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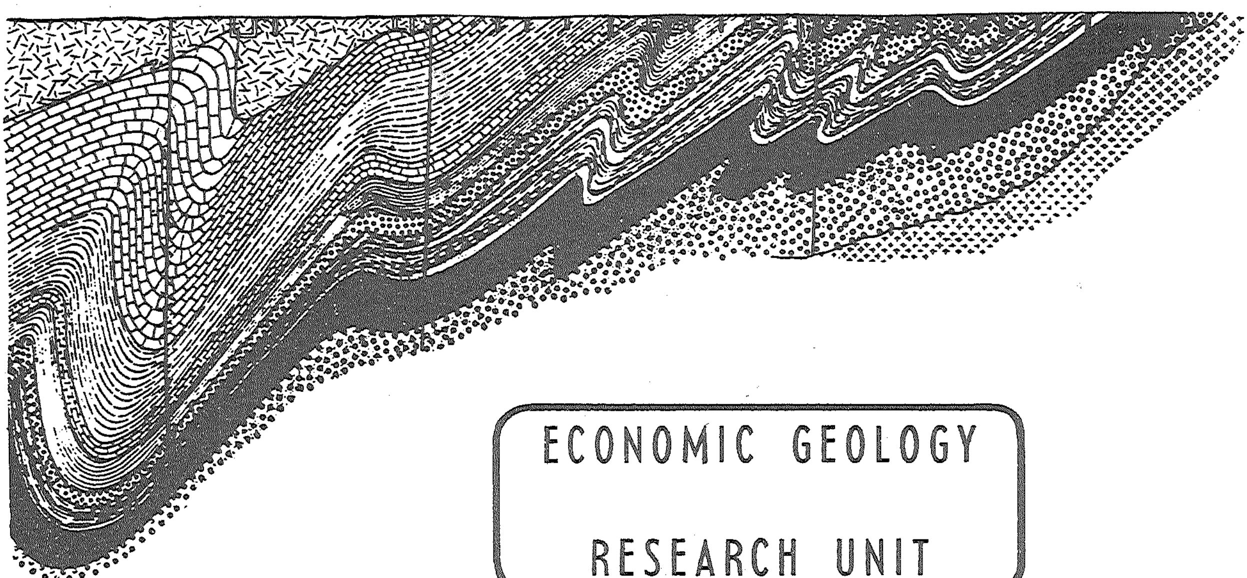

## ECONOMIC GEOLOGY RESEARCH UNIT

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# CONCEPTUAL GEOLOGICAL MODELS IN THE EXPLORATION FOR GOLD MINERALIZATION IN THE WITWATERSRAND BASIN

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## ABSTRACT

It is contended that insufficient use has been made of geology in the procedures of ore valuation and in the prediction of the distribution of gold in the Witwatersrand deposits. Of the more than sixty measurable parameters of a normal conglomerate reef, only three are currently employed for extrapolation and interpolation of the tenor of gold mineralization between and beyond individual mines. As a result, it has become necessary to devise progressively more refined techniques of statistical treatment to abstract, from the limited range of information, the data necessary to solve the ever-increasingly more complex problems involved in the exploration for new ore and the extensions of known pay-shoots, and in the valuation of blocks of ore in developed sections of a mine. The extent to which time-consuming and expensive methods of statistical analysis can be aided, and in some cases replaced, by more economical geological observations and measurements is a function of the extent to which the geological approach to exploration, valuation, and prediction can be transformed from the present qualitative and semi-quantitative basis to a fully quantitative one. How this can be accomplished is shown in eight conceptual geological process-response models that indicate the manner in which the geometry of a Witwatersrand goldfield and the distribution pattern of gold within it can be determined from the measurement and analysis in one dimension of the properties of the reef zone, the presentation and analysis in two dimensions of these parameters, and the geological interpretation of the resultant trends, residuals, and harmonics. The level of confidence attached to ore prediction can be raised by considering not simply the gold, which is a very small and erratic part of a particular rock, but the whole rock itself.


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# CONCEPTUAL GEOLOGICAL MODELS IN THE EXPLORATION FOR GOLD MINERALIZATION IN THE WITWATERSRAND BASIN

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# CONCEPTUAL GEOLOGICAL MODELS IN THE EXPLORATION FOR GOLD MINERALIZATION IN THE WITWATERSRAND BASIN

## INTRODUCTION

The ultimate objective of all exploration within the Witwatersrand Basin is the location of concentrations of gold which can be exploited economically. The scale of such exploration ranges from the search for extensions of the Witwatersrand System beyond the present assumed limits of the basin to that for further pay-shoots beyond and between the limits of development in individual mines. The means for looking for additional deposits of gold in new goldfields within the basin, or in new mines within the goldfields, or in new pay-shoots within the mines is essentially a process of extrapolation and interpolation from the known loci of optimum mineralization. It cannot be disputed that such operations are most effectively carried out, and that the consequent predictions attain their maximum level of confidence, when the data considered are quantitative rather than qualitative. Geology, as the foundation stone of any philosophy of exploration, must, therefore, evolve towards a quantitative basis if the future of the Witwatersrand gold mining industry is dependent on the discovery of new sources of ore.

The history of the development of the Witwatersrand Basin is, for the most part, an account of the introduction of new approaches to, and techniques of, exploration. For the first 28 years of the story, between 1886 and 1914, new finds resulted from the qualitative study of the surface geology of the Central Rand, the West Rand, the peripheral portions of the East Rand, the South Rand, the Vredefort area, and the western portion of the Klerksdorp field. During the next 18 years, between 1914 and 1932, the full potential of the whole of the East Rand was realised as a result of qualitative subsurface geological investigations. Qualitative geophysics was added to subsurface geology, and led to the discovery of the West Wits Line in 1932. Geophysical and subsurface geological prospecting methods advanced to a semi-quantitative level, and were responsible for the discovery of the Orange Free State Goldfield in 1938, the eastern portion of the Klerksdorp area in 1947, and the Evander Goldfield in 1950. During these years, although there was a growing tendency to transform observations into numbers, geology in the Witwatersrand Basin remained mainly in the realms of subjective identification, description, and correlation. Success attended exploration more because of good geologists, with a high degree of intuitive understanding, than because of the use of geology in a rigidly objective manner.

The 15 years that have passed since the first indications were obtained of the economic importance of the Evander area represent the longest period in which no new goldfield has been discovered in the Witwatersrand Basin since South Africa went off the gold standard. It is possible that no further goldfields remain to be found, but it is also possible that the failure of exploration might be due to the difficulties of discovery having moved beyond the range of solution which can be reached by present approaches and techniques. New methods, or improvements in the present ones, seem to be required. That those currently employed are still basically sound has been proved by the discovery since 1950 of a number of new mines in existing goldfields. Such results lead to the belief that what is required to improve the chances of success in prospecting known goldfields, and to make the breakthrough in the exploration for new fields, is probably a refinement in the present methods rather than the development of radically new techniques.

The suggestion is here put forward that the refinement can best be achieved through the transformation of geological thinking and investigation from a qualitative and semi-quantitative basis to a fully quantitative approach. The success of exploration can be enhanced through geological techniques employing more numbers and less words.

The aim of this paper is to show that sufficient geological knowledge of Witwatersrand gold deposits has been, or can be, accumulated to permit the design of conceptual models for

(b) A Model of the Targets and the Scope of Exploration

The scales of exploration activities within the Witwatersrand Basin can be regional, areal, or local. The targets sought under each type vary from the delineation of the boundaries of the whole of the original basin to the outlining of the limits of individual pay-shoots in sections of individual mines, and the nature of the investigations carried out on each scale of operation varies accordingly. Figure 1 is a conceptual model showing the relationships between the targets of exploration, the scale of exploration activities, and the scope of geological knowledge required for the attainment of the targets.

This paper is concerned with prospecting within, and immediately adjacent to, established goldfields, and consideration is therefore given only to fields of investigation encompassed by areal and local exploration. The problems of regional geological search for extensions of the Witwatersrand Basin are of sufficient magnitude to justify a paper devoted to this topic alone. Before construction can be undertaken of conceptual models as preliminaries to the design of mathematical models for the transformation of areal and local prospecting techniques to a quantitative basis, it must be ensured that sufficient data have been gathered in each of the fields of geological investigation set out in Figure 1.

The volume of published data on the Witwatersrand System is substantial, and the papers and other articles which are mentioned below must be regarded as only some of those which have contributed to the present ideas on the nature of the goldfields within the basin, and to the design of the various models. The listed publications have been singled out because they describe in detail the backgrounds of many of the conclusions which have been incorporated, without qualification or amplification, in the models.

The reinterpretation of the broad structure and the paleogeography of the north-eastern portion of South Africa, in the light of modern principles, is still in the early stages, but a preliminary assessment has been made by Pretorius (9). There is a considerable amount of unpublished information in the files of mining companies on the geophysical properties of the rocks in this part of the country. These data have been acquired during the course of the many magnetometric and gravimetric surveys carried out over the whole of the Witwatersrand Basin and adjacent areas. The regional patterns of structure and sedimentation within the basin have been discussed by Borchers (10), Papenfus (11), and Brock and Pretorius (12). The paleogeography, particularly as it bears on the origin and mode of formation of the Witwatersrand System, has received the attention of Reinecke (13), and Brock and Pretorius (14). The latter authors have also attempted a synthesis of the structural, sedimentological, and paleogeographic aspects of the history of the basin in order to provide a new foundation for alternative philosophies of regional and areal prospecting. New descriptions have been prepared of almost all the individual goldfields, such as those by Pretorius (15) for the Central Rand, de Kock (16) for the West Wits Line, and Pretorius (17) for the South Rand.

The most valuable recent advances in knowledge of the geology of the Witwatersrand System have been in connection with the detailed structure and sedimentology of the stratigraphic units constituting the various goldfields. This new knowledge has been applied successfully in areal and local investigations aimed at defining the limits of goldfields, mines, and pay-shoots. The usefulness of sedimentology on a macroscopic scale as a prospecting tool was fully appreciated by Pirow (18), Reinecke (19), and Sharpe (20). However, the full potential of the sedimentological approach has only recently been disclosed through the work of Hargraves (21) on the Main Reef Leader of the East Rand, of Armstrong (22) on the Kimberley Reef of the East Rand, of Steyn (23) on the Livingstone Reefs of the West Rand, of Steyn (24) on the White Reef of the West Rand, of Winter (25) on the Vaal Reef of Klerksdorp, and of Knowles (96) on the Ventersdorp Contact Reef of the West Wits Line. That microscopic sedimentology is also an exploration tool of considerable promise has been shown in the studies of Koen (26), Viljoen (27), and Snyman (28). The value of structural investigations, and the close relationship between tectonic structures and sedimentological features have been discussed by Pretorius (17, 29, 30, 31, 32).

### (c) A Model of the Development of a Goldfield

Before attempting to construct a model, it is essential to know of what it is to be a model. In the case of a Witwatersrand goldfield, the aim of the model is to show the distribution of the auriferous reefs, and of the localities of optimum concentration of gold within these reefs. To be concerned with parts of a goldfield, the model must be concerned, in the beginning, with the whole which contains the parts. It is necessary to know what, geologically, constitutes a goldfield, and to what processes it is the final response. It must be established whether a goldfield formed in a desert, a river, a lake, or a sea, whether the sediments were deposited on a sea-floor, a delta, a beach, a floodplain of a river, or in some other physiographic environment. The distribution pattern of the gravels and of the heavy minerals will be different for each case. The greater the degree of precision attached to the definition of the origin and environment of the whole, the more valid will be the prediction concerning the behaviour of the separate parts.

Although there are many different theories on the mode and environment of deposition of the Witwatersrand strata, there is general agreement that the source of the sediments and the gold lay to the northwest of the present basin, that the material was transported from there to the basin by rivers, and that the conglomerates and the contained detrital gold particles were laid down close to the edge of the depository and there reworked and reconcentrated. The gold was originally contained in hydrothermal replacement and quartz-vein deposits in schists, shales, banded ironstones, cherts, greywackes, quartzites, and lavas belonging to the Swaziland System which accumulated in a geosyncline trending east-northeast, and of which the Barberton Mountain Land is possibly the easternmost extremity. Other remnants of this geosyncline are contained in many exposures of the basement of the Witwatersrand System, and have also been intersected beneath post-Witwatersrand rocks in drilling operations in and around the basin. Recent sedimentological work has suggested that the original edge of the basin in Upper Witwatersrand times was not far from where the present outcrops of the West Rand, Central Rand and East Rand are today, and that the northwestern-most limit of the drainage areas feeding the major transporting rivers was possibly not more than about 30-40 miles from the edge of the basin. It would appear that only a relatively narrow width of sediments originally deposited along the edge of the basin has been eroded in the 2,500 million years or so that have elapsed since the time of formation of the sediments.

A conceptual model of the manner in which a goldfield developed in the basin from material transported from the source-area is presented in Figure 2. It will be seen that the mode of formation favoured is that of the sediments of a goldfield accumulating in the form of a large alluvial fan at the point of discharge of a major river into the depository, which took the form of a long, east-northeast-trending lake, in which the water was relatively shallow. At certain periods the lake might have dried up almost completely. The material on these fans was deposited by the river, and was subsequently reworked by the waters of the river and the lake when the general water level in the depository rose.

At least four such rivers are believed to have flowed into the basin along its northwestern edge, and to have formed fans which today constitute the main gold-bearing areas of the basin. The Orange Free State field represents one such fan, and the Klerksdorp area another. A third fan embraces the West Wits Line, the West Rand, and the western half of the Central Rand, while the fourth river discharged its sediments into the area that is now the eastern portion of the Central Rand, the East Rand, and the South Rand. The fans were roughly triangular in shape, with the left side of the area of maximum conglomerate development (looking towards the centre of the basin) generally longer than the right, so that the perimeter of the area of coarser sediments resembled the curve of a positively-skewed

Each substage in the Upper Division, such as the Carbon Leader Substage between the bottom of the North Leader and the top of the Green Bar, or the Main Substage between the bottom of the Main Reef and the top of the Black Bar, or the Bird Substage between the bottom of the lowest band of the Bird Reefs and the bottom of the Bird Amygdaloid, is formed of the sediments which accumulated during the development of a single fan. The strata of a goldfield thus represent the aggregate of a number of superimposed alluvial fans which formed, probably at fairly regular intervals of time, at the mouth of the same river. Two such entry points of material into the basin, which remained virtually constant in their position throughout the whole of Upper Witwatersrand times, were located at relatively small distances northwest of Krugersdorp and east of Kempton Park.

During the time required for the deposition of a sufficient thickness of sediments to form one of the series of the Witwatersrand System, the apices of successive superimposed fans constituting the substages of sedimentation might have transgressed or regressed, depending on which was respectively greater, the rate of subsidence of the basin, or the rate of uplift of the source-area. However, from series to succeeding series, the dimensions of the basin grew progressively smaller, so that there is a regressive relationship between the mean positions of the apices of fans formed from Jeppestown times to Main-Bird times to Kimberley-Elsburg times. This would mean that, for example, vertically above a fanbase facies of the Veldschoen Reef in one locality might be a midfan facies of the Main Reef, and above this, in turn, might be a fanhead facies of the Elsburg Reefs.

Because the gold is restricted to certain rock-types, and the maximum concentrations of the gold to certain facies of such rocks, and because these facies are confined to certain portions of a goldfield, it is of critical importance to know as precisely as possible the position, in the geometrical arrangement of the fan, of any locality under investigation. The overall economic potential of any segment of a reef in any section of a goldfield is primarily a function of the position of that section in the original alluvial fan.

### (e) A Model of the Areal Distribution Pattern of Gold Mineralization

It has been stated previously that the gold occurs mainly in conglomerates and carbon seams, the products of two very different environments, and therefore having their areas of typical development in different parts of the same fan. A conglomerate is essentially a response to a high-energy environment, whereas carbon seams, believed to represent the remains of algae, are low-energy products most likely to have accumulated in stagnant swamps where such primitive organisms could have flourished undisturbed and have precipitated dissolved or suspended gold from the waters in the swamp. Carbon-rich conglomerates are thought to be the products of contamination brought about by a high-energy environment having developed over portions of a fan where a low-energy environment prevailed during a previous substage. The carbon thus belongs to an earlier cycle of sedimentation, and was broken up by, and incorporated in, the gravels which were washed over the earlier environment during the first pulse of the succeeding cycle.

In the ideal fan, a high-energy environment was best developed at the apex of a fan, and changed gradually into low-energy regimes radially away from this point as the gradients of the fluvial channels flattened once the river passed from the highland surrounding the basin into the depository, and as more and more water sank into the porous gravels covering the fan. Low-energy environments therefore prevailed towards the margins and base of each fan. The amount of gold transported beyond the boundaries of the alluvial fan into the surrounding lacustrine environment was virtually negligible. The size of the fan developed during each substage varied according to the initial energy-level, and the ratio of the area of the high-energy regime to the area of the low-energy environments also varied from substage to substage. In this manner, conglomerate reefs overlapped underlying carbon seams in those instances where the overlying substage was formed at a higher energy-level. In other cases, where earlier the material brought to the fan, and the locality of deposition of any segment of the reef occupies a fixed place in this pattern. The potential of the relevant segment of the reef is not at a uniform level, there being alternating zones of greater or lesser payability. It is obvious that a second major control must have operated, on a local scale, to have influenced the development of pay-shoots of higher values. This factor is believed to have been the effect of irregularities in the depositional floor on the hydrodynamics of the local dispersal system of the water moving and winnowing the material in the locality of deposition.

At the apex of an alluvial fan, the river from the source area divided into a limited number of master streams and these, in turn, bifurcated into numerous channels of varying width and depth which formed a braided, centrifugal pattern. These channels were generally broad and shallow, as a result of the stream shifting from side to side and spreading its excess load of gravel and sand. The preserved channels, when measured over a sufficient distance to minimize the effects of small-scale meanders, now project back to intersect at where the mouth of the river was, and are thus a valuable means for fixing the apex of the fan for any particular substage. Material was laid down on the fan as channel deposits, when the flow of water was confined to the streams and channels; or as streamflood deposits, when the streams and channels overflowed their banks during times of flood, and sediments were spread out over areas between channels; or as sheetflood deposits, when exceptional flood conditions caused the material to surge out turbulently over the whole surface of the fan without any control being exerted by the master streams or channels. When channels became choked with their own bed-loads, a new branch developed upstream, and swamp conditions possibly formed where stagnant bodies of water remained in the choked channels or in the inter-channel areas into which the dammed-up water had overflowed. Such conditions were far more likely to have developed in the low-energy environments along the marginal and basal portions of the fan.

Figure 5 is a conceptual model constructed to show in which local environments, reflecting different parts of the depositional floor, the main rock-types of a goldfield were deposited. The quartzites, argillaceous quartzites, and shales are normally devoid of significant mineralization. If the models shown in Figures 3, 4, and 5 are studied jointly, it will be seen that any exploration program aimed at finding carbon seam reefs has, as a primary goal, the location of the marginal portions and the fanbase section of the original alluvial fan constituting the goldfield, and, as a secondary target, the identification, in such areas, of sediments which show evidence of having been deposited in a swamp environment.

Streamflood conglomerates in the inter-channel areas, or sheetflood conglomerates in any portion of the fan are generally relatively poorly sorted, and deficient in heavy minerals, forming reefs which are either unpayable, or have a low degree of payability with moderate to low average values. Many of the reef zones occurring between pay-shoots are composed of what were originally streamflood gravels. Optimum conditions for the deposition of well-sorted conglomerates with a relatively high percentage of heavy minerals, and for the laying down of auriferous pyritic quartzites occurred in the channels, and most of the pay-shoots in conglomerate reefs are now found along certain zones within channel deposits. In many instances, where the original channels were shallow, and the differences in the nature of the channel gravels and the streamflood gravels were slight, the boundaries of the original channel cannot be distinguished in the present conglomerates, but have to be determined analytically by means of heavy mineral counts or gold assays. Where an overlying gravel was deposited by a stream or streamflood which eroded and reworked a previously laid-down auriferous gravel in the footwall, local concentrations of such reworked and incorporated gold have produced pay-shoots unrelated to channels in the overlying reef. However, in the main, exploration for conglomerate reefs should first be directed towards locating the central and intermediate portions of the lower fanhead, midfan, and upper fanbase sections of the goldfield, and then towards searching for stream channels in the conglomerates of these areas.

with abundant quartzite pebbles might be of lesser importance than those with fewer such pebbles.

Scalar and directional parameters can be measured and treated numerically, and are, therefore, the essentials of quantitative exploration. At present, only three scalar parameters — two relating to relative concentrations of components of the aggregate and the third to the geometry of the conglomerate zone — are consistently and systematically employed in the solution of problems of ore prediction and valuation. In certain special studies of specific problems, some of the other properties have been treated quantitatively by investigators in the past, but there have been no attempts to incorporate such techniques into the routine assessment of the trends of gold mineralization. It can be shown that there are more than 60 other geological parameters which can be measured and used for extrapolation and interpolation of pay-shoots. It is suggested that, if some of these are studied concomitantly with the values of gold and uranium in the reef and the thickness of the conglomerate horizon, then many ambiguities in the interpretation of trends of pay-shoots might be resolved, and a much higher degree of confidence might be attached to any predictions made concerning the distribution patterns of the gold values.

### (b) A Model of the Defining Detailed Parameters of a Pay-Shoot

Figure 7, which is an extension of Figure 6, is a conceptual model of the specific, detailed attributes, scalar properties, and directional properties which can be observed or measured in the conglomerate reef and its adjacent rocks as means of determining the nature of the source-material, the competency and dispersal patterns of the transporting currents, and the place of deposition of the segment of the reef under study.

The competency of the currents to transport gold and other materials can be gauged by an investigation of the composition and texture of the conglomerate itself, the pebbles and the grains of the matrix being regarded as separate populations. An average conglomerate might contain four different types of pebbles, and have the light fraction of the matrix composed of four minerals, and the heavy fraction of six minerals present in readily measurable amounts. The modal percentage of each of these 14 constituents is a parameter in its own right, and the ratios of the percentages of certain selected minerals are further parameters. The four moments of the size-frequency distribution of all the pebbles treated collectively, and of, say, three of the heavy minerals in the matrix yield a further 16 parameters. The pebble density factor, and the shapes (roundness and sphericity) of, say, one type of pebble and one mineral in the matrix represent another five parameters. The number of scalar properties which can be used to classify numerically and analyze one aspect of the local hydrodynamic conditions under which the average conglomerate reef was formed thus amounts to at least 37, of which only two, namely gold and uranium values, are used in current ore prediction and valuation procedure.

The other aspect of the hydrodynamic system which operates on a local scale is the dispersal pattern of the currents, and the directions of flow can be measured by the fabric of the aggregate of the conglomerate and the local trends of the conglomerate zones. Generally, the orientation and degree of imbrication of all pebble-types as one population and of the quartz grains only of the matrix are considered, yielding two directional parameters. The manner in which the original material moved can be measured by four further directional parameters, namely the direction of dip of the foresets of cross-bedding, and the strikes of the axes of ripple-marks, sand-waves, and scour-troughs. Trends obtained from the contouring of scalar properties, lithofacies, and structure elevations are of secondary derivation, and represent the processing of parameters mentioned under other headings. Thus, a further six parameters of the conglomerate can be measured in connection with the current dispersal patterns, none of which is considered in present processes of ore valuation.

Properties of the rock which help to identify the place of deposition belong to the lithofacies of the conglomerate zone. Of the five parameters falling under this heading, mud-folding, faulting, and intrusion by dykes and sills. The measurable parameters of the conglomerate zone, listed in Figure 7, must first be analyzed in one dimension in order to establish the degree of reliability of each of the properties as an indicator of conditions favourable to the accumulation of gold, and in order to identify the most meaningful parameters for subsequent analysis in two dimensions. The necessity for the initial statistical analysis in one dimension of the measured geological data hinges on the fact that, as stated by Krumbein and Griffith (40), 'by knowing the range of values of any variable in the environment, and the laws which express the change, it is possible that important information can be gained about the physical factors of the environment which control the characteristics of the deposit'.

The application, in general, of statistics to geology, as an adjunct to normal intuitive analysis, has been described, in varying amounts of detail, by Strahler (41), Miller and Kahn (42), Wilks (43), Folk (44), Pettijohn, Potter and Sieve (45), and Agterberg (46). The following brief descriptions of one-dimensional univariate and multivariate analysis represent some of the methods which appear to have particular application to the quantitative study of the properties of Witwatersrand conglomerates.

(d) <u>Statistical Analysis in One Dimension</u>

The fundamental analysis is the determination of the frequency distribution of the particular parameter under consideration, whether it be of the sizes of grains in the matrix of one sample of conglomerate or of the number of pebbles per square foot of conglomerate at each site in an area containing a hundred sampling sites, and the calculation of the statistical moments as measures of the departure of the distribution from normality. These methods are well described by Folk (44) with respect to the analysis of the texture of the conglomerates as an indicator of the competency of the transporting currents. The mean defines the centre of gravity of the distribution, the standard deviation measures the uniformity, or degree of sorting, which is a reflection of the range of variation in the process, while the skewness and kurtosis reveal the asymmetry and peakedness of the distribution. That frequency distributions and statistical moments have application in fields other than textural studies of sediments has been shown by Drew and Griffiths (47). A computer program for calculating the mean, standard deviation, skewness, and kurtosis in grain-size analysis has been drawn up by Kane and Hubert (48). The analysis of variance sorts out the variations produced by the geological factors, helps in the interpretation of the pattern of variability, indicates the reliability of the averages, and improves the efficiency of the sampling procedure. It segregates the within-group variance from the between-group variance, and provides a test, in terms of two independently distributed variances, of the equality of the within- and between-group means. Its use in the quantitative study of sediments has been described by Krumbein and Miller (49), Olson and Potter (50), and Krumbein (51).

Multivariate analysis is an essential process in classifying and sorting the parameters measured in the conglomerate zone, and in determining the interactions and correlations between genetically interrelated variables. It translates the interrelationships into probability terms, and isolates the critical variables which exercise the most control on the responses. It can be used to test hypotheses formulated from independent criteria. The uses of multivariate analysis, in general, in different types of geological problems has been discussed by Potter (52) and Harris (53).

Multiple linear regression is one of the methods, according to Krumbein (54), for sorting out empirically the relative effects of the first-order independent variables. It identifies those variables among a group of variables which exert most control on a selected dependent variable. Sequential multiple linear regression, as described by Krumbein, Benson and Hempkins (55), ranks the independent variables in order of importance, and develops an effective prediction equation that uses the minimum number of such variables to achieve a desired level of prediction. This method is useful where sets of data have a dependent variable which can be specified, but independent variables which may be interrelated. Principal component analysis has

Many one-dimensional analyses of the possible relationships between pebble-size and gold content, pyrite content and gold values, reef thickness and gold content, among others, have yielded results which varied too widely from one segment of the reef to another to permit the investigators to conclude, with any degree of confidence, that sympathetic relationships existed between differences in these parameters and fluctuations in gold values. Consequently, the usefulness of these parameters in ore prediction and valuation has remained a matter of debate, and their measurement and analysis have not been incorporated in routine geological work. However, recent sedimentological work has shown that, when analyzed in two dimensions, the components of the patterns of areal distribution of the gold value and many of the other geological parameters show a high order of correlation. The areal trends, and the local deviations from these trends, of the various properties of the conglomerate reef are, in many instances, similar to the extent of being almost identical. In the past, correlation has been sought between trends plus deviations in one dimension, with only a very limited amount of success. Recent research has shown that, if trends are correlated with trends only, and deviations with deviations only, and the correlation is carried out in two dimensions, then the usefulness of the many geological parameters, other than gold and uranium values and reef thicknesses, for predicting the location and extent of pay-shoots can be unequivocally demonstrated.

Profiles showing relationships in one dimension must be succeeded, as the favoured means for attempting correlations between different geological parameters of the reef, by maps in which a sampled point is a function of two independent variables — the geographic co-ordinates — and one dependent variable — the parameter measured in the rock and subsequently subjected to univariate analysis. When contours are drawn through points of equal value or number on these maps, they become isoline maps. To many investigators, the terms 'isoline maps' and 'isopleth maps' are synonymous, but, because maps of the isopleths of several parameters have been given their own distinctive names, it is preferable to use 'isoline maps' as a collective term for all contour-type maps, and to reserve the term 'isopleth map' for those isoline maps which have not yet been distinctively named. The different types of isoline maps which can be prepared for the different geological parameters are indicated in Figure 8.

Potter and Pettijohn (38) have stated that the study of a sedimentary basin is essentially concerned with the development of a conceptual model based on the stratigraphic geometry (isopach maps), the sedimentary lithology (lithofacies maps), and paleocurrent data. Isopach maps have been used extensively in Witwatersrand ore valuation procedures in the representation of the areal variations in the thickness of the conglomerate zone, misleadingly called 'channel width' in local mining terminology. However, neither lithofacies nor paleo-current maps have been systematically utilized. Except for isocon and structure contour maps, none of the other isoline maps mentioned in Figure 8 has been considered, except in a few research studies, as being of practical value in delineating pay-shoots. The recent sedimento-logical investigations of Hargraves (21), Armstrong (22), Steyn (23 and 24), Winter (25), Viljoen (27), and Knowles (96) have clearly shown that the neglect, in the past, of the potentialities of isomegathy, paleocurrent, ratio and percentage maps, and of isopleth maps of the relative abundance of particles, the moments of size distributions, and the packing of pebbles has been unjustified, and that such maps provide information on the distribution patterns of the conglomerate reefs of a level of significance equal to that accredited to isocon, isopach, and structure contour maps.

As stated previously and as depicted in Figure 6, the two main controls in the development of a pay-shoot are an areal factor relating to the place of deposition on the original alluvial fan, and a local factor dependent upon the hydrodynamics of the transporting medium at the place of deposition. Isocon, isomegathy, and isopleth maps of other compositional properties of the conglomerate reflect the competency of the transporting currents, one aspect of the local hydrodynamic conditions, while paleocurrent maps are portrayals of the dispersal pattern of the currents, the other aspect. The place of deposition can be ascertained from isoline maps depicting the lithofacies and external geometry of the conglomerate zone, and the vertical variability in such a zone. Forgotson (67) has compiled a review of the properties and that, when the number of measurements ranges between twenty and several hundred, then the method of least squares is possibly the most practicable to employ, but when the number is measurable in thousands, then the moving average approach might more readily result in a fair approximation of the trends which could be obtained only by fitting polynomial trend surfaces of a very high order. The general methods of computing and the advantages and limitations of trend surface analysis have also been described by Baird, McIntyre and Welday (79) and Whitten (80). The applicability of such analysis to the study of the areal variations in the physical and chemical properties of rocks has been discussed by Whitten (81), Ragland and Wagener (82), and Harbaugh (83), in aspects of sedimentology by Miller (84), Stewart and Gorsline (85), Duff and Walton (86), Harrison, Krumbein and Wilson (87), and Chorley (88), and in structural geology by Loudon (89) and Whitten and Thomas (90).

Trend surfaces, according to Merriam (60), do not reveal features that cannot be perceived in the original data by close scrutiny, but serve to accentuate those of less than regional magnitude by bringing out details previously unnoticed. This method of analysis, by reducing complex situations to simple patterns of separately assessable components, is particularly suitable to extrapolation and interpolation of the data surface. Whitten (91) has indicated that low-order trend surfaces — linear, quadratic, and cubic — are ideal for regional or areal predictions, because the simple regression operation involved in the method smooths the data to an appreciable extent. High-order equations — quartic, quintic, sextic, and above — defeat the purpose of regression for geological purposes by not smoothing the data sufficiently, but they are most valuable for predicting accurately gold values in conglomerates within small areas. Hempkins (71) has stressed that there is a difference of approach in the processing of isocon maps for predicting the distribution pattern of gold for valuation purposes, and of isoline maps for predicting the trends of geological features. In the former case, what is required is as complicated and complete a surface as can be made to fit existing data, and, in the latter, a simplified and systematic representation of the data surface. Second-rank surfaces, such as that representing the difference between eighth-order and third-order surfaces, have been suggested by Whitten (91) as a possible means for screening out very local variability and analytical errors in order to reveal significant local geological features. Deviations from the very high eighth-order surface might be due to 'noise' only, whereas deviations from the third-order surface (regional trend) might include the effects of local geological phenomena plus 'noise'.

Harmonic analysis in two dimensions is possibly best performed by a double Fourier series, and its extension into autocovariance and power spectrum techniques. The Fourier expansion could be used, according to Hempkins (71), to study the harmonic components of a response surface above the surface determined as the trend, which, in itself, might reflect a regional harmonic. Harbaugh and Preston (64) have stated that the configuration of the surface portraying the geological features which vary in a more or less cyclic manner depends on the number of terms in the Fourier series and the values of the coefficients of the terms, the coefficients providing the means for isolating and identifying the contributions of the various underlying harmonics. By rejecting more and more of the higher harmonic terms accounting for the fine variations in the contours and for the smaller anomalies, the residual values are generally lost, and only the harmonics of the regional or areal trend are left, as demonstrated by Bhattacharyya (92). If a Fourier series analysis does not represent the data convincingly, then it can be concluded that the variations are not due to causes which vary in some periodic manner, and that conventional trend surface analysis must be resorted to as a mathematical means of representation. Horton, Hempkins and Hoffman (93) have employed autocovariance and power spectrum techniques of harmonic analysis to determine the degree of homogeneity of the characteristics of a rock-unit across an area by comparing the harmonics in any sub-area with those of any other sub-area. The spectral analysis serves to identify the amplitudes and frequencies of the component cycles which contribute to the periodic portion of the oscillatory phenomena. The autocovariance function contains the same information as the power spectrum, except that it is given as a function of distance in the case of the former, and of frequency in the latter. Double Fourier series analysis provides an effective approximation of gross variations, but not of local fluctuations, according to Harbaugh and Preston (64), and is suspension, gold and other materials decreases radially away from the apex, and downstream in each channel. Krumbein (99) and many other investigators have shown that a profile of parameter against distance is an exponential curve for most sedimentary processes. The competency of the streams thus decreases rapidly in the fanhead section, but much more slowly in the midfan and fanbase sections. The velocity, as distinct from the competency, increases downstream in a subaerial environment, but decreases where the stream encounters the braking power of the relatively quiet waters of the lacustrine environment. The latter regime is characterized by shallower depths, smaller waves, and weaker currents than are found under marine conditions. In such a low-energy regime, transport is mainly by traction, and the longshore currents do not erode the fan to any marked extent, but assist in the reworking of the fluvial sediments and in their redistribution parallel to the shoreline of the depository. One important factor that has to be borne in mind in assessing the effects of the currents on the material transported is that some of the sediment is probably the erosion product of an antecedent sedimentary stage either in the source-area or the depository. Pebble and matrix components of a conglomerate might thus possess properties inherited from a previous cycle of erosion, transportation, and deposition, and thus give misleading results if their parameters are interpreted as being the products of one cycle only. It should also be remembered that the material could have been brought on to the fan in three different ways — by streams, streamfloods, or sheetfloods — each of which left its characteristic imprint on the response products. It would seem that precipitation in the highland source-areas of the Witwatersrand Basin might have been above that normally prevailing in arid and semi-arid climates, which would imply, according to Blissenbach (33), that streamfloods might not have taken place often in the history of Witwatersrand sedimentation.

Competency of the transporting currents can best be studied through the areal distribution patterns of the components and textures of the conglomerate reefs, as shown in the models of Figures 7 and 8. Trends of these patterns will represent the positions and orientations of channels, and residuals the irregularities in the depositional floor, which caused anomalous sedimentation both within and outside the channels, while the values of the contours and their rates of change will be indicators of the distance of the place of deposition from the apex of the fan. According to Allen (100), conglomerates in stream channels are of two types — those representing depositional gravels which formed from the lateral accretion of gravel point bars, and those that were originally lag gravels formed by the removal of fines from the matrix of depositional gravels with which the lag gravels interfinger. Steyn (24) has discussed the difference in the economic potential of these two types as they are developed in the White Reef of the West Rand, and has shown that sedimentological analysis can distinguish one from the other.

The pebbles, which include all particles above 4 mm. in diameter, decrease in size downstream away from the entry point of material, and laterally away from the channel. The percentage of pebbles per unit area also decreases away from the source, according to Fuller (101), and the degree of packing, measured by the differences in the relative amounts of sand and gravel, is thus a measure of differences in stream competency. Pebbles of granite, carbonate-rock, shale, greywacke, and schist do not persist far downstream, as shown by Sneed and Folk (102), and their apparent absence in Witwatersrand conglomerates is a possible indication of the erosion of the fanhead sections of the original fans, so that present outcrops represent midfan deposits for the most part. The percentages of quartz, quartzite, chert, and lava pebbles consequently increase downstream, with the quartz varieties persisting farthest and tending to become the sole variety of pebble. The shape of a pebble is a function of roundness and sphericity. The latter appears to be more a function of original size of the pebble than of the distance of transportation, according to Sneed and Folk (102), and, therefore, cannot be reliably used to indicate the place of deposition of a conglomerate reef. Although Krumbein (98) has stated that roundness increases with the distance of transport, and Blissenbach (33) has observed marked differences in roundness between pebbles at the apex and base of modern fans, Potter and Pettijohn (38) doubt whether roundness has much value. This, coupled with the fact that many of the Witwatersrand pebbles might be recycled pebbles from the Moodies Series of the Swaziland System, suggests that isoline maps depicting variations in pebble roundness might not be particularly useful in helping to predict patterns of gold mineralization in the conglomerate

Cadigan (105) has found that the skewness and kurtosis of the grain-size distribution measure the discrepancies in the proportion of material of various sizes being deposited in the same environment at the same time. High values of either moment are not found in poorly sorted sediments, but well-sorted gravels can contain both very high and very low values, indicating an appreciable degree of reworking adjacent to the point of deposition. Potter (104) and Plumley (107) have found that skewness decreases away from the source area, mainly as a result of the decrease in grain-size in the same direction. In the bimodal Witwatersrand conglomerates, skewness is largely a measure of the magnitude of the primary (traction load) and secondary (suspension load) modes. In the linear dynamic pattern of fluvial sedimentation, the distribution of grain-sizes is generally positively skewed. Changes towards normality or negative skewness can therefore be used to indicate a change in the hydrodynamic conditions of the transporting and depositing medium. The ratio of skewness to standard deviation can also be employed to indicate changes in the depositional environment. Martins (108) has found that kurtosis is a less sensitive indicator of changes in local conditions, and is more closely allied to the distance of transportation. Even with no other differences in the grain-size parameters, the modal class becomes progressively more peaked downstream. The change from platykurtic distributions, in which the tails are better sorted than the central portion, through mesokurtic, to leptokurtic distributions, where an excessively peaked curve is brought about through better sorting of the central portion of the distribution than of the tails, can thus be used on isoline maps of kurtosis as an indication of the areal energy-level which is a function of the distance of the place of deposition from the original point of entry of material into the basin.

### (i) Variations in the Internal Geometry of Conglomerate Zones as Guides in Interpretation

Pebble orientation, a means for ascertaining the direction of current flow, also serves to help interpret the energy-level which existed at the place of deposition. With rapid deposition, not an ideal condition for the maximum concentration of heavy minerals, the long axes of pebbles tend to lie normal to the current direction, but are generally parallel to it when the settling of grains takes place more slowly. Krumbein (96) has stated that the spread of the long axes of pebbles about a mean azimuthal trend increases downstream, due mainly to more rapid deposition and increased roundness.

Cross-bedding is the most definitive of the parameters indicating the internal geometry of the conglomerate zones. It reveals the general direction of the paleoslope down which the gravels and sand were transported, and deviations from this trend are frequently the product of local variations in the morphology of the depositional floor, which either enhanced or diminished favourability for gold concentration. Trends of cross-bedding azimuths are usually parallel to the trends of one set of pay-shoots, and the deviations are often parallel to the orientation of the second set. A bimodal distribution of cross-bedding azimuths can indicate a channel in which the stream shifted from side to side during lateral accretion, or it can point to reworking and redistribution by lacustrine currents. Unimodal cross-bedding might be more frequently developed in the fanhead section over which there was a minimum encroachment of lake water, and in which channels were more deeply entrenched. Jopling (109) has shown that an angular planar cross-bedded unit changes to a tangential concave unit with increasing velocity of flow. Since velocity, as distinct from competency, increases downstream, according to Leopold, Wolman and Miller (106), planar cross-bedded units with steep angles of foreset slope are more likely to have developed closer to the entry point of material where a relatively lower velocity regime prevailed, while tangential cross-bedding with moderate foreset slopes formed in the high-velocity environment further down the fan. Bluck (37) has observed this to be the case in consolidated fan conglomerates. He also found that trough cross-bedding develops preferentially in stream channels, increasing in abundance downstream, and thus presenting a diagnostic feature for the location of channels in the lower portions of a fan. The axes of the troughs containing such cross-stratification are usually parallel to the direction of flow of the currents, as shown by Winter (25) in the case of the Vaal Reef of the Klerksdorp area. Cross-bedding is more derived essentially from disintegrated footwall material and not from detrital particles washed in from the source-area with the pebbles and matrix material, is likely to persist into localities where the other properties of the conglomerate (reef thickness, pebble size and density, amount of pyrite, among others) show definite signs of deterioration, as is the case with the Vaal Reef eastwards across the Klerksdorp area, and the Basal Reef northwards up the Orange Free State Goldfield.

The number of separate conglomerate bands in a zone is generally greatest over a channel, where the mean thickness of the total number of bands also reaches its maximum. The total number of conglomerate horizons, both gold-bearing and barren, is highest where a channel has persisted in its position throughout the whole of the formation of the substage. Eckis (35) has shown that, in modern fans, the number of coarse beds and their aggregate thickness in a section of the reef zone or substage increases in the direction of the apex of the fan. The number and aggregate thickness of horizons of finer-grained material increase towards the margins and base of the fan. The appearance of exploitable conglomerates at certain horizons only has been investigated by Sharpe (20), and the cyclic nature of such beds suggests that the analysis of the harmonics of the vertical variability might assist in predicting where in the stratigraphic column mineralized horizons, overlooked in the past, might merit investigation.

### (k) Variations in the External Geometry of Conglomerate Zones as Guides in Interpretation

Channels on an alluvial fan, according to Blissenbach (33) and Eckis (35), can be either sites of deposition of material, when the stream is aggrading, or of erosion, when degradation is taking place. The latter process is best developed in the fanhead section when relief decreases in the periods between pulses of tectonic uplift, and the water flowing from the source-area contains a much smaller load. Erosion channels are thus more likely to be found in the higher-energy environments, and they tend to decrease in frequency of development away from the fanhead section and the portions of the fan containing the master streams. Where erosion channels were rapidly abandoned, they were filled with gravel, sand, and mud by vertical aggradation in an alternating scour-and-fill process. The prominent erosion channels in the footwall of the Main Reef Leader of the East Rand and Central Rand are fine examples of development under the conditions mentioned above. They radiate from the original fan apex near Kempton Park, they become less numerous towards the centre of the basin, the amount of conglomerate in them becomes progressively smaller downstream, the intensity of the banded pyritic quartzite development also decreases, and the gold content diminishes away from the apex. The channel index factor (ratio of width to depth) of the larger erosion features in the Central Rand increases downstream. Bluck and Kelling (110) have observed that the channel index is a function of relative current energy, the lower the index is, the more rigorous the current regime, as in the fanhead section. High channel indices are more characteristic of the lower-energy environments towards the extremities of the fan. Aggrading channels, in which the conglomerates were optimally developed, were generally broad and shallow, with a braided pattern. Trends of the areal variations in the channel index are thus a further means for studying the distribution pattern of economically mineralized conglomerates. Low indices serve to indicate areas susceptible to erosion, medium values the areas most favourable to the formation of conglomerate reefs, and higher indices the extremities of the fan where conglomerate reefs are unlikely to be of major importance, but where environments might have existed suitable for the development of carbon seam reefs. Leopold, Wolman and Miller (106) have observed that, in present-day streams and rivers, the channel has an undulating bed with alternating pools (deeper portions) and riffles (shallower portions). The energy-level drops more rapidly per unit length over the riffle than over the pool, and consequently such riffles are the sites of optimum gravel bar development. These riffles are more-or-less regularly spaced down the channel at intervals of five to seven times the width of the channel. If similar conditions held during the deposition of gold and conglomerates in the channels within Witwatersrand rocks, then harmonic analysis of the periodicity of areas of in a much younger basin in the United States mirror those which influenced the distribution of gold in the Witwatersrand Basin. During deposition, 'growing anticlines' exercised control on the character, shape, and distribution of lithosomes, and the direction of flow of currents. The anticline-elevations acted as sediment-winnowing sites, barriers to dispersal, and secondary sources of sedimentary material, while the syncline-depressions were relatively passive elements forming traps for gravels moving down the paleoslope. The structures persisted in their development after the end of sedimentation in the Witwatersrand Basin, and the same tectonic pattern which affected the pre-depositional floor of a conglomerate horizon was imprinted on the sediments in post-depositional times. Andresen and Rowett (112), in their study of basin sedimentation in eastern North America, found that structural trends are recurrent and self-perpetuating, a phenomenon which certainly applies to the history of geological events in the Witwatersrand Basin. The paleoslope directions of the depositional floors of the various conglomerate reefs might therefore be inferred from present structural trends which are parallel to the older trends that controlled sedimentation.

It has also been demonstrated that, as Bishop (70) observed, each tectonic environment has a characteristic pattern that is repeated on a smaller scale in the local structures. The broad structural pattern that was imprinted on the whole of the Witwatersrand Basin and surrounding country is exactly the same as that which controlled the deposition of strata in a goldfield, a section of a goldfield, and even a mine in some cases where the deformation was relatively more intense. The harmonics of the whole range and system of folding, as present over an area of 1,900 square miles in the Witwatersrand Basin has been analyzed in a preliminary manner by Pretorius (17). It is obvious that, with the high degree of correlation between the distribution patterns of structure and sedimentation, a two-dimensional harmonic analysis of the periodicities and amplitudes of folding in the Witwatersrand Basin might prove to be one of the most useful statistical techniques in providing a quantitative base for the planning of prospecting operations.

One set of folds trends approximately north-northwest, and remains relatively constant in direction over the whole of the basin. Compression normal to this direction appears to have persisted as a relatively strong force into the final stages of the deformational history, and these folds appear, in general, to be superimposed on the other set. However, there is ample evidence to prove that both were concurrently active throughout the deposition of the Witwatersrand System, and that there was not one distinct and discrete pattern of folding imprinted at one time. The other set of folds originally trended east-northeast, parallel to the direction of elongation of the basin, but these longitudinal folds were bent about the transverse north-northwest-trending folds, possibly as a result of the stress field responsible for the former waning in intensity before that which produced the latter set of folds. As a result of this bending, the longitudinal folds in the Orange Free State Goldfield trend slightly west of north, in the Klerksdorp area northeast, in the West Wits Line east-northeast, in the West Rand north-northeast and east-southeast, in the Central Rand east-southeast and east-northeast, and in the East Rand southeast. Transport directions of sediments, elongation of pay-shoots, erosion channels, and most of the trends and deviations revealed by trend surface analysis of the isoline maps of almost all geological parameters, are parallel to one or other of these fold directions. The configuration of virtually every distribution pattern, so far determined, of every component of the rocks — gold values or pebble sizes, cross-bedding azimuths or conglomerate:quartzite ratios, reef thickness or degree of sorting of heavy mineral particles — can be related to the interplay of the trends of the folds, and to the relative intensity of each set of folds in any particular area.

The interference pattern produced by the superimposed fold trends is of considerable importance in interpreting the trends, residuals, and harmonics derived from two-dimensional operations. The part has been overemphasized with the result that the significance of the whole — the host-rock itself — has not been fully appreciated, nor has the usefulness of the whole been exploited. This is mainly the fault of geology itself. The analysis of information concerning the rock has remained on a subjective, intuitive basis essentially, while the treatment of data on the intensity and distribution of gold mineralization has advanced to the higher plane of objective, mathematical analysis. The full value of geology as a solver of problems of Witwatersrand ore formation can be realised only if geological investigation is transformed from its present qualitative and semi-quantitative approach to a fully quantitative one.

The first step in this direction is the development of models to provide a framework within which geological data can be classified, analyzed, and interpreted, instead of being left as recorded information only, which is frequently the case at present. There is no doubt that sufficient knowledge has been acquired of the geology of the Witwatersrand Basin to permit the construction of conceptual geological process-response models as a prelude to the design of deterministic mathematical models — the ultimate goal of a quantitative approach. The purpose of the models presented in this paper is to show that each Witwatersrand goldfield can be represented as a separate ancient alluvial fan formed in a large lake surrounded by highlands of considerable relief which were subjected to periodic tectonic uplift. The delta-like fan formed where a major river, flowing from a source area in the highlands, debouched from a canyon into a depository, the apex of the fan thus representing the entry point of material into the basin. By analogy with present-day alluvial fans and those formed in the more recent geological past, models can be constructed to portray the development, geometry, and gold distribution pattern of a goldfield. From these it can be seen that the overall economic potential of any segment of a reef within a goldfield is primarily a function of the place of deposition on the original fan of the particular segment and of the nature and intensity of the tectonic and sedimentological processes operating at that place. The gold reefs take three different forms — conglomerate reefs, carbon seam reefs, and carbon-bearing conglomerate reefs in which an underlying carbon seam reef has been incorporated in an overlying conglomerate — and each form has its own typical area of development on the fan and its own peculiar conditions of formation. Any system of ore valuation and prediction which regards the gold as belonging to one population, by failing to take recognition of these variations in the nature of the mineralization, is susceptible to misrepresentation of the facts and to misinterpretation of the analysis of the data.

The type and metal content of a reef are responses to the particular energy-level which prevailed in the environment of deposition. Conglomerate reefs belong in high-energy regimes, and carbon seams in ones of low intensity, while carbon-bearing conglomerates are the products of the transgression of a succeeding high-energy environment over a preceding low-energy regime. The energy-level decreased radially away from the apex of the fan, on an areal scale, and laterally away from the channels of master streams, on a local scale. The favourability of a locality as a site for the preferential development of pay-shoots of higher gold values can thus be depicted in the form of an energy factor, and an estimate of this factor can be arrived at through a study of the composition, internal geometry, lithofacies, external geometry, and vertical variability of the reef zone, which properties reflect, in turn, the nature of the source-material containing the gold, the competency of the currents to transport this material from the apex down the fan, the dispersal pattern of the currents over the fan, and the place of deposition on the fan. Conceptual geological models can be constructed to show the interrelationships of these properties, and the parameters of the rock by which they can be measured.

In a normal conglomerate reef there are more than 60 parameters which can be studied quantitatively in an attempt to identify the place and mode of deposition and the consequent overall potential for gold mineralization. At present only three of these — gold content, uranium content, and reef thickness — are employed in ore prediction and valuation, pointing to the fact that only five per cent of the information which can be abstracted from the rock is actually being used to assess the significance of the rock. In routine geological work, one other parameter — the elevation of the reef zone with respect to a particular datum — is measured, Most of the geological data required for the preparation of such maps is not being gathered during the course of routine operations by the geological departments of the mines, because such departments are fully occupied in solving the geological problems implicit in maintaining ore production within developed sections of a mine. To fully abstract and exploit all the geological information contained in the whole of the reef zone, at least one exploration geologist with specialized training in structural and sedimentological techniques should be added to the geological staff of a mine. To obtain data relating to the three parameters currently used for ore valuation and prediction, it is estimated that the cost incurred in exploratory development plus sampling and assaying is of the order of R21 per foot. To obtain the 15 parameters required, it is thought that the cost would be increased to R23 per foot. Thus, a 500 per cent increase in information can be obtained for a 10 per cent increase in cost of underground exploration.

It is believed that, if there is a shift, from qualitative and semi-quantitative to fully quantitative, in the way the geological approach to exploration, valuation, and prediction is viewed, then the results obtained would be of sufficient value to management in planning that the stigma would be removed from the geologist of what D.P. Harris described as 'being blind in foresight, and of having only fair hindsight'.

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## Key to Figures



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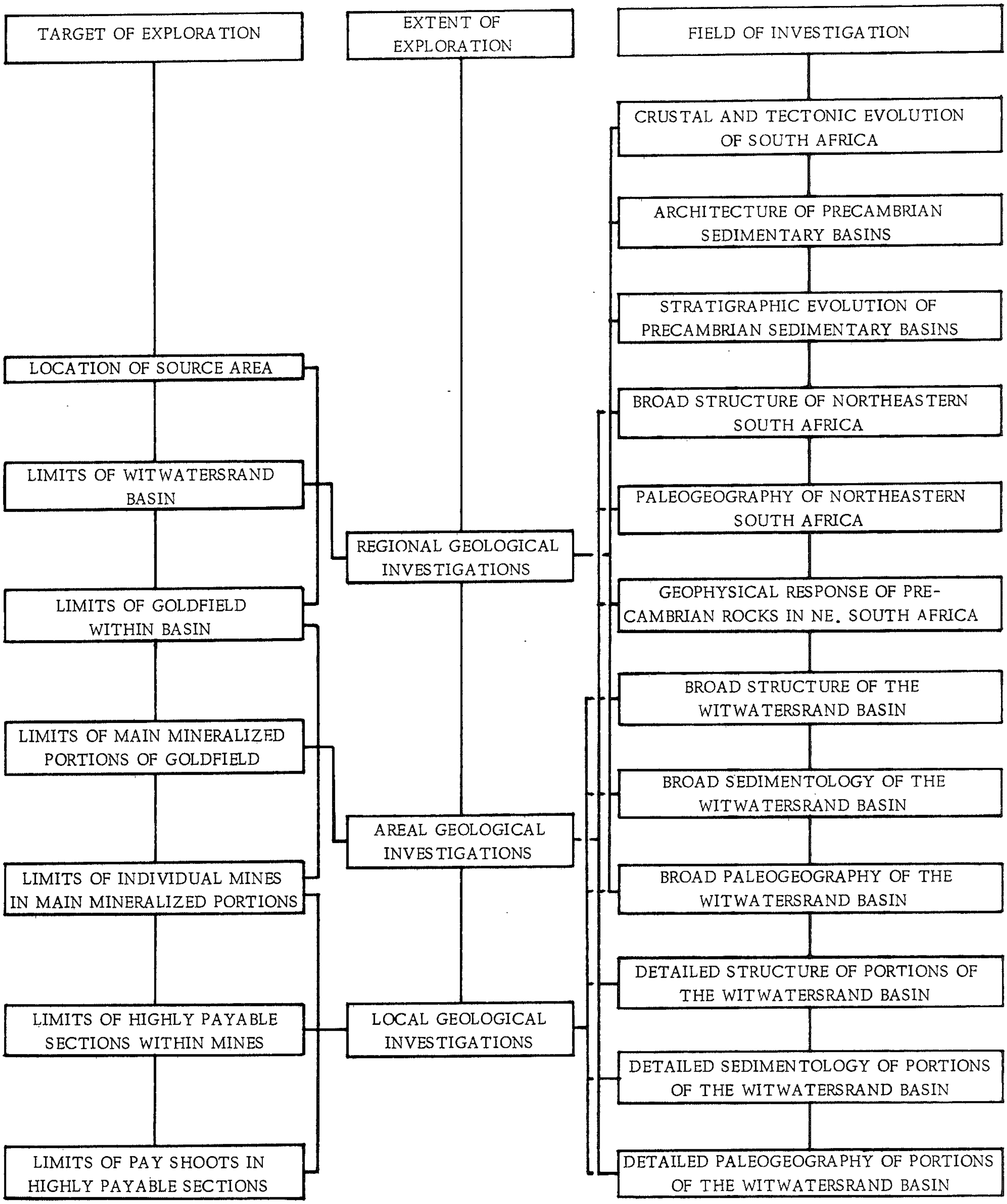


FIGURE 1 : CONCEPTUAL MODEL OF SCALES, TARGETS, AND FIELDS OF GEOLOGICAL EXPLORATION FOR GOLDFIELDS, MINES, AND PAY SHOOTS IN THE WITWATERSRAND BASIN

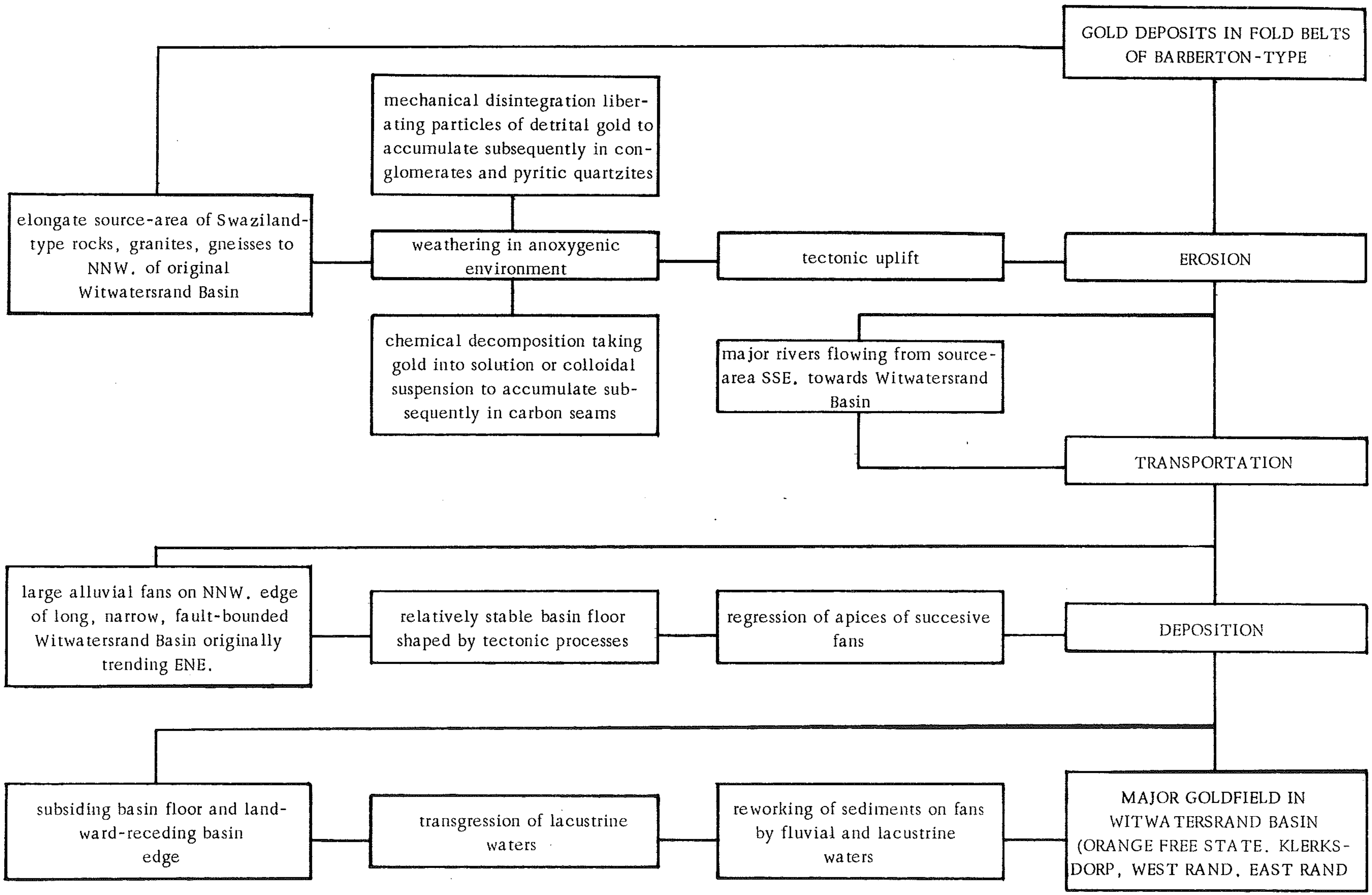


FIGURE 2 : CONCEPTUAL MODEL OF TECTONIC, PHYSIOGRAPHIC, AND SEDIMENTOLOGICAL FACTORS CONTROLLING THE DEVELOPMENT OF A MAJOR GOLDFIELD IN THE WITWATERSRAND BASIN

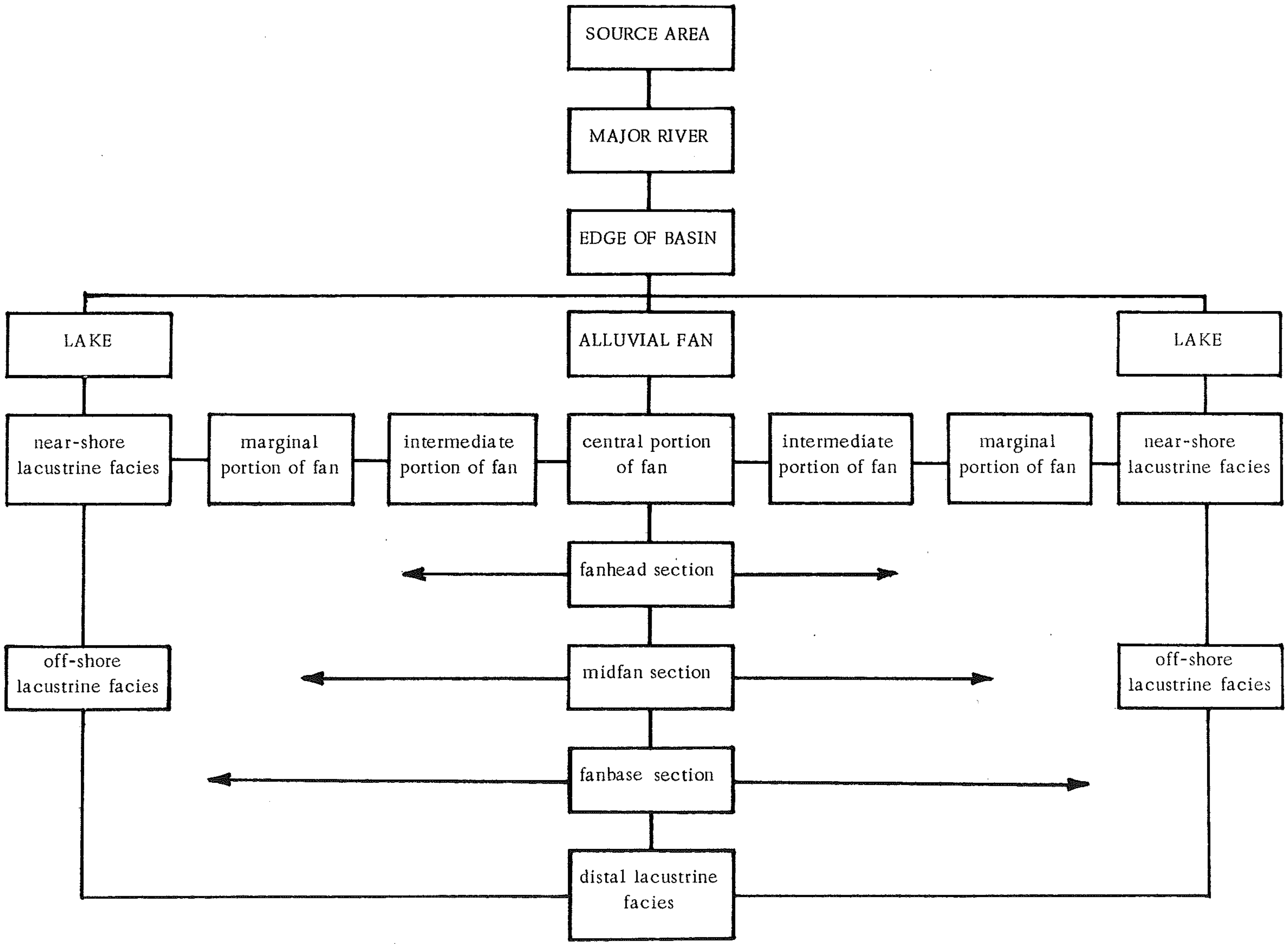


FIGURE 3 : CONCEPTUAL MODEL OF RADIAL AND LATERAL GEOMETRY OF AN ALLUVIAL FAN LOCATED ON THE EDGE OF A LAKE TO FORM A MAJOR GOLDFIELD IN THE WITWATERSRAND BASIN

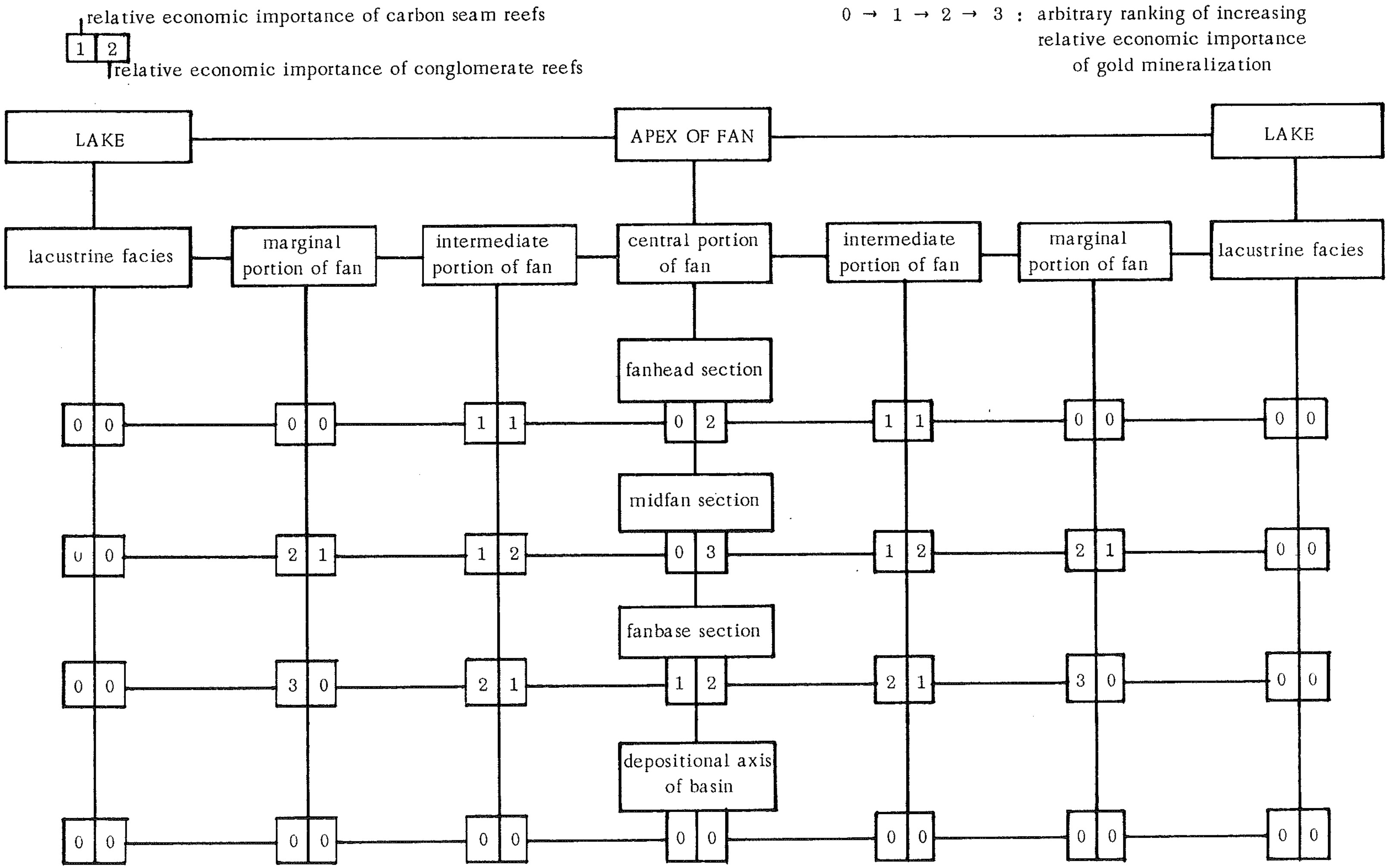


FIGURE 4 : CONCEPTUAL MODEL OF THE GEOMETRY OF OPTIMUM CONDITIONS FOR GOLD MINERALIZATION IN CONGLOMERATE AND CARBON SEAM REEFS IN A MAJOR GOLDFIELD IN THE WITWATERSRAND BASIN

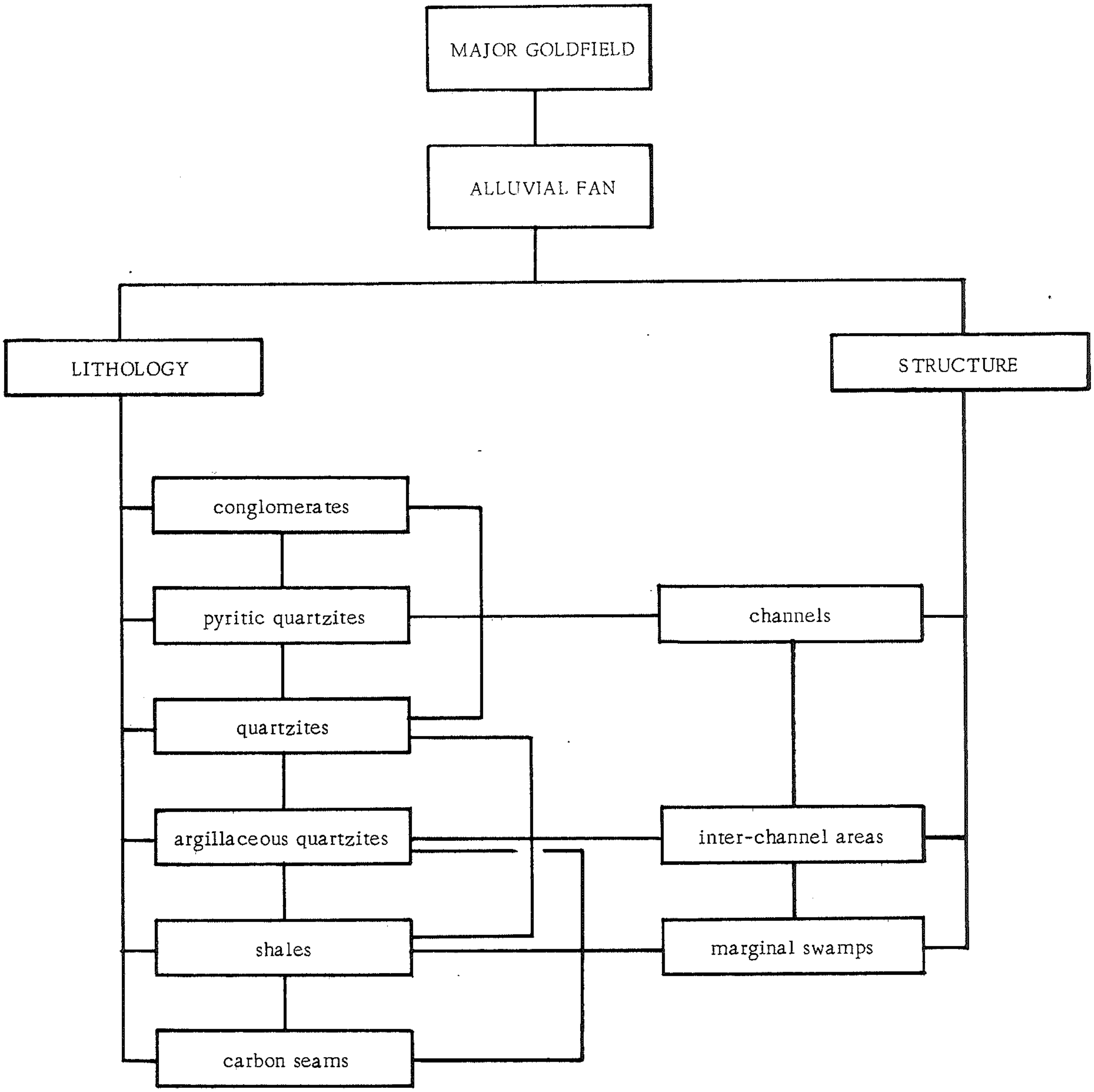


FIGURE 5 : CONCEPTUAL MODEL OF THE LITHOLOGY AND STRUCTURE OF AN ALLUVIAL FAN CONSTITUTING A MAJOR GOLDFIELD IN THE WITWATERSRAND BASIN

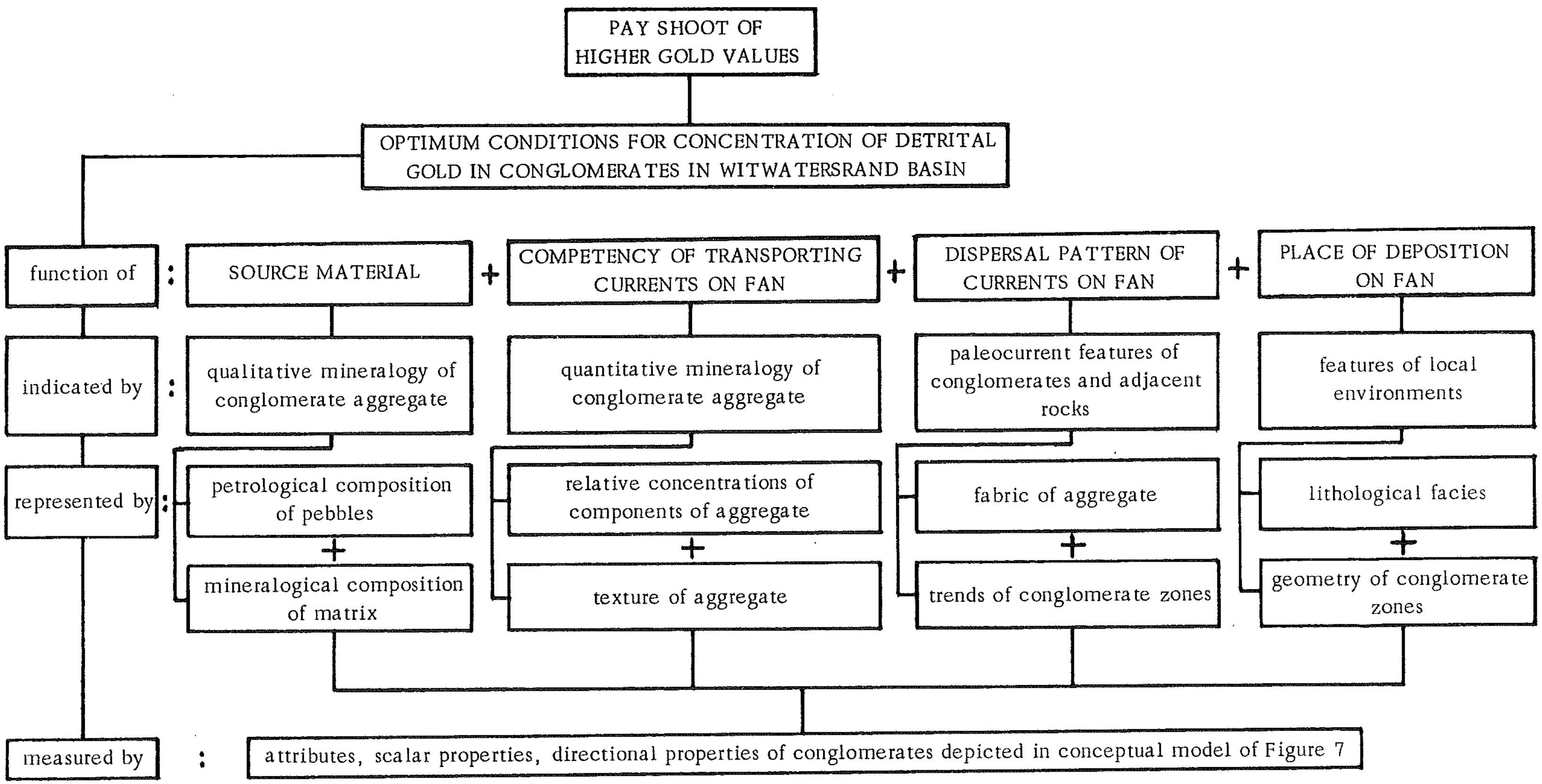


FIGURE 6 : CONCEPTUAL MODEL OF GEOLOGICAL FACTORS CONTROLLING THE DEVELOPMENT OF PAY SHOOTS IN CONGLOMERATE REEFS OF THE WITWATERSRAND BASIN

| FACTOR | REPRESENTED BY | MEASURED BY |
|---|---|---|
| SOURCE MATERIAL | composition of pebbles | 1. pebbles of different rock-types |
| | composition of matrix | 2. quartz, phyllosilicates, heavy minerals, uranium, gold |
| COMPETENCY OF TRANSPORTING CURRENTS | relative concentrations of components | 3. relative abundance of different pebble-types<br>4. modal percentages of individual minerals of light fraction of matrix<br>5. modal percentages of individual minerals of heavy fraction of matrix<br>6. weight concentration of uranium<br>7. weight concentration of gold |
| | texture of aggregate | 8. average grain-size of pebble and matrix fractions (mean)<br>9. degree of sorting of pebble and matrix fractions (standard deviation)<br>10. symmetry of size variations in two fractions (skewness)<br>11. concentration within certain size-class in two fractions (kurtosis)<br>12. density of pebbles per unit area of aggregate<br>13. shapes of pebbles and matrix grains |
| DISPERSAL PATTERN OF CURRENTS | fabric of aggregate | 14. orientation of long axes of pebbles in conglomerate zone<br>15. orientation of long axes of grains in matrix |
| | trends of conglomerate zones | 16. orientation of cross-bedding foresets in and adjacent to conglomerate zone<br>17. orientation of axes of sand-waves in and adjacent to zone<br>18. orientation of axes of current ripple-marks in and adjacent to zone<br>19. orientation of trough axes of erosion channels<br>20. configuration of contoured scalar properties of components of zone<br>21. configuration of contoured lithofacies of components of zone<br>22. configuration of structure elevation contours of base of zone |
| PLACE OF DEPOSITION | lithological facies of conglomerate zones | 23. conglomerate : quartzite thickness ratio for conglomerate zone<br>24. conglomerate + quartzite : shale thickness ratio in stratigraphic unit<br>25. percentage of conglomerate in conglomerate zone<br>26. percentage of carbon in conglomerate zone<br>27. presence or absence of mud-cracks and oscillation ripple-marks |
| | geometry of conglomerate zones | 28. length of long axes of individual conglomerate lenses in zone<br>29. width of conglomerate zone<br>30. thickness of conglomerate zone<br>31. number of individual conglomerate bands in zone<br>32. aggregate thickness of individual conglomerate bands in zone<br>33. strikes and dips of bedding planes in and adjacent to zone<br>34. pattern of folding of conglomerate zone and adjacent strata<br>35. pattern of faulting of conglomerate zone and adjacent strata<br>36. structure elevation contours of base of conglomerate zone |

FIGURE 7 : CONCEPTUAL MODEL OF ATTRIBUTES, SCALAR PROPERTIES, AND DIRECTIONAL PROPERTIES AS MEASURES OF GEOLOGICAL FACTORS CONTROLLING THE DEVELOPMENT OF PAY SHOOTS IN WITWATERSRAND CONGLOMERATE REEFS

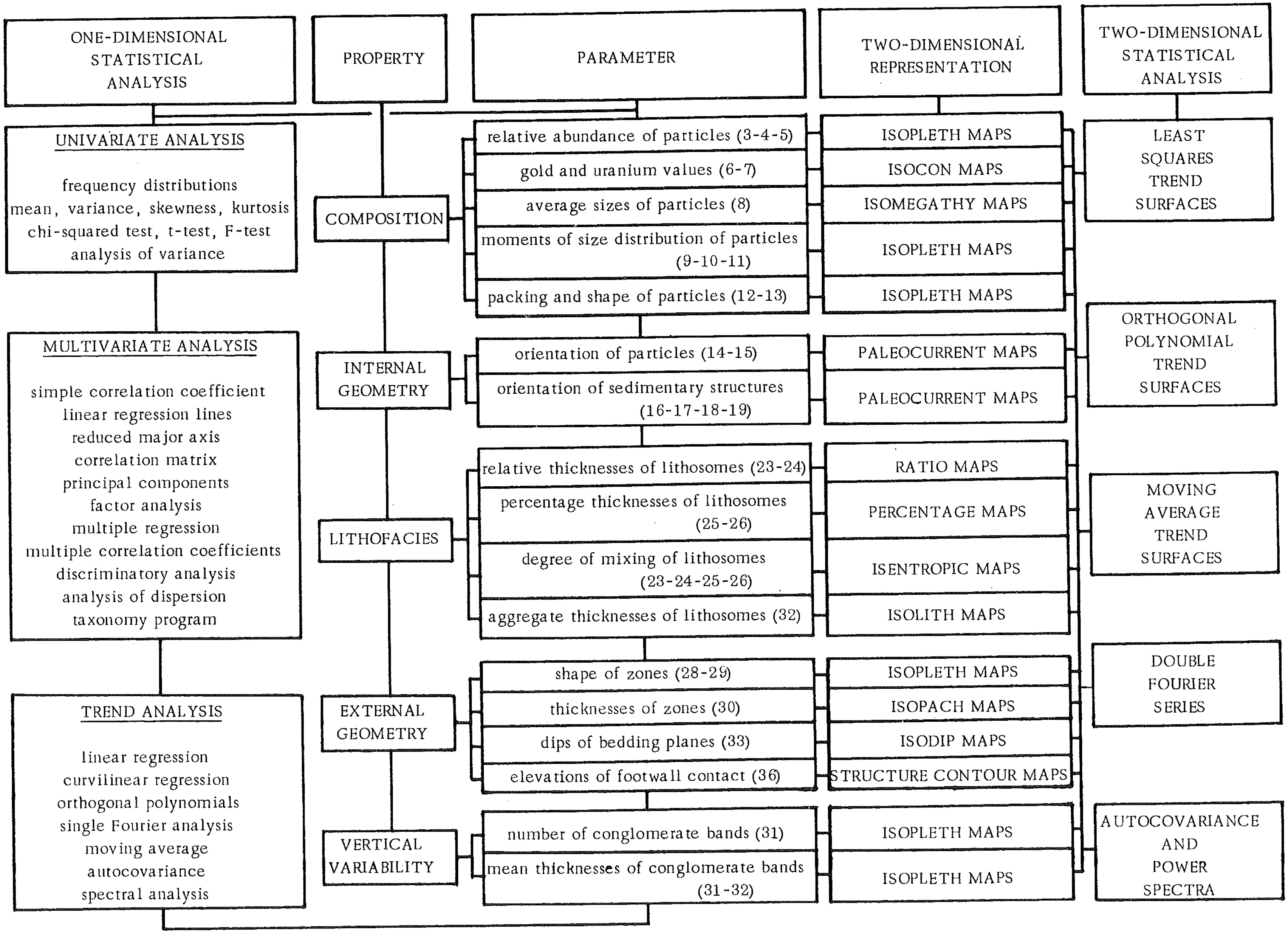


FIGURE 8 : CONCEPTUAL MODEL OF TWO-DIMENSIONAL REPRESENTATION AND TECHNIQUES OF STATISTICAL ANALYSIS OF GEOLOGICAL PARAMETERS OF CONGLOMERATE REEFS OF THE WITWATERSRAND BASIN