Africa south of the Congo consists of a number of cratons and mobile belts, the location and geometry of which have been depicted by Anhaeusser et alia (1968). Clifford (1966) has recognized differences in the ages and styles of mineralization in these tectono-metallogenic units. Most of the mobile belts have been active during the last 1200 million years, whereas the cratons became stable prior to that time. The major deposits of gold, platinum, uranium, iron, chromium, manganese, asbestos, and diamonds are restricted to the stable cratons, whereas the more significant concentrations of copper, lead, zinc, cobalt, tin, tungsten, vanadium, beryllium, and niobium have so far been found in the mobile belts. Thus, evidence can be seen to exist of patterns of mineralization within a temporal and spatial context. Any new data which relate to the components and controls of the patterns must contribute to the sharper definition of future exploration targets.

(ii) Models and Targets

Mitcham (1968) has concluded that *"new conceptual models for various types of ore-bodies and their settings ....."* will lead to the *"definition of better places for deployment of exploration efforts ....."*. The results of research into the processes and responses of mineralizing phenomena have to be integrated into a framework for *"..... raising questions regarding the target characteristics, which must be answered before search strategy or tactics can be successfully optimized ....."*. (Griffiths, 1967). Because much of the information available on the distribution of ore deposits through time and space is of a qualitative nature, it is possible, at present, to construct only non-numerical, conceptual process-response models. The necessity of a more quantitative approach to the solving of geological, geophysical, and geochemical problems connected with mineral exploration has been stressed by Pretorius (1966a). It is possible that, during the course of the next twenty years, probabilistic models will be developed to describe the inter-relationships of definitive parameters of the main types of ore deposits in Southern Africa, but it is believed impossible for mathematical models ever to be formulated, because of the large number of complex variables, the full nature of which will never be understood, particularly with respect to the time component.

In addition to being devised within the constraints of the temporal and spatial characteristics of the metallotects of Southern Africa, the models will have to take recognition of several other factors, including (1) that ore-bodies, in general, are distributed according to Poisson's Law, but that their parameters, such as size and grade, follow a lognormal distribution; (2) that geological, geophysical, and geochemical anomalies are not necessarily indicators of ore; and (3) that a unifying denominator of primary and secondary processes might lie in the field of energetics.

It is believed that one new approach which will assume ever-increasing importance in the employment of models of exploration targets will be mathematical simulation. With the aid of progressively more sophisticated digital computers, imitations will be effected of the major geological processes, and these will be channelled into interactions with each other to produce symbolic outcomes, thereby creating dynamic probabilistic models which will compare consistently well with geological features of the real world. Geological processes and responses will be simulated by a sequential arrangement of equations and decision-making evaluations. This trend towards a systems approach to exploration strategy has been forecase by Griffiths (1967) : *"One future development which holds great promise is to construct a simulation model of the entire system with physical and economical restraints and then, by gaming, to decide what the optimal strategy requires and how it may be modified to maintain an optimum under changing environmental conditions"*.

Whatever the nature of the model, it should be aimed at permitting the decomposition of complex geological, geophysical, and geochemical situations into simpler constituent elements which can be readily and effectively identified and measured in the target area. The ranking of each element as a positive indicator of ore should also be a primary prerequisite. With such a model of the target to be sought, the odds must favour an enhanced probability of success attending the exploration effort.

As knowledge of ore-forming processes and controls increases in the next twenty years, so new targets will emerge. Not only hitherto neglected areas within the metallotects will receive attention, but previously ignored rock-types will be examined as possible sources of, or hosts to, mineralization. New discoveries of ore in Southern Africa might well be made in :

(1) more precisely delineated Late Precambrian sedimentary sequences, such as the Tsumis Formation of South West Africa and Botswana, which chrono-tectonic correlation now favours as the equivalent of members of the Lomagundi copper province of Rhodesia;

(2) better mapped assemblages of Early Precambrian basement rocks, such as the Messina Formation of the Limpopo metallotect, which have been subjected to mobile-belt reworking, as a consequence of which the primary nickel-copper content of the rocks of the initial magmatic phase has been concentrated into potential ore-bodies;

(3) more closely studied Late Precambrian Waterberg strata in which the paucity of sedimentological investigations in the past might account for the apparently anomalous absence of ore deposits in a middle member of a well-established sequence of mineralized Precambrian basins on the Kaapvaal crustal fragment;

(4) hitherto unexamined dolomitic siltstones and other carbonate facies rocks of the Middle Precambrian Transvaal Sequence, in which might be developed finely disseminated gold deposits similar to those recently found in younger rocks of this composition in Nevada and Yakutia;

(5) only recently identified (Viljoen and Viljoen, 1967) subaqueous volcanic piles of Early Precambrian greenstone belts, in the pillow lavas, pyroclastics, and volcanic sediments of which might be found concentrations of gold, silver, and base metals of a type similar to the 'black ores' of northern Honshu;

(6) yet-to-be investigated Phanerozoic detrital fill of grabens interiorily adjacent to the topographically-elevated and erosion-scarred rim of the Transvaal Basin, from which low-grade auriferous material could have been recycled;

(7) potential source-rocks, in recorrelated Precambrian depositories (Pretorius, 1967a), that take the form of shales, particularly graphitic, pyritic shales, which are most favourable for lead, zinc, copper, arsenic, antimony, gold, and silver, and of volcanics, from which could be derived gold, silver, and copper - (these rocks would have to be present in areas subjected to metamorphism, where according to Boyle (1968), the elements mobilized in the source-rocks were deposited in receptacle-rocks, such as brittle quartzites, acidic lavas, diabases, and limestones);

(8) transitional structural regimes between provinces of relatively thicker and thinner granitic crust under sub-continental arches and warps, respectively, which are possibly the most favourable environment for the emplacement of pipe-like ore-bodies of the Palabora carbonatite-type or the Premier kimberlite-type;

(9) the postulated post-Pongola and Pre-Witwatersrand sedimentary basin (Pretorius, 1966b and 1967b), occurring beneath a cover of predominantly Karroo-age rocks in the southeastern Transvaal and northern and western Orange Free State, in which the intensity of mineralization might be progressive between that of the sporadic gold showings of the Pongola Basin and the spectacular gold-uranium fields of the Witwatersrand Basin; and

(10) as-yet undiscovered extensions of the Witwatersrand Basin of which the present limits, as was proved to be the case in all previously-assumed terminations, represent post-depositional structural boundaries between elevated portions of the original basin, from which the gold-bearing strata have been eroded, and depressed segments, where preservation of ore has been favoured - (no stratigraphical or sedimentological evidence has been produced in the course of extensive mining and exploration activities to support a conclusion that the original depositional limits of the Witwatersrand Basin have been recognised - these might well lay beneath the extensive cover of younger rocks to the northeast of the Evander Goldfield and the southwest of the Welkom Goldfield.

All these possible future target areas lie within the continental boundaries of Southern Africa. Also destined for exploration in the next twenty years is the oceanic domain, particularly that of the continental shelf. There are 70,000 square miles in the Indian Ocean off South Africa, and 30,000 square miles stretching into the Atlantic from South West Africa. The first successful exploration of this terrain has already culminated in the exploitation of diamonds on the sea-bed off the southern portion of South West Africa. It is believed that the most promising target areas on the continental shelf will prove to be the deltas and estuaries of the many rivers which enter the sea from a well-mineralized interior.

(b) Designing Future Search Procedures

(i) A General Philosophy

Any operational philosophy of exploration for ore has to take recognition of the multi-variate character of geological, geophysical, and geochemical phenomena. To bring decision-making to its most effective level, search strategy has to be formulated in accord with Chamberlin's

(1890) method of multiple working hypotheses. The construction of target models takes place in an area of science where there is a high potential for error, and an early, exclusive emphasis on a single genetic hypothesis must reduce significantly the probability of success of the exploration effort. Chamberlin (1890) has warned : *"The habit of precipitate explanation leads rapidly on to the development of tentative theories"*. A tentative theory can easily become an adopted theory which, in turn, can transform, with equal facility, into a ruling theory. The progress of the exploration venture then becomes the victim of a premature assessment within a parochial framework.

King's (1968) remarks, made in another context, also apply to the problems of revising approaches to maintaining or increasing the future discovery rate. Difficulties which will be encountered in modifying strategy in the light of new knowledge will stem from the fact that past successes tend to produce, both in attitudes and procedures, a traditionalism and a rigidity that block dynamic advances in new directions.

The need for a change in exploration philosophy from a tactical to a strategic approach has been stressed by Griffiths (1967) in his statement that the underlying concepts of search should be *"..... based on theoretical models of the probable arrangement of targets rather than on empirical models constructed by direct observation and experience"*. Further strategy will develop from a viable philosophy which rests on the belief that there are inherent patterns and orders to the occurrence of ore.

(ii) Systems Approach and Phased Evaluation

The task of strategy is to direct all efforts towards attainment of the exploration goal, and this is accomplished by planning, organizing, and controlling all the elements within the total system of attack. This systems approach directs study to the whole spectrum of operations, not to a few selected components only, identifies the parameters of pertinent aspects, analyzes the interactions between the parameters, as well as between the attributes of the parameters, and then gauges the sensitivity of the system to alternative schemes of attack. It involves the repetitive sequence of analysing and synthesising, up and down the scale of microscopic viewing, through normal viewing, to wide-angled viewing, advocated by Brock (1960). To accomplish this, the systems approach leans heavily on computer-based techniques of collating, classifying, processing, and interpreting exploration data.

The basic requirements for the design and control of any system is the construction of an accurate and reliable model of the target to be sought. The next phase is the introduction of a sequential arrangement of exploration techniques which have a high discriminatory power for ore, mineralization, and barren rock. The design must incorporate an understanding of all tactical methods of attack, and must take recognition of the fact that each has an optimal value at some time, in some place, for some purpose. The third step is the identification and interpretation of the geological, geophysical, and geochemical patterns present in the results. Through all phases, the system is optimized by charting a path involving the minimum sequence of steps. Flexibility is introduced through the application of the principle of multiple working hypotheses, as additional data from field and laboratory investigations become available (Cook, 1968). The system remains continually sensitive to recognizing unformulated problems, in addition to solving known problems. Resistance to change is minimized.

The operations research methods so far mentioned are aimed at providing a quantitative basis for decisions regarding control of all components of the system. The difference between the manner in which strategy has been formulated in the past, where qualitative considerations and subjective intuition were dominant, and future processes of designing search procedure is essentially in this quantitative approach to optimal decision-making.

Exploration may well be Markovian, with the next move dependent only on the present state of the venture, and ergodic, with the end-state probability distribution independent of the initial state, but it still remains, in the final analysis, a gamble in which improvements in strategy and evaluation are likely to produce a greater pay-off in new discoveries of ore than are extensive modifications in the money, personnel, and tactics components of the total system.

MONEY

Money is the connecting link between the formulation of strategy and the tactical execution of the exploration effort. Without adequate financial backing, the search for new ore deposits, no matter how sophisticated the strategy and effective the tactics, will be abortive. The progressively greater difficulty attending an increase in discovery rate means that the exploration risk will assume expanded proportions. The reality must be faced that much more money will have to be spent annually on search operations in Southern Africa in the next twenty years than has ever been required in the past.

In the decade ending in 1966, R30 million was spent on exploration for new districts, fields, and deposits in the Witwatersrand metallotect (Cooke, 1967). About R10 million of this amount was incurred in activities which resulted in the discovery of four new mines - Southvaal, Kloof, Elsburg, and Kinross. The remaining two-thirds produced only further understanding of the geology of the basin. The total value of gold recovered during this ten-year period was of the order of R6,060 million, and of uranium R790 million. The gross revenue from mining operations in the Witwatersrand Basin amounted to R6,850 million. The exploration budget thus was equivalent to only 0.44 per cent of this gross revenue. No comprehensive figures are available for the exploration for other metals and minerals in Southern Africa, but it is doubted whether search activities were allocated a substantially greater percentage of revenue than that for gold and uranium. It can be assumed that exploration in the immediate past has absorbed only about one-half of one per cent of the value of minerals produced in Southern Africa.

With South Africa's total mineral production for 1967 being R1,287 million, it is estimated that the amount expended on exploration during the year was possibly of the order of R6 million. In 1966, no less than R57 million was spent on exploration in Canada - almost ten times the figure for Southern Africa - although the gross value of metallic mineral production was about the same, viz. R1,208 million. The exploration budget for metals and minerals in Canada in 1966 absorbed 4.63 per cent of the gross revenue from mining. Brant (1968) estimated that the oil industry in Canada directed the equivalent of about 3.6 per cent of its gross revenue into exploration. He calculated that the yearly cumulative growth rate of exploration expenditure in Canada is 11 per cent, of which about half represents the effects of higher costs, so that the tempo of exploration is increasing at about 5 per cent per annum. Using these figures, the average annual allocation to exploration in Canada, during the decade ending in 1966, has been determined at about 3.5 per cent of the gross revenue from mining operations - approximately eight times the percentage spent on exploration by the gold mining industry in South Africa.

The mean cost of finding a new Witwatersrand gold mine can be put at about R7.5 million, on the basis of the figures given above. Cook (1968) has calculated that approximately R10.5 million, on the average, is spent in exploration for every significant new deposit found in Canada. If the present rate of expenditure is not increased, and if other factors remain equal - a most unlikely state of affairs - then, at the end of the next twenty years, Canada might anticipate having made 100 new major discoveries, while South Africa might have no more than 15 to its credit.

The upper limit of an acceptable exploration budget has been determined by Brant (1968) as 5 per cent of the gross revenue from mining activities. If a more conservative approach in Southern Africa fixes the figure at only 3 per cent, then a justifiable expenditure on the search for new ore would be of the order of R35 million per year, instead of the present R6 million. With improved strategy and evaluation of exploration and this amount of money, the theoretical discovery rate might be increased from the present four new significant ore-bodies every five years to four per year.

The comparatively small amount of money voted for exploration in the Precambrian terrain of Southern Africa, which has an economic potential equal to that of the Canadian Shield, has already been pointed to in Busschau's (1968) statement that "..... *the search for new economic deposits is not now as intense as it should be*". Better strategy, backed with more money, will certainly avert the anticipated decline in mining productivity in the next twenty years.

In future exploration budgets, adequate probision will have to be made for the cost of research implicit in the formulation of new strategy. Constructive change is dependent on the acquisition of new knowledge. For such knowledge of the processes and responses of mineralization to be generated within its own structure and at universities, the mining industry will have to support more basic and applied research than it does at present. A very approximate estimate would place the total amount of money contributed directly and indirectly by the mining industry to the furtherance of research specifically relevant to mineral exploration at no more than R100,000 per year. This figure, if anywhere near the truth, represents 1.5 per cent of the estimated amount allocated to exploration.

King (1968) has indicated that, in the United States, the amount of money spent on research and development is equal to 3.4 per cent of the value of the gross national product, and, in Great Britain, 2.3 per cent. Using such figures as guides only, and considering the cost of exploration, and not the total revenue from mineral production, it is suggested that doubling the research share of exploration expenditure to R200,000 per year would optimize the prospects of obtaining, sufficiently soon to be useful, the new knowledge vital to progress in the search for new ore-bodies.

PERSONNEL

The human input into the systems approach to exploration is of no less importance than the financial and tactical aspects. Both the quantity and quality of exploration personnel will have to reach higher levels if future problems of ore search, characterized by greater complexity, are to be solved. Cook (1968) has stated : *"A well-conceived exploration program is dependent for its success on the quality of the personnel assigned to it. The requirements for imaginative capabilities cannot be over-emphasized"*. Such demands can be met only if the present style of education is changed, and if the status of earth scientists in the mining industry, particularly, and in the social structure, generally, is elevated by several orders of magnitude.

Perhaps, the ideal situation exists in Russia. The earth sciences there are well supported financially, and enjoy a level of prestige second only to space exploration. Recruits to the profession, already claiming over 90,000 members, are influenced by the popular glamour attached to geology, geophysics, and geochemistry, and the publicity received, particularly on Geology Day, the first Sunday in April. The fact that there are a hundred times as many geologists in Russia as in Southern Africa is not the only reason for the high discovery rate which is reported from that country. The frequency with which new goldfields are found in the U.S.S.R., when compared with the outcome of exploration activities for the same metal in Southern Africa, possibly also reflects a higher percentage of earth scientists with higher intellectual capabilities. Some of the best potential scientists are attracted to geology as a career, in contrast to so many South African tyros who have drifted into geology as rejects from other scientific disciplines.

A start to improving the numbers and qualities of exploration geologists can emanate from the universities. There is no institution in Southern Africa at present which has a department of earth sciences specifically catering to the exploration needs of the mining industry. As King (1968) has said of British universities in general, departments arose in response to the requirements of an utterly different world, with *"..... individual professors appointed for life (with an advanced retirement age) on the assumption that a single person is capable of representing, more or less on his own, a scientific discipline throughout his life span, although with the rapid advances of knowledge there is need for wave upon wave of new men and new ideas"*. There is an urgent necessity today in South Africa for at least one department which can provide the interdisciplinary foundations of education in mineral exploration.

As geological problems become more intricate, so the geologist must become more of a thinker and less of a technician. Much of present-day teaching produces graduates equipped to become nothing other than unimaginative, disinterested data-gatherers. To meet the evolving needs of exploration geology, a broader background has to be provided in the physical sciences and their applications to geology, geophysics, and geochemistry. In particular, greater emphasis has to be placed on advanced mathematics and statistics and on computer applications in the earth sciences. Without these, the systems approach and operations research techniques cannot be introduced into exploration strategy. Economics, business administration, mine valuation, and certain aspects of mining engineering will also have to form part of the curriculum. In addition to an undergraduate department, the university should establish a formal graduate school in which much of the research necessary to improve strategy can be conducted. On a less formal basis, the same graduate school can assume, on behalf of the mining industry, responsibility for "..... *upgrading performance of exploration personnel through educational publications, seminars, workshops* ....." (Mitcham, 1968). Education on all levels is always improved in an atmosphere vitalized by research activity producing new knowledge.

There must be one university willing to accept the challenge of leadership in introducing a dynamic program of undergraduate and graduate education in mineral exploration that will help geologists in coping with the problem of saving the mining industry from decline in the next twenty years. It is to be hoped that King's (1968) observation on British universities does not prove to be equally applicable to South African universities, without exception : "*The university, from which so many of the discoveries of science have come, on which innovation in society and industry depend, is, of all national institutions, one of the most impervious to innovation from within*".

More than ever in the past, exploration in the two decades ahead will need the type of person specified by Busschau (1968) as a "..... *geologist with his curiosity ..... a leader who appreciates all the various elements required for success ..... an entrepeneur in the best sense of the word*".

TACTICS

Less need is seen, at present, for radical changes in the tactical procedures employed in exploration. It is believed that significant discoveries can still be made by exhausting the potentialities of existing field and laboratory techniques, and before committing search to the promise of a whole array of new geological, geophysical, and geochemical data-gathering methods.

Among the many new developments that are likely to take place in the next twenty years, the following can be put forward as probabilities :

(1) More accurate regional geological maps will become available, preferably from government institutions. Remapping of many areas of Southern Africa is vital to providing the basic data for formulating new strategy. The geological map still remains the most useful tool in the repertoire of the exploration geologist. In return for the substantial amounts of money which taxation claims, the mining industry is entitled to more services of higher quality from the various governmental departments which are concerned with the earth sciences.

(2) Increasingly sensitive geophysical equipment of more sophisticated design will be forthcoming to increase the depth penetration of various techniques. At present, mining operations can take place at depths ten times those which can be effectively reached by geophysical exploration methods. The new techniques will also be able to discriminate more successfully between mineralization of a sub-economic tenor and ore.

(3) Many of the remote sensing techniques developed for space exploration will be adapted to the requirements of ore search. The full spectrum of multiband photography, infrared sensing, and radar mapping will be added to continually improving airborne geophysical techniques which will probe the gravitational, magnetic, electromagnetic, and radiation fields of the Earth. As better solutions are found to the problems of depth penetration, so will a greater proportion of geophysical prospecting be carried out by means of airborne instrumentation.

(4) Chemical analytical methods will improve, with respect to sensitivity, speed, and cost. This will permit more routine and systematic sampling of all rock-types in the quest for new sources and receptacles of mineralization. There is a conspicuous paucity of quantitative data on the metal contents of the wide variety of plutonic, volcanic, sedimentary, and metamorphic rocks which occur within, and removed from, the metallotects. New targets in the form of disseminated mineralization in shales, dolomitic siltstones, subaqueous volcanics, and other stratiform rocks will be delineated only if geochemical analyses become an integral part of any search procedure. Isotope studies in connection with age measurements belong in the realm of geochemistry. Because of the time-dependent nature of many types of mineralization, geochronology will prove of appreciable value, provided that larger numbers of determinations can be carried out more rapidly.

(5) Geochemical prospecting techniques will improve to the point where a ready distinction can be made between anomalies caused by ore and those produced by other geological factors unrelated to the significant concentration of metal in bed-rock. At present, reconnaissance geochemical exploration, whether of stream sediments or soils, serves only as a coarse filter through which can pass, far too frequently, many of the more subtle indications of the presence of mineral deposits. Refinement in these reconnaissance techniques requires more urgent attention than does modification of existing methods of detailed geochemical prospecting. Geobotany will also assume greater importance, as the total surface environment becomes more accepted as worthy of examination.

(6) Of three geological techniques, structural mapping is probably the one most in need of far-reaching changes in the years ahead. In a terrain where so many ore-bodies have been clearly shown to be structurally controlled, the quality of structural investigations in the past has been of a disturbingly low standard. Very few attempts have been made to study any but the most obvious and elementary structures, and these have been subjected to Brock's (1960) normal viewing only. Only recently, and then by a very limited number of investigators, have attempts been made to decipher the total tectonic imprint in the rocks. This is essentially a process of viewing down the scale. Wide-angled viewing of the regional structural fabric of metallotects is still in its infancy.

(7) The second geological technique which will be more extensively employed in future prospecting operations is sedimentological mapping. The Precambrian sedimentary basins of Southern Africa are the hosts to possibly 80 per cent of the mineral deposits which have been exploited so far. Sedimentary environments and structures have played a major rôle in localising the concentration of minerals, whether by detrital, chemical, or biogenic processes, but little quantitative data exist on these parameters. Within the last decade, a start has been made on remedying this situation, and sedimentological knowledge is now accumulating at a faster rate than structural information. Progress is these two geological fields should be compatible, since all aspects of sedimentation are controlled to a greater or lesser degree by tectonism.

(8) Quantitative stratigraphic mapping is the third geological exploration technique which will occupy a conspicuous position in the improvement of search procedure in the next decade. The oil industry has long recognized that the technique of basin analysis is a powerful tool in understanding the overall geometry of, and full array of environments in, a depository. The quantitative mapping techniques essential to basin analysis have been described by Forgotson (1960). Only some of the more conventional of these have been employed in exploration of basins in Southern Africa. Systematic use of the other techniques will facilitate a finer appreciation of the history of formation and infilling of the sedimentary basins, in the context of which the episodes of ore formation can be identified and characterized.

(9) It will be found that organisms have played a far greater rôle than previously thought in the localisation of ore and mineralization. Study of biofacies will become as important as lithofacies in basin analysis. Since organisms become progressively smaller, the further back in Precambrian time the rocks were deposited, much of the search will be for ultramicroscopic forms and chemical fossils. Organic geochemistry might become as valuable a tool in mineral exploration as it has proved in the quest for oil.

(10) Techniques of studying and measuring physical phenomena, currently commonplace in other disciplines, will be adapted to the needs of mineral exploration. One that immediately

suggests itself is the employment of moiré patterns in determining the flatness of surfaces on which geological processes have acted, and in deciphering the interference effects of superimposed fold systems.

A detailed analysis of some aspects of future tactical search procedure in the Witwatersrand Basin has been presented by Pretorius (1966a). The elements, and their inter-relationships, of this quantitative structural, sedimentological, and stratigraphical systems approach accord with the type of basin analysis which it is envisaged will become standard practice in future exploration of all well-mineralized Precambrian depositories in Southern Africa. Nel (1968) has ascertained that, in the past 40 years, of the order of 2000 boreholes, totalling about 9 million feet in depth, has been drilled during the search for further goldfields in the Witwatersrand Basin. It is submitted that somewhere near half of these would have proved unnecessary had a systems approach of basin analysis been followed in the past decades to the extent that it will have to be employed in the next twenty years in order to maintain the Witwatersrand Basin's status as one of the greatest metallotects in the history of mining.

EVALUATION

The evaluation of interim and terminal results of exploration activities involves three steps : (i) data processing and analysis, (ii) data interpretation, and (iii) data storage and retrieval.

The first step is aimed at integrating the complete range of results from all tactical procedures employed, and at extracting the maximum amount of useful information from the data. The possibility always exists that a proliferation of data, some relevant to interpretation, and some not, can enter and confuse the analytical processes. To minimize this problem, it will become more and more necessary to introduce progressively more refined statistical techniques into the system of evaluation. The manner in which this can be done has been discussed by many investigators of late, including Agterberg (1964 and 1967) and Pretorius (1966a). These advanced techniques of quantitative analysis should be specifically directed towards recognizing and ranking all the variables and limitations affecting interpretation. Multiple regression and factor analysis are but two of the techniques which will have to be improved to assist in isolating the most important ore-finding criteria in the volume of information which will accumulate from future exploration efforts. New approaches will also have to be developed towards pattern recognition and classification. Statistical filters will have to be employed to separate the simpler components and controls in complex patterns of interrelated structural, stratigraphic, petrological, sedimentological, biogenic, and mineralization parameters. Brock (1960) anticipated this in his dictum : *"When a pattern makes sense, prediction becomes possible"*. In the end *"..... consistently successful prediction is the goal of all exploration philosophies and activities ....."* (Pretorius, 1966a).

The final interpretation of the outcomes of tactical operations will always remain a highly subjective undertaking. The advances which the future will bring in evaluation will be primarily in the techniques of preparation and classification of results before they are submitted for interpretation. The ultimate assessment of all phases of an exploration program will be at an optimum where creative thinking dominates decision-making. Attracting a larger number of creative thinkers into the earth sciences is dependent on solving the problems of improved status of geologists in the mining industry and in society and of changing the style of university education.

Once interpretations have been made and decisions reached, the details of all the preceding steps and of the knowledge gained should be placed on record in such a manner that any particular aspect can be readily recalled for incorporation in the systems approach to any succeeding search venture. As the volume of information grows, it will become progressively more difficult to do this, unless a computer-based program of data storage and retrieval has been made an integral part of the total system of formulating strategy, executing tactics, and evaluating results. To reduce costs and save time in the early stages of assessing the potential of a target area, it is foreseen that a central data bank will have to be established by the mining industry in the not-too-distant future, which will, at first, classify and sort for ready recall all the information that has been published previously on the area. In the second half of the next twenty years, it is possible that even the unpublished exploration results of individual mining companies will be included in the contents of the data bank. If something has been done competently once, and the full details of the outcome placed in an efficient data storage and retrieval system, then there should be no need to repeat the operation. It would be illuminating to learn how many times the same basic information has been gathered from the same sources by different mining companies about to engage in the same type of examination of the same target area.

PROGNOSIS

A look into the future, from the promise of present trends, must lead to agreement with the statement of Mr. T. Reekie, former President of the Chamber of Mines of South Africa, made at the 78th. Annual General Meeting in June, 1968 : *"We are in the midst of momentous times as far as the gold mining industry is concerned but we can meet them with confidence ....."*. Greater understanding is being gained at an ever-faster rate of the fundamental controls of ore emplacement, and with better understanding must come increased success in predicting the location of undiscovered new ore. The underlying patterns of the distribution in time and space of mineralization in Southern Africa are being recognized and categorized. The earth sciences are passing from a mainly descriptive phase into the more sophisticated one of analysis and synthesis. There are being made definite, but as-yet limited, attempts at cross-fertilization with ideas and techniques developed in other disciplines. In the past, it has taken between five and ten years for new approaches to mineral exploration to find their way from North America and Europe to Southern Africa. Now, the lag is being reduced in many instances, and, more encouragingly, new philosophies and strategies are being generated within the sub-continent itself. Only with respect to tactical procedure and techniques does there still appear an inbuilt tendency to wait for a lead to be given by other major mineral-producing countries.

The climate seems favourably set for new discoveries in the next twenty years. Busschau (1968) has succinctly summed up the prospects : *"..... this vast country in a geological sense is still far from being fully explored, and even if the limits of economic gold mining are found to be near in time, there are still vast possibilities of other mining development"*.

Ten broad potential exploration targets have been defined as worthy of attention in the years ahead. Undoubtedly, others will emerge. There is an old belief among economic geologists that, for every ore-body exposed at surface, there is another concealed at depth. So far, at least 75 per cent of the mines established in Southern Africa have been located on outcropping ore. Only in the Witwatersrand Basin has systematic and sustained exploration taken place for the concealed deposits. The ore, whether it be of gold or any other metal or mineral, is there to stave off the decline in mineral production, considered by non-geologists essentially as being unavoidable in the next twenty years.

It is the task of exploration geology to find that ore. There can be no denying that it will be a difficult task, which might even become impossible of achievement if some revolutionary changes are not effected in all aspects of the approach to the search for new mineral deposits. The most drastic changes are believed to be necessary in the formation of strategy and the evaluation of results. The strongly intuitive basis to both, which has prevailed in the past, will have to be replaced by a systems approach aimed at providing an objective quantitative environment for optimum decision-making. The precise nature and extent of the changes can only be determined by basic research which will have to form an integral part of all future exploration activities. It is believed that the amount of money allocated for research relevant to exploration, carried out within the industry itself and at universities, will have to be doubled in the immediate future. If the discovery rate in Southern Africa in the next two decades is to measure up to that anticipated in Canada, where the overall mineral potential would appear to be of the same order, then the sober fact must be faced that annual exploration budgets will have to be increased seven-fold. More geologists will have to be attracted to exploration in order to satisfactorily execute the expanded programs that the future will bring. Creative thinkers, competent to employ multidisciplinary knowledge, will be the new leaders of ore-search ventures. At least one university in Southern Africa will have to found an outstanding school of mineral exploration, integrating at both undergraduate and graduate levels the fields of geology, geophysics, geochemistry, geomathematics, and mineral economics. Changes will be necessary in tactical search procedure, but it is believed that the full potential of many current prospecting techniques still has to be exhausted, and that new discoveries can still be made without having to employ immediately a whole array of new instrumentation.

In the stimulating years of challenge and change that lie ahead, there seems adequate room for confidence in success attending exploration ventures. Perhaps, Pliny the Elder was, for that moment, a prophetic prospector when he uttered the statement : *"Ex Africa semper aliquid novi"*.

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