A PHOTOGEOLOGICAL INVESTIGATION OF THE MAJOR CONTROLS OF FLUOR-SPAR, LEAD AND ZINC ORES IN THE ZEERUST AREA, WESTERN TRANSVAAL.

by

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ABSTRACT

In the Lower Proterozoic Dolomite Series south of Zeerust, three types of mineral deposit are found that are of direct relevance to the object of the photogeological investigation. Deposits of Type I contain epigenetic galena, zinc-blende, and fluor-spar in bodies of brecciated dolomite, and they are restricted, entirely, to the zone of disrupted dolomite that accompanies the Vergenoegd Fault. Deposits of Type II are galena deposits in which the galena replaces dolomite and forms irregular nodules, masses, and disseminations in concordant zones in the uppermost portion of the dolomite. They are localised within the zone of structural influence of the Bokkraal Fault, or are demonstrably associated with fractures which trend north-north-west and are therefore roughly parallel to both of the above zones of faulting. If a number of very small occurrences of galena in the study-area are included with the deposits of Type I and II, 22 out of the 23 deposits are, in their geographic location, related to the two major zones of faulting or to the fractures and shears which are parallel to them.

The region has been mapped in the field on at least five occasions, and intensive exploration activity has taken place for many decades, but the Bokkraal and the Vergenoegd Fault-zones were recognised for the first time as a result of the overview that was provided by the photogeological mapping. Both of the faults represent gravity-dislocations of the roof of the Dolomite Series. They entered the dolomite from above and they ceased to exist in the form of discrete planes of dislocation shortly after their emergence from the Pretoria Series, which overlies the Dolomite Series.

The Bokkraal and the Vergenoegd Fault-zones, and the fractures which are related to them, are the major local controls of the mineral deposits of Types I and II. In the dolomite the zones of faulting are demonstrably accompanied by structural arches, warps, plastic distortion, and, in places, bodies of breccia which developed in the crestal portions of folds. The mineralisation of the relatively irregular bodies of this tectonic breccia led to the formation of deposits which are classed as Type I. In two of the breccia-type deposits, however, the bodies of mineralised breccia are regular and are shaped like pipes. They represent chimneys of slump-breccia that resulted from "point-solution" in the underlying dolomite. The evidence indicates that similar, but barren, pipe-like slump-breccias are not uncommon in the dolomite in the study-area. They were not subjected to mineralisation

because, unlike the mineralised pipes, they do not coincide fortuitously with a zone of faulting which acted as a major channelway for the ore-bearing solutions.

In regional terms, the Bokkraal and the Vergenoegd Faults belong to a set of major faults in the Transvaal which trend in a north-north-west direction and which correspond with linear zones of tectonic adjustment of the floor of the Bushveld Complex.

The deposits of Type III are fluor-spar deposits in which the fluor-spar exists in layers, and as disseminations in the dolomite, in zones and horizons which are concordant with the sediments; a fact that was shown by previous workers. Limited evidence was provided in this connection by the photogeology, but the results tended to confirm that, in these deposits, the major, local, control is exerted by stratigraphic relationships. On the regional scale, however, there is a definite coincidence of the fluor-spar deposits of Type III (and the deposits of Types I and II) with a fundamental, long-lived tectonic lineament which trends in the east-north-east direction, parallel to the trend of one of the two dominant sets of local lineaments in the study-area. Before the last-mentioned relationship was recognised it was necessary to plot the location of every deposit of fluor-spar in the Transvaal on a geological base-map. The result proved that, in the Bushveld, the deposits of fluor-spar, alkalic and carbonatitic intrusions, kimberlites, and deposits of cassiterite, are all confined to a sparse, but definite grid of fluorine-rich linear zones which correspond with fundamental tectonic lineaments. The fluorine-rich geographical zones trend west-north-west and east-north-east and they are individually up to 650 kilometres in length and 30 kilometres in width. The structural elements which conform with the former direction are related to tensional stresses which attended the Koppies continental arch and, hence, to the zones of adjustment of the floor of the Bushveld Complex. The east-north-east direction is the well-known Murchison tectonic direction. Of the fluorine-rich geographical zones which are parallel to this direction, the dominant one was named the "Murchison Zone". It is a direct reflection of the tectonic line that is represented, in part, by the Murchison Greenstone Belt, of Archaean age, with which it is co-axial, and it is this zone that incorporates the entire locus of mineralisation in the dolomite south of Zeerust.

The Dolomite Series in the Transvaal basin is thickened greatly within a narrow tectonic trough that coincides exactly with the tectonic lineament in the basement that corresponds with the Murchison Zone. As concerns the Series in general, but the major tectonic trough in particular, the palaeoenvironment in which the sediments were deposited was very favourable in respect of the sedimentary precipitation and accumulation, of lead- and zinc-sulphides (near the base), and fluorite (towards the top, close to the Giant Chert). In relation to lead and zinc, particular sediments concentrated proto-ore (and, perhaps, ore which is yet undiscovered) which acted as the "source-beds" from which the elements were later dissolved, and reprecipitated in the deposits that are classed as Types I and II. In the deposits of Type I, in particular, the sulphides are accompanied by fluor-spar, in significant amounts, which was derived from the source-beds that are equated with the low-grade and the high-grade sedimentary deposits of fluor-spar of Type III.

The dissolution of elements from the source-beds, and their reconcentration in structural traps, was a function of heat- and structural-effects that were a consequence of the emplacement of the Bushveld Complex, but the Bushveld granite was not the source of any of the ore.

Major linear slump-structures exist in the dolomite south of Zeerust. They are identical with certain structures which carry ore in lead- and zinc- and fluor-spar-mining areas in the United States. Up to the present they have not been tested and they warrant a thorough investigation. These structures were recognised for the first time during the photogeological reconnaissance-mapping of the study-area. Without the photogeological overview these structures would not have been defined very well, nor would their nature be understood. More importantly, had photogeological mapping not taken place, the major controls of the deposits of ore-minerals in the study-area would not have been recognised, and would still be unknown.

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UITTREKSEL

In die Onder-Proterosoïese Serie Dolomiet suid van Zeerust word drie tipes mineraalafsettings aangetref wat regstreeks verband hou met die doel van die fotogeologiese ondersoek. Afsettings van Tipe I bevat epigenetiese loodglans, sinkblende en vloeispaat in liggame gebreksieerde dolomiet, en hulle is geheel en al beperk tot die sone van verbreekte dolomiet wat saamgaan met die Vergenoegdverskuiwing. Afsettings van Tipe II is loodglansafsettings waarin die loodglans dolomiet vervang en onreëlmatige knolle, liggame en disseminasies in konkordante sones in die boonste gedeelte van die dolomiet vorm. Hulle is gelokaliseer binne in die sone van strukturele invloed van die Bokkraal-verskuiwing of daar kan bewys word dat hulle verbonde is met breuke wat noord-noordwes strek en derhalwe naastenby ewewydig is aan albei bovermelde verskuiwingsones. Indien 'n aantal baie klein voorkomste van loodglans saam met die afsettings van Tipes I en II in die gebied wat ondersoek is, ingesluit word, is 22 uit die 23 afsettings, wat geografiese ligging betref, verwant aan die twee hoofsones van breukvorming of aan die breuke en skuifskeursones ewewydig daaraan.

Die gebied is by ten minste vyf geleenthede in die veld gekarteer en intensiewe eksplorasiebedrywighede het oor baie dekades plaasgevind, maar die Bokkraal- en Vergenoegdverskuiwingsones is vir die eerste maal as sodanig herken as gevolg van die oorsig wat verskaf is deur die fotogeologiese kartering Albei verskuiwings verteenwoordig swaarteverplasings van die dak van die Serie Dolomiet. Hulle het die dolomiet van bo af binnegedring en het opgehou om te bestaan as afsonderlike versteuringsvlakke kort nadat hul uit die Serie Pretoria, wat die Serie Dolomiet oordek, te voorskyn gekom het.

Die Bokkraal- en Vergenoegdverskuiwingsones en die breuke wat aan hulle verwant is, is plaaslik die hoofbeheermiddels van die mineraalafsettings van Tipes I en II. In die dolomiet gaan die verskuiwingsones bewysbaar saam met strukturele boë, verbuigings, plastiese distorsie en, op plekke, breksieliggame wat in die kruingedeeltes van plooie ontwikkel het. Die mineralisering van betreklik onreëlmatige liggame van hierdie tektoniese breksie het gelei tot die vorming van afsettings wat as Tipe I ingedeel word. In twee van hierdie breksie-tipe-afsettings is die liggame gemineraliseerde breksie egter reelmatig en pypvormig. Hulle verteenwoordig pype van instortingsbreksie wat in die onderlêende dolomiet ontstaan het as gevolg van oplossing by 'n punt. Getuienis is ingewin wat daarop dui dat soortgelyke maar barre (d.w.s. nie-gemineraliseerde)

pypvormige instortingsbreksies algemeen in die dolomiet voorkom binne die gebied wat bestudeer is. Hulle is nie gemineraliseer nie aangesien hulle, anders as die gemineraliseerde pype, nie toevallig saamgeval het met 'n verskuiwingsone nie, wat gedien het as hoofvervoerweg vir die ertsbevattende oplossings.

In regionale omvang gesien, behoort die Bokkraal- en Vergenoegdverskuiwings by 'n stel hoofverskuiwings in die Transvaal, wat in 'n noord-noordwestelike rigting strek en ooreenkom met lineêre sones van tektoniese aanpassing van die vloer van die Bosveldkompleks.

Die afsettings van Tipe III is vloeispaatafsettings waarin die vloeispaat voorkom in lae, en as disseminasies in die dolomiet, in sones en op horisonne wat konkordant met die afsettings is - 'n feit waarop vorige werkers reeds gewys het. Beperkte getuienis ten gunste hiervan is deur die fotogeologie verskaf maar die resultate het geneig om te bevestig dat, in hierdie afsettings, die hoofbeheer ter plaatse uitgeoefen is deur stratigrafiese verwantskappe. Op 'n streekskaal is daar egter 'n duidelike samevalling van die vloeispaatafsettings van Tipe III, en die afsettings van Tipes I en II, met 'n fundamentele, langdurige tektoniese lineament wat in 'n oos-noordooswaartse rigting strek, ewewydig aan die strekking van een van die twee oorheersende stelle plaaslike lineamente in die gebied wat bestudeer is. Voordat hierdie verwantskappe herken is, was dit nodig om die ligging van elke vloeispaatafsetting in die Transvaal op 'n geologiese basiskaart uit te teken. Die uitslag het bewys dat, in die Bosveld, die afsettings vloeispaat, die alkaliese en karbonatitiese intrusies, die kimberlietvoorkomste en die afsettings kassiteriet almal beperk is tot 'n yl maar nietemin duidelike netwerk van fluoor-ryk, lineêre sones wat ooreenstem met die fundamentele tektoniese lineamente. Die fluoor-ryk geografiese sones strek wes-noordwes en oos-noordoos en elkeen is tot 650 km lank en tot 50 km wyd. Die struktuurelemente wat by eersgenoemde rigting aanpas, is verwant aan rekspannings wat gepaard gegaan het met die vorming van die Koppies-kontinentale boog, en dus met die sones van aanpassing van die vloer van die Bosveldkompleks. Die oos-noordoosrigting is die welbekende Murchisonse tetoniese rigting. Van die fluoor-ryk geografiese sones wat ewewydig aan hierdie rigting is, is die oorheersende een die Murchisonsone genoem. Dit is 'n regstreekse weerspieëling van die tektoniese rigting wat ten dele verteenwoordig word deur die Murchisonse Groensteenstreek, van Argeïese ouderdom, met die as waarvan dit saamval. Dit is hierdie sone wat die hele lokus van mineralisasie in die dolomiet suid van Zeerust insluit.

Die Serie Dolomiet in die Transvaal word aansienlik dikker in 'n smal tektoniese trog wat presies saamval met die tektoniese lineament in die vloer en ooreenstem met die Murchisonsone. Sover dit die Serie in die algemeen aangaan, maar die hooftektoniese trog in die besonder, was die paleo-omgewing waarin die sedimente afgeset is besonder gunstig met betrekking tot die neerslaan en versameling van lood- en sinksulfiede (naby die basis) en fluoriet (na die topkant toe, naby die Reusechert). Met betrekking tot lood en sink het sekere afsettings proto-erts gekonsentreer (en moontlik ook erts wat nog onontdek lê); hulle het gedien as bronlae waarvandaan die elemente later opgelos en weer neergeslaan is, om afsettings te vorm wat onder Tipes I en II ingedeel is. In die afsettings van Tipe I in die besonder gaan vloeispaat saam met die sulfiede, en wel in betekenisvolle hoeveelhede, wat afkomstig is van die bronlae wat gelykgestel word met die laegraadse en hoëgraadse sedimentêre afsettings van vloeispaat van Tipe III.

Die oplos van elemente vanuit die bronlae en hulle herkonsentrering in strukturele opvangplekke was 'n funksie van hitte- en strukturele effekte wat voortgevloei het uit die inplasing van die Bosveldkompleks, hoewel die Bosveldgraniet nie die bron van enige van die erts was nie.

Groot lineêre instortstrukture is aanwesig in die dolomiet suid van Zeerust. Hulle is identies aan soortgelyke strukture wat erts dra in die lood-, sink- en vloeispaatmyngebiede in die Verenigde State. Tot hede toe is hulle nog nie getoets nie en hulle regverdig 'n deeglike ondersoek. Hierdie strukture is vir die eerste keer herken tydens die fotogeologiese verkenningskartering van die gebied wat ondersoek is. Sonder die fotogeologiese oorsig sou die strukture nie so goed afgebaken en hul aard begryp kon word nie. Van nog groter belang is die feit dat, indien fotogeologiese kartering nie onderneem is nie, die hooffaktore wat die afsetting van die ertsminerale beheer het in die studiegebied nie herken sou gewees het nie en dus tans nog onbekend sou wees.

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I. INTRODUCTION

A. General

This thesis has a three-fold purpose.-

To record for the first time in a unified form, and in the correct perspective, a significant amount of historical and descriptive information that concerns the occurrence and the exploitation of deposits of fluor-spar, galena and zinc-blende in the Proterozoic dolomite of the Zeerust area;

To describe the results of photogeological mapping in the Zeerust area, and to note, simultaneously, some advantages and disadvantages that are inherent in photogeology; and by the derivation of an unique appreciation of the structural control of the mineralisation, to illustrate the application and the value of photogeology as a distinct phase in programs of mineral exploration, even in areas that have been actively explored and mapped in the field, provided that the photogeology is applied correctly;

To relate the controls of mineralisation, as recognised locally, to regional tectonics and fundamental tectonic lineaments; to discuss the latter in relation to preferential magmatic and hydrothermal activity, and in relation to the tectonic control of local sedimentation in early Transvaal time, and, ultimately, to discuss the origin of the fluor-spar, galena and zinc-blende deposits near Zeerust in the light of the aforegoing.

It will be shown that the expanded perspective or overview afforded by adequate interpretation of aerial imagery, and the regional scale of thought that is induced, can and does generate valuable new geological concepts which can be applied validly during further exploration. The information can be unique.

The essence of the descriptive text concerns the Zeerust dolomite region, which includes what has been called the Marico Lead Belt (Wagner, 1929, p.190). Reference is made, in addition, to relevant details and exploration concepts which crystallised after the results of the photogeological mapping in the Zeerust area had been evaluated in a broader, regional, context. Brief reference is also made to other photogeological studies, that were conducted or proposed by the writer, which allow for a fuller understanding of a main theme in this thesis - namely, the importance of fundamental tectonic features in the control of mineralisation in the Zeerust area, and in the Transvaal in general; and the key role that occurrences of fluor-spar play, and can play, in elucidating these relationships.

Without the synoptic view afforded by the aerial photographs, and without their diligent annotation and interpretation, the required results, namely the elucidation of the major controls of lead, zinc, and fluor-spar mineralisation, would not have been achieved.

The photogeological mapping and the inconsiderable amount of field-work which forms the basis of this thesis was undertaken by the writer in the period late-1969 to mid-1970. Many of the significant conclusions that are presented here were included in a report dated October 1970 (Wilson, 1970). Other conclusions that are relevant to the final interpretation of the results of the Zeerust project were expanded from the results of photogeological mapping in the Moloto-Rust der Winter area, 60 kilometres north-east of Pretoria, that was completed by the writer early in 1969 (Wilson, 1969a).

A note on reference material is desirable because abnormal problems beset the writer in his attempts to gain access to specific references in Australia, to which country he was transferred in February 1971, for business reasons.

The thesis was prepared on a part-time basis under very trying circumstances, when access to library facilities proved to be extremely difficult and sporadic, and when unbroken periods of library use proved to be impossible. Initially, a considerable amount of reference material was obtained in the form of reprints, extracts, and copies, following an intermittent stream of correspondence with various institutions in South Africa. Some of the reference data were incomplete inasmuch as page-numbers, or the source, were not incorporated in some of the material that was received. Later, advantage was taken of impromptu and unscheduled visits, always very brief, to various geological libraries in Australia, in order to gain access to other reference material. Relevant extracts and summaries of particular publications and papers were carded and filed for future use and, during that period, page numbers were not always recorded. When the final synthesis of data commenced in late 1974 easier circumstances made the literature-search more systematic, and details of page-numbers were not overlooked, but it was impossible to remedy all the previous deficiencies in this regard. Therefore page numbers do not accompany a number of the references which are recorded in the text, although all the references that are cited were consulted.

Generally, selected reference material that was published up to the end of 1973 is included in the thesis. In a few instances later publications are noted where the dual prerequisites, of both their specific relevance and their availability in Australia, were met.

The proposed lithostratigraphic terminology for Southern Africa is still far from being finalised, and it is still in a state of considerable flux. The text therefore adheres to the existing, or "old", "chronostratigraphic" nomenclature - except when the discussion relates to the work and to the nomenclature of recent investigators.

In the following pages "fluor-spar" is used in preference to its synonym "fluorite", except when the discussion relates to mineralogy or geochemistry, because in most cases the word is used in the context of fluorite-ore. The same convention has been applied to the synonyms zinc-blende and sphalerite.

B. Area, Location and Access

The study-area is situated in the Western Transvaal, immediately south of the pastoral town of Zeerust which is approximately 256 kilometres west of Pretoria by road (Fig.1). The boundaries are represented on the west by longitude 25°45'E, on the east by longitude 26°37'E, and in the south by latitude 26°00'S (see Figs.1 and 2). The total area is approximately 4300 square kilometres. The railway from Johannesburg westwards to Botswana traverses the mapped area, through Zeerust and Slurry, and links with Mafeking 20 kilometres beyond the south-western limit of the photogeological map. Good sealed roads connect Zeerust, Mafeking and Lichtenburg. Lichtenburg is situated 20 kilometres south of the southern limit of the mapping.

Within the area that was mapped cross-country traversing by vehicle is restricted by rugged, low outcrops of dolomite and chert. Nevertheless the access is generally good, by virtue of secondary provincial roads (unsealed) and farm tracks, some of which follow accurately the strike of decomposed dykes in the dolomite.

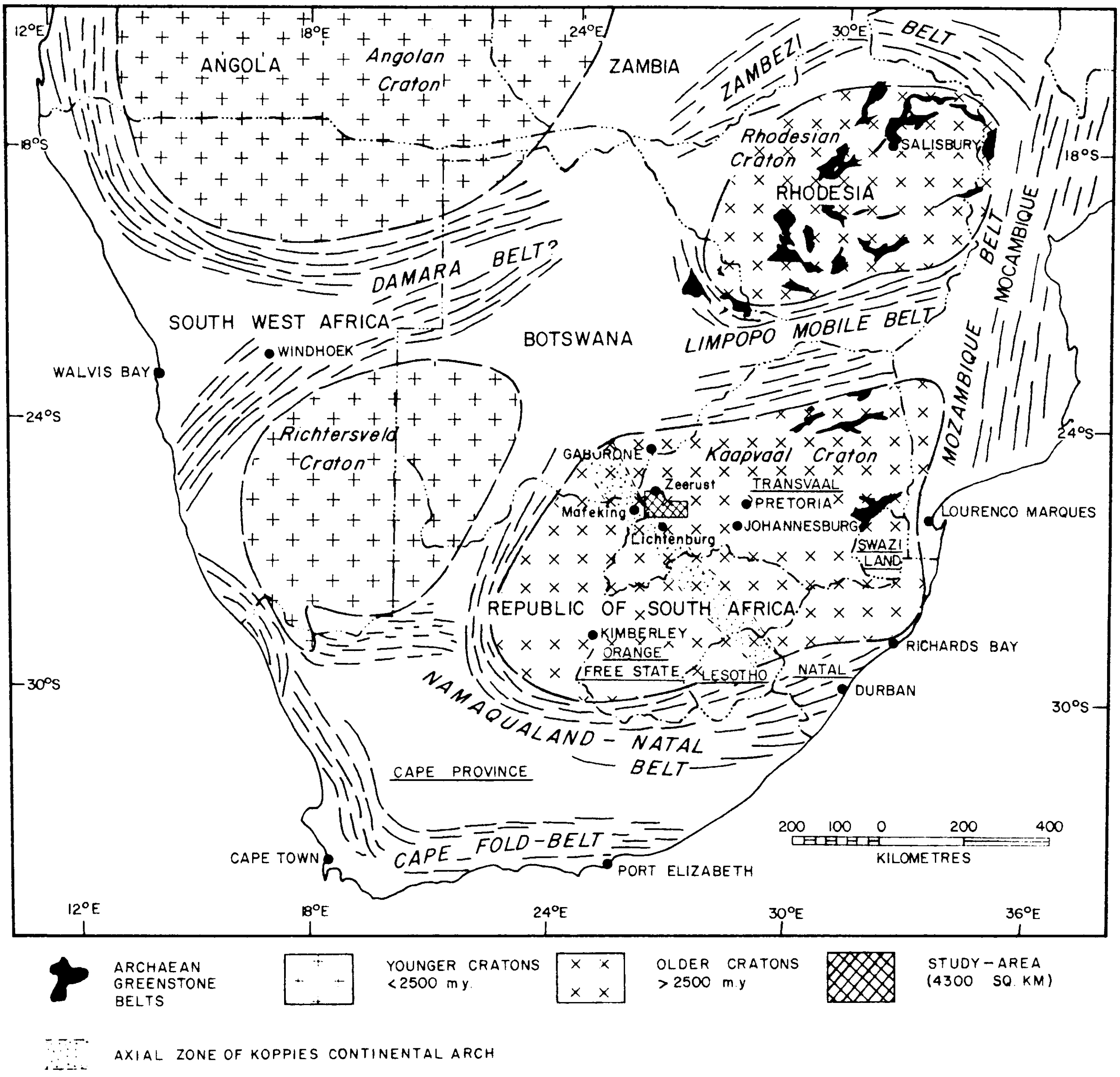

Fig. 1 GENERALISED GEOTECTONIC MAP OF SOUTHERN AFRICA SHOWING THE LOCATION OF THE STUDY-AREA IN THE TRANSVAAL. (After Anhaeusser and Button, 1974, fig 1. The location of the axis of the Koppies continental arch is after Pretorius, 1974, figs 1 and 4, and Hunter, 1974, fig 2.)

The investigation of photogeological detail in the field was limited for the lack of time, and for reasons of secrecy, to areas where access by a vehicle was possible. At the time of the very brief field-investigation which complemented the photogeology, many farm gates were locked, effectively prohibiting access. (A major advantage inherent in the photogeological approach was the ability to map the area secretly and to derive relevant information without trespass). Field-traverse routes are marked by small arrows on the photogeological maps on the scale of 1:50 000 which accompany the thesis (Figs.4a and 4b, in pocket).

On the accompanying maps, and in this text, the names and the numbers of farms correspond with those marked on the topocadastral maps numbered 2524 (Mafeking) and 2526 (Rustenburg), dated 1966 (scale 1:250 000), and with those listed in the 1974 edition of the "Alphabetical list of Farms in the Province of Transvaal".

The relevant topographic maps on the scale of 1:50 000 which incorporate the study-area are indicated in Fig.2 (8 sheets). Figure 2 also records details of the photography.

C. Object, Method, Context

The object of the photogeological study was to determine the major controls of the deposits of galena, zinc-blende and fluor-spar that are found within the Dolomite Series in the Zeerust region, and to project the results elsewhere in the Transvaal as a particular phase in the evaluation of the base-mineral potential of the entire "Transvaal Dolomite". The photogeological study involved the following two main phases.

1. Photogeological test-mapping of an area which encompassed approximately 640 square kilometres, using black-and-white photographs on the scale of 1:50 000, with concurrent reconnaissance in the field. (Total time 12 days).

2. Detailed photogeological mapping of a total area of approximately 4300 square kilometres (including the test-area), using black-and-white photographs that were specially commissioned on the scale of 1:20 000, followed in the field by the confirmation of photogeological data.

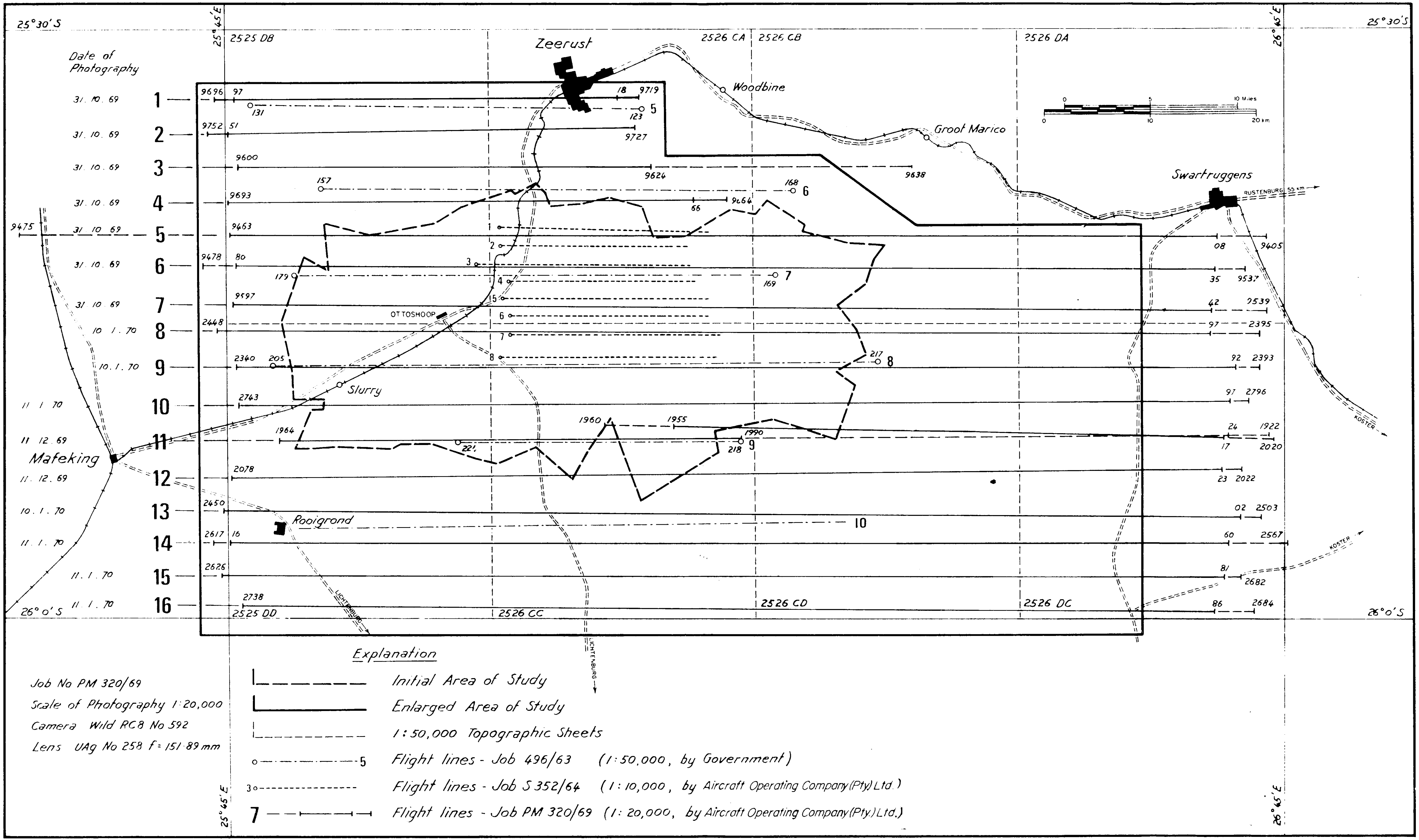

Fig.2 PLAN SHOWING PHOTOGRAPHIC COVER UTILISED DURING PHOTOGEOLOGICAL INTERPRETATION OF INITIAL AND ENLARGED STUDY-AREAS

Both of the areas are shown on Fig.2. During both phases a Zeiss "Aerotopo N2" mirror-stereoscope (with a binocular magnification of 6) was used, and photogeological annotation was made directly on to the semi-matt, contact-scale, panchromatic paper-prints. In the first phase the compilation of annotated detail was done by tracing the detail on to existing topographic maps which were on the scale of 1:50 000, and the final map was presented on the same scale. For purposes of this report it is presented as Fig.3 (in pocket), on the reduced scale of 1:100 000.

In the second phase, the compilation of photogeological detail was achieved by its transfer to 23 mosaics that were prepared specially on the scale of 1:20 000. For present purposes the 23 resultant map sheets were combined to form the composite map that is shown by Figs.4a and 4b (in pocket). This map is now on the approximate, reduced, scale of 1:50 000. During the aerial photographic survey, conditions of poor weather forced the aircraft to adopt different flying-heights for runs that were completed at different times. The resultant variations in the photographic scale made it impossible to produce undistorted mosaics. Severe mismatches of photographic detail within individual mosaic-sheets, and between adjacent mosaic-sheets, became unavoidable. As a consequence, the composite photogeological map that is represented by Figs. 4a and 4b embodies a corresponding amount of distortion and mismatching of the internal detail. Provided this unavoidable situation is borne in mind, the detraction from the over-all outcome of the photogeological survey is minimal.

The photogeological mapping was carried out at a time of intense and competitive local exploration for fluor-spar. It was executed on a consultancy basis under conditions of strict security, and there was a need for secrecy and haste. Access to many mineralised localities was impossible because of the competitive exploration atmosphere that was prevalent at the time, for example the deposits on Witkop 302 JP, Buffelshoek 301 JP, and Wintershoek 303 JP. Mapping was, perforce, carried out with subordinate field-work. However, as the emphasis was on the determination of geological interrelationships and on the major controls of the localisation of ore-minerals(for which purposes photo-interpretation was deemed most suitable), the apparent imbalance was not inappropriate.

D. Physiography

The area which was mapped is situated in the south-western portion of the Transvaal Highveld, at an average elevation about 1524 metres above mean sea-level. The climate is moderate, with frosty winters and an average annual rainfall of 500 to 625 millimetres. Rain falls mainly during the summer months. Trees and scrub grow most abundantly in the areas where the bedrock is exposed the best, that is, adjacent to the upper contact of the Dolomite Series. Elsewhere, the natural vegetation is virtually confined to grass-veld. Commonly, thickly vegetated, narrow, linear zones in the dolomite terrain correspond with decomposed dykes. The vegetation in the study-area corresponds with Acocks' "Mixed Grassveld" and "Sour Grassveld" types (Acocks, 1953, Map 2).

The relief is generally subdued, and local differences in elevation are generally less than 100 to 130 metres. The greatest dissection has taken place along a zone which follows the contact between the Dolomite Series and the sediments of the overlying Timeball Hill Stage, which lies at the base of the Pretoria Series (see Figs.5 and 6). Elsewhere the region expresses itself as a gently undulating plain with occasional isolated knobs and flat hillocks of chert. A great proportion of the area is underlain by flat-lying dolomite or chert, but much of the region is mantled by soil, and chert rubble, and in the western extremity, by surface-limestone. This cover seriously inhibits the recognition of the bedrock during geological mapping in the field, and to a different but sometimes lesser extent, during photogeological mapping. Good general exposure of the dolomite exists only in the broad belt of north-trending dolomite and chert west of Zeerust, northwards from Ottoshoop. In the remainder of the region the dolomite terrain is particularly monotonous, particularly that which corresponds with, and adjoins, the "Lichtenburg Plain" that exists to the south (King, 1942, p.271).

The expression of karst-features in the dolomite terrain is widespread and obvious, but it is nowhere particularly strong. Apart from scattered sink-holes which are clear-cut, subdued soil-covered depressions, or dolines, are common throughout the areas of poor exposure of the bedrock. Some of these are linear and reflect an obvious response to some form of structural control in the underlying dolomite.

It is apparent that the stage of the karst cycle in the study-area corresponds with the stage of "maturity", according to the cyclic framework of Cvijic (in Brink and Partridge, 1968, p.13). This stage is characterised by maximum underground drainage, with surface drainage limited to short, sinking streams that end in shallow holes and blind valleys. The extensive cavern networks that also characterise this stage must exist within the study-area, but they are not known to be linked with caves that open to the surface.

Relatively detailed summaries of the surface and the underground hydrology have been given by Hall (in Hall and Humphrey, 1910, pp.10-15) and by Humphrey (1908, pp.142-145). The numerous very strong springs, or "eyes", which arise in the dolomite are worthy of particular mention. The Malmani, Groot Marico, and Molopo Rivers arise this way; moreover it is obvious that the ground water in the dolomite terrain is compartmentalised and dammed by dykes and large veins of quartz.

Widespread alluvial gravels cover the Lichtenburg Plain, and they are diamondiferous in places (Du Toit, 1951). They indicate the former existence of a river system, which includes the main channel of the paleo-Harts River, which was beheaded in its upper reaches by eastern tributaries of the Molopo River after Tertiary crustal warping (Mayer, 1973).

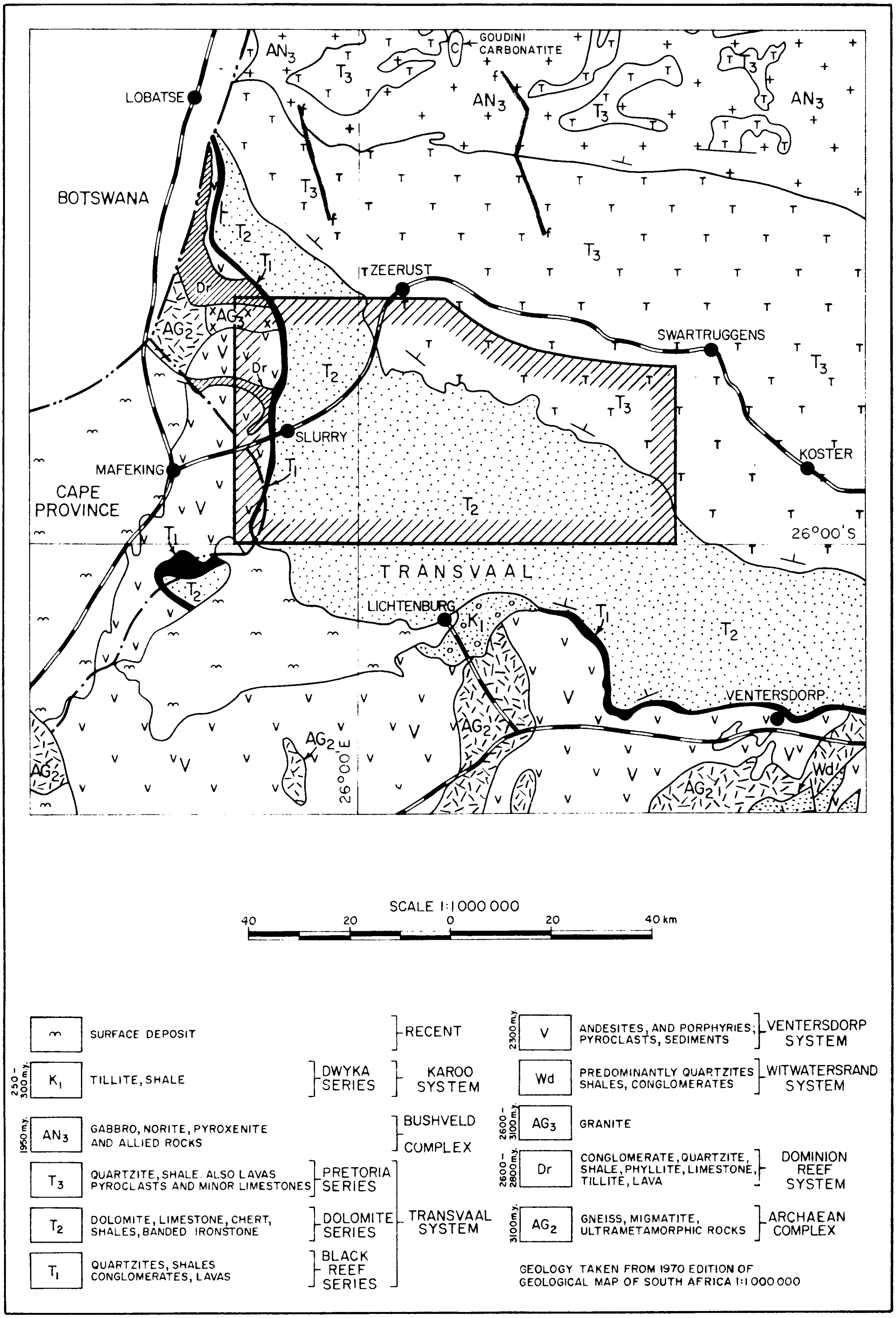

Fig. 5 GEOLOGICAL SETTING OF STUDY-AREA

II. GEOLOGICAL AND TECTONIC SETTING OF AREA MAPPED

Essential information is illustrated in Figures 1 and 5. The area of interest is situated on the long-lived, rigid, crustal plate of the Kaapvaal Craton, which developed at about 3,0 b.y. The area is situated in the north-western portion of this craton, close to the northernmost of the bounding mobile belts, the Limpopo Mobile Belt. The latter is a broad, linear zone of continuous tectonic instability from early Precambrian until the present, in which deformation and metamorphism reached a peak at about 2,69 b.y. (Van Breemen and Dodson, 1972, in Hunter 1974b, p.305), and in which a major tectonothermal event took place between 1900 and 2000 m.y. (Mason, 1973, pp.477-480, and table). The latter event coincides with the formation of the Bushveld Complex, and included major transcurrent dislocation along the flanks of the mobile belt (Mason, 1969, pp.93-96; 1973).

The Kaapvaal Craton is characterised by gently inclined Precambrian basin-deposits that are largely unmetamorphosed. That portion of the craton which corresponds with the present study-area incorporates, mainly, strata which correspond to the lower portion of a very major Lower Proterozoic basin (maximum age 2,3 b.y.). A portion of this basin exists as an erosionally separate basinal entity in the Transvaal, and is known as the "Transvaal basin". The Dolomite Series which comprises most of the area of immediate interest near Zeerust thus forms part of the far south-western extremity of the Transvaal basin. The central portion of the Transvaal basin is occupied by the younger igneous complex of the Bushveld which, in its western extremity, is exposed less than 30 kilometres due north of Zeerust (Fig.5). The study-area is situated partly within the broad aureole of contact-metamorphism which surrounds the Bushveld Complex (see Hall, 1932, pp.386 to 408, especially pp.388 and 401).

Immediately to the west of the study-area the axial zone of a geanticlinal arch of continental proportions trends roughly north-north-west. (see Fig.1). The arch is a fundamental tectonic unit of the craton and it was operative continuously from a time prior to the deposition of the Transvaal System to some time after the deposition of the Waterberg System. It was named the "Koppies continental arch" by Pretorius (1974, Fig.2).

The area of interest straddles, and coincides with, the sedimentary axis of the Dolomite Series in the Transvaal basin, which trends in an east-north-east direction, and in coincidence with which the thickest succession of dolomitic strata was deposited (Visser, 1970, Fig.2). The thickness of dolomitic sediments in the study-area, which exceeds 2000 metres, is therefore anomalous in a regional context.

Deposits of galena and zinc-blende, and very important deposits of fluorspar, are found in the dolomite a short stratigraphic distance below the contact with terrigenous sediments which constitute the bulk of the overlying Pretoria Series. Underlying the Dolomite Series is the arenaceous Black Reef Series which forms the basal unit of the Transvaal System. The latter rests on older Lower Proterozoic formations which comprise mainly basic and acidic volcanic rocks, and on even older granite, which is probably both Archaean and post-Archaean.

The relevant lithostratigraphic succession is illustrated diagrammatically in Figure 6 (after page 24).

The study-area is situated on the western limit of the so called "Pilanesberg Alkaline Province" that was defined by Ferguson (1973). Evidence of fenitisation in the extreme west of the study-area, near Buhrmannsdrif railway siding, would effectively shift this limit westwards, and would lead to the conclusion that the area of interest lies within the western extremity of this Province.

III. PREVIOUS WORK

In this section relevant information is given at fair length on purpose. This is for two main reasons. Firstly, to unify information from previous publications and studies so that the results of the photogeological mapping can be appreciated fully in relation to previous work; particularly various attempts to define the controls of lead, zinc and fluor-spar mineralisation in the study-area. Secondly, to clarify the confused mining history, partly as an aid towards understanding the relative importance (past, present and future) of the various relevant ore-types. This has a bearing on the photogeological study which would not have been taken to completion had the excellent fluor-spar potential of the area not been recognised in recent times - notwithstanding initial interest in the deposits of lead and zinc minerals which are considered to have affinities with deposits of "Mississippi Valley"-type. What follows also explains why, in spite of the latter association, interest in the deposits that contain galena and zinc-blende gradually yielded to an emphasis on fluor-spar, which later constituted the prime motivation for the continuance of the photogeological study. Lastly, interest in the Zeerust region is strong at the time of writing (1975) and the information that is given will provide other students of the area with a guide to the relatively few publications that are of direct relevance.

By way of introduction it is recorded that the area which was mapped possesses a wide variety of economic minerals and ores, including gold (in quartz veins), alluvial diamonds (in fossil placer deposits), manganese oxide, surface-limestone, and vanadinite. During the period of execution of the work on which this thesis is based (1969-1970) only residual fluor-spar ("Kokerman ore"), and surface-limestone, at Slurry west of Ottoshoop, were being exploited.

A. Published Literature

Hatch (1905) was one of the first to publish a sketch-map of the south-western portion of the Transvaal; his map includes the present area. He described general aspects of the geological succession, and noted correctly the broadening of the outcrop of the Dolomite Series south and south-west of Zeerust. He did not mention, or map, any mineral occurrences other than the Malmani gold-quartz veins near Ottoshoop.

Hall and Humphrey (1910) mapped and described the geology around Zeerust and Mafeking, and included a description of the Malmani Gold Field and the deposits of ores of lead and zinc south of Zeerust. They are the same as those which are known at the present time. To this day, their geological map, "Sheet 5, Zeerust", mapped on the scale of 2,347 miles = 1 inch, represents the only official geological map sheet that covers this area. Portions of the Zeerust region, specifically the areas in which fluor-spar and ores of lead and zinc are present, have been re-mapped by the Geological Survey in the last 30 years, but no revised geological map sheet has been produced. The geological maps of a reasonable vintage that are available freely,but are restricted areally,are those which accompany the Geological Survey publications by Willemse and others (1944), and by Hammerbeck (1971).

Hall and Humphrey's mapping of the Zeerust and Mafeking Sheets, Sheets 5 and 6 respectively, was prompted by the construction of the Krugersdorp-Botswana Railway (It was completed in 1907). Immediately thereafter, Humphrey (1911) described the geology of the Marico Sheet, Sheet 9, which covers the north-westerly extension (along strike) of the Dolomite Series as it is present in the area covered by this report. Most of the relevant information appears in the Annual Report of the Transvaal Mines Department for 1908, pp.123-160. (Humphrey 1908, Hall 1908).

Both Hall and Humphrey (1910) and Humphrey (1911) recognised the general distribution and the structure of the major geological formations, including members of the Transvaal System. Humphrey (1911, p.12 and figure) remarked on the role of strike-faulting in the reduction of the width of the area of outcrop of the Dolomite Series as it approaches the Botswana border, and crosses into the area since documented fully by Crockett (1971a, 1971b, and 1972). Humphrey (1911, p.16) and Hall and Humphrey (1910, p.16) both noted folding and faulting in the normally undisturbed dolomite, south-west of Zeerust, and Hall, in the last-named publication (p.18), noted the considerable amount of metamorphism that is apparent in the upper beds of the Dolomite Series west of the Groot Marico River. Humphrey (1911, p.16) averred that, at the estimated thickness of between 7500 feet and 8000 feet (2286 to 2438 metres) "the Dolomite attains its maximum thickness in the Transvaal in the Marico District", thus pre-empting similar conclusions by recent workers (Visser, 1970, Fig.2). Hall noted the ubiquitous occurrence of soft manganese earth near the top of the dolomite in the Zeerust sheet area (Hall and Humphrey, 1910, p.38). The galena and zinc-blende deposits on Doornhoek 305 JP, Rhenosterhoek 343 JP, Buffelshoek 301 JP and Witkop 302 JP were noted and described briefly, and the mineralisation was attributed to hydrothermal emanations from the Bushveld Complex (Hall and Humphrey, 1910, p.40).

In 1915, W.A. Anderson discussed the deposits of lead and zinc ores at somewhat greater length, and he noted that galena had been located on numerous specified farms. He divided these deposits into two classes, namely localised circular areas (later to be named "pipes" by others) and disseminated deposits and aggregates. He discussed "circles" that were located on a number of farms. The only mineralised "circles" were two, on Witkop 302 JP and on Buffelshoek 301 JP. Anderson drew the following conclusion. "The occurrence of the ores is of an exceedingly irregular character, and shows no general principle which could be applied as a reliable and invariable indicator for guidance in the prosecution of prospecting". (Anderson, 1915, p.128).

Rounded beads of a carbon mineral, up to 3 centimetres in diameter, that were noted by W.A. Anderson (1915) to be present in the calcite breccia-cement in the Witkop pipe, were described by C.A. Anderson (1915).

McDonald (1915) was aware of the occurrence of lead- and zinc-ores in the Zeerust belt, but he added no information that was new.

Wagner was apparently the first to document publicly the exploitation of fluor-spar deposits in the dolomite, in a note in the South African Journal of Industries in 1919. He also added to local information by describing briefly the vanadinite deposit on Kafferskraal 306 JP (Wagner and Marchand, 1920). He gave a general review of the deposits of galena and zinc-blende, and the important fluor-spar deposits, in 1929 (Wagner, 1929, pp.188-190).

Kupferburger (1928) published the first detailed account of the deposits of fluor-spar ore as they were then known in the Western Transvaal, as the result of a relatively comprehensive investigation which included the lead- and zinc-bearing deposits. In passing, he noted a depositional break that is represented by chert conglomerate at the top of the Dolomite Series, thus confirming Hall's earlier observations (Kupferburger, 1928, p.12). In the same paper (p.49) Kupferburger argued in favour of a vertical or a stratigraphic zonation of the ore minerals within the upper portion of the dolomite. He believed that the mineral deposits which were discussed by him, including the layered, concordant "impregnations" of fluor-spar in the dolomite (which were apparently considered to be unimportant, relative to his "gash-vein" and "massive fluor-spar" types) were due to "emanations from some hidden and unknown intrusion" (p.56). He speculated on a possible system of fractures and zones of brecciation in the dolomite, related to the abrupt change in strike of the base of the Pretoria Series southwest of Zeerust (Kupferburger, 1928, pp.50 and 55) and he favoured local structural control as having been a major factor in the concentration of ore minerals. The igneous source, he considered, could have affinities with either the Bushveld Complex, or an alkalic suite such as the Pilanesberg.

Kupferburger's publication in 1928 represents a valuable contribution to the understanding of the economic geology of the region. Moreover, he made an attempt to examine and record features of the Dolomite Series away from the mineralised areas. He recognised that the upper portion of the dolomite in the area was dark-coloured, and distinctly carbonaceous, and yielded inflammable gases and a tan sublimate on being heated in a closed tube. He noted ripple marks in chert, and also pisolitic dolomite, and he made obvious reference (p.16) to algal structures (stromatolites) which he was unable to recognise at the time. Finally, after a considerable amount of work in the area, he records (p.18) that, apart from some diabase outcrops near Ottoshoop village, "no intrusive rocks were noticed in the Dolomite Series over the whole area under discussion" (see Figs.4a and 4b). He also concluded (p.50) that "definite structural lines . . . which would explain the locations of the various deposits have not been made out".

Some sixteen years later, during World War II, when the massive bodies of acid-grade fluor-spar had been exhausted, and the exploitation of ores of lead and zinc was virtually nil, Kent and others (1943) reported on fluor-spar in South Africa, including the deposits in the south-western Transvaal. They added very little to the description by Kupferburger. The bedded "gravel deposit" of fluor-spar on Buffelshoek 301 JP (and Witkop 302 JP) received attention, but analagous "irregular replacements" of fluor-spar in undecomposed dolomite beneath the Giant Chert were disregarded, and were not appreciated in relation to their potential as reserves of fluor-spar ore (Kent and others, 1943, pp.18 and 53). At this stage the total reserve of fluor-spar ore in South Africa and South West Africa was estimated at three-quarters of a million tons.

Willemse and others (1944) reported on "Lead deposits in the Union of South Africa and South West Africa". Much attention was devoted to the Marico Lead Belt, that is,to the present study-area. Every known occurrence of galena was re-examined and re-described, and in the field the old lead mines received particular attention.

The work by Willemse and by Kent, and their co-authors, was done under the direction of the same agency, namely the Geological Survey, in the same period: it is peculiar that neither publication makes reference to the other, even although one and the same ore body (for example that on Buffelshoek 301 JP; D in Table 2) was noted from both points of view. (Artificial compartmentalisation of descriptive information on the basis of emphasis directed at a single mineral is a puzzling feature of the literature, and confirms the need for a unification of the information.)

The war-time circumstance which prompted the investigations that were the subject of the reports in 1943 and 1944, encourages the conclusion that the cataloguing of resources was of paramount importance, and any results of a more academic nature, for example, the fundamental controls of mineralisation, were produced incidentally. Willemse and others (1944, Plate XI), however, produced a greatly improved geological map (compared with that of the equivalent portion of the sheet that was mapped by Hall)in which broad patterns were discernible that relate to the distribution of the Giant Chert and the intruded dykes. For the first time a strong east-north-easterly trend of dykes was apparent in the dolomite and in the sediments of the Pretoria Series. However, faults that had been inferred to exist in the folded strata south-west of Zeerust, or had been postulated abstractly by previous investigators on the basis of prognostication, (see Hall and Humphrey, 1910, p.16; Kupferburger, 1928, p.10) were not detected, even after a considerable amount of work in the field.

Willemse and others (1944) summarised the available information on galena occurrences and they provided statistics of production in the Marico Lead Belt. Much of Willemse's material was derived from unpublished reports by the Geological Survey, but he drew directly on previous publications. He classed the galena occurrences in the dolomite as "Replacement Deposits" (p.117), and he confirmed that they all are found very close to the contact between the local Dolomite Series and the overlying sediments of the Pretoria Series. He stressed the association of galena with the large-scale development, by the leaching and removal of the carbonate rock, of manganiferous earth. He noted (p.118) that the latter is developed most abundantly in the upper portion of the dolomite where ground-water circulation has been very active. He considered that manganisation of the dolomite was brought about by the near-surface leaching by ground water, and not by CO_2-rich, late-magmatic solutions as was suggested by Kupferburger (1928, p.52). Willemse and his co-authors believed that the acid phase of the Bushveld Complex was the most likely source of the fluor-spar, and the lead- and zinc-ores, in both the study region and the "Transvaal Dolomite" as a whole. They suggested that mineralising solutions were trapped in the upper part of the Dolomite Series by an overlying barrier, for example, chert and banded ironstone. No philosophy or theory of exploration resulted from the war-time work of Willemse and his co-authors, and it is clear that the structural controls of the ore deposits (and the minor deposits of galena and or zinc-blende) were not deduced.

The same investigators noted that sedimentary chert breccia was strongly developed west of Rhenosterhoek 343 JP, at the base of the Pretoria Series, and concluded, in confirmation of the earlier observations by Hall and Humphrey (1910, pp 18, 19) and by Kupferburger (1928, pp 11, 12), that this horizon corresponds with an intraformational disconformity, caused by a distinct break in the cycle of sedimentation (Willemse and others, 1944, p.23).

After 1944 the geology and the mineral deposits in the area which corresponds with Figs. 4a and 4b (in pocket) were disregarded (except, probably, during unpublicised exploration efforts by various mining companies) until an investigation of the fluor-spar by W. Simpson of the Geological Survey in 1962. (Simpson, 1965). Regretably, the results of this work, including the maps, were never published on their own. (Simpson, personal communication, 1969).

The post-war period is significant in that at some stage after 1959 and prior to 1966 (see Oertel, 1966), the vast potential of the relatively low-grade fluor-spar-in-dolomite south of Zeerust was considered and recognised for the first time. Presumably this resulted from Simpson's work in the early 1960's. Certainly, the potential of the layered fluor-spar deposits was not appreciated even as recently as 1959 (see "The Mineral Resources of the Union of South Africa", pp.406, 407).

Apart from a brief summary of the fluor-spar deposits in the Republic of South Africa and South West Africa by Simpson (in Oertel, 1966, pp.14-15), which included a brief reference to "Occurrences in Dolomite", no published record of renewed interest in the geology or minerals of the Zeerust area appeared between 1944 and 1970[1].

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[1] The layered, low- to high-grade, fluor-spar deposits, which correspond with what Kupferburger (1928, p.22) classed as "... impregnations of the dolomite" have some characteristics which are remarkably similar to those of deposits overseas, in well-known fluor-spar-mining areas which have attracted considerable attention; for example the Rosiclare region of Illinois and Kentucky (personal observation). It is symptomatic of the general lack of attention that the geology and the documentation of the dolomite region of the south-western Transvaal has received, that the fluor-spar deposits, comprising reserves estimated by Oertel in 1966 to represent "half of the world's total known reserves", are unmentioned in other, otherwise relevant, geological publications. Two specific omissions are the monograph of the Symposium on the Genesis of stratiform Lead-Zinc-Fluorite-Barite deposits (1967, J.S. Brown, Ed.) and the publication by the Geological Society of South Africa, The Geology of some Ore Deposits in Southern Africa (1964, S.H. Haughton, Ed.). Another more recent omission is in The Geology of the Republic of South Africa. An Explanation of the 1:1 000 000 Map, 1970 Edition (Van Eeden, 1972). In the latter, important mineral deposits in the Republic are summarised, but fluor-spar is overlooked.

Simpson's findings, communicated partly in the conclusions drawn by Oertel (1966), were of paramount importance in revitalising interest in the potential of the fluor-spar deposits in the dolomite terrain south of Zeerust. His conclusions warrant discussion since they influenced re-thinking on the potential of the low- to high-grade deposits of fluor-spar-in-dolomite. The following is based on personal contact (1969), and on Simpson's contribution in the report by Oertel (Oertel, 1966, pp.14-16).

Approximately 780 square kilometres (300 square miles) of the area which contains mineralised dolomite was mapped by field-traversing, and geological detail was inserted on to aerial photographs on the scale of 1:18 000. The prime object of the investigation was the fluor-spar. The well mineralised area was defined as elliptical in plan, extending from "Wintershoek 303 JP eastwards across the northern portion of Rhenosterfontein 304 JP, Strydfontein 326 JP and Doornhoek 305 JP to the western portion of Witrand 325 JP". Simpson believed that the intensity of mineralisation and the thickness of the mineralised zone decreased outwards, from a known maximum thickness of "40 feet" (12 metres). The most intense mineralisation corresponds with a maximum grade of about 80 per cent CaF_2 (see Oertel, 1966, p.15, and Fig.2). He estimated that the average content of CaF_2 in the mineralised dolomite was 15-20 per cent, and he deduced that the reserves to a depth of 10 feet (3 metres) were 50 million tons at an average grade of 15 per cent CaF_2. Simpson considered that the fluor-spar formed by hydrothermal replacement of the metamorphosed dolomite immediately below the Giant Chert, and he believed in the possibility of a concealed magmatic intrusion of Bushveld granite, or of alkalic rocks of Pilanesberg-type, as the source of the fluorine. He believed that the hypothetical intrusion existed below the mineralised area in the neighbourhood of Witkop 302 JP and Buffelshoek 301 JP, and that it was responsible for the "anomalous flat doming" of the surrounding dolomite.

In regard to the so-called "breccia-bodies" or "pipes" that contain lead- and or zinc-minerals and fluor-spar, on the farms Oog van Malmani 333 JP ("Gubbins Hole"), Buffelshoek 301 JP, and Witkop 302 JP, Simpson (in Oertel, 1966, p.15) stated that "the majority of them have been proved not to be true breccia pipes". He believed that the chances of finding others were remote, but his reasons were not given. (Hammerbeck (1971, p.5) recorded that drilling below the Kaalplaats "breccia pipe" encountered no clearly delineated breccia body). Simpson recognised an "east-west" dyke system and contended that the fluorine-rich solutions ascended along east-west tension-fractures, some of which had been filled by diabase dykes, and were trapped at the top of the dolomite where they spread laterally along bedding planes, and resulted in the replacement of the dolomite by fluor-spar. Simpson (personal communication, 1969) stated that the "lead-zinc pipes" formed at or near loci of fractures, or adjacent to large fractures, but no specific details are available to support the contention. No major faults were recognised. A bore-hole of about 1300 metres and "a geophysical survey" were envisaged by Simpson to locate and test the hypothetical intrusion. The drilling of a hole was recommended near the "Witkop Zinc Pipe" (Table 2,and locality A in Fig.16). A large airborne magnetic survey, the results of which have only recently become available (see Fig.14), may have a connection with Simpson's "geophysical survey".

In 1966, Oertel's estimate of the "potential ore reserves" (as opposed to proved and estimated ore reserves) of fluor-spar in the whole of South Africa was in excess of 50 million tons of contained fluor-spar (over 300 million tons at 15 per cent CaF_2) - composed almost entirely of those deposits in the Zeerust area. The figure for the proved and inferred reserves, of a higher grade, for the whole of South Africa and South West Africa, was given as 34 million tons of 44 per cent CaF_2 (Oertel, 1966, p.24).

Gossling (1972) reviewed the World's fluor-spar industry with particular reference to South Africa, to ascertain the proportion of the market held by the Republic. Although he added nothing to the geological knowledge of the deposits he stressed forcibly the "...national importance of fluor-spar ... particularly the ores from the dolomites of the Western Transvaal" (Gossling, 1972, p.8). At this stage the corresponding reserves were estimated to be 40 million tonnes at a grade exceeding 15 per cent CaF_2 (Gossling, 1972, Table 8, p.5).

The light that was shed previously on the nature and the potential importance of the fluor-spar-in-dolomite in the Zeerust area as a result, probably, of the initial impetus provided by the researches of Simpson and Oertel, led to a program of aeromagnetic and geochemical survey by the Geological Survey.

The entire area of present interest was surveyed aeromagnetically during March 1966, and the adjoining area to the north and the east was aeromagnetically surveyed during May 1969 (see Fig.14). The last-mentioned coverage is more directly related to the Geological Survey's program of countrywide magnetic coverage, but the two surveys together are of interest as far as the fluor-spar and the lead and zinc minerals are concerned. Data from both blocks became available in the form of aeromagnetic contour-maps, in pre-release form, only in 1975. The blocks cover the entire area between 25°45'E to 25°00'E and

and 25°00'S to 26°15'S. Flight-lines were directed north-south, at an approximate spacing of 2 kilometres. No written record of the results of this airborne magnetic work has been published. However, Kleywegt and Weder (1972), and Hammerbeck (1971), make incidental mention of particular magnetic anomalies. One particular anomaly (E in Fig.14) is roughly circular, and has been tested by drilling. At the time of this writing (Jan. 1975) the drilling is still in progress.

The geochemical survey of an area 465 square kilometres in extent apparently commenced in 1967 and was completed in 1970. The prime object of the soil-sampling was lead and zinc ore, and much of the dolomite terrain that is stratigraphically just below the basal contact of the Pretoria Series was sampled between Buffelshoek 301 JP in the west, and Bokkraal 344 JP in the east. This area comprises the major portion of the "Marico Lead Belt" and it excludes only those scattered occurrences of galena that exist in the north-south strip of country west and south-west of Zeerust.

The final results of this particular survey were recorded by Hammerbeck (1971), who discussed the geochemical data for lead, zinc and copper on a farm-by-farm basis. During the taking of soil samples, on a grid 400 metres by 200 metres, detailed geological observations were made, including information on the metamorphism of the dolomite. The results were presented in the form of a geochemical contour-map for each of the three elements, that was superimposed on a geological base. An important accompaniment was a set of base-maps which show the aeromagnetic contours. Until then the magnetic data were not available for public reference in any form.

In relation to the descriptions given in the text of his publication, Hammerbeck's conclusion (p.10) that "the field relationships seem to indicate that the lead and zinc mineralisation is structurally controlled" is seen to be based on unpredictable local associations of trace-element concentrations with joints and or local fold-structures, and with synformal outliers of sediments of the Pretoria Series. Hammerbeck (1971, p.3), nevertheless did recognise a major north-south fault on the farms Rietspruit 318 JP and Rhenosterhoek 343 JP, and he noted that the old lead mine on Rhenosterhoek is situated on the side of the valley which coincides with the fault.

The geochemical survey defined a large number of anomalies of Cu, Pb and Zn, the greater majority of which are unexplained and untested. An extensive, strongly developed, geochemical plateau was located on portions of the farms

Strydfontein 326 JP, Witrand 325 JP and Doornhoek 305 JP, and significant increases in Cu, Pb and Zn were detected,with a peak adjacent to, and south of, a linear zone of outliers of shale and quartzite (Hammerbeck, 1971, Folders 1-4). Hammerbeck noted that the latter zone is associated with a coincident magnetic anomaly of much greater length which "is not due to the usual dyke intrusion" and it appears that the recommendation to follow up the coincident geochemical anomalies was partly provoked by the unexplained magnetic feature.

No over-all deductive synthesis of the controls of mineralisation in the Zeerust area was presented. Hammerbeck lamented (1971, p.10) that "until the nature of the mineralisation and the source-rock are better understood nothing further about the possibilities of finding further ore in the Marico district can be said".

In 1970 the same writer published a short report on the possible sedimentary origin of the layered fluor-spar-in-dolomite. Such a proposal had not been made previously in print (Hammerbeck, 1970).

No details have ever been published of studies of lead-isotopes or the fluid-inclusions in minerals in the area in question, and it is doubtful whether any research of this type has been undertaken. This fact highlights the neglect that this highly mineralised region has suffered, and it is observed in passing. It is more important to realise that the work summarised above, which encompasses over a century of relatively localised, field-oriented, geological investigation, produced no specific facts which allowed the recognition or the explanation of the controls of the deposits of fluor-spar, and lead- and zinc-ores,in the dolomite.

B. Mining History

Two prime factors motivated the photogeological mapping : firstly a comparison between the lead- and zinc-ores in the Marico Lead Belt and the well known class of important lead- and zinc-ore deposits, known as "Mississippi Valley-type": secondly, the recognised potential of the disseminated and layered deposits of fluor-spar-in-dolomite. Details of the history of mining in the Zeerust region are particularly relevant because they have a bearing on the above.

In relation to fluor-spar, the summary which is given here supplements the information that was given in the preceding pages. The fact is elucidated that

TABLE 1.- Production of Lead Ore in the Marico Lead Belt from 1904 to 1938.

(After Willemse and others, 1944; preface, p37, and Table 5.)

Name of Farm	Period of Exploitation	Average Annual Production, Lead Ore*	Maximum Annual Production, Lead Ore*	Minimum Annual Production, Lead Ore*
	Years	Tons	Tons	Tons
Rhenosterhoek 343 JP	7	70	200	16
Kuilfontein 324 JP	1	7	7	7
Kafferskraal 306 JP	9	56	118	1
Kaalplaats 330 JP	3	89	154	26
Buffelshoek 301 JP	5	49	202	3
Doornhoek 305 JP	18	177	1619	8

*Includes ore of 30 per cent lead and also metal of 99 per cent lead, but the average is probably 60 to 70 per cent.

Detailed Statistics, Doornhoek 305 JP

Year	Lead Ore. Tons	Lead. Per cent
July to Dec. 1907	53	?
Jan. to June 1908	226	70,80
lead slags	330	60
July to Dec. 1908	1061,7	60-81
Jan. to June 1909	657,2	60-81
July to Dec. 1909	48,2	80
Jan. to June 1910	8	80
1919	142	80
1920	188	75,82
1922	42,50	80
1923	74,95	73,89
1924	27	80
1925	35,50	80
1926	71	73,91
1927	43,5	71,11
1928	10	72,95
1929	22,91	78,34
1931	57,52	75,47
1936	9	80
1937	23	72,2
1938	53	81
Total	3184,98	

photogeological study directed at the low- to high-grade deposits of fluor-spar-in-dolomite (see classification, page 27) was justified - if only for the reason that the deposits had hardly been evaluated previously. In relation to ores of lead and zinc, details of past exploitation, when studied in conjunction with Table 1, enforce an understanding that was not in evidence at the time the photogeological study was commissioned. That is, that the deposits of lead- and zinc-ores in the Marico Lead Belt are, or were, really very small, and justified only primitive, intermittent exploitation. The summary of past mining activity also allows the fuller understanding by the reader, of the intimate association of fluor-spar, galena and zinc-blende in some of the ore deposits of Type 1.

Each of the three relevant ore-minerals has been won from deposits in dolomite in which it was the dominant ore, or a "by-product". The records show that at different times one ore body may have been exploited for different ore-minerals: the situation also existed that essentially similar ore deposits on adjacent farms were mined simultaneously for different minerals. For example, one ore body on Buffelshoek 301 JP (C in Table 2, opposite p.29) was a producer of galena, zinc-blende and fluor-spar at different times, and the least abundant ore-mineral, galena, was exploited first, and the most abundant, fluor-spar, last. This state of affairs, and the imprecise naming of some of the deposits, causes confusion during literature research and it is difficult to identify the characteristics of a number of the ore-bodies. In any attempt to define and discuss the major controls of the deposits it is obvious that this aspect is important. Therefore details of mining history are recorded partly as an important aid to the understanding of Tables 2 and 3 which summarise the combined features of some of the various deposits.

1. Lead

Discounting the probable earlier exploitation of "Vlei-limestone" (Wybergh, 1920, pp.60-65) for local agricultural purposes, the history of mining in the Zeerust-Marico area commenced with the discovery of galena on Rhenosterhoek 211 (now 343 JP) in the "early seventies" (Hall and Humphrey, 1910, p.34). Shortly thereafter galena was discovered by accident on Kuilfontein 82 (now 324 JP) and on Doornhoek 32 (now 305 JP). Both the latter discoveries of ore, like that on Rhenosterhoek, were made not far from the contact between the Dolomite Series and the Pretoria Series.

Mining took place sporadically on Rhenosterhoek at what later became known as the "Old Lead Mine" (also known as "Bray's Lead Mine") between the time of the ore-discovery, and 1886. Little work was done on Doornhoek 305 JP or on Kuilfontein 324 JP (probably, in part, because of the far greater attraction of the nearby Malmani Gold Field at Ottoshoop south-west of Zeerust, where gold was discovered in 1875, in large, vertical veins of quartz in the dolomite). Ore from Rhenosterhoek was smelted on the site, and was probably used in the manufacture of bullets during the various "Kaffir Wars", and in the early days of the Boer Republics. Work was discontinued in 1886 (Willemse and others, 1944, p.22).

There is no available record of mining activity in the region between 1886 and 1907 (by which latter date the rail-link between Johannesburg and Botswana, through Zeerust, was completed), except in regard to the diminishing number of miners on the Malmani Gold Field (Hall and Humphrey, 1910, p.32). The railway prompted exploration activity along the entire upper contact of the Dolomite Series between Zeerust and Rhenosterhoek 343 JP, a distance of 75 kilometres. Willemse's summary (1944) indicates that, from the rapidity with which occurrences of galena were investigated after the completion of the railway, all the galena deposits that are presently known, were discovered prior to 1907. The Kafferskraal Vanadium Mine, which briefly produced some galena was,however, discovered by accident in about 1920 (Willemse and others, 1944, p.22, and Wagner and Marchand, 1920).

From about 1908 onwards, sporadic exploitation of various deposits resulted in the production of galena on its own, or as an ancillary commodity during the mining of zinc-blende and, later, during the mining of fluor-spar.

The mine on Rhenosterhoek was blown up during World War I. Mining operations started again in 1937 and by 1944 mining was being carried out actively (Willemse and others, 1944, pp.22 and 29). Although data are not available to the writer it is expected that this phase was short-lived and was confined to the war period. On Bokkraal 344 JP dormancy since 1914 was followed by the resumption of prospecting operations in the period 1938 to 1940 with little result, although considerable quantities of ore and waste-rock were excavated and dumped (Willemse and others, 1944, p.27). The mine on Doornhoek 305 JP had an intermittent, but relatively prolonged total period of activity, and was in production for 18 years between 1907 and 1938, since when it has been dormant except for temporary periods of prospecting, the records of which are not available.

Table 1 proves that, in terms of size, and the production of ore, a comparison between the lead-ore deposits of the Marico Lead Belt and the Mississippi Valley is unjustified.

2. Zinc

Zinc-blende was the dominant ore only in the Witkop Zinc Pipe and in the body of breccia on Kaalplaats 330 JP, although the exploitation of the last deposit was for its galena content. In one of the ore bodies on Buffelshoek 301 JP (C in Table 2) zinc-blende was more common than galena, and both were present in much smaller quantities than fluor-spar, but apparently most interest was centred on the galena (Kupferburger, 1928, p.43). Willemse and others (1944, table on p.43) summarise the available statistics which indicate that the Witkop Zinc Pipe, including subordinate amounts of ore from Buffelshoek, produced 6400 tons of zinc ore between 1907 and 1935.

Although interest has been shown intermittently in the development of the old mines, particularly during the years of the second World War, the negative results tend to prove that their reserves of ore have been exhausted. At present there are no lead or zinc mines operating in the Zeerust area, and certainly this was the case more than 15 years ago. (The Mineral Resources of the Union of South Africa, 1959, pp.249 to 251). At present only fluor-spar is being exploited commercially.

3. Fluor-Spar

Outcrops of fluor-spar were known to the local inhabitants before the turn of the century and the massive varieties of "spar" were used to decorate graves. Commercial exploitation of the fluor-spar commenced in 1917, concurrent with the development of an export market for acid-grade material (98 per cent CaF_2) to America. From 1917 onwards, ore bodies which contained massive fluor-spar were quarried in the dolomite on Oog van Malmani 333 JP, Witkop 302 JP and Buffelshoek 301 JP (B, D and F in Table 2), but this ore was largely exhausted by 1936. Between the time of its discovery in 1940, and 1943, a "massive fluor-spar vein" was mined in dolomite and chert on Stinkhoutboom 84 JO (Kent and others, 1943).

Reliable records of production are scant, but Kupferburger (1928, p.9) estimated that by 1927 over 40 000 tons of export-grade fluor-spar had been produced from the first three deposits that are noted above. In 1942 it was recorded that some of those deposits had produced over 50 000 tons of fluor-spar. Kent and others (1943, p.53) recorded that apart from two deposits on Buffelshoek 301 JP, namely the "gravel deposit" and the "zinc-blende-fluor-spar deposit" (see Table 2, Item C), "the upper and easily worked parts of the known occurrences in the dolomite of the Marico district may be considered as practically worked out". The South African Mining and Engineering Journal, November 28, 1942 (p.277) states that "acid grade fluor-spar ... was obtained from freak deposits which by 1938 had petered out".

After 1943, the fluor-spar that was produced consisted of secondary "Kokerman" ore that was extracted by primitive methods that were defined as "pig-rooting" by Oertel (1966, p.28). Substantial tonnages were produced from widely scattered localities on a number of farms within the mineralised area south-west and south of Zeerust, but details are not available.

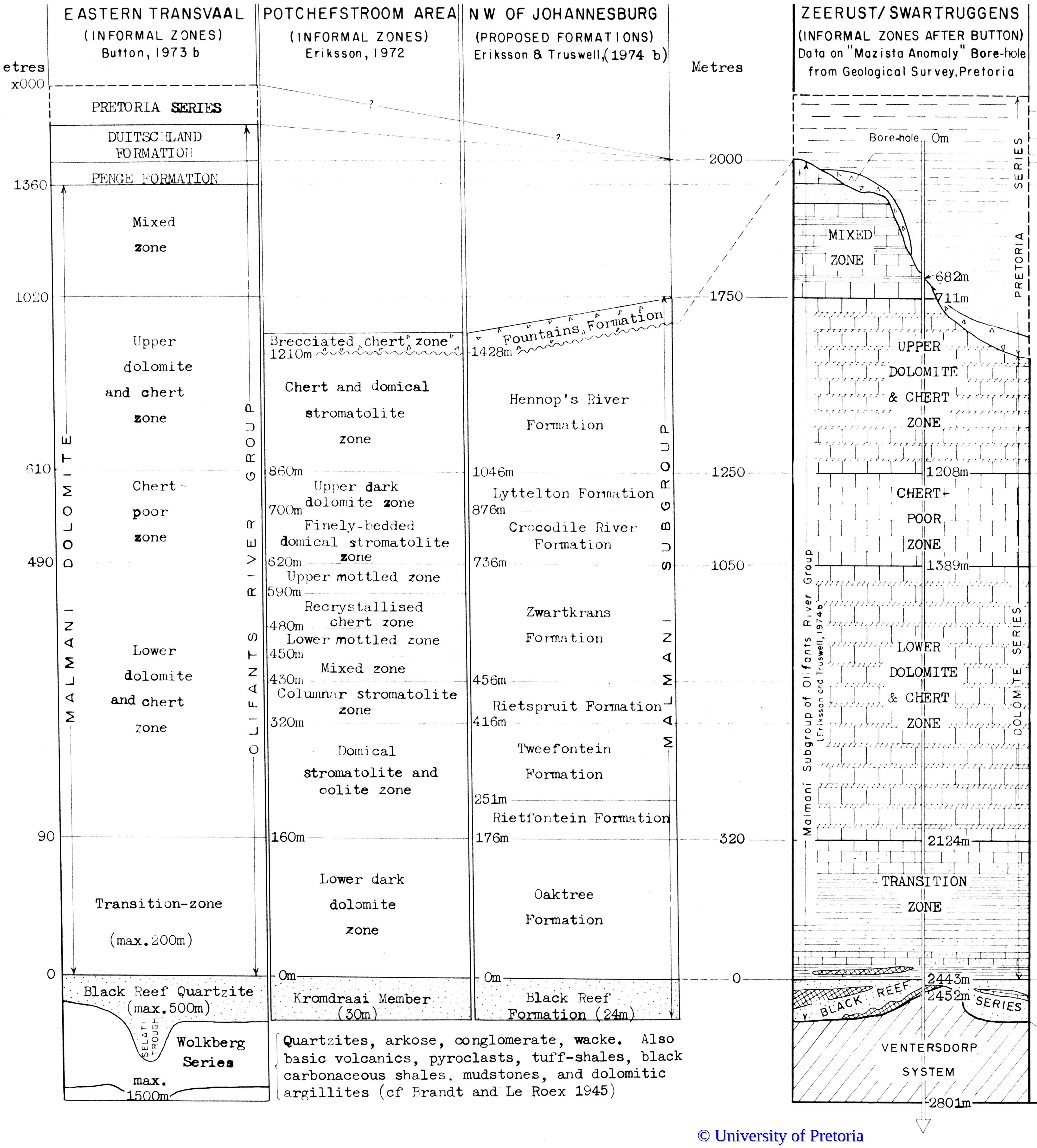
Expectations and indications of a world-wide shortage of fluor-spar in the late 1960's prompted exploration of the vast tonnages of the layered deposits of fluor-spar-in-dolomite. Recently, the advent of large-scale, mechanised, open-cast mining of this type of ore has been announced (personal communication, U.S. Steel International, N.Y., Inc.). Primitive "pig-rooting" for residual kokerman ore is still applied widely.

IV. REGIONAL STRATIGRAPHY AND SEDIMENTARY PALAEOENVIRONMENT OF THE DOLOMITE SERIES

The Lower Proterozoic Dolomite Series, in particular that part which composes the area of interest in the Western Transvaal, has been studied very poorly. In the study-area the stratigraphy and the palaeoenvironment of the Dolomite Series have been neglected almost totally. Whatever is known about these matters has been derived from a comparison of the stratigraphic, the lithological and the palaeoenvironmental information which has been obtained from the Dolomite Series elsewhere in the Transvaal basin, and from the equivalent group of rocks in the northern Cape Province.

The Transvaal Dolomite Series was mapped as a single unit until very recently. Button (1973b) effectively recorded the results of the first systematic study of the regional stratigraphy of this formation, based on the recognition of variations in the gross lithology in the eastern Transvaal, both in the field and on aerial photographs. He recognised five regionally persistent lithological units which represent three major depositional cycles separated by two intra-formational disconformities. Of the five zones, namely the <u>transition</u>, <u>lower dolomite and chert</u>, <u>chert-poor</u>, <u>upper dolomite and chert</u>, and <u>mixed zone</u>, Button was able to recognise the lower four in a composite stratigraphic column that was prepared previously for the Potchefstroom synclinorium south-west of Johannesburg, by Eriksson (1972) (see Fig.6). The column was based on Eriksson's detailed macroscopic study of drill-cores of dolomite, in which ten lithological units were recognised. In the four informal zones that are common to both areas, discrepancies in the correlation between the Eastern Transvaal and the Potchefstroom area were minor.

No information has been published on the subject of the stratigraphy of the Dolomite Series in the study-area, except for brief notes by Button (1973c, p.21), and Grootenboer and others (1973, pp.660, 663, and Fig.4). The last-named were able, on the basis of the interpretation of a single ERTS-1 (LANDSAT-1) colour-composite image, to demonstrate the existence of a mappable stratigraphic succession in the dolomite for a distance in excess of 200 kilometres between limits north-west of Johannesburg and north of Lichtenburg. Grootenboer and others (1973) found that they could correlate the ERTS-1 zones with field-data that were derived from spaced traverses between Ventersdorp and Lichtenburg, and, in particular, with the generalised succession in the better-exposed area near Zwartkops, north-west of Johannesburg, where the detailed stratigraphy of this portion of the Dolomite Series has been established recently (Eriksson and Truswell, 1974b). The zones that were recognised on the satellite images project



After Visser, 1970; Eriksson and Truswell (1974 b)
Button, 1973 b; Eriksson, 1972;
Visser and Grobler, 1972; Brandt and Le Roex, 1945;
Grootenboer, Eriksson and Truswell (1973) and
Geological Survey (personal communication)

AVERAGE COMPOSITION OF INFORMAL ZONES OR FORMATIONS

Basal "Chert Breccia" of Pretoria **Series**

Banded ironstone

Giant Chert

Dolomite and chert with heterogenous alternations of mudstone, black shales, limestone lenses and tuffaceous shale.

Light-coloured stromatolitic dolomite with ubiquitous chert in bars up to 2 **metres thick.** Thin **beds of black carbonaceous mudstone and shale.**

Dark grey stromatolitic dolomite, weathering brown or dark grey. Minor chert; some mudstone, quartzite and limestone; tuffaceous mudstone near base.

Light grey, grey-weathering, stromatolitic dolomite with abundant chert. Black carbonaceous mudstone common.

Dark grey, brown-weathering, Fe- and Mn-rich stromatolitic dolomite with a paucity of chert and abundant gritty or carbonate-rich quartzites. Black carbonaceous shale and mudstones universally developed. Clastic sediments relatively significant. Lava near base. (cf Visser and Grobler, 1972).

Basal pebbly quartzites or conglomerate and black carbonaceous shales, with some thin lenses of intercalated limestone. Also thin lava flows and tuffaceous layers.

Andesitic to basaltic lavas, acid lavas, agglomerates and terrigenous sediments.

into the eastern portion of the area which was mapped photogeologically, and the fact suggests that the (mineralised) Dolomite Series in the Zeerust region should be comprised of a comparable set of lithologic and stratigraphic formations. This suggestion is confirmed by the fact that the Geological Survey, whilst drilling a single hole on a magnetic anomaly near Swartruggens, very close to the north-eastern corner of the present study-area, penetrated stratigraphic representatives of the five zones that were defined by Button (1973b), between 682 metres and 2443,30 metres (Geological Survey, personal communication, Oct. 1974). It may therefore be expected that the stratigraphic and the lithologic character of the Dolomite Series in the study-area will in the future be proved to correspond with that already established elsewhere in the Transvaal. The diagrammatic, comparative lithostratigraphic succession for the Dolomite Series in the Zeerust area, presented as Figure 6, has been erected on this premise, since the photogeology was able to contribute little in this regard. It is relevant that Young (1933, p.134) concluded that "it is not unlikely that the principle phase groups in the Dolomite ... will prove to be of considerable lateral extent".

Matters relevant to the palaeoenvironmental conditions of deposition of units of the Dolomite Series have been investigated in the northern Cape Province and (or) in the Transvaal by Young (1932, 1933, 1934 and 1940), Young and Mendelssohn (1948), Eriksson (1972), Truswell and Eriksson (1972, 1973 and 1975), Eriksson and Truswell (1974a and 1974b), and by Visser and Grobler (1972).

It is abuntantly clear that the Dolomite Series is composed mainly of stromatolite rock produced by dominantly non-clastic sedimentation in cyclically submerged regions of a very extensive, shallow, saline, epeiric oceanic embayment. The facts are in accord with accepted general environmental parameters for stromatolite growth, as documented by Logan, Rezak and Ginsburg (1964), and by Logan, Davies, Read and Cebulski (1964).

Sedimentation was related overwhelmingly to the tidal flats of the upper intertidal to lower supratidal zone, and subtidal deposition was subordinate. Variations in the conditions of pH, salinity, and alkalinity, particularly in restricted lagoonal environments behind subaqueous bars, is the probable cause of variation in the proportions of chert and carbonate. Relatively rapid reductions in the alkalinity of the shallow ocean water, owing to influx of meteoric water, were probably the cause of oversaturation with silica, with the resultant precipitation of chert.

The dark, chert-free dolomite is related to highly saline conditions.

Occasional prolonged subaerial exposure of the sediments took place, leading to their desiccation and to the brecciation of chert layers. It is probable that evaporite deposits, for example halite, long-since dissolved, were formed during such periods (Truswell, personal communication).

Widespread horizons of tuff and a significant development of argillaceous sediment in the transition zone (transition-beds of Visser and Grobler, 1972,p.66 and Fig.3) at the base of the dolomite indicate that this zone is unusual in that it was deposited at a time of explosive volcanicity.

The regional lithostratigraphic predictability and the palaeoenvironment of deposition of the Dolomite Series is relevant to the consideration of sedimentary processes of ore genesis in the Zeerust area and in the tectonically related environments. The matter receives significant support from the results of the photogeological study, after they have been expanded in their regional context, and the information given in this section is very relevant to the main object of the investigation.

V. CONDENSED DESCRIPTIONS OF THE DEPOSITS THAT CONTAIN GALENA AND ZINC-BLENDE AND FLUOR-SPAR IN THE DOLOMITE SERIES NEAR ZEERUST

A. Introduction

It is necessary for the reader to have a basic appreciation of the nature and the size of the ore deposits (and the smaller mineral occurrences) which contain one of the three relevant ore-minerals and, very commonly, lesser amounts of the others. There is no single reference which deals with all three ores and their corresponding deposits, so a summary description must perforce be given here.

For descriptive purposes three relevant classes of primary ore deposit (mineral occurrence) may be defined as follows :

TYPE I Breccia-type (Epigenetic)	Mixed galena, zinc-blende, fluor-spar and gangue in variable proportions within irregular bodies of breccia, zones of gash-veining, or pipe-like bodies of breccia in dolomite.
TYPE II Doornhoek-type (Epigenetic)	Galena in the form of irregular nodular masses, bodies, and disseminations in concordant zones of replacement in the uppermost portion of the dolomite. Secondary wad is universal and zinc-blende and fluor-spar are present in negligible amounts.
TYPE III Layered-type (Possibly syngenetic)	Widespread, finely or coarsely disseminated fluor-spar, and also layered fluor-spar, in low-grade to high-grade deposits in dolomite host-rock in concordant zones just below the horizon of the Giant Chert ("Fluor-spar-in-dolomite").

B. Mixed Deposits of the First Type (Breccia-type)

This class of deposit includes the exhausted, but locally important bodies of massive, "acid-grade" fluor-spar, and certain of the deposits in the class have been mined for all three of the relevant ore-minerals, namely zinc-blende, galena, and fluor-spar. On this account they have been described "piecemeal" in the literature, depending on which ore-mineral was important at the time of description. To overcome the very real difficulty that is encountered in trying to obtain an over-all appreciation of the various ore bodies in this class, which were mined at an early time, it was necessary to summarise all available references. Table 2 unifies the information from the available sources in a tabular form, and this constitutes the basis for the comment that is made below.

In this class of mineral deposit it is apparent that the fluor-spar, the zinc-blende and the galena are associated intimately. The table shows that, in all probability, only two of the several related bodies had a true pipe-like form. These were the Witkop Zinc Pipe, and "the zinc-blende and fluor-spar deposit" on Buffelshoek 301 JP (A and C in the table). Willemse and his co-authors (1944) were zealous (perhaps over-zealous) protagonists of the term "pipe-like" and it is apparent that the bodies that are listed in Table 2 are, generally, irregular brecciated zones, or zones of gash-veining. The mineralised body on Kaalplaats 330 JP (E in table), that was described as "more or less pipe-like" by Willemse and others (1944, p.44), proved on recent drilling by ISCOR not to be of this shape, because three inclined holes which penetrated the root-zone encountered brecciated dolomite, and inconsiderable quantities of sulphides and fluor-spar, but no clearly delineated body (Hammerbeck, 1971, p.5).

Metamorphic minerals such as tremolite, talc, chlorite and brucite are commonly developed in the dolomite host-rock near the ore-bearing zone.

In the ore bodies which belong to this class, the depth to which the excavation of the ore proceeded was generally less than 20 to 30 metres, although the Witkop Zinc Pipe was mined underground to a depth of approximately 100 metres, and one body on Buffelshoek 301 JP was mined to a depth of about 50 metres. The workings in each of the latter bodies included several vertical shafts.

At a number of the occurrences, notably the bodies on Witkop 302 JP and Buffelshoek 301 JP, layers of "shale" and "indurated shale" are found in the dolomite host-rock, at or near the top of the ore bodies. Kupferburger (1928, p.35) noted that the same horizon of shale was present close to the bodies of

Table 2.- Mineralised bodies of Brecciated Dolomite south of Zeerust. (Includes Ore bodies of Type 1 as Classified in Section VA. of the text)

The table was compiled from the following publications.
(For details see list of references which follows the text)

1. Lead Deposits in the Union of South Africa and South West Africa - Willemse and others, 1944.
2. Description of a Carbonaceous Mineral occurring in the Witkop Mine, near Zeerust, Transvaal - C.A. Anderson, 1915.
   On the Zinc and Lead-ore Deposits near Zeerust, Western Transvaal, South Africa - W.A. Anderson, 1915.
3. The Fluorspar, Lead and Zinc Deposits of the Western Transvaal - Kupferburger, 1928.
4. Fluorspar in the Union of South Africa and South West Africa - Kent and others, 1943.
5. The Geology of the Country round Zeerust and Mafeking - Hall and Humphrey, 1910.
6. Mineral Resources of the Union of South Africa, 1959 edition.
7. Handbuch der Regionalen Geologie. Volume 7, Union of South Africa - Wagner, 1929.

	1 NAME(S) OF MINERALISED BODY, AND FARM NAME.	2 LOCALITY	3 ORE BODY	4 PRINCIPAL ORE EXPLOITED; BY WHOM, WHEN	5 OTHER ECONOMIC MINERALS	6 SIZE AND SHAPE OF THE DEPOSIT, ON SURFACE OR OTHERWISE	7 METAMORPHISM	8 COUNTRY ROCK	9 BRECCIATION	10 NATURE OR FORM OF ORE	11 POSSIBLE ORIGIN OF ORE BODY	12 GENETIC SEQUENCE OF ORE MINERALS	13 ORIGINAL OUTCROP; SURFACE EXPRESSION; GOSSAN; ZONING	14 PRESENT MINING ACTIVITY	15 DEPTH OF MINING OR EXCAVATION AT THE TIME OF DESCRIPTION	16 REMARKS
A	"WITKOP LEAD AND ZINC MINE".(1) "WITKOP ZINC MINE".(4) Witkop 302 JP	10,4 kilometres east of Ottoshoop and 900 metres east-north-east of Witkop trigonometrical beacon.(1)* (*Note there are two Witkop trigonometrical beacons).	Cone-shaped pipe.(5) Pipe-like body.(1) "Remarkable pipe".(7)	Zinc-blende and subordinate galena 1907 to 1913.(1) Blane-Witkop Zinc Company 1909 to 1911.(3) F.T. Blane Mining Company 1921 and 1922.(2)	Pyrite, pyrrhotite, chalcopyrite.(1) (3) Marcasite, arsenopyrite, subordinate fluorite (2), and carbonates of zinc and lead.(5)	Roughly circular, 54 metres by 45 metres.(1) 50 metres north-south by 54 metres east-west.(5) The surface diameter of 27 metres widened gradually in depth.(3)	The core consisted of fragments of altered dolomite cemented by calcite.(1) Tremolite, talc and brucite were formed, especially at a distance of 0,6 metres from the outer margin of the pipe.(1) A circular area is defined by an outcrop of highly altered tremolitic dolomite.(5)	Dolomite. The outer walls of the cone consist of dark blue tremolitic dolomite grading outwards to normal dolomite.(3)	The core is of barren dolomite breccia.(1) The core is of tremolitic dolomite breccia cemented by calcite.(3)	The ore formed the periphyry of a pipe-like breccia-body and varied in thickness from 2,5 centimetres to 6 metres.(1) The ore varied in thickness from 10 centimetres to 0,6 metres.(5) In places, veins of zinc-blende penetrated the centre of the pipe. Subordinate galena developed in the western portion of the mine.(5) The width of the ore body varied from a "few inches" to a "few feet".(3)	"Geyser as at Mount Morgan".(2) "Thermal action......from one point in a fissure".(5) "There is no reason for supposing that this deposit represents a volcanic pipe or blow".(5)	Pyrrhotite, pyrite, chalcopyrite, galena, sphalerite.(3) Sphalerite replaces tremolite.(2) Sphalerite and galena replace the calcite which cements the breccia.(2)	Brownish cellular gossan to a depth of 3 metres. Zinc-blende gives way to soft pyrite at a depth of 76 metres.(3) A tremolite rim "a few feet thick".(3) In places the gossan projected 0,6 to 1 metre above the ground(3) Circular outcrop.(7)	None.	88 metres.(1) Over 91 metres.(2) Vertical shafts and circular drives to a depth of 75 metres.(3)	The zinc-blende is dark (iron-rich).(1) Near the top of the deposit layers of shale are found in the dolomite.(3) Fluor-spar was totally absent as a gangue material.(3) With depth the proportion of zinc-blende to galena increased.(6) (See Fig.7 in text)
B	"WITKOP FLUOR-SPAR PIPE". "NO.2 QUARRY OF WESTERN QUARRIES LIMITED".(3) "BLANE'S NO.2 QUARRY".(6) Witkop 302 JP	90 metres south of the northern boundary of the farm and 1,6 kilometres north-west of Witkop trigonometrical beacon.(4) In line with and due south of the No.1 Fluor-spar Quarry and the zinc-blende and fluor-spar deposits on Buffelshoek.(3) In the western portion of Witkop and close to the northern boundary.(5) 0,8 kilometres east of the road.(6)	Crescentric mass of fluor-spar on the northern and western sides, elsewhere fluor-spar in irregular branching veins.(7)	Fluor-spar. Mining took place between 1925 and 1936 by Western Quarries Limited.(4) From 1917 onwards.(3) From 1924 to 1926. The deposit was still in the early stage of development in 1927.(3)	Galena and sphalerite, near the outer limits of the deposit.(4)	In 1927 the hole was 45 metres from north to south, 36 metres wide and 18 metres deep.(4) The diameter of the circular area was 45 metres.(3) A large flat vein extending downwards as a "pipe" composed of irregular branching fluor-spar veins.(6)	Talcose dolomite is exposed in the quarry. The surrounding dolomite is more or less normal.(3)	Dolomite.	"Rather brecciated dolomite" in the centre, surrounded by more or less normal dolomite.(3)	A crescentric mass of fluor-spar, exposed on northern and western sides. It appeared to dip away beneath the dolomite.(3) In the quarry fluor-spar formed irregular branching veins up to 1 metre across, cutting shale and talcose dolomite.(3?) A large flat vein beneath thin layers of shale.(6)	Possibly related to the action of a geyser.(2)	Sphalerite apparently replaces galena.(3?)	-	None.	At least 18 metres.(4) Shaft on western side of Quarry.	Shale bands are intercalated in the dolomite and in some places are cut by fluor-spar veins. Elsewhere the shale-bands formed an unbroken cover over the deposit. The shale-bands are on "the same horizon as those found near the No.1 Quarry on Buffelshoek".(3)
C	"BUFFELSHOEK LEAD-ZINC MINE". "THE ZINC-BLENDE AND FLUOR-SPAR DEPOSIT".(4) Buffelshoek 301 JP	0,8 kilometres south of the Zeerust-Ottoshoop road in the south-western portion of the farm.(1) 1,6 kilometres north-east of the south-western beacon of Buffelshoek 284.(Now 301 JP).(4) In the south-western portion of Buffelshoek and only 0,8 kilometres from the main road between Ottoshoop and Zeerust.(3) South of the No.1 Quarry on Buffelshoek.(3)	Probably pipe-like in form.(1) Zinc-blende as disseminated replacements of the dolomite; fluor-spar in irregular patches but more often as a branching network of gash-veins.(3) "From the mine plans......it appears that the zone of mineralisation is pipe-like in shape".(4)	Galena. From 1908 (1),(until at least 1924). From 1908 to 1913 (1). (By Blane-Witkop Zinc Company?). Also in 1927, 1929 and 1930.(1) From 1908 to 1914 the deposit was partially developed as a source of zinc-blende.(4)	Fluorite was the most common ore mineral by far, followed in quantity by sphalerite.(1)	A roughly circular mineralised area with a diameter of about 90 metres.(1)(4) "No particular shape" but could possibly be included in a circle 90 metres in diameter.(3) No distinct structural boundaries were recognised.(3) Very probably pipe-like in shape.(6) Circular outcrop.(7)	The dolomite in the impregnated zone is fairly normal but is tremolitic in places. If mineralised the dolomite is more highly altered and is full of flakes of talc.(3)	Chert.(2) Principally dolomite, "chert being less conspicuous". Shale bands were noted in the dolomite.(3) The rim-rock is chert.(2) Chert probably formed a cap over the deposit.(4)	Only very little brecciation of the dolomite.(1) Brecciation is not prominent.(3) Brecciated dolomite in the centre and large blocks of indurated slate,(3) the latter impregnated with pyrite.(2) In some places the rock has the appearance of a dolomite breccia cemented by zinc-blende.(3)	A zone in the dolomite impregnated with zinc-blende and fluor-spar. Impregnation took place both inside and outside of the rim.(3) Fluor-spar in the form of an irregular branching network of gash-veins.(1)(3) Zinc-blende and galena associated with fluor-spar or as disseminated replacements of dolomite.(1)(3) Occasionally resembles dolomite breccia cemented by zinc-blende.(3)	-	Sphalerite replaces dolomite and talc.(3)	A slightly elevated circular rim of black hard rock, commonly with large cubic crystals of pyrite. The rim did not extend in depth.(3) Fluor-spar outcrops made up about 7% of the mineralised area.(4)	None. A flotation plant was erected in 1914 to treat Witkop zinc-ore and Buffelshoek zinc-ore. It was a complete failure and no actual production of zinc-blende took place.(3)	46 metres.(1) Several vertical shafts.(3)	Note that the deposit was originally mined for ores of lead and zinc although fluor-spar was most abundant. In the dolomite host-rock "indurated slates", similar to the "shale bands" above, are found.(3) The deposit differs from those on Witkop and Kaalplaats (A,B, and E in table) in that brecciation of the dolomite is limited and fluor-spar was very abundant. With depth the proportion of zinc-blende to galena increased.(6)
D	"QUARRY".(3) "NO.1 FLUOR-SPAR QUARRY OF WESTERN QUARRIES LIMITED".(3) "BLANE'S NO.1 QUARRY".(4)(6) Buffelshoek 301 JP	In the south-western part of Buffelshoek, about 0,8 kilometres east of the road from Zeerust to Mafeking. 9,6 kilometres from Ottoshoop.(3)	Roughly rectangular.(3)	Fluor-spar. The deposit was mined to at least as late as 1927. 15,000 tons had been mined by 1917.(3)	Pyrrhotite, pyrite, galena, sphalerite, marcasite.(3)	The quarry in 1927 was 30 metres long by 18 metres wide by 18 metres deep.(3) The shape was determined more or less by bedding and joint planes in the dolomite.(6) In 1943 the quarry was 30 metres long by 18 metres wide by 24 metres deep.(4)	Talcose dolomite was noted in the floor of the quarry, i.e. at 18 metres.(3) The dolomite is distinctly recrystallised but is otherwise not strongly altered.(3)	Well-jointed dolomite.(3) Decomposed dolomite with manganese earth,and massive dolomite lower down.(3)	-	The outline of the deposit is controlled by joint planes. Fluor-spar cuts completely across the country rock and has completely replaced the dolomite.(3) Fluor-spar and sulphides in veins.(3)	By mineralising solutions permeating along zones of fracturing.(3)	Marcasite replaces pyrite and pyrrhotite and is later than galena.(3) Pyrite replaces pyrrhotite. Galena veins clearly cut pyrite and pyrrhotite.(6)	-	None.	18 metres.(3) 24 metres.(4)	The fluor-spar is generally white but grey and green varieties were found.(3) A thin shale-band acted as a barrier to the mineralising solutions.(6) (See Fig.10in text)
E	KAALPLAATS BODY. KAALPLAATS MINE. Kaalplaats 330 JP	6,4 kilometres due east of Ottoshoop, 2,4 kilometres south of the Witkop Zinc Mine and about 90 metres south-west of Witkop trigonometrical beacon.(1)	"A more or less pipe-like body of dolomite breccia with calcite as cementing material". The brecciated zone was elliptical in outline.(1) Pipe.(6)	Galena.(1) The deposit was worked and prospected in 1918, 1919 and 1929.(1) The brecciated zone had been mined in only two places by 1944.(1)	Sphalerite, chalcopyrite, pyrite. (Fluorite) (Bournonite).(1) Sphalerite was more common than galena.(1)	An elliptical zone of brecciation 54 metres by 27 metres.(1)	Tremolite is not developed conspicuously in the surrounding dolomite.(1)	Dolomite.	The ore body is a coarse breccia consisting of blocks of dolomite in a matrix of calcite, quartz and fluor-spar.(6)	Zinc-blende and galena (and fluor-spar) were more or less uniformly distributed throughout the breccia.(6)	-	Exsolution of both chalcopyrite and pyrrhotite is found in the sphalerite.(1)	A cellular gossan on surface did not completely surround the brecciated body.(1)	None.	About 9 metres.(1)	The deposit was stated to be very similar to the "Witkop Mine".(1) With depth the proportion of zinc-blende to galena increased.(6) (See Fig.8 in text)
F	"GUBBINS' HOLE". "GUBBINS' MINE". "GUBBINS' FLUOR-SPAR QUARRY". "MINE ON OOG VAN MALMANI". Oog van Malmani 333 JP	Next to the tar road from Lichtenburg to Ottoshoop, 90 metres south-east of the point where the gravel road branches to the north-east through Naauwpoort.(3) 1,6 kilometres north-west of the eye of the Malmani River.(3)	Massive fluor-spar.(3) A huge mass of practically pure fluor-spar in the uppermost beds of the Dolomite Series .(4) "A funnel-shaped pipe-portion in the ore body".(7)	Fluor-spar. From 1917 to after 1921, by Dr. Gubbins (also after 1927). Over 30,000 tons were extracted.(3) 1940. Syndicate L.R. Heilman.(3) From 1917 to 1926 over 30,000 tons were extracted.(4)	Pyrite, pyrrhotite, chalcopyrite and rare sphalerite and galena were noted on the floor of the deposit.(3)	Roughly oval in shape, with the long axis trending east-west. The roof is domed and the floor also rises in the centre.(3) Shoe-shaped body with the toe pointing to the east.(4) Huge elongate mushroom with a stem of brecciated dolomite cemented by fluor-spar.(6)	The dolomite is recrystallised. In places it contains talc, chlorite, penninite, brucite, jefferisite and sphene.(3) Talcose material is found at the contact between dolomite and fluor-spar.	Dolomite and chert.(3) The side-wall is generally sharply defined and distinct but contains minor fluor-spar veinlets.(3) "Somewhat disturbed" dolomite and chert.(7)	The floor of the deposit is made up by brecciated dolomite. The cementing medium is fluor-spar which carries sulphides.(3)	Massive fluor-spar (3) in the upper part of the dolomite.(4)	Chert acted as a barrier with respect to the fluorite-precipitating solutions which then caused total replacement of the dolomite, starting from east-west vertical joints.(3) "Probably due to replacement laterally along the crest of a shallow dome-fold in the dolomite overlain by impervious layers".(3)	Pyrite, pyrrhotite, chalcopyrite, sphalerite.(3)	The original outcrop was roughly circular and about 3 metres in diameter.(3) Brown-stained well-cleaved fluor-spar was exposed on the surface.(3) The "pipe" measured 37 metres by 37 metres on the surface and at 12 metres the dimensions had decreased to 24 metres by 18 metres.(7)	None.	26 metres as an open quarry.(3) The bottom of the quarry was 24 metres east-west and 12 metres north-south.(4) Measurements were 24 metres by 18 metres at a depth of 26 metres.(7)	Pale-green fluor-spar covered an area 2 metres by 4,5 metres on the bottom of the quarry where rubble was removed.(4) The massive fluor-spar passed downwards into a number of irregular fluor-spar veins.(7) (See Fig. 9 in text)
G	STINKHOUTBOOM BODY OR VEIN. Stinkhoutboom 84 JO	Near the south-eastern beacon of the farm and about 6,4 kilometres from Ottoshoop.(4)	Three continuous concordant fluor-spar layers in chert, 8 to 30 centimetres thick and 2 to 3,5 metres apart, dipping 5 to 8° to the south-west.(4)	Fluor-spar. Between 1940 and 1943.(4)	None.	Did not outcrop.(4,	None?	Giant Chert.	None?	Three concordant fluor-spar layers in chert (Giant Chert).(4)	By replacement of chert along bedding planes.(4)	-	None.	None.	Measurements were 12 metres by 12 metres, by 9 metres deep.(4)	The ore body supposedly did not crop out on the surface. The deposit was discovered in 1940 by Abdullah Sulliman.(4) On the surface gossanous outcrops and brecciated chert are obvious. (Personal observation).
H,I	RELATED OCCURRENCES. (i) Oog van Malmani 333 JP (ii) Karreebosch 329 JP	About 1,6 kilometres south of Gubbins' Hole on either side of the main road to Lichtenburg. 1,2 kilometres north-west of Gubbins' Hole about 0,4 kilometres west of the main road to Lichtenburg.	A branching network of gash-veins in brecciated (?) dolomite with subordinate amounts of disseminated sulphides.	Fluor-spar. Were apparently prospected prior to 1927 but were never exploited.	Sphalerite, galena.	- Two separate areas of unknown shape. - Could possibly be enclosed in an area 30 metres in diameter.	Sericitisation, talcification.	- Dolomite, just below the Giant Chert. - Dolomite. Probably very close to the top.	Gash-veins of fluor-spar produce a brecciated effect.	Network of veinlets and veins in dolomite,up to 5 centimetres thick.	?	?	Not known.	None.	- Estimated. 2 to 3 metres as a maximum, the small excavations are about 3 metres across. - Estimated size is 15 metres by 18 metres, by 4 to 6 metres deep.	These small deposits were examined by the writer in June 1970. The deposit on Karreebosch is possibly of the same character as that noted in this table under Item C.

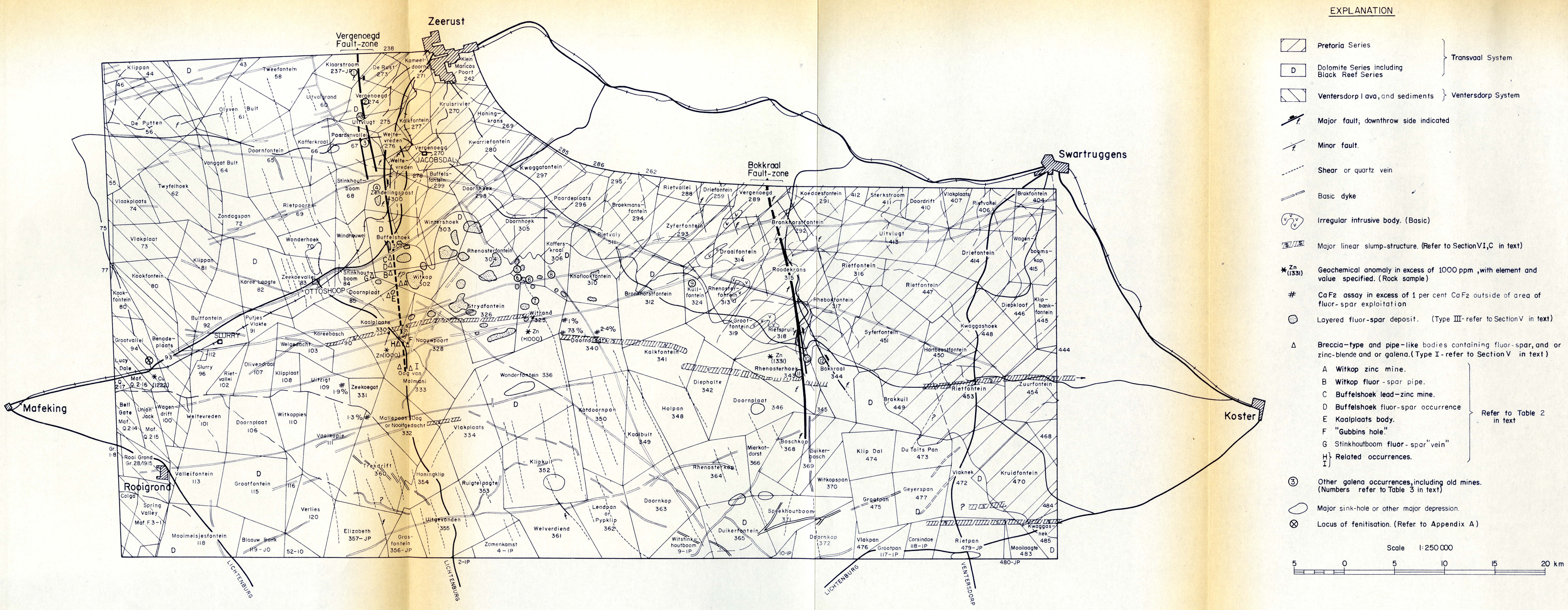


Fig. 16 DIAGRAMMATIC ILLUSTRATION OF MAJOR LINEAMENTS IN RELATION TO DEPOSITS OF FLUOR-SPAR, GALENA, AND ZINC-BLENDE : REGION SOUTHWARDS FROM ZEERUST

fluor-spar ore on Witkop 302 JP and Buffelshoek 301 JP (B and D in Table 2). In the former he noted that the shales in places formed an unbroken cover over the mineralised rock, whereas in other places within the same ore body the fluor-spar cut across the layer of shale.

The absolute and the relative proportions of fluor-spar, zinc-blende and galena varied greatly between the individual ore bodies. Zinc-blende constituted a significant part of the ore in only three bodies (A, E and C in Table 2), and they were also the only breccia-type bodies from which galena was mined. Of the three ore bodies, zinc-blende was produced only as a by-product (of the mining for galena) on Kaalplaats 330 JP, whereas in the other two deposits, on Witkop 302 JP (A in Table 2) and Buffelshoek 301 JP (C in Table 2), zinc-blende was the dominant ore-mineral.

The deposit of zinc-blende on Witkop 302 JP was unique and it warrants special mention. The ore body was a true pipe-like body which had the shape of an inverted, truncated cone, the measurement of which, in the plan, was approximately 52 metres by 40 metres on the surface. The periphery was surrounded by an annular zone of tremolite-rock which formed a characteristic ring-shaped ridge on the surface that projected 0,6 to 0,9 metres above the surrounding country. The tremolite-rock merges outward into dolomite which displays progressively less metamorphism with increasing distance from the pipe. The maximum alteration of the dolomite thus took place adjacent to the pipe-like ore body. The interior of the pipe was occupied by a coarse breccia composed of blocks of dolomite and shale which were cemented by calcite, fluor-spar and quartz. Zinc-blende with gangue minerals, and some galena and pyrite, followed the outer rim of the pipe as an annular vein of varying width. This constituted the ore. Occasional branch-veins that carried ore-minerals penetrated into the centre of the body, and random masses of ore developed in the central breccia.

The surface-expression of the pipe on Buffelshoek 301 JP (C in Table 2) was also in the form of a circular or ring-shaped ridge, similar to that of the Witkop Zinc Pipe. Wagner (1929, p.190) related these features to the "zinc-circles" of the Joplin district, U.S.A. W.A. Anderson (1915) named these features "ore-circles", or "circles", and noted, too, a similarity to the mineral occurrences of the Joplin-type in Kansas, U.S.A. Siebenthal (1915, p.207), stated that "the circles of the Joplin region have originated by the dropping down of the central area, owing to solution of the underlying limestone". McKnight and Fischer (1970, pp.2 and 78) agree with this mechanism, by which structurally analagous "slump-pipes" were produced in other parts of the Tri-State mining district. It seems quite clear, by comparison, that the "circles" near Zeerust reflect the equivalent "spot-solution" and "gravity caving into leached ground" (McKnight and Fischer, 1970, pp.3 and 79). The origin of the less regular bodies of breccia-type ore, that is, the majority, which are not shaped like pipes, is more obscure, but they are thought to be tectonic in origin.

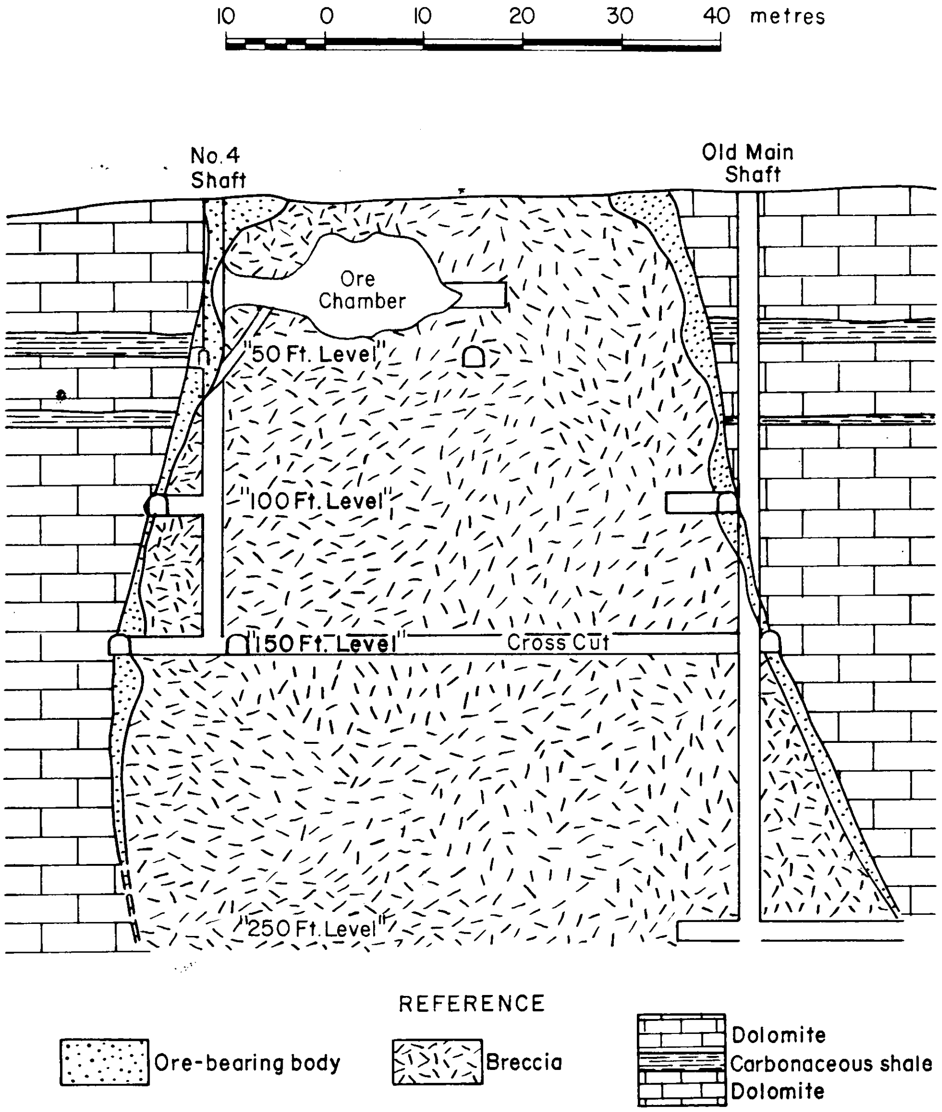
Illustrations of the Witkop Zinc Pipe, the mineralised body of breccia on Kaalplaats 330 JP, and the fluor-spar ore bodies on Oog van Malmani 333 JP and Buffelshoek 301 JP, are reproduced as Figures 7, 8, 9 and 10, respectively.

In consideration of the ore bodies above, Kupferburger (1928, pp.48, 50-53) and Willemse and others (1944, pp.117-123) concluded, in effect, that there must be a genetic relationship between the fluor-spar, the galena and the zinc-blende. Certainly the bodies listed in Table 2 possess a number of common characteristics which are sufficient to relate them to one another, and to group them in one class of mineral deposit. This is in accord with comment by Wagner (1929, p.190), who postulated that the ore body on Buffelshoek 301 JP (C in Table 2) formed the connecting link between the pipe on Witkop 302 JP (dominantly zinc-blende) and the ore body on Oog van Malmani 333 JP (dominantly fluor-spar).

C. Conformable Deposits of Lead Ore of the Second Type

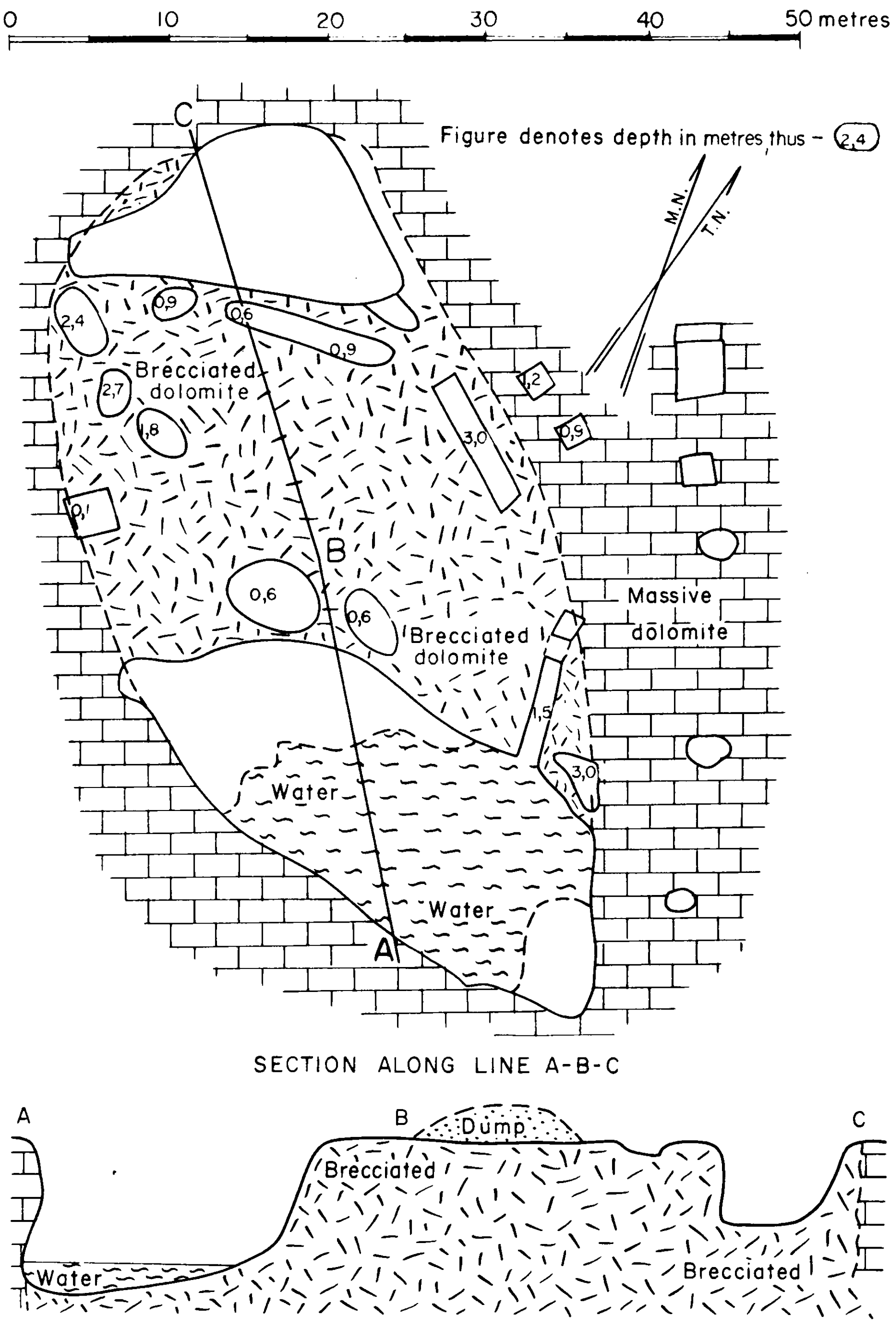
Under this heading fall only galena deposits, particularly those of the relatively important stratabound (Stanton, 1972, p.541) type that were exploited or prospected on Bokkraal 344 JP, Rhenosterhoek 343 JP, Kuilfontein 324 JP and Doornhoek 305 JP. Willemse and others (1944) have described all the important lead occurrences in the Zeerust area at some length, and the detailed information in respect of each of the above deposits need not be repeated here. A summary of their common characteristics is as follows.

Each was very close to the top contact of the dolomite, not far from the scarp formed by the sediments of the overlying Pretoria Series. They comprise(d) a succession of irregular nodular masses, or disseminations, of galena (or of secondary minerals derived from it) within flat-lying dolomite, or, commonly, within soft, brownish-black manganese earth which over wide areas completely replaces the uppermost horizons of the dolomite (Wagner, 1929, pp.188-190; Kupferburger, 1928, pp.52-54; Willemse and others, 1944, p.118). The first-named author records that the replacement of the dolomite could (in some places?) be seen". . . clearly proceeding from fissures traversing the dolomite" and,



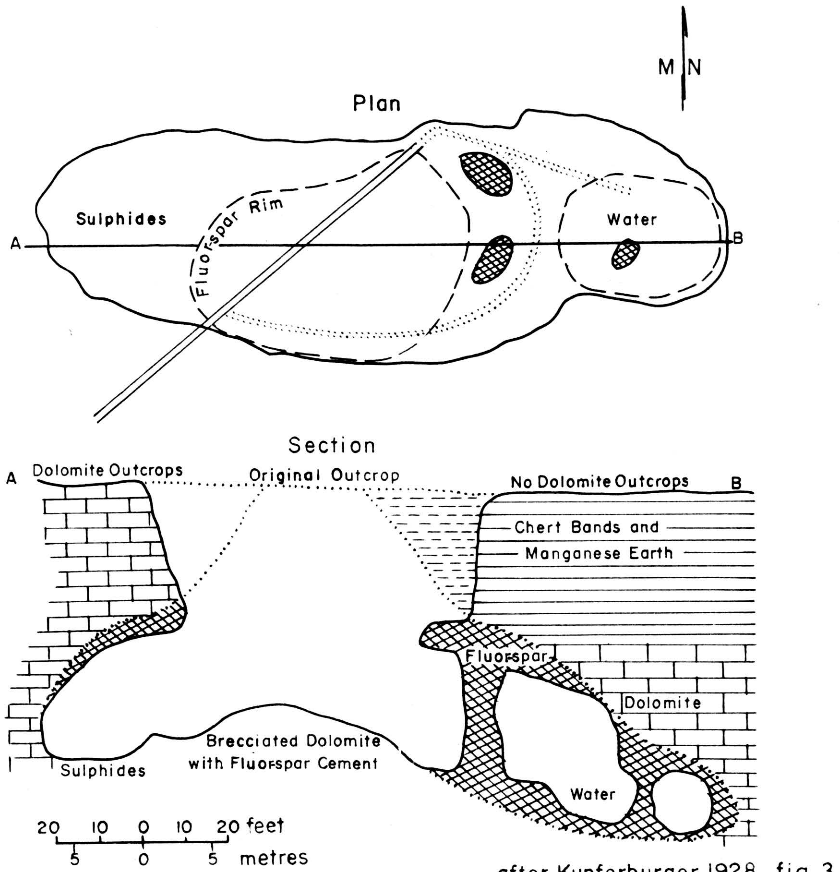
after Willemse and others, 1944, fig II
and Humphrey, 1908, fig. II
(Note: In both of the source-figures the orientation of the section was omitted)

Fig. 7 DIAGRAMMATIC SECTION THROUGH THE WITKOP ZINC MINE



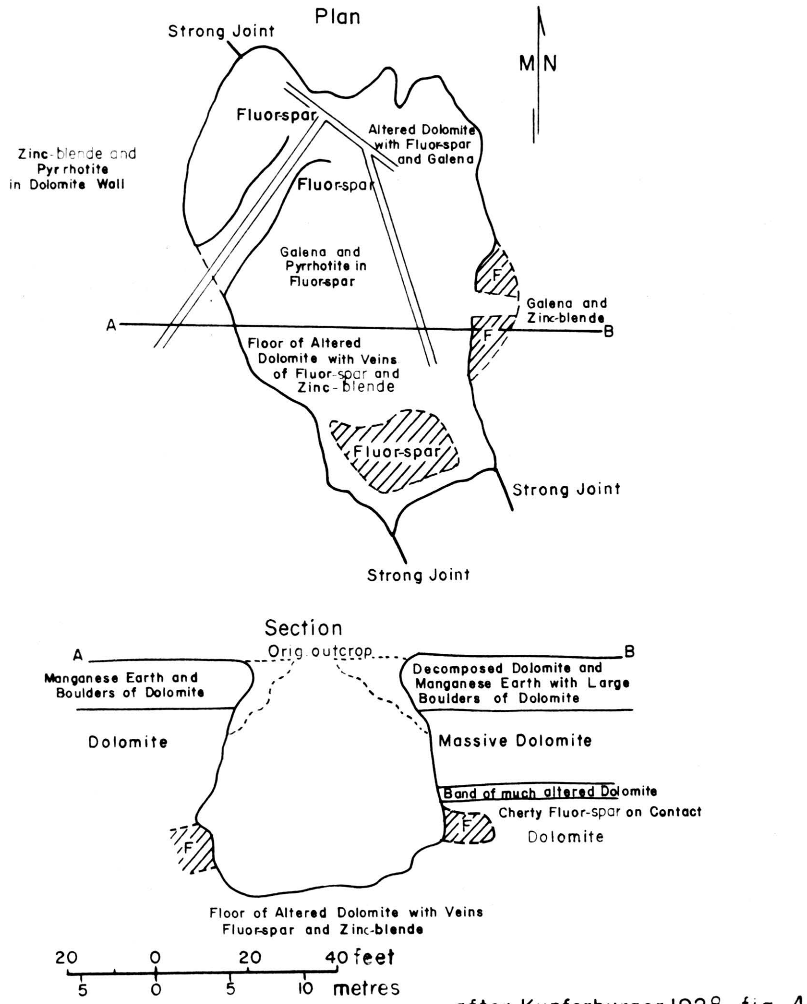
after Willemse and others,1944, fig 12.

Fig.8 WORKINGS FOR GALENA AND ZINC-BLENDE ON KAALPLAATS 330 JP



after Kupferburger, 1928, fig. 3

Fig. 9 SKETCH-MAP OF THE FLUOR-SPAR DEPOSIT ON OOG VAN MALMANI 333 JP ("GUBBINS HOLE")



after Kupferburger, 1928, fig. 4

Fig. 10 FLUOR-SPAR DEPOSIT ON BUFFELSHOEK 301 JP

". . . that the galena has developed by the replacement of dolomite is proved by the fact that the original bedding planes of that rock are often clearly discernible on the surfaces of the solid nodular masses of galena [which] . . . range in weight from a few grams to several tons". Figure 11 illustrates the nature of the deposit that exists on Bokkraal 344 JP.

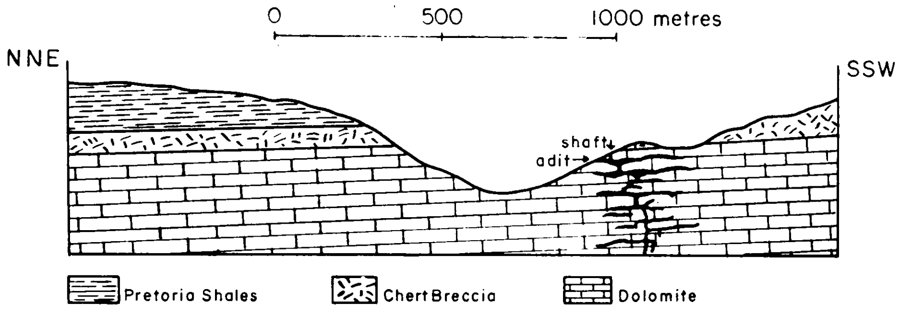
The deposit on Doornhoek 305 JP was the most important. Here galena was present in soft manganese earth which occupied an irregular area between two well-defined fissure-zones, 228 metres apart, that strike north and south, and in an adjoining site farther east, in irregular masses associated with fluor-spar and talc in unreplaced dolomite. "The galena occurs along the bedding planes of the dolomite near fissures traversing that rock" (Wagner, 1929, p.188). Figure 12, after Willemse and others (1944), is biased by his feeling that the ore body was pipe-like, whereas Wagner's observations, made at the time the body was exposed, and was still being worked, are probably the most accurate.

Apart from the larger galena deposits, Table 3 reveals that small amounts of galena exist south-west of Zeerust in association with small veins of quartz in dolomite, and elsewhere in scattered localities in the dolomite in the form of lumps, blebs and specks. These occurrences are unimportant,except in a statistical sense when the relationship that exists between the mineral deposits and geological structure,is illustrated.

D. Conformable, Layered, Fluor-spar Deposits, of the Third Type

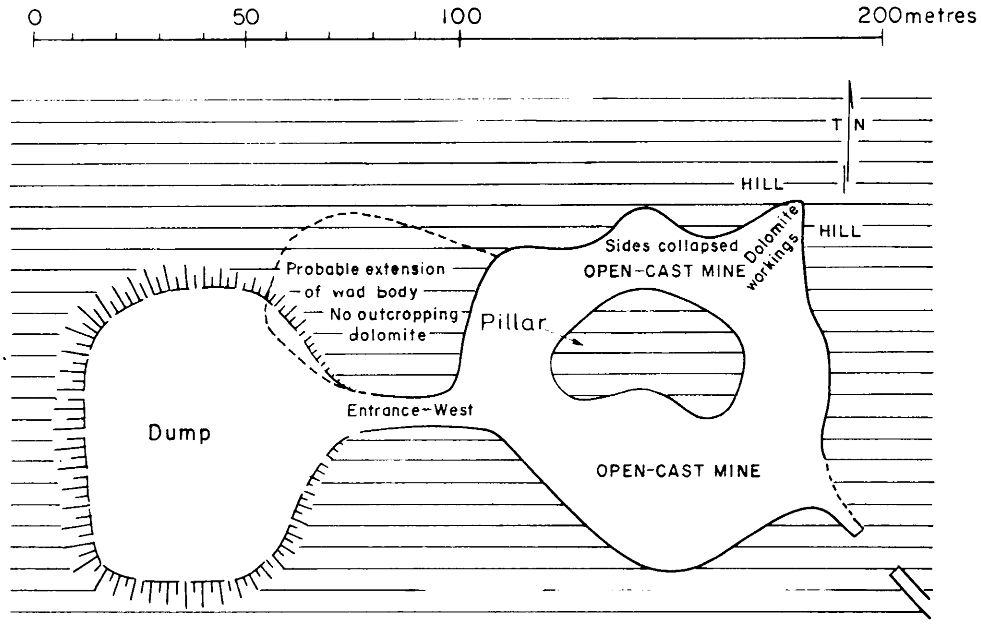
Prior to 1962 the only deposits of fluor-spar which received much attention were those of Type I. Only Hammerbeck (1970) and Simpson (in Oertel, 1966) have emphasised the fluor-spar ore of Type III, but at the time of writing (1975) a description of these deposits has not appeared in the literature. The brief period that was devoted to field-work during the photogeological programme did not allow time for the adequate study of these deposits, but general details are given below.

They are widespread, of low- to high-grade, and comprise sparsely to densely disseminated, or layered, fluor-spar in the dolomite, in conformable stratigraphic zones below the horizon of the Giant Chert. Much of the higher-grade ore is in stromatolitic dolomite in which fluor-spar occupies the crestal portions of small lateral-linked hemispheroids.



after Kupferburger, 1928, fig. 5

Fig. 11 DIAGRAMMATIC SECTION SHOWING THE GALENA AND ZINC-BLENDE DEPOSIT ON BOKKRAAL 344 JP



after Willemse and others, 1944, fig 9.

Fig. 12 PLAN OF OLD MINE ON DOORNHOEK 305 JP

TABLE 3.- Deposits of Lead Ore in the dolomite of the Zeerust Region, including those which are economically insignificant.

Descriptive data was condensed mainly from information given in the publication by Willemse and others (1944). The numbers 1 to 13 in the first column correspond with those given in Figs. 4 a , 4 b and Fig. 16 , as do the letters. In addition the letters (A,E,C,) correspond with those given in Table 2.

Farm	Condensed Description	Economic Significance
1. Klaarstroom 237 JP	Sporadic specks of galena are found in a vertical quartz vein 15 to 20 centimetres thick, in chert and dolomite.	None.
2. Vergenoegd 274 JP	Sparse disseminations of galena are found in two small quartz veins, each 5 to 10 centimetres wide, which strike north-south. The veins are in a shale horizon belonging to the Pretoria Series, and each has a very limited length of strike.	None.
3. Paarden Vallei 67 JP	Galena and zinc-blende, and small amounts of fluor-spar, are found within dolomite, in association with calcite.	None.
4. Zendelingspost 300 JP	Disseminated blebs and streaks of galena are found in the dolomite a few metres below the upper contact of this unit. Galena can be traced intermittently for about 100 metres along the mineralised horizon.	None.
5. Doornhoek 305 JP "Doornhoek Lead Mine"	Galena formed nodules and masses which were scattered throughout a zone of maganiferous earth in the dolomite, near the top of the unit. Veinlets, masses, blebs and disseminations of galena were also found in fresh, massive, dolomite. Relatively small amounts of vanadinite, zinc-blende and fluor-spar were encountered during mining operations.	The major lead producer in the Marico Lead Belt, now defunct. (See Table 1)
6. Doornhoek 305 JP	In two close but seperate localities small amounts of galena are found, either in the form of veins and stringers in dolomite or within veins of calcite and fluorite in the dolomite. None of the veins is wider than 10 centimetres.	None.
7. Witrand 325 JP	Small lumps of galena are found with cerussite in a layer of limonite, 4 centimetres thick, along a bedding-plane in dolomite.	None.
8. Kafferskraal 300 JP "Kafferskraal Vanadium Mine"	Galena and the secondary ore-minerals vanadinite, pyromorphite, anglesite and cerussite are found in the uppermost portion of the dolomite, within interbedded manganiferous earth. The deposit was better known for its vanadium-ore.	Relatively major, but minor in absolute terms. (See Table 1)
9. Kuilfontein 324 JP	Galena forms masses within manganiferous earth at the top of the local dolomite succession and is also found in massive dolomite in association with thin stringers of quartz.	Almost negligible. (See Table 1)
10. Rhenosterhoek 343 JP "The Old Lead Mine" "Brays Lead Mine"	Galena was found in solid dolomite in the form of veins, stringers and lens-shaped bodies, and in manganiferous earth in irregularly shaped lumps, some of which had a mass of several hundreds of kilograms. Bodies of ore were vertical and flat-lying and were more or less connected, constituting one complete network. The manganiferous earth contained (contains) a fair amount of finely-disseminated galena. A zone containing chalcopyrite and pyrite was encountered in the lower workings.	A relatively important producer in the early days of the Lead Belt. (See Table 1)
11. Rhenosterhoek 343 JP	Galena and secondary minerals are found in manganiferous earth along bedding planes in dolomite, and in solid dolomite which is veined by stringers of quartz.	None.
12. Bokkraal 344 JP	Galena and secondary lead and zinc minerals are found as lumps in irregular bodies of manganiferous earth which follow joints and bedding planes in the top part of the Dolomite. In places the galena is intimately associated with vein-quartz; in others, patches and disseminations of galena and zinc-blende are found in outcrops of solid dolomite.	Negligible. The deposit was extensively prospected underground but all the ore was dumped on the surface and no lead was produced.
13. Uitvlugt 275 JP	Galena is found "associated with cherty manganese not far from the boundary of the Pretoria Series". (Humphrey, 1908, p155).	None.
A Witkop 302 JP E Kaalplaats 330 JP C Buffelshoek 301 JP	For geological details see Table 2.	

All fluor-spar-in-dolomite is known colloquially by the local population as "Klipspar", and different varieties are recognised, which depend on the character of the ore, which varies according to the nature of the mineralised dolomite - that is, whether it is stromatolitic, well stratified, massive, and so on.

"Blokspar" is the name given to a variety of fluor-spar ore which breaks into flat, blocky fragments, commonly 2 to 3 centimetres thick, because the dolomite host-rock is thinly bedded. This ore may be fine-grained and dark, and it may be difficult to recognise even when the grade is very high. It resembles many of the chloritic bands or darker layers within the dolomite in the areas in which the rock is metamorphosed most strongly. Some blokspar is almost pure CaF_2.

Klipspar may take the form of the complete or partial occupation, by fluor-spar, of the crestal portions of superimposed, crescentric stromatolites which exist in layers. Also common are very fine-bedded alternations of fluor-spar and dolomite, which give rise to generally pale, striped ore that comprises,commonly, thirty per cent CaF_2, or more. More intense mineralisation resulted in klipspar which is virtually pure, granular, or microgranular fluor-spar (see Hammerbeck, 1970, p.104), which may resemble a clean quartzite in its habit. Examples of the stromatolitic klipspar may be seen in the southern portion of Rhenosterfontein 304 JP, and of the finely striped klipspar, on the central part of Naauwpoort 328 JP, where it is exposed in dolomite immediately below the horizontal Giant Chert.

The distribution of the layered, conformable, fluor-spar ore is within an irregular area which extends for 22 kilometres from west to east (Stinkhoutboom 84 JO to Knoflookfontein 310 JP) and for approximately 12 kilometres from north to south (from Zendelingspost 300 JP, 16 kilometres south-south-west of Zeerust, to Naauwpoort 328 JP). Within these confines hundreds of small, scattered, shallow prospecting pits and abandoned workings exist in the dolomite. The workings appear to be scattered more-or-less at random. Those farthest east, on Knoflookfontein 310 JP, are situated between two subparallel dykes which trend east-north-east through the area. The latter are approximately 5 kilometres apart (see Figs. 4a and 4b, in pocket).

In this class of fluor-spar deposit a definite stratigraphic control is exercised by the layered dolomite, although in individual deposits the immediate stratigraphic associations appear to be very localised.

Button (1973c, p.21), in the briefest of notes, recorded that the (conformable) fluor-spar deposits are restricted to the mixed zone (see Figure 6). There is no doubt that the ore lies in a stratigraphic position immediately below that of the Giant Chert. Simpson (in Oertel, 1966, Fig.2) limited the present type of fluor-spar deposit to a zone within 13 metres (that is, "40 feet") below the Giant Chert. That this is incorrect was proved by traverses up the flanks of hills on Rhenosterfontein 304 JP and Strydfontein 326 JP, where fluor-spar was noted in dolomite more than 30 metres below the contact of dolomite and Giant Chert.

The conformable, layered, fluor-spar deposits (unlike the ore deposits which conform to the first two classes, and are clearly epigenetic) have been ascribed to both the syngenetic sedimentation of fluorite with the dolomite, and to epigenetic mineralising agencies.

E. Kokerman Ore

"Kokerman" is the local name given to the secondary, residual, fluor-spar ore which is produced by the release of blebs, veinlets, and masses of fluor-spar, when mineralised dolomite undergoes solution, and is changed to manganiferous wad and soil. Depending on the original form of the klipspar, the individual fragments of fluor-spar (which collectively constitute the kokerman ore) vary from flat to curved flakes, though flat, solid, or granular slabs of small size, to irregular cellular masses, and aggregates.

Kokerman ore is always embedded in soil, or in dark, fine-textured manganiferous earth that was derived from the surface-weathering of dolomite. The ore-material commonly occupies solution-cavities and depressions, or passage-like, solution-widened joint-planes in the bedrock. Excavations for kokerman ore are commonly confined to solution-widened joint-planes within those horizons which actually contain primary, layered fluor-spar (Type III). Because the strata are generally nearly horizontal it is possible, from the photo-interpretation, to verify the stratigraphic conformity of some of these mineralised horizons by the manner in which the shallow excavations for kokerman ore form complete circles around isolated chert-capped hills, and(or) low hummocks of dolomite, reflecting the annular outcrop of the preferred horizon on the flanks of the hill,(For example, in the north-western portion of Rhenosterfontein 304 JP).

F. Ore Circles

The peculiar, circular surface-expression of the Witkop Zinc Pipe and one of the mineralised bodies of brecciated dolomite on Buffelshoek 302 JP has been mentioned on page 29, and has also been noted in Table 2. C.A. Anderson (1915) noted the circular pattern on the surface and he applied the name "ore circle" to each of these features. He recorded the existence of similar features on the surface on a number of other farms, and because it was not known at the time whether these circular outcrop-features were related to mineralised bodies beneath, he applied the term "circle" instead of "ore circle".

The similar nature of the "circles" and the known "ore circles" is summarised from C.A. Anderson (1915), Kupferburger (1928) and Garrard (1916).

Most are confined to country which is underlain by dolomite or chert. They are characterised by a depressed circular area that is surrounded by a rim of altered country-rock, or gossan, up to 1 metre in height. The rim is discontinuous and is broken on the downslope side, probably on account of the effects of surface-drainage. The diameter varies greatly, from "a few chains ... to over 100 yards" (Anderson, 1915, p.119). The rim-rock is much altered, with the development of tremolite and other metamorphic minerals, but this is not necessarily so. The cores of the known "ore circles" were proved, during mining, to be composed of brecciated dolomite.

C.A. Anderson (1915) recorded "circles" on Witkop 302 JP, Buffelshoek 301 JP, Strydfontein 326 JP, Rhenosterfontein 304 JP, Stinkhoutboom 68 JO, Paardenvallei 67 JP and Wintershoek 303 JP. He also recorded an "apparent circle" on Doornhoek 151 (now 298 JP) that is surrounded completely by "slates" which belong to the Pretoria Series. The location of this "circle" is described as being over 3,2 kilometres from the nearest outcrop of dolomite. The rim is formed of an "altered calcareous rock". Anderson (1915, p.119) noted that a "40 foot shaft" (13 metres) in the centre of the "circle" struck only "shales", and that a similar shaft was sunk in the rim. He also recorded that a shaft had been sunk to a depth of about 30,5 metres ("100 feet") "in slates" in the centre of a circle on Strydfontein 326 JP, and down to about 13 metres on the rim ("40 feet").

During the early photogeological mapping, a number of circular depressions were noted in Giant Chert and in the adjacent dolomite, in the central portion of Doornplaats 340 JP, and one was noted in the extreme south-eastern corner of Strydfontein 326 JP. On the examination of the features in the field, the depressions on Doornplaats were not enlightening, but the shallow depression on Strydfontein proved to have all the characteristics of a "circle". In particular a low, ferruginous, broken rim almost encircles the soil-filled depression. The surrounding rock, namely horizontal Giant Chert, is bleached adjacent to the elevated rim, which is about 0,5 metres higher than the general land surface. Dolomite is exposed below the chert 50 metres to the north of the "circle". The lack of any excavations proves that this "circle" is not the same as that which was noted on the same farm by C.A. Anderson in 1915.

The "circles" are (or were) all obvious and they are easy to recognise on the ground, so it is to be expected that all these features would have been located by early prospectors - but not necessarily recorded in specific terms. Certainly the "circle" in the extreme south-eastern corner of Strydfontein is an example in point, and C.A. Anderson (1915, p.119) substantiates this general contention by remarking that in addition to the "ore circles" on Witkop and Buffelshoek, there are "*many other circles*", of a somewhat similar nature, on various farms; but he was not specific. (Italics by the writer).

The "circles" are obvious on the ground; they are generally similar in their expression; two were definitely related to ore bodies; and the diligence and fortitude of the "old timers" (as well as their ability as prospectors) is generally acknowledged. It is thus entirely reasonable to conclude that all the "circles" that exist in (and around) the study-area were evaluated thoroughly in one way or another at a very early stage - *and in every case but two*, as shown by history, *they were found to be wanting, as far as the association with ore is concerned*.

If it is accepted, as it was accepted by C.A. Anderson (1915, p.127), that the general similarity in the expression of the "circles" on the surface is a reflection of similar bedrock attributes or structures in the dolomite strata, that is, the result of a common mode of origin, then the vital question is "why did only two suffer mineralisation?".

The answer is provided, for the first time, by the outcome of the photogeological mapping.

The stage has now been set for the actual discussion of the results of the photogeological study, which follows. A disclosure of the limitations of the photogeological interpretation on which the discussion is based is necessary however, and follows first-of-all.

VI. PHOTOGEOLOGICAL RESULTS

A. General Considerations, and Limitations of the Photo-interpretation

The detail and the overview afforded by stereoscopic study of the aerial-photographs allowed the recognition and the understanding of both local and broad-scale relationships of a geological and a geomorphological nature.

Figures 3 and 4 (in pocket), when compared with the results of field-mapping (Hall and Humphrey, 1910, "Sheet 5"; Kupferburger, 1928, Fig.2; Willemse and others, 1944, Plate XI; and Hammerbeck, 1971, Folders 1 to 4) illustrate the relatively great wealth of geological detail which resulted from application of the technique of photogeology. In this particular study the information which relates to lineaments represents the most important outcome of the photogeology, and the role of the recognition of lineaments cannot be over-stressed. There is no way in which the lineament-detail which is recorded on the accompanying maps (Figs. 3, 4a and 4b) could have been obtained - let alone quickly, accurately and cheaply - other than by the diligent interpretation of aerial photographs.

The most serious limitations of the photo-interpretation, which affect the veracity of the map when it is compared with the outcome of a hypothetical optimum standard and accuracy of future field-mapping, are related to the following two sets of circumstances :

1. The limited time that was devoted to work in the field, including general orientation and the examination of selected problem-areas, and

2. problems associated with the recognition of "*in situ* chert"

The limitations are complementary, but they are also related to independent factors.

The time-limitation in respect of field-work was not the writer's responsibility, nor his prerogative. The problem was unavoidable and was compounded by the writer's transfer to Australia. However, more field-work would not necessarily have eliminated the problems noted under (2) above, and this fact was proved in a number of locations in the field where particular investigation took place.

The problem of the photogeological recognition of Giant Chert, and Chert Breccia in situ (see Fig.6), is elucidated by Du Toit's description of the dolomite terrain.

> "Over wide areas the formation is hidden by a deep, red, sandy 'residual' soil ... full of lumps of the insoluble chert, blackened by a coating of manganese oxide, below which come angular chert rubble, masses of 'rottenstone' and shattered beds of chert ... " (Du Toit, 1954, p.135).

It was recorded on page 15 that the Chert Breccia in the study-region was accepted to represent the plane of an erosional disconformity within the Transvaal System. It was derived from the Giant Chert at the top of the local Dolomite Series by erosional disintegration in situ. The basal unit of the Pretoria Series is thus commonly represented by a thick bed of angular chert breccia. In places this breccia obviously lies on a plane of erosion and stratigraphic disconformity, but elsewhere, particularly where the remaining strata of the Pretoria Series have been removed by erosion, this relationship is not easily seen.

Even where they crop out on the surface, the Giant Chert and the Chert Breccia (which, because of their relationship are of a similar composition and habit) could not be differentiated under the stereoscope. Considerable difficulty attended the attempted photogeological distinction of the Giant Chert from the Chert Breccia in certain gently undulating areas of poor exposure of the bedrock, which are underlain by almost horizontal strata. In these situations all gradations exist from outcropping Giant Chert to fragmented Giant Chert, (in situ), in places buried under a thick or thin layer of residual, surficial, chert rubble; to dolomite covered by a variable thickness of residual chert rubble, with or without an intervening layer of Chert Breccia - the latter still in a lithified state or "rotten".

The photogeological maps do not differentiate amongst the various units and associations mentioned above. It is worth noting that those areas where the problems associated with the recognition of chert in situ were greatest, were also those areas where the greatest agricultural disturbance of the natural landscape had taken place. Mapping on the ground would be attended by serious problems of a nature similar to those which affected the photogeological interpretation. However, notwithstanding the poor rock-exposure in these areas, had the natural vegetation not been decimated, and had the natural micro-relief not been destroyed by the plough, the photogeological problem would certainly not have existed to the extent that it did. The existence of the problem should not be allowed to detract from the general value of the photogeological mapping because the attendant inaccuracies are only marginally deleterious to the useful outcome of the work.

Where both the topographic relief and the exposure of bedrock are best, that is, in the general area north of an east-west line drawn right across the region that was mapped, through the middle of Strydfontein 326 JP, the annotated areas of chert correspond very largely with chert _in situ_. The areas of chert include non-distinctive zones of Chert Breccia _in situ_ east of Bronkhorsfontein 312 JP, Giant Chert, and intercalated chert-rich zones in the dolomite. Immediately adjacent to the lower contact of the Pretoria Series, as mapped, the mapping-unit marked "C" in Figs. 4a and 4b comprises mainly Giant Chert and Chert Breccia _in situ_.

The study of the photographs on the scale of 1:20 000 tended to exaggerate the interpreted distribution of Giant Chert _in situ_, for example in the belt north of Ottoshoop. This is indicated by the original reconnaissance photogeology which made use of a smaller scale of photograph (1:50 000). The latter photographs, by virtue of the smaller scale-factor and, probably, other factors such as seasonal changes in the image (see Grootenboer, 1973) enabled the distinction between areas of "Chert" and "atypical Chert" (see Fig.3, in pocket). The second category is now believed to correspond with areas of thick, recent, chert rubble which rests on dolomite bedrock. On the photographic scale of 1:20 000 these areas are indistinguishable under the stereoscope from some areas of poorly exposed "_in situ_ chert". Thus the different scales of photography allowed different degrees of distinction between chert _in situ_, and chert rubble. In this particular case the smaller scale possessed certain advantages.

Likewise, on Wonderfontein 336 JP and in the southern part of Strydfontein 326 JP both "Chert" and "atypical Chert" were distinguished during the photogeological reconnaissance mapping on the photographs that were taken on the scale of 1:50 000 (Fig.3). Farther southwards and eastwards, where only the one scale of aerial photography, namely 1:20 000, was applied during detailed photogeology, the overview was _not_ sufficient to enable the differentiation between chert rubble, and chert _in situ_, and both associations were included in the one mapping-class. (That marked "C" in Fig.4). In this south-eastern portion of the study-area it is considered that much of the cultivated terrain is actually underlain by superficial chert rubble. The conclusion was vindicated by examination of a borrow-pit on Doornkop 372 JP, where dolomite is exposed below 1,5 metres of unconsolidated chert rubble.

In this region the ability to differentiate chert *in situ* from unconsolidated chert rubble is thus *partly related to the scale of the examination*. Bearing in mind the aforegoing and the fact that most of the problem-area is covered by soil and is cultivated extensively, examination in the field (an effective scale of 1:1), is of limited use. Partial distinction between the two classes becomes easier as the scale decreases from 1:20 000 to 1:50 000. This reflects a general but unpredictable photogeological attribute, and is one reason why high-altitude, small-scale photography and imagery on occasion allows the interpreter to distinguish bedrock relationships notwithstanding the presence of superficial materials. (It is pertinent to note that farther west on the Kaapvaal Craton, on the basis of examination of ERTS-I scenes, (scale 1:1 million) Viljoen (1973, Abstrac records that "in some instances older stratigraphic trends can be deciphered through thin flat lying cover sequences", thereby confirming the validity of the conclusions in this paragraph).

The difficulty that was encountered in the photogeological mapping of the unit marked "C" in Figures 4a and 4b, is reflected in the figures where some boundaries do not coincide at the edges of some of the 23 reduced map-sheets which comprise the composite map that is represented by Figs. 4a and 4b. On occasion a contact between chert (*in situ*) and dolomite, which was traced northwards across the boundary of the east-west photo-run on the basis of subtle relative differences in the stereoscopic photographic elements (on the scale of 1:20 000), was found to not correspond with supposedly the same geological contact which was traced southwards, in an analogous manner, on the adjacent photo-run to the north. This discrepancy is ascribed to a manifestation of the principle of "convergence of evidence" (see Appendix C) by which stereoscopic relationships suggested a particular, but slightly different, set of criteria by which the relevant geological contact should be distinguished on each run. In this context it may be repeated that, were the problem of sufficient moment, the solution could be obtained by a combination of field-work and "saturation annotation" (see Appendix C) in which emphasis would be placed, in this particular case, on *smaller* scales of photography. In the area in question, field-mapping to the standard of accuracy that is potentially obtainable from saturation annotation which is allied with field-orientation in selected localities, would be much the more laborious method. For the required investigation of the major controls of mineralisation in the dolomite, however, the minor mismatches of the contact between the mapping units "chert" (including chert-rubble), and "dolomite", were acceptable as a normal manifestation of the specified photogeology, and they are not particularly disadvantageous. The effects are to be seen on Figures 4a and 4b (in addition to the much more serious mis-matches of detail that are attributable to the unavoidable distortion of the photo-mosaics).

The following conclusions therefore summarise the limitation and the shortcomings of the accompanying photogeological maps (Figs.3, 4a and 4b).

1. The most important deficiency lies in the inability to differentiate between Giant Chert and Chert Breccia, and in the limited ability to distinguish each of them from recent, superficial chert rubble in areas of sparse outcrop of the bedrock.

2. Independent mapping of "in situ chert" in the field would encounter great problems on account of the ubiquitous superficial material and poor rock-exposure, and the problem would be without a potential solution other than by laborious pitting, or by geophysics. (The single mapping-class for chert, as applied during mapping in the field by Willemse and others (1944, Plate XI), and by Hammerbeck (1971, Folders 1 to 4), illustrates this point.).

3. Had saturation annotation been warranted in the problem areas, in this instance by the additional application of smaller-scale photographs (including satellite imagery), aided by limited investigation of the geology at selected sites, the problem could have been overcome with rapidity and accuracy, as a cost-effective photogeological exercise.

B. The Dolomite Series: Local Stratigraphic Information, Evidence for Truncation of the Succession, and some Implications

After photogeological mapping the writer reported the following information. " ... it was not possible to identify or recognise various stratigraphic groups within the dolomite except in a very general way in the north-west quadrant. [Of the study-area]. Here five major groups were tentatively annotated on the basis of photogeological tones and slight changes in stereoscopic expression". (Wilson, 1970, p.14). At the time no attempt was made to verify or extend these stratigraphic subdivisions. It is now considered likely that they correspond with the five informal stratigraphic zones that were recognised in the "Malmani Dolomite" in the Eastern Transvaal by Button (1973b), (see Fig.6), and also with those recorded more recently in a bore-hole that was drilled to define the "Mazista Anomaly" (Kleywegt and Weder, 1972; Geological Survey, personal communication, 1974) which exists immediately to the north-east of the study-area (see Fig.14). The conclusion is prompted by the evidence of a similar basin-wide stratigraphic succession, and by the fact that Button's five zones were, in part, recognised and defined as photogeological entities (Button, 1973, pp. 231 and 232).

Previous evidence of a recognisable stratigraphic succession in the Dolomite Series in the Zeerust region was virtually non-existent. The lack of data is related to the poor exposure of the bedrock in the dolomite terrain. During photogeological mapping the problem was compounded by the inability to distinguish Giant Chert _in situ_ from Chert Breccia _in situ_, and chert rubble. Consequently, it was believed initially that almost horizontal Giant Chert underlay the entire south-eastern portion of the area which was mapped (see Fig.4b) and in turn, obviously, was underlain conformably by horizontal dolomite.

The research by Grootenboer and his co-authors (1973) proved that the Dolomite Series is _not_ flat-lying in the particular area under discussion: the recognised megastratified zones would not have been visible _had_ this been so, for the terrain is very flat. In other words, the proof is that the dolomite, which is virtually not exposed beneath the soil-covered plain in the south-east part of the study-area, inclines gently to the north. This fact indicates that the flat plateaux and horizontal outliers of "_in situ_ chert" that were recognised under the stereoscope on Vlaknek 472 JP, Rietpan 479 JP, Veld 480 JP, and Mooilaagte 483 JP, (Fig. 4b) cannot be Giant Chert, and some explanation is demanded. The obvious conclusion is that the chert horizon corresponds with the Chert Breccia and it defines, in this region, a large expanse of terrain that coincides almost exactly with the plane of the major erosional disconformity that exists between the Dolomite Series and the overlying Pretoria Series.

The evidence indicates that the Chert Breccia rests on successively lower units of the dolomite as one progresses to the south-east. The transgression is more obvious when account is taken of areas farther to the north-west. For example, west and north-west of Zeerust a relatively thick succession of banded ironstone lies at the top of the dolomite (personal observation, also Hall and Humphrey, 1910, pp.19-20; and Humphrey, 1911, p.12). It is present at least as far east as Rhenosterfontein 304 JP (personal observation), whereafter it is absent above the Giant Chert and the latter is itself then represented, going eastwards, by the Chert Breccia.

This regional transgression is an exact parallel of the situation in the Eastern Transvaal, described by Button (see Button, 1973b, Fig.4), and it confirms that the transgressive overlap is a fundamental characteristic of the Pretoria Series with respect to the older Dolomite Series.

Deposits of ores of lead and zinc in the Zeerust region are acknowledged to possess characteristics somewhat akin to ore bodies of Mississippi Valley-type. Callahan (1965) has discussed the origin and the exploration of this type of ore deposit. Following Callahan (pp.6, 7, 9 and 10), one particularly favoured environment is constituted by "dissolution collapse breccias" below an unconformity like that discussed already. An important conclusion that was espoused by Callahan on the basis of his fundamental premise that "paleophysiographic" features control the formation of this type of ore body is that " ... structure _per se_ is not a condition precedent to localization of such deposits".

On first appearance selected aspects of Callahan's data would seem to apply particularly well to the south-eastern part of the study-area, and this suggests the possibility of the existence of mineralised "dissolution collapse breccias" (cave-collapse breccias) over a wide area. However, using as a basis the known deposits, the recent photogeological results alone prove that new discoveries of ores of lead and zinc in the study-region will probably be subject to distinct structural controls. Without the detailed photogeological mapping that covered a wide area, it would have been easy to justify, on apparently sound, comparative, grounds, the wrong exploration strategy in this region. In contrast with the advocation of widespread grid-drilling by Callahan(1965, Abstract, and pp.44 to 46), the photogeological evidence presented on pages 69 to 72, proves that well-defined, linear structural zones warrant preferential investigation for ore bodies of lead and zinc of the types that are known to be present in the region.

C. Lineaments and their Relationships

1. General

A very significant factor in the application of photogeological mapping is the general ability to recognise both the details and the broad relationships of a multitude of lineaments and classes of lineaments. For the present purpose the latter are the following: dykes, joints and fractures (including quartz veins), faults, and major and minor linear slump-structures (including small grabens).

The discussion will not centre on the elements or manner of photogeological expression of the lineaments, because the concept of the importance of subjective, continually variable, meaningful relative differences under the stereoscope should be understood (see Appendix C). The identifications and details are considered to be reliable - on the scale of the study - with the main proviso that some lineaments have been interpreted to be dykes whereas they may actually be fractures. Examples are the very long Diepkloof Lineament which passes through Rhebokfontein 317 JP (named from reference to "Diepkloof" by Willemse and others, 1944, p.23), other deeply incised lineaments in the Pretoria Series, and dykes that were mapped below thick calcrete and soil near Slurry.

2. Dykes, and Transgressive Basic Intrusions

Intrusive dykes were overlooked almost totally by early investigators because they almost invariably do not crop out on the surface. On aerial photographs they are obvious, to the extent that pinching, swelling, ramification and refraction at rock interfaces, lateral offshoots, forking, displacement by faults, and termination of the intrusive magma against "tight" zones of silification, are all apparent on adequate stereoscopic interpretation. Table 4 lists explicit examples of relationships displayed by dykes, and illustrates the ease with which the photogeology achieved the result. (Note the evidence that relates to age-relationships). In the field the recognition of the details noted in Table 4 would be incomparably more difficult.

The width of the dykes varies from about 30 to 60 metres. Commonly, a dyke decreases in width to a few metres before it wedges out completely along a fracture in the dolomite. The separate identities of the dykes are unknown in nearly all cases. Kupferburger (1928, p.18) identified "quartz-diabase or dolerite" at Ottoshoop, and this obviously relates to the dyke which passes beneath the village (the "Ottoshoop Dyke" in this text). Willemse and others (1944, p.24) record diabase as the dyke-rock on Wintershoek 303 JP, and also "west of the vanadium occurrence on Kafferskraal 214" (now Kafferskraal 306 JP). The latter identification was confirmed by the examination in the hand-specimen of rock from the same outcrop that was mentioned by Willemse, which is in the extreme southern corner of Doornhoek 305 JP. Apart from those mentioned above, no other outcrops of dyke-material are known. The existence of the dyke which crosses Rhenosterfontein 304 JP was confirmed in the field by a single, loose boulder of diabase, that was located after a full one-day search.

TABLE 4.- Summary of Relationships of Fractures, Faults and Dykes; with Locations.

Feature or Relationship	Locality and Remarks
Dyke wedges-out along pre-existing fracture.	Strydfontein 326 JP, Zondagspan 72 JO, Rietpoort 69 JO, Trekdrift 360 JP (dykes en echelon), Rhenosterkop 364 JP, Mierkatsdorst 366 JP, Bronkhorstfontein 312 JP, Doornfontein 65 JO, Vlakplaats 335 JP, Mallepoosoog 332 JP, Naauwpoort 328 JP.
Dyke forks.	Kaalbult 349 JP, Bronkhorstfontein 312 JP, Doornkop 363 JP, Doornfontein 65 JO, Strydfontein 326 JP, Welgedacht 103 JO, Naauwpoort 328 JP, De Putten 56 JO.
Lateral dyke off-shoot follows a trend different from that of the parent.	Kafferskraal 306 JP, Uitvalgrond 60 JO, Doornplaats 340 JP, Kareebosch 90 JO, Naauwpoort 328 JP, Doornfontein 65 JO, Kaalplaats 330 JP, Tribal Land west of Zeerust, Oog Van Malmani 333 JP.
Abrupt change in the strike-direction of a dyke, because the dyke follows a different fracture-trace.	Naauwpoort 328 JP(extreme eastern portion), Trekdrift 360 JP(influence of orthogonal jointing), Elizabeth 357 JP, Kaalbult 349 JP, Christinas Home (Katdoornpan) 350 JP, Vlakplaats 335 JP.
Refraction of a dyke at the boundary between two different rock-types.	Klippan 81 JO (contact between Ventersdorp Lava and Black Reef Quartzite), Stinkhoutboom 68 JO (refraction by quartz vein in dolomite), Olyven Bult 61 JO (southern corner, contact between chert and dolomite), Tribal Land west of Zeerust (relationships similar to those that exist on Klippan and Olyven Bult).
Forking of dykes on account of intrusion in a zone of horse-tail fracturing.	Rietpoort 69 JO.
Radial convergence of dykes.	Naauwpoort 328 JP, Doornkop 363 JP. A major focal-point exists in the general area of Schilpad Verdriet 10 IP.
Clustering of dykes.	De Putten 56 JO.
Calcrete ridge coincides with a buried decomposed dyke.	Bultfontein 92 JO.
Dyke faulted by faults which trend north-north-west.	Roodekrans 315 JP, Rietspruit 318 JP, Rietspruit 318 JP (north), Draaifontein 314 JP, Christinas Home (Katdoornpan) 350 JP, Rhenosterkop 364 JP, Strydfontein 316 JP (a spring exists at the point where the dyke is faulted), Olyven Bult 61 JO.
Dyke cuts quartz vein which strikes N20°-30°W.	Doornfontein 65 JO, Kafferkraal 66 JO, Stinkhoutboom 68 JO, Christinas Home (Katdoornpan), 350 JP, Duikerfontein 365 JP.
Dyke cuts linear slump-structure ("Trough" in Table 5).	Karee Bosch 329 JP, Doornplaats 340 JP, Naauwpoort 328 JP.
Fault displaces the trace of a linear slump-structure ("Trough" in Table 5).	Mabalanes location (i.e. Rietfontein 453 JP), Rhenosterhoek 343 JP, Naauwpoort 328 JP.

Hammerbeck (1971, pp.2 and 9) makes brief mention of "the diabase dykes" and "a series of diabase dykes", but the source of the identification is not acknowledged. Simpson (personal communication, 1969) referred to three sets of dykes, one of which consists of "pre-Karroo-diabase", and the other two of which were defined as "post-Karroo" - presumably dolerite.

a. Trends of Dykes.- On considering the entire area that is covered by Figs.4a and 4b, by far the most obvious trend that is followed by the intruded dykes is east-north-easterly, with a variability of about 15°. This general direction of strike is expressed so strongly that it was concluded at an early stage of the photogeological study that it must conform with some fundamental tectonic trend. That this tectonic direction is expressed by intruded dykes over a wide region is indicated by an anonymous sketch-map of the entire area of dolomite that exists between Zeerust and Lichtenburg (scale 1:250 000) which was made available by the Geological Survey, and by aeromagnetic data. (See Fig.14). Strong confirmation of the dominance of the east-north-east tectonic direction in the region is provided by Crockett (1971b, pp.232 and 233).

The 15° variation in the direction of strike of local dykes which belong to the overall east-north-east direction is not considered to be important in the context of the regional, east-north-east tectonic trend. However, the deviation of some of the dykes from the average trend may be meaningful in a different, more local, context. For example, concerning the Ottoshoop Dyke and the dyke which crosses the southern part of Doornhoek 305 JP, the tendency to diverge, going eastwards, may reflect splayed fractures that can be related theoretically to the very gentle, convex, flexure which curved the outcrop of the Black Reef quartzite to the east over the entire distance between the northern and southern limits of the mapping (see Fig. 4a). The gentle convex flexure has an easterly-trending axis and the structure has been recognised by Hunter (1974b, Fig.2) to be an antiform, and divergent fracturing is common at the termination of antiformal structures.

Within the dominant set of lineaments which trend east-north-east, the most obvious feature is a set of twin, parallel dykes which are about 4 kilometres apart. They traverse the entire area that was mapped, through the centre, for a distance that exceeds 95 kilometres. It is notable that where this megalineament intersects the Pretoria Series the sediments of the latter rest directly on dolomite and not on the Giant Chert, or the basal Chert Breccia. This relationship implies the existence of a significant relative palaeoelevation of the dolomite at this point, and indicates that the Twin-dyke Lineament may have been associated with preferential, early, structural disturbance, that is, preferential tectonic expression.

After the dominant east-north-east trend, other trends of dykes are less impressive because they are relatively non-repetitive. The Diepkloof trend, roughly N100°E to N130°E, is well-marked by two main *en échelon* lineaments that are about 20 kilometres apart, and are both mapped as dykes; and others farther south which are similar but are much less obvious, for example the *en échelon* dykes on Trekdrift 360 JP.

The most important member of this trend, the Diepkloof Lineament, is continuous across the entire area. It extends for a distance in excess of 100 kilometres from De Putten 56 JO in the north-west, to at least as far as Hartebeesfontein 450 JP in the east, and it is represented by deep valleys for much of its length. The dip of the Pretoria sediments away from the gorge over a distance of many miles, as recorded by Hammerbeck (1971, p.2) was not photogeologically recognised to be a characteristic feature of the lineament. This is possibly a function of the fact that most of the effort was directed at the dolomite terrain during the stereoscopic study of the photographs.

A second main component of the Diepkloof trend extends for about 60 kilometres in an *en échelon* manner from Klippan 81 JO in the west, to Doornkop 363 JP and Kaalbult 349 JP in the south, at which locality it merges with a dyke which strikes N20°W to N25°W. A third member of the Diepkloof trend is situated south of the other lineaments which have the same trend, and it extends across the study-area for more than 60 kilometres, from Benadeplaats 93 JO in the west. In the west it is roughly parallel to the second-mentioned lineament but it converges towards the latter in the neighbourhood of the southern portion of Duikerfontein 365 JP. A general convergence of lineaments is apparent in this area.

The second and third *en échelon* dykes which represent the Diepkloof trend in the dolomite, and the dyke mentioned above, which strikes N20°W to N25°W, are very probably all of the equivalent age and origin. The bulk evidence in the photogeological relationships suggests that they are branches and lateral offshoots from the twin dykes mentioned previously, and from other dykes which correspond with the same dominant regional trend. Examples are found on Doornkop 363 JP where a cluster of dykes gives rise to the dyke mentioned above, namely that which strikes N20°W to N25°W, which in turn forks to provide a left branch that follows the second-mentioned *en échelon* dyke that is aligned on the Diepkloof trend, and a right branch which maintains the original north-north-westerly trend. The left-branch dyke pinches out on Wonderfontein 336 JP although the trace of the fracture is still visible. The en échelon feature is nevertheless continued to the west-north-west by smaller dykes which appear to have issued as offshoots from the twin dykes seen on Strydfontein 326 JP, Kaalplaats 330 JP and Zeekoevallei 83 JO. The dyke which corresponds with the right branch has itself a similar and associative relationship with the twin dykes, as revealed by the photogeological mapping in the northern corner of Doornplaats 340 JP and Kafferskraal 306 JP.

Other north-north-westerly and east-north-easterly directions of ramification of a single phase of intrusion of dykes are seen clearly on Uitvalgrond (Wolwekoppies) 60 JO, west of Zeerust, and on Tribal Land west of Tweefontein 58 JO.

A third but less significant dyke-trend is slightly variable about the north-north-east direction. Within the dolomite region dykes which display this trend are side-branches of the twin dykes. Along strike, in the Pretoria Series, dykes are visible that trend roughly north-east, but their relation to the Diepkloof Lineament is uncertain.

In the literature only Hammerbeck (1971, pp.2 and 19) has paid any attention to the directions that are displayed by the dykes. He recognised three directions of joints which were followed by dykes, namely N15°E to N20°E, N75°E to N85°E, and N150°E to N160°E. These directions, determined in an area smaller than that which was mapped photogeologically, correspond adequately with the directions which are revealed by the photogeology. The second direction that is noted above, corresponds with the major east-north-east tectonic direction that is displayed particularly by the twin dykes. The Diepkloof Lineament was recognised by Hammerbeck (1971, p.2) as a significant structural feature that strikes N100°E to N110°E, but he did not recognise that this lineament is a representative of a trend that is followed by dykes. Simpson (personal communication, 1969) referred imprecisely to sets of dykes that trend roughly "east-west", "north-east", and "north-west". The "east-west" set would correspond with the direction to which the Twin-dyke Lineament is related. The relevance is that Simpson apparently believed that the last-named trend was associated with "pre-Karroo" diabase dykes, and the other two with "post-Karroo" dolerite(?) dykes. The fact is that the associated dykes are commonly continuous in the physical sense. That is, the photogeological evidence suggests that many, perhaps most, of the dykes are obviously related to the same period of intrusion, and that diabase is the dominant rock that composes these dykes.

b. Unusual Basic Intrusions.- In the lower part of the Pretoria Series there exists a series of concordant diabasic sills which have been described adequately by Hall and Humphrey (1910, pp.29 to 30). Not described previously from the area are a number of unusual transgressive to semi-concordant basic intrusive bodies within the sediments of the Pretoria Series in the area east of Kuilfontein 324 JP. These comprise four or five peculiarly shaped, large, discordant intrusive bodies which were noted on the farms Zyferfontein 293 JP, Draaifontein 314 JP, Vergenoegd 289 JP, Rhenosterfontein 313 JP and Grootfontein 319 JP. They are distributed along a northerly-trending zone, about 15 kilometres long, to the north-west of the old lead mines on Rhenosterhoek 343 JP and Bokkraal 344 JP. The most northerly, on Zyferfontein 293 JP, appears, on photogeological evidence only, to be about 3,5 kilometres long and dyke-like in the north-east, and concordant and sill-like in the west. Others are elongated, sausage-shaped, or bent, up to 1,8 kilometres or more in length, apparently completely isolated, and in places they are displaced by faults. In places vertical or steep contacts are in evidence, some of which may be controlled by fractures. At least one, that on Grootfontein 319 JP, appears to have a sill-like offshoot.

The most interesting is the body on Rhenosterfontein 313 JP which is shaped in plan like an angular hoop with points that are almost closed. The contact appears to be vertical and the country-rock (shale) appears to be contorted. The Rhenosterfontein body forms an obvious, roughly lyre-shaped valley, with steep sides up to 400 metres apart that indicate the thickness of the limbs. The southern limb strikes roughly north-east, and it is probably controlled by a fracture. It is about 3,5 kilometres in length. The "hoop" is open to the south-west, and the arch of the hoop is about 2 kilometres long, very gently convex in the plan-view, and it strikes roughly west-north-west. The remaining limb is about 2 kilometres long and strikes approximately north-north-east. A patch of country-rock appears to lie on one of the limbs, and it is possibly a remnant of the roof. Were the ends of the hoop closed the body could be considered reasonably to be an imperfect ring-dyke.

The Rhenosterfontein body is traversed by the Diepkloof Lineament, in the form of a steep-sided, straight, transgressive valley. The relative ages of the lineament (which is here unidentified) and the hoop-shaped intrusive body are unknown. On inspection in the field the igneous rock was noted to be mesocratic with an even, medium-grained texture. It was composed of almost equal proportions of off-white felspar and a dark mineral.

Half a kilometre to the east of the eastern limb of the hoop an area of sediments, approximately one kilometre across, which is intensely jointed, was noted in coincidence with the north-western boundary of Grootfontein 319 JP. It is interesting that the "peculiar circular depression ... which ... occurs in flat lying shale which displays no structural disturbance ...", noted by Hammerbeck (1971, p.8), is situated within the area of intense local fracturing.

Whatever the age and the origin of these unusual basic intrusives, and the circular depression which Hammerbeck obviously thought might represent a pipe, it is significant that the zone straddles the east-north-east-trending Twin-dyke Lineament which has already been suggested, on independent grounds, to reflect preferential tectonic expression.

In recapitulation of the above, the important factors are the following:

(i) The indications that many, perhaps most, of the dykes are continuous physically, and they thus represent a single period of dyke-intrusion.

(ii) It is likely that the overwhelming majority of the recognised dykes are composed of diabase.

(iii) The dominant tectonic direction that is displayed by dykes is roughly east-north-east, and this is part of a tectonic framework that is expressed widely, beyond the boundaries of the study-area. The Twin-dyke Lineament is a main component of the regional east-north-east trend and indirect evidence suggests that this megalineament reflects preferential tectonic and magmatic activity. The first was manifested by positive palaeotopography, and the magmatic activity was expressed by the intrusion of unusual transgressive bodies of basic rock.

3. Linear Slump-structures.

a. General.- In the study-area small grabens, linear soil-filled depressions, and linear slump-structures of all dimensions exist in the dolomite and chert, as well as in the rocks of the Pretoria Series. The fact that their specific existence and nature has not been recorded previously, nor the apparent mineral potential of some, is a reflection on both the applicability of adequate air-photo interpretation, and the difficulty with which these features are recognised in the field. They include effects which are accountable by decomposed dykes, small grabens, and stratigraphic intercalations in the dolomite. They are discussed very briefly, in sequence, below.

(i) Numerous narrow, linear, soil-filled depressions were noted in the area of chert and dolomite, particularly in the region of Oog van Malmani 333 JP, within an approximate radius of 10 kilometres from that farm (see Fig.4a). On the panchromatic photographs these lineaments display dark-grey tones except when they incorporate chert rubble, when the tone is pale, and the texture rough. These lineaments have a length from 1 to 4 kilometres, and a width of a few tens of metres. Some lie on the direct line of prolongation of dykes and are, apparently, merely soil- and rubble-filled depressions which result from the extreme chemical decomposition, and consequent negative weathering, of the dyke. They are unimportant.

(ii) Narrow linear entities, perhaps up to 3 kilometres in length, have been mapped in which the lateral limits are expressed as fractures, between which small strips of chert appear to have been dropped down. They are wider than the features which result from the decomposition and the negative-weathering of dykes, and are considered to represent true, small, grabens. Examples are seen on Zeekoegat 331 JP, and Uitzigt 109 JO. Detailed photogeology, and the mapping of Portion 7 of Rhenosterfontein 304 JP in the field on the original scale of 1:5 000, illustrates the proof of the existence of these grabens. Here the western limit of the klipspar ore that is exposed in the main (kokerman) workings is clearly truncated by a fault which forms one flank of a graben which is about 1,5 kilometres in length, and one hundred metres in width.

(iii) In the extreme south-eastern portion of the mapped area, on Vlaknek 472 JP, Kruidfontein 470 JP and Rietpan 479 JP, vague, linear tonal units bear a partial resemblance to some of the photographic features that are described above, but they were not noted to preserve outliers of chert (or other strata) in subsided zones. It is postulated that these linear entities, which are dominantly tonal, are due to narrow, shaly intercalations within the northwards-inclined dolomite. They are expressed photographically, notwithstanding the soil-cover.

The three classes described above are not to be confused with the very common sink-holes and dolines of all dimensions which are distributed erratically, and dot the map (Figs. 4a and 4b). They are also totally different from a major and important fourth class of linear slump-structures which is described below. The latter are hereinafter called "troughs" according to similar American usage of the word. They warrant full appreciation, and the purpose in summarising the first three classes is to prove to the reader that the troughs are unique features which have not been misconstrued during photogeological mapping. (They should not be confused with the Selati Trough, mentioned on page 78, which is not related to these slump-features).

b. The Strydfontein, Doornplaats, Diepholte and Mabaalstad Troughs.- During the photogeological reconnaissance mapping of the central, highly mineralised portion of the initial area of study (see Fig.2) a long, narrow, rectilinear feature was recognised. It was expressed tonally, texturally and geomorphically. It was recognised as a single, major, photogeological unit for a distance in excess of 25 kilometres, from Welgedacht 103 JP in the west-south-west to Witrand 325 JP in the east-north-east. At that time (1969) it was described as a "down-faulted trough of brecciated chert and occasionally some overlying Pretoria shales" (see Fig.3, in pocket). The feature was expressed clearly on the photographs that were utilised during the reconnaissance, which were on the scale of 1:50 000. Initially its nature was not understood. Subsequent mapping of the larger area which corresponds to that of Figures 4a and 4b, revealed three other analogous structures which extend along an approximate east-west zone through the central latitude of the mapped area, east of the trough which was recognised first. The detailed photogeology, which made use of panchromatic ("black and white") aerial photographs on the scale of 1:20 000, when viewed in relation to the earlier reconnaissance mapping, portrayed clearly the relative advantages and disadvantages of the two scales of photography in aiding recognition of the troughs. It is evident that they are much more easily noticed, and recognised as unified structural features, on the small-scale photographs. It requires detailed and diligent annotation and appraisal of the stereoscopic model, and thereafter compilation of the photogeological detail from a number of relevant photographs before these features reveal their unity, nature and identity to an investigator who relies solely on moderately large-scale photographs, for example those on the scale of 1:20 000.

The westermost trough is the longest, and it is also the one that is defined most clearly. Because only the larger-scale of photograph was available in the relevant areas, the nature of the three eastern troughs is suspect on casual photo-interpretation. It is evident that Hammerbeck (1971) was attracted most by the linear magnetic anomalies with which the troughs are associated. He derived little benefit from aerial photographs, possibly owing to a lack of appreciation of the principles of photogeology (Appendix C), with the consequence of immature stereoscopic study, and incomplete annotation and interpretation of the images.

Regarding the longest and westernmost trough, Hammerbeck recorded that "the feature producing this anomaly is hardly recognisable on air photographs" (Hammerbeck, 1971, p.9). Figure 13, which shows the linear structure clearly, proves that this is not so. The figure reproduces two of a set of 23 photomosaics, originally on the scale of 1:20 000, which were produced to provide synoptic coverage of the entire area of study. The same benefit and result in regard to synoptic coverage is obtained from small-scale aerial photographs, which explains why the trough was so readily recognised during the early independent photogeological reconnaissance on the scale of 1:50 000. Application and mosaicing of the photographs on the scale of 1:20 000 allowed both the detailed stereoscopic appraisal of the geology as well as the vital regional overview. This is an accepted principle in practical photogeological mapping and is highly relevant when it is appreciated that when the principle is applied in practice, important features may be recognised which are not easily visible in the field - like the troughs. To the investigator in the field the expression of the troughs is vague, inconsistent, discontinuous and subtle, and spread over considerable distances - a sufficiently valid reason for all earlier investigators never to have recorded, or even suspected, their existence.

The essential features of the distribution, size and nature of the four recognised trough-structures are summarised in Table 5, for the purpose of which the structures have been named from west to east as follows:-

(i) Strydfontein Trough
(ii) Doornplaats Trough
(iii) Diepholte Trough
(iv) Mabaalstad Trough

It is apparent that the troughs possess basic, overlapping similarities and are unique within the area, thus leading to the conclusion that they are related to the same causative process(es). Taking the Strydfontein Trough as the type-example, with modification where necessary on account of the three remaining troughs, the characteristic features are those that follow.

Each trough consists of a linear combination of syncline and graben, with an inconsistent variation in the relative importance, and the degree, of synclinal-sag and down-faulting along the length of the structure. In places the trough is flanked on one or both sides by fracture-traces which apparently represent faults which are nearly vertical. In places none of the flank-fractures is visible, and the slumping was obviously accommodated by synclinal

Fig.13. Mosaic of Forty-eight Aerial Photographs showing Major Linear Slump-structures ("Troughs") in the Dolomite Series south of Zeerust.

Note 1. The figure corresponds with Sheets 10 and 11 of a set of 23 mosaics which cover the area that was mapped. See key diagram in Fig.4b (in pocket).

2. For orientation see also Fig.16 in relation to the farm "WITRAND 325 JP".

3. The scale of the original photographs and mosaics was 1:20 000. Fig.13 is on the same scale as Figs.4a and 4b, that is, approximately 1:50 000.

TABLE 5.- Major Linear Slump-structures in the Zeerust Area ("Troughs").

Name	Farms	Country-rock	Approximate (a) Length (b) Width (Kilometres)	Average strike	Linearity and Photogeological Expression	Remarks
1. Strydfontein Trough	Welgedacht 103 JO Kareebosch 90 JO Kaalplaats 330 JP Karee Bosch 329 JP Naauwpoort 328 JP Strydfontein 326 JP Witrand 325 JP	Dolomite and overlying Giant Chert	(a) 25 (b) 0,2-0,5	N80°E	A narrow, rectilinear zone of fracturing, minor down-faulting, linear soil-filled depressions and elongate remnants and outliers of chert (Giant Chert). A linearly disposed synclinal outlier of sediments belonging to the Pretoria Group is found at the eastern extremity of the trough which has, over-all, a unified linear air-photo expression. Fractures, which flank the trough and are parallel to it, are obvious in some places.	The trough is situated centrally between the two long dykes which together constitute the Twin-dyke Lineament and it is almost parallel to the trend of this major lineament. It is cut at oblique and acute angles by intrusive dykes of a younger age and near the mid-portion by a small fault which trends north-north-west. See Fig. 4a.
2. Doornplaats Trough	Doornplaats 340 JP Bronkhorstfontein 312 JP Kalkfontein 341 JP	Dolomite and overlying Giant Chert	(a) 13 (b) Average 0,3	N100°E	A relatively non-rectilinear but unified zone, expressed largely by continuous photo-tones and a linear, soil-filled, shallow depression. The linear depression contains tilted outliers of sediments belonging to the Pretoria Series, as well as three or four large, elongate, down-slumped outliers of Giant Chert. The parallel flank-fractures are less obvious than in 1 above.	For half of its length the trough is sub-parallel to the general trend of the contact between dolomite and the Giant Chert. It is intersected at an oblique angle by a major dyke which strikes from roughly north-north-west to south-south-east and which forks adjacent to the southern flank of the slump-structure. See Fig. 4b.
3. Diepholte Trough	Diepholte 342 JP Doornplaat 346 JP Rhenosterhoek 343 JP	Dolomite and chert (Giant Chert?)	(a) Minimum 6 Possibly 12 (b) 0,4	N95°E	An elongate, soil-filled depression 6 kilometres long, giving way to a conterminous fault with a limited down-throw on the north side. The fault extends eastwards for more than 6 km to beyond the Rhenosterhoek Fault-zone. Contorted chert (Giant Chert?) is found alongside the depression, in which sediments belonging to the Pretoria Series are found in the form of scattered outliers. The conterminous fault is displaced 0,4 km by the Rhenosterhoek Fault.	Except for the western 6 kilometres this slump-structure is the least prominent of the four troughs.
4. Mabaalstad Trough	Brakkuil 449 JP Rietfontein 453 JP Zuurfontein 454 JP (Doornpoort 455 JP) (Mabalane's Location)	Shale and quartzite of the Pretoria Series, and an intercalated basic sill	(a) 9-12 km within the area mapped. Extends eastwards from the limit of mapping for more than 14 kilometres. (b) 0,4	N85°E	An obvious, shallow, soil-filled depression within sediments belonging to the Pretoria Series. The slump-structure is clearly seen as a single entity by its geomorphic continuity and photo-tones.	Faults and fractures were not observed to define the flanks of the linear tonal unit. Slumping may have been accomodated mainly by warping. The trough appears to transgress a basic sill and is clearly displaced for a distance of 200 to 300 metres by a fault which strikes north-south. See Fig.4 b .


Zeerust
TTOSHOOP
Strydfontein
Trough
WITRAND 325 JP
Doornplaats
Trough
Lichtenburg
SHEET INDEX
SHEET INDEX
TN

or monoclinal flexuring of the affected strata. Therefore, along its length of strike, the graben grades locally into narrow "sag-synclines". The topographic expression of the troughs is suppressed, and in the field it is inconspicuous. Positive expression is limited to strips of included chert, for example, on Strydfontein 326 JP, but even a relative relief of three metres is unusual. Commonly, portions of the troughs are represented by smooth, linear, soil-filled depressions. The downward displacement of strata, whether by faulting or by sagging, is inconsiderable - at the most 10 to 15 metres (estimate), and it is generally considerably less. In places the chert within and outside the structure is almost at the same elevation, and this indicates that the displacement was almost negligible. In these instances the continuity of the structure is proved by the linearity of the outlier of chert, and by its parallel sides. Elsewhere there is no apparent displacement downwards, nor the existence of linear strips of chert within the zone of the trough. In these localities, for example, on Naauwpoort 328 JP, obvious parallel fractures in flat ground provide a basis for the recognition of the trough.

The host-strata on either side of the trough are always nearly horizontal, and minor disturbance of the down-slumped rocks is occasionally visible where the latter show anomalous local dips under the stereoscope. Beds of shale and thin sandstone, which obviously belong to the Pretoria Series, in places occur as isolated down-slumped outliers up to 1,5 kilometres in length, and they are inclined rather than contorted. Small lineaments within the slumped ground indicate a degree of physical breaking, and even minor faulting, of the included sediments.

Displacement of the troughs by small cross-faults is evident in the Mabaalstad Trough, the Diepholte Trough and, possibly, in the Strydfontein Trough. On Rietfontein 453 JP, 1 kilometre west of Mabaalstad (Fig. 4b), the first-named trough, as portrayed by dark tones and negative relief within Pretoria sediments, is displaced a few tens of metres, in a left-lateral sense, by a clear-cut lineament which is about 2 kilometres long. On Rhenosterhoek 343 JP, the Rhenosterhoek Fault apparently displaces the Diepholte Trough about 250 metres to the south on its eastern side, and on Naauwpoort 328 JP a strong fracture transects the Strydfontein Trough, although the evidence for displacement is ambiguous. The recognised faults all trend in the northerly to north-north-westerly direction and this fact is relevant to the strike of a major tectonic direction which is noted later. The relationship between certain dykes and the troughs has been specified in Table 4 where evidence is presented which proves oblique and acute cross-cutting intrusion of the Strydfontein and

Doornplaats troughs by dykes. The dykes belong to one period of intrusion so the troughs were formed prior to this period.

The positive aeromagnetic expression of the individual troughs is very marked (see Hammerbeck, 1971, p.9). Magnetic data which have recently become available (see Fig.14) suggest, if not prove, that the four troughs described are actually en échelon representatives of a much larger feature which is expressed as a wavy east-west-trending magnetic lineament for a distance that exceeds 200 kilometres. It extends for a long distance beyond the eastern limit of the photogeological map, and it actually extends westwards from the recognised western extremity of the Strydfontein Trough into the Ventersdorp lavas at Buhrmannsdrif on the western extremity of the map.

As far as is known, the original photogeological recognition of the troughs (Wilson, 1969b) constitutes a unique record of these features in South Africa and no comparative information is available from the Republic. McKnight and Fischer (1970), and Brockie, Hare and Dingess (1968) have, however, described identical structures in the very important Tri-State lead-zinc mining-district of Kansas, Oklahoma and Missouri, and similar slump-structures have been described from the fluor-spar mining areas in Illinois and Kentucky. (Grogan, 1949; and Grogan and Bradbury, 1968). In the former region the Miami Trough and the Seneca Graben are exact analogues of the individual troughs near Zeerust. In the Illinois-Kentucky region the slump-structures are shorter than those in the dolomite near Zeerust, but they are comparable structurally.

A brief independent appraisal of the troughs in the Western Transvaal leads to the conclusion they must have been formed by slumping, which almost certainly presumes underlying solution of the carbonate strata. The information presented by McKnight and Fischer (1970) is based on over 60 years of underground mining, and on exploration-drilling in and around the troughs, and it fully confirms this supposition. In addition, proof is provided of the possible origin of these troughs in pronounced "tectonic breaks" in the basement, which have been accentuated in the overlying carbonate rocks as a result of solution and down-slumping of the superimposed strata (McKnight and Fischer, 1970. p.2 and pp.72 to 75).

Hammerbeck (1971, p.9) postulated that the magnetic anomalies which correspond with the recognised troughs were due to en échelon emplacement (in the dolomite?) of some kind of intrusion. Because intrusions, for example, dykes, have been proved by mining operations, and by drilling, not to exist in the post-Basement strata of the Picher portion of the Tri-State mining area, below the

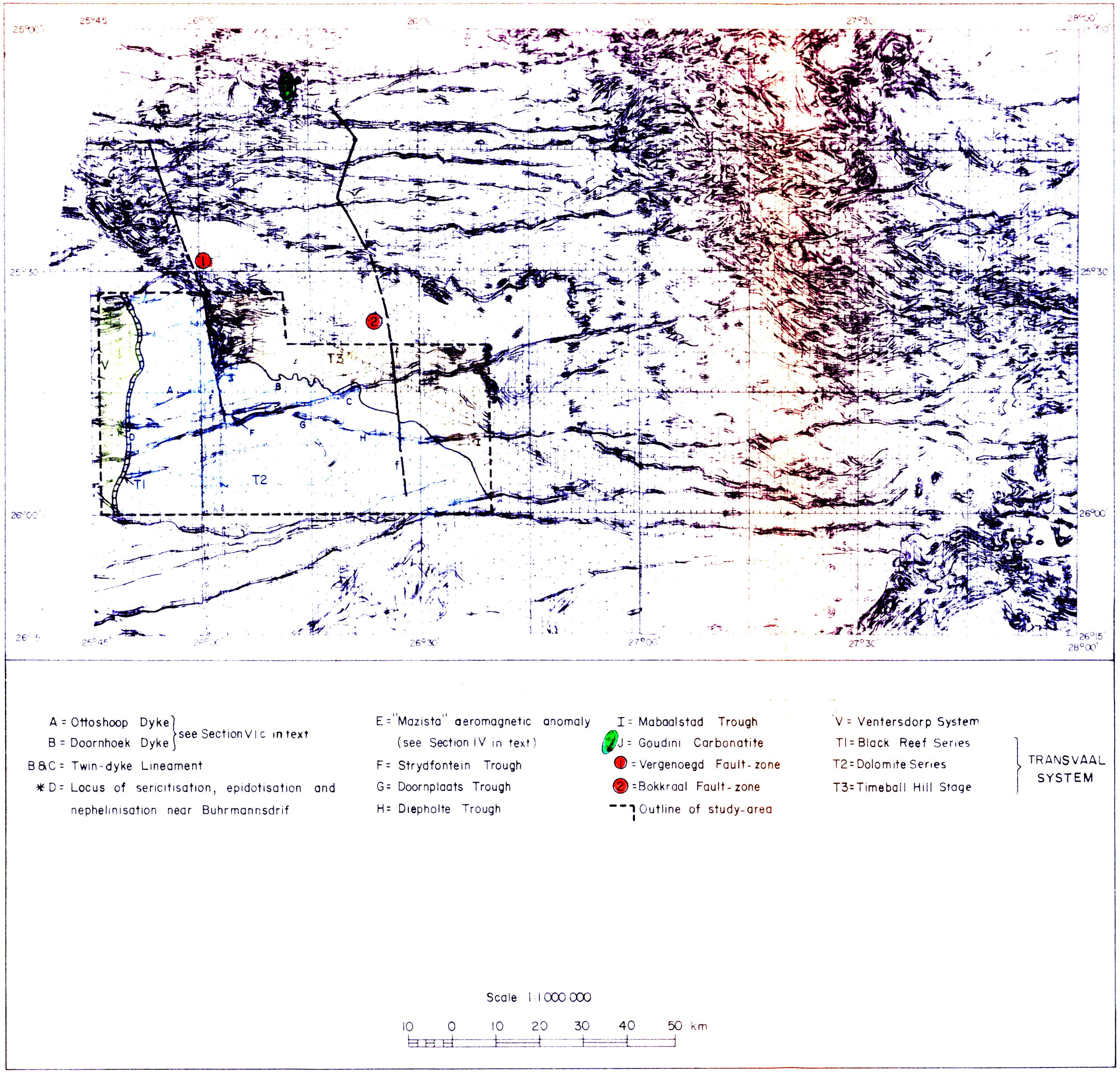


Fig. 14 AEROMAGNETIC CONTOURS, ZEERUST-LICHTENBURG-BRITS AREA, IN RELATION TO SELECTED PHOTOGEOLOGICAL DATA

Official information from the 1:250 000 aeromagnetic map "Lichtenberg – Zeerust – Brits", reproduced in accordance with Government Printer's Copyright Authority No 5478, dated 28-8-1975

Miami and the Seneca troughs, and because the sag-synclines are not related to dykes (or other intrusions) in the Illinois-Kentucky region, it is considered that the troughs in the Western Transvaal will, very likely, prove to be unrelated to dykes in the dolomite. Information is not readily available in regard to the magnetic expression of the Miami and the Seneca troughs. If it were, it would be possible to be more specific regarding the probability, or otherwise, that dykes in the basement, or in the basement and the dolomite, are related to the formation of the troughs in the Zeerust region. At the present stage there is no concrete justification for describing the troughs in relation to dykes.

It is notable that the magnetic expression of the zone of trough-structures is constant and continuous whereas the expression on the surface is inconsistent and discontinuous. This fact implies that the constancy and continuity exists only at depth, below the dolomite. The relative antiquity of the troughs, when they are related to cross-cutting faults and dykes, has already been indicated. Other factors which confirm the supposition that the troughs represent early-formed surface manifestations of even earlier tectonic breaks <u>in the basement</u> are the following.

1. The magnetic anomaly which coincides with the troughs is more than 200 kilometres in length, and this implies a very major discontinuity (Fig.14). It is unlikely that a structure of this nature would have developed in isolation and in a way that its manifestation on the surface would be discontinuous and relatively suppressed, had it been generated at a time which post-dated the lithification of the Dolomite Series (and lithification of the sediments which comprise the Pretoria Series).

2. Three of the four troughs in the dolomite are unrelated in their general and individual trends to any of the major lineament-directions which were recognised in the strata of the Transvaal System during photogeological mapping. This fact is taken to indicate that the major trends of lineaments in the dolomite were incapable of exerting an influence on the strikes of the troughs, and the indication tends to confirm that the "roots" of the troughs are older than the dolomite. In the single instance where a trough is parallel to a major set of photogeological lineaments (namely, the coincidence of the Strydfontein Trough with the axis of the Twin-dyke Lineament) the corollary is that the latter lineament reflects the direction of the very early tectonic

> lineament that is presumed to exist in the basement of this locality. This particular association is collaborative bilaterally, since it has been suggested already that the Twin-dyke Lineament represents a more fundamental tectonic "line" than any other which is represented by other dykes which are roughly parallel to the dominant east-north-east trend.

The significance of the troughs in the Zeerust region, as far as the economic geology of lead, zinc and fluor-spar is concerned, is direct, and is on two accounts. Firstly in that " ... a few ore deposits in the Picher field were obviously localised along the Miami trough". (McKnight and Fischer, 1970, p.136) and secondly, in that similar structures are accompaniments to fluor-spar ore in the Illinois-Kentucky region. (Indirectly they provide a major link in the pattern of similarity of the Zeerust lead-zinc region to that of the Picher area of the Tri-State region. This similarity will not be expanded apart from pointing out the following: both are within thick successions of carbonate-rocks; the latter are virtually horizontal; each is situated on a "broad low structural dome environment of relatively mild structural deformation characteristic of the craton"; each is within the sphere of influence of an alkaline province, yet there is no direct link with any particular igneous body; both areas are characterised by "slump-pipes" or "circles"; and both are of limited areal extent).

The direct observation of the localisation of ores of lead and zinc by the Miami Trough is interesting, and the association is obviously of potential application to a search for ore in the Zeerust region, if it is accepted that the troughs formed at a very early stage, prior to the episode of epigenetic lead and zinc (and fluor-spar) mineralisation. This knowledge may perhaps allow some exploration for ore bodies of lead and zinc in the dolomite in the Zeerust area to proceed with better effect than has been the case in the past. For example, Hammerbeck's regional geochemical survey revealed an area of peak concentration of zinc, lead, and copper on the boundary between Strydfontein 326 JP and Witrand 325 JP, where zinc, lead, and copper values over 1000 ppm and up to 600 ppm and 400 ppm, respectively, were confined on a broad geochemical plateau (Hammerbeck, 1971, Fig.4, Plates 1a, 2a and 3a). The plateau is about 2 kilometres across in a north-south direction and, what is interesting, it actually straddles the eastern portion of what has been described as the Strydfontein Trough. The coincidence of anomalous geochemistry and the trough (which by comparison with identical structures in the United States has a good possibility of being associated with lead- and zinc-sulphides in economic concentrations) would obviously have drawn attention to the trough itself during follow-up exploration, had its identity and nature been known, or even suspected, at the time.

That this was not the case is proved by diamond-drilling that was executed by ISCOR on the strength of Hammerbeck's results, probably in 1971. ISCOR (personal communication, Dr. A.L. Zietsman, 1972) drilled five vertical exploratory holes, each to a depth of approximately 62 metres, within an area 150 metres by 150 metres which corresponds with the area of the strongest geochemical response on Witrand 325 JP. The area in which drilling was done is 450 metres south of the trough, and immediately east of the common boundary between Strydfontein 326 JP and Witrand 325 JP. Insignificant specks of sphalerite were noted in some of the core. On chemical analysis the highest zinc values were barely 1 per cent over short intervals, and the values of lead and copper were negligible. The existence of the trough was not appreciated and the area was consequently disregarded.

To Hammerbeck's credit must be acknowledged his recommendation (1971, p.10) that, in drilling to test the geochemical base-metal anomaly under discussion, " ... one inclined hole will be needed to examine the magnetic anomaly ... to test its possible relation to mineralisation in this area". This was not done.

As regards fluor-spar, comparative information from the United States also suggests that the recognised trough-structures possess a significant potential. Grogan (1949), and Grogan and Bradbury (1967, 1968) have noted the correspondence of what have been called "sag-synclines" , with zones of ore-grade fluor-spar in the Illinois-Kentucky region. The ore, although it has the form of a "bedding-replacement deposit", is disposed linearly along lines of fractures, and zones of ore coincide with slump-structures or elongate depression in the carbonate-strata.

The similarity of the over-all geological environment in the Zeerust area, when compared with the Tri-State lead- and zinc-mining area, has been noted in passing. Likewise, the geological environment of the mineralised region near Zeerust also bears and undeniable similarity to many of the features which are present in the fluor-spar mining region in Illinois and Kentucky. (See Grogan and Bradbury, 1968). Therefore it is quite permissible to assume that the trough-structures south of Zeerust may be accompanied in places by (epigenetic) fluor-spar, galena, and zinc-blende.

The troughs should be investigated very thoroughly. As far as is known, even at the present time (1975), not one exploratory drill-hole has probed the mineral potential of any of these structures, nor have any been drilled to test the source of the magnetic anomaly.

The rewards which will attend a proper investigation of the troughs could be very high.

4. Joints and Fractures

From the information summarised in Table 4 it is clear that the intruded dykes followed pre-existing planes of weakness, which represent both joints and large fractures. Many examples are available of dykes which become thinner and thinner when traced along the strike, eventually to peter out altogether, although the trace is continued by a fracture. The deflection of dykes along fracture-traces and large joints is so common that it is inconceivable that the intrusive igneous material did not follow pre-existing fractures. Likewise, the refraction of a dyke where it crosses a quartz vein indicates the relative antiquity of both the fracturing and the later silicification: in other cases the actual termination of the vein on the contact of the dyke can be seen. The same relative age can be seen on occasion where a dyke passes through a slump-structure.

It is clear from the aforegoing that the trends that have been described already in relation to dykes, also correspond directly with most of the recognised traces of joints and fractures. In the case of the strong, east-north-easterly trend of the Twin-dyke Lineament, the correspondence between the direction of strike of dykes and fractures is obvious, as shown by a multitude of fracture-traces of a short to medium length, particularly west and south-west of Zeerust where the dolomite is exposed reasonably well. The relatively uncommon dyke-trend, N20^{O}W to N25^{O}W, mentioned before (p.45), is correspondingly subordinate in terms of joints and fractures.

The north-north-westerly trend of fractures is so strong that it is at first glance surprising that dykes and offshoots in this general direction are rare. The answer lies in the extreme and general silicification of this class of fracture, for it is readily apparent that by the time the dykes were intruded these fractures were already "tight". This implies that the family of fractures which trends roughly north-north-west are relatively old, and silicification, which in places resulted in the formation of very large veins of quartz in the dolomite, also took place at a relatively very early stage. The veins include the very large, long, and auriferous quartz veins which were mined actively at the Malmani Gold Field around Ottoshoop between about 1875 and about 1928. They have been described adequately by Humphrey (1908, pp.157-160).

In a combined summary of the most important trends that are displayed by both fractures (including joints) and dykes, it is obvious that general east-north-easterly and north-north-westerly trends are paramount. Both are clearly and strongly portrayed by fracture-traces, but only the east-north-easterly direction is strongly and repeatedly portrayed in the pattern of the intruded dykes. Other directions of lineaments, whether they are represented by fracture-traces or dykes, or both, are not nearly so strongly repetitive as the two main trends. The east-north-east direction has already been associated with a regional tectonic framework; likewise, it is concluded that the strength and the regularity of the north-north-west trend must be a result of its control by regional tectonic stresses.

5. Major Faults

The photogeological recognition of two major zones of faulting which were not recognised by all previous investigators, who lacked the overview afforded by aerial photography, is testimony to the value of adequate photogeological appraisal, even in areas of long-sustained exploration activity and mapping in the field. These two major fault-zones have a fundamental impact on the results of the study. Prior to the independent phase of photogeological mapping that was conducted by the writer in 1969 they were unknown, although in one case a fault has been recognised since (Hammerbeck, 1971, p.3), and in the other, faulting was the subject of speculation, but no fault was ever traced,or proved to exist.

For the purpose of the original description (Wilson, 1969b) the two major zones of faulting were named the "Bokkraal Fault-zone" and the "Vergenoegd Fault-zone". The first-named is the easternmost of the two, whereas the Vergenoegd Fault-zone is situated in the western half of the mapped area, about 10 kilometres west of Zeerust (See Figs.4a and 4b, in pocket).

a. The Bokkraal Fault-zone.- This photogeological feature extends right across the eastern part of the mapped area in the approximate north-north-west direction, from beyond Vergenoegd 289 JP in the north to beyond Doornkop 372 JP in the south. The lineaments which constitute the zone are discontinuous but obvious, particularly in the Pretoria Series where they correspond with well-marked valleys. On entering the dolomite terrain their geomorphic expression is all but lost, and their recognition depends on shadowy lineaments which are expressed tonally in the chert rubble and in the dolomite.

Within a broad zone in the sediments of the Pretoria Series a number of strong lineaments, some of which are obviously faults as evidenced by the displacement of dykes, tend to identify themselves with the Bokkraal Fault-zone. These faults and fractures also strike north-north-west, and they constitute a zone that is about 15 kilometres wide. On its prolongation southwards, and on its projection in to the dolomite country, the photogeological expression of the zone, as a whole, is not marked, and it is apparent that the strongest lineaments are confined to a more-or-less centrally-situated zone up to 4 kilometres wide. For the present purposes of definition this narrow central zone of faults and fractures corresponds to the Bokkraal Fault-zone. In places the Bokkraal Fault-zone is represented by a number of close-spaced lineaments, within an even narrower zone, perhaps only 1 to 1,5 kilometres in width, in which only one lineament displays obvious evidence, in the plan-view, of fault-displacement. In other places, for example, on Bronkhorstfontein 292 JP, the zone of displacement is apparently condensed to a single fault, which, nevertheless, is situated in line with the central zone which has a maximum width of 1,5 kilometres, as mentioned above.

There is a tendency for some of the related fractures and faults to splay from the central zone, for example, on Rietspruit 318 JP and Bokkraal 344 JP; and on Boschkop 363 JP and Suikerbosch 369 JP.

On diligent study of the photographs the interrelationships of the linear fault-zone, the individual lineaments, the dykes, and the sedimentary formations - all in a three-dimensional, geomorphological context - is clear. Considering the plan-view, on the eastern side of the fault-zone there has been a marked displacement of the lower contact of the sediments of the Pretoria Series southwards. In the plan the displacement is about 4 kilometres. This is five or six times greater than the observed maximum displacement of dykes which are cut by the fault-zone, for example on Bronkhorstfontein 292 JP, Roodekrans 315 JP, Rietspruit 318 JP; and perhaps Boschkop 368 JP, and Speekhoutboom 371 JP. As the dykes are vertical, as shown by their rectilinear, undeviating strikes, and because the base of the Pretoria Series is inclined gently, it is possible to reconcile the discrepancy in the apparent displacement (in the plan-view) by invoking dominantly vertical movement across the zone of faulting. This conclusion would be substantiated by the otherwise anomalous fact that strong lineaments which are parallel to known faults, in the plan-view seem to hardly displace the vertical dykes through which they pass. This relationship is to be seen on Draaifontein 314 JP and Grootfontein 319 JP.

An alternative solution of the relationships would be the acceptance of a major displacement of the Pretoria Series southwards, for the distance mentioned, with minor rejuvenation of the movement after the dykes had intruded the sediments. However, the relatively braided pattern, the passive bifurcation, and the exchange of displacement between individual megafractures, is considered to favour vertical movement rather than the intense shearing that would otherwise be necessary to provide an explanation for the right-lateral displacement.

It is relevant that Willemse and others (1944, pp.25, 28) noted that "the main occurrence [of ore] on Rhenosterhoek is on the eastern side of a prominent, almost N-S Valley" and that on Bokkraal 344 JP "the lead ore is found at two localities ... situated east and west respectively of a prominent valley running in a NNW-SSE direction". Faulting was not suggested and was apparently not suspected.

More recently, Hammerbeck (1971, p.9) recognised "... a prominent fault striking N10^{o}W through the eastern portions of Rietspruit and Rhenosterhoek ...". He noted that the fault coincides with a valley and he remarked (1971, p.3) " ... it is noteworthy that the old lead mine on Rhenosterhoek 343 JP is situated on the eastern flank of this valley". Hammerbeck (1971, p.9) referred to the structure as the "Rhenosterhoek fault zone" and he noted that on its eastern flank the Pretoria Series seemed to have been displaced southwards for about 1,5 kilometres. He did not recognise that both the "Rhenosterhoek fault zone" and the displacement of 1,5 kilometres (when they are viewed in plan) are part of a much more significant zone of faulting which is up to 4 kilometres wide, and which is responsible for more than thrice the displacement (in plan) that he observed. Nor was it appreciated that the central zone, in turn, is part of a broader zone of fracturing and faulting. Although Hammerbeck presented the results of "a photogeological interpretation" beyond the fault which he recognised on Rhenosterhoek 343 JP, his mapping and description indicate that he did not appreciate the structural control of the Bokkraal Valley and he was thus not in a position to understand the close relationship that exists between the galena deposits and the major Bokkraal Fault-zone.

b. The Vergenoegd Fault-zone.- Like the Bokkraal Fault-zone, the Vergenoegd Fault-zone extends into the mapped area from beyond the northern limit of mapping. Unlike the Bokkraal Fault-zone, the Vergenoegd Fault-zone is not clearly visible in the form of lineaments in the dolomite, after emerging from the Pretoria Series.

The Vergenoegd Fault-zone, as mapped, extends from Klaarstroom 237 JP in the north, southwards through the farms Vergenoegd 274 JP, Uitvlugt 275 JP, Paardenvallei 67 JO, Weltevreden 278 JP, Zendelingspost 300 JP, to Buffelshoek 301 JP. It consists of two main faults which trend north-north-west. They are related in a pattern that would be called en échelon if it was expressed over a longer distance. The northernmost of the two faults is also the westernmost of the pair, and it extends to the south as far as Paardenvallei 67 JO, a mapped distance of about 6 kilometres. The southern member, which represents the Vergenoegd Fault-zone from Weltevreden 278 JP southwards for a distance of 12 kilometres, is about 3 to 4 kilometres east of the termination of the northern lineament on Paarenvallei 67 JP. There is a direct linkage between the two by a short fault on Paardenvallei 67 JP. The average over-all strike within the mapped area is about N10°W.

Detailed photogeological mapping produced no real evidence (in terms of lineaments) that supports the prolongation of the Vergenoegd Fault-zone southwards into the dolomite terrain. (See Figs.3 and 4a).

Where it is expressed obviously in the form of photogeological lineaments, the Vergenoegd Fault-zone has a downthrow of an unknown amount on its eastern side. Along much of its length of strike the displacement has resulted in the juxtaposition of Giant Chert and Timeball Hill shale. South-west of Zeerust the displacement appears to be greater than that which is evident to the south-south-west of the town. For example, on Vergenoegd 274 JP, dolomite and terrigenous sediments oppose each other across the plane of the fault, whereas on Zendelingspost 300 JP chert and Timeball Hill sediments, and then chert and chert, become opposed as one proceeds southwards. A large fault has been mapped by the Geological Survey in the Pretoria Series about 20 kilometres north-north-west of Zeerust and it is shown on the current geological map of the Republic. (Scale:- 1:1 000 000). This fault strikes in a north-north-westerly direction and on its prolongation about 20 kilometres to the south-south-east it coincides exactly with the Vergenoegd Fault-zone, as mapped (See Figs.5 and 14). The reasonable conclusion is that the throw on this major fault decreases towards the south and, as represented by the Vergenoegd Fault-zone, the fault seems to "die out" on entering the dolomite.

In the plan-view, the apparent displacement of the Pretoria sediments towards the south on the eastern side of the Vergenoegd Fault-zone, corresponds with the situation that exists at the Bokkraal Fault-zone. The Pretoria sediments east of the plane of the Vergenoegd Fault have a general shallow dip towards the east and the north, a factor that was taken into account in concluding, as was done in regard to the Bokkraal Fault-zone, that the predominant movement was vertical.

In the dolomite south of the Vergenoegd Fault-zone the lack of evidence for the displacement of strata along (and by) lineaments is problematical at first sight - particularly when both the lineaments and the displacement are obvious farther north. On deeper consideration it becomes apparent that the causes can be twofold, as suggested by Cousins (1962), and as discussed by Wulff (1963).

In the evaluation of faulting in the Pretoria Series at the Western Areas Gold-mine (170 kilometres to the south-east of Zeerust) Cousins (1962) concluded that "slump faulting" was the probable cause. He reasoned that " ... the faulting must be due to subsidence of the Pretoria sediments into the dolomite, whether due to plasticity in this formation or to the removal by solution of the carbonate rocks". He favoured the solution hypothesis as the only cause.

Cousins projected his conclusion into the area north of the Pilanesberg, to which Wulff took exception, and pointed out that the supposed "slump faulting" in the area is " ... so regular in orientation that a tectonic origin is more probable than one by slumping into solution cavities". Wulff (1963, p.64) considered it more likely that these faults, which are dip-faults, are due to an adjustment under regional stress in which the Pretoria beds have yielded as competent formations "floating" upon a mass of incompetent dolomite. He observed that the forces involved would be dissipated in the distortion of the dolomite, and the influence of the fault would, in effect, die out progressively on entering the dolomite from above, and would leave the lower part of the Dolomite Series and the Black Reef Series undisturbed on their " ... firm foundation of older rocks".

Cousins' Figure 2 reveals his clear understanding that the gravity-faults which displace the Pretoria Series die out rapidly in the upper part of the dolomite. Cousins' preference for the solution mechanism was prompted by the recognition of a thick bed of chert breccia at the top of the dolomite that, he considered, was a residual product of the solution of the carbonate rocks. In fact this breccia probably corresponds with the Chert Breccia, and this means that it is essentially a sedimentary bed. It is most likely that "slump faulting" that was induced by solution of the dolomite is not the cause of the Vergenoegd Fault-zone, and by analogy, the same view is held for the Bokkraal Fault-zone. The faults are therefore vertical tectonic features, in which distortion in the dolomite is a direct function of the manner and the nature of its disruption. The general conclusion is also confirmed by Crockett (1971b, pp.220, 221).

The fact that both of the major faults enter the Dolomite Series from above explains the existence of fracture-traces on the line of extension of the Bokkraal Fault-zone in the dolomite terrain, whereas similar traces are not seen in the dolomite south of the Vergenoegd Fault-zone. The explanation is that south of the Bokkraal Fault-zone the erosion-surface on which the sediments of the Pretoria Series were deposited is preserved: that is, the upper part of the dolomite that is just below the contact is still intact, and the fractured and contorted dolomite which existed just below the (faulted) Pretoria Series has been preserved from erosion. In the Vergenoegd Fault-zone, however, the displacement is minimal and the fracture-zone did not penetrate very far into the incompetent dolomite. Moreover, the present land-surface is stratigraphically below the plane of the contact between the two sedimentary groups, and the very uppermost horizon of the dolomite in which fractures were developed (in this zone, relatively weak fractures) has been removed by erosion.

So far, the details have concentrated on the major fault-zones in relation to the manner in which they are represented by visible faults and fractures. That the structural zones actually do continue downwards for some greater distance into the dolomite, albeit in a modified form, is indicated later.

c. Relative Ages of Faults and Dykes.- It was concluded that all the dykes in the study-area appear to have been emplaced at approximately the same time. The dykes which comprise the Twin-dyke Lineament pass through the zone of the Vergenoegd Fault without suffering displacement, as do other dykes. (Fig.4a). Clearly, this fault was generated at a time which preceded the intrusion of the dykes. On first appearances the reverse sequence of events seems to apply to the Bokkraal Fault, for the twin dykes are definitely displaced within, and by, the zone of the Bokkraal Fault. The obvious inference is that the Vergenoegd and the Bokkraal Faults were formed at (widely?) different times. In fact, however, tectonic relationships which are evident on the regional scale (see pp.73 to 75), provide sound grounds for concluding that the Bokkraal and Vergenoegd Faults were formed by identical tectonic processes within the same period of geological time.

The contradiction is solved by acknowledging the possibility that there has been a reactivation of the Bokkraal Fault since the time that the dykes were intruded. No proof is available which defines the time of this proposed reactivation, and it could even have been fairly recent.

It is proposed that the rise of the Griqualand-Transvaal axis, which extends in a north-east direction just south of the study-area, could be responsible for recent movement across the Bokkraal Fault. Mayer (1973) described the marked effect that this tectonic axis had on the courses of the Vaal, the Harts, and the Molopo Rivers. The area which was considered by Mayer (1973, Figs.8 and 9) adjoins the present study-area, and the tectonic effects were obviously also imprinted, in some manner, in that area. It is plausible that the manifestation of the Tertiary crustal-warp included a moderate reactivation of the Bokkraal Fault, even although similar effects were not produced within the zone of the Vergenoegd Fault. The acceptable explanations are two, namely, the greater distance of the Vergenoegd Fault from the Griqualand-Transvaal axis, and secondly, the fact that, at the present level of erosion, the Bokkraal Fault includes a zone of discrete planes of fracture. Relative to the Vergneoegd Fault-zone, these fractures are seated more deeply (as shown by the lack of fractures in the dolomite south of the Vergenoegd Fault) and they could have accommodated the reactivation of disruptive forces more easily.

Confirmation of the hypothesis hinges on the expectation that, if it is valid, geomorphic effects similar to those noted by Mayer (1973) should be recognisable in the relevant area - particularly where the Marico River follows the course of the Bokkraal Fault through the Pretoria Series. (In this locality the evidence for the displacement of the dykes is strongest, and direct). It is significant that Hall and Humphrey (1910, p.13) made particular reference to the course of the Marico River in this precise area. (See Fig.4b). They stated "It is possible that the remarkable doubling back of the stream from Vergenoegd, Rondavelskraal and Koedoesfontein is due to a *secondary deviation of the original line of drainage* which ran from the sharp bend near the centre of Vergenoegd in a south-southeasterly direction towards Bronkhorstfontein ... ". They also noted the following fact. "There is nothing in the present distribution of harder and softer rocks to account for the remarkable degree of meandering seen *in this part of the Marico*". (Italics by the present writer.).

It seems, therefore, that there is adequate justification for accepting that there was a reactivation of earth-movements in the pertinent area. These movements were relatively recent, as judged by their geomorphic imprint. However, their very existence suggests that similar, but older movements, could have taken place.

The writer draws the reasonable conclusion that the Bokkraal Fault-zone has suffered a reactivation of the relative movement at different times. From this follows his acceptance that both of the major faults in the study-area pre-date the intrusion of the dykes.

It is instructive to any geologist who concentrates his mapping in small areas that the regional overview allows the recognition of relationships which justify the contradiction of local geological relationships which appear to be indisputable.

D. Folds in the Dolomite

Within the Dolomite Series, non-brittle deformation generally corresponds to two extremes of disturbance, namely, broad tectonic warping, and what appears to be intense, erratic, local, small-scale crumpling. The first may be recognised as a part of the regional geological framework and can be disregarded for the present. On the other hand, the small, local, features probably include the manifestation of very large stromatolites which on rapid scanning and appraisal in the field can be confused with structural crumpling. They could not be defined on the aerial photographs on the scale of 1:20 000, although their effects were recognised. At no stage was it possible to derive a pattern in respect of these small-scale relationships, and it is apparent that the "distortion" on this scale is general and unpredictable. It is unimportant as far as this thesis is concerned.

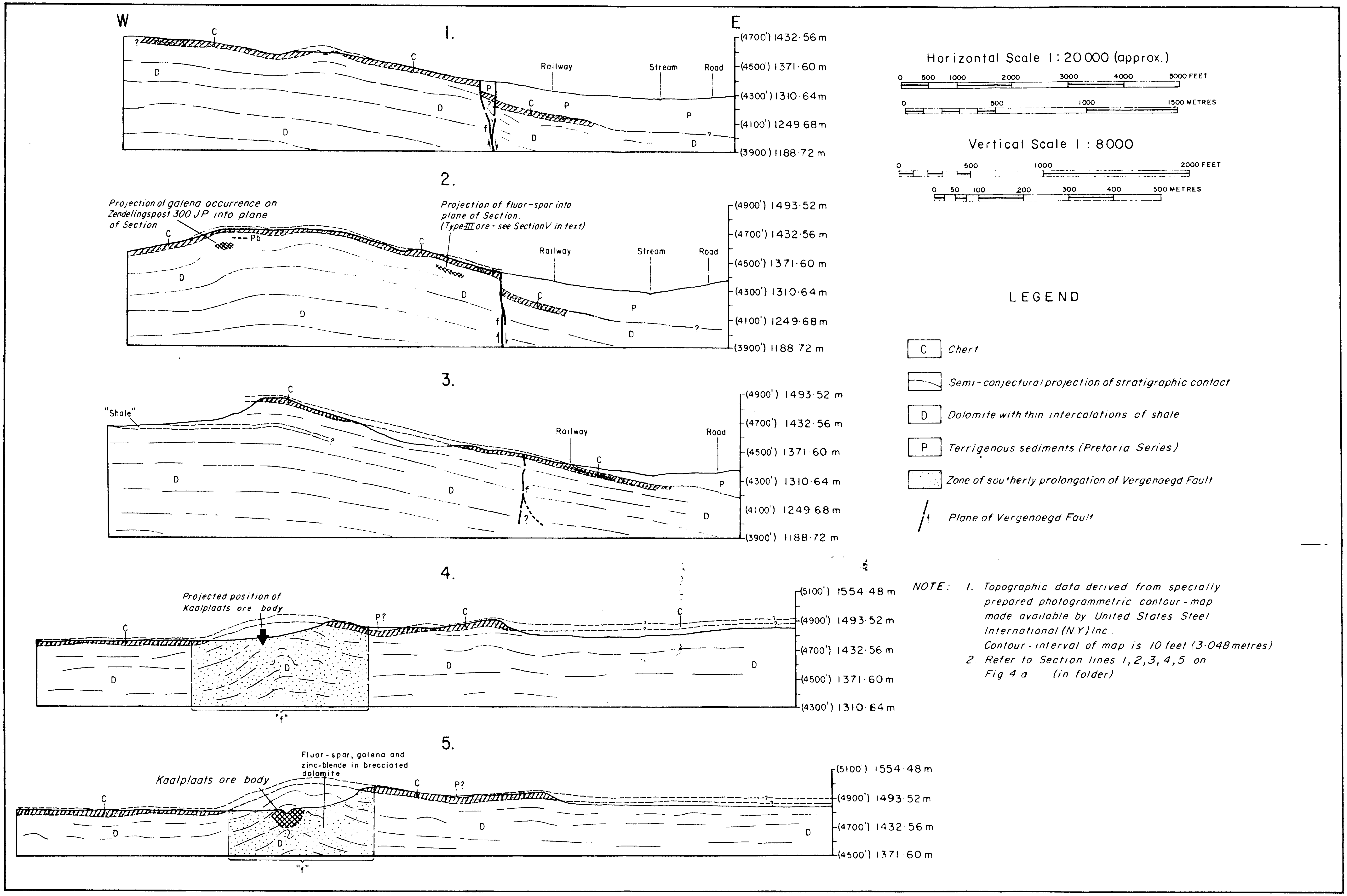
Besides gentle regional flexuring, and the very small-scale contortion mentioned above, a very important third scale of deformation of the dolomite became apparent on diligent annotation of the aerial photographs on the scale of 1:20 000. Owing to the lack of visible stratification in the dolomite, these structures were partly recognised by relationships in the distribution and the attitude of the Giant Chert and the Chert Breccia, or by variations in the elevations of the bases of these respective units. In the field these structures would be considered to be relatively large and would be difficult to define. Photogeologically, they are of an intermediate scale, but they are, nevertheless, sufficiently large not to be recognisable, on occasion, within a single stereo-overlap when they are studied on the photographic scale of 1:20 000. Dimensions of a number of kilometres can be applied as a mental guide. In instances their existence was inferred initially by the anomalous, local, structural attitude of the strata (e.g. alongside the Vergenoegd Fault-zone), before a study of the adjacent photographs revealed the fact of the arching of the chert. The arching is indicated by the disposition and the arrangements of outliers and remnants of chert, which provide a clue to the nature of the underlying structure.

The third class of deformation therefore includes relatively large flexures and folds which are not easy to prove by localised mapping in the field - for reasons of their size, their expression and their exposure. They are important in that, as recognised photogeologically, they are confined to the Vergenoegd Fault-zone and to the Bokkraal Fault-zone.

The nature and the scale of the deformation that is noted above, corresponds to the "distortion" and the "plasticity" that was expected to characterise the dolomite beneath gravity-induced faults in the Pretoria Series, by Wulff (1963) and by Cousins (1962).

Apart from arching that is evidenced by the disposition of the chert which caps the dolomite, the plastic deformation of the dolomite itself is most obviously and strongly developed adjacent to the Vergenoegd Fault-zone in certain places (See Fig.15). Here the dolomite crops out; it has a relatively strong topographic expression, and under the stereoscope it can be seen to be very highly deformed and folded, for example on Vergenoegd 274 JP. (See Fig.4a). Farther south, the evidence is less direct, and it includes outliers of chert which have been variably elevated, west of, but adjacent to, the visible fault-trace. On Zendelingspost 300 JP there is clear factual evidence of marked anticlinal folding. Here the Giant Chert which caps the prominent hills of dolomite has been arched up immediately west of, and adjacent to the trace of the fault, which is clearly visible. It is noteworthy that in this locality Giant Chert opposes Giant Chert across the fault-plane, a fact which indicates that the actual throw is negligible and that the role of competent fracturing in the expression of the fault-zone has tended to be superseded by folding and the anomalous inclination of dolomitic strata.

As one proceeds southwards from Zendelingspost 300 JP, the direct evidence for folding decreases, although the effects of distortion are still visible under the stereoscope - as evidenced by the traces of bedding planes. Southwards, on the southern half of Buffelshoek 301 JP, and on Witkop 302 JP, the poor exposure of the dolomite, and the low relief, prohibit the direct recognition of folding;



NOTE: 1. Topographic data derived from specially prepared photogrammetric contour-map made available by United States Steel International (N.Y.) Inc. Contour-interval of map is 10 feet (3·048 metres)

2. Refer to Section lines 1, 2, 3, 4, 5 on Fig. 4 a (in folder)

Fig. 15 GENERALISED CROSS-SECTIONS THROUGH THE VERGENOEGD FAULT-ZONE

Showing related arching of the Chert and contortion of the Dolomite but even farther south, on Kaalplaats 330 JP (in the northern corner), a north-trending corridor of dolomite that is nearly 1 kilometre in width, separates two areas of Giant Chert which have very marked differences in the elevation of their basal contacts under the stereoscope. No lineament is visible which could correspond to the plane of a fracture or a fault. It is concluded that the difference in elevation is on account of folding that was produced in a manner identical to that discussed previously, and as a consequence, this folding defines the extension of the Vergenoegd Fault-zone into the dolomite. Had erosion removed the Giant Chert from the northern corner of Kaalplaats, the flexure and the extension of the fault would not have been recognised.

Farther south the mapping shown in Figure 3 (in pocket), which is more reliable (in this context) indicates that no chert exists *in situ* above the dolomite. Therefore the detection of folding, by the indirect method that was just discussed, is not possible. In addition, the exposure of the bedrock is very poor (in this area the unit marked C on Fig.4b actually refers to chert rubble) so direct evidence of contortion of the bedding planes in the dolomite is not to be expected. The lack of photogeological evidence for folding in the dolomite in this area should therefore not be accepted as proof that the Vergenoegd Fault-zone has no effect on the dolomite this far south.

It is concluded that the zone of disturbance extends at least as far as Kaalplaats 330 JP, and it very probably extends farther south for a limited distance.

E. Brecciation of the Dolomite

There is proof that the cores of some of the fold- or arch-structures which accompany the two major fault-zones, as recognised, are brecciated strongly. The proof is found in the northern part of Rhenosterhoek 343 JP, where an elongate inlier of dolomite forms a prominent, low hill that is flanked by Giant(?) Chert which is present at a lower elevation than the exposed dolomite. The dimensions of the inlier are about 2,5 kilometres (in a north-north-east direction) by 1 kilometre wide. On stereoscopic evidence, the hill which is composed largely of very strongly brecciated dolomite, is considered to represent the core of an antiformal flexure, or arch, which resulted from the structural disturbance of the dolomite alongside the Bokkraal Fault-zone.

Obviously the dividing-line between plastic distortion and competent brecciation in the dolomite, under stress, is very largely a function of local phenomena and (or) local constraints. Obviously, too, these constraints would vary from place to place. Therefore it is in order to talk of zones or bodies of brecciated dolomite (tectonic breccia) that are related essentially to major zones of fracture-dislocation which die out in the dolomite because of its overall relative plasticity. (The difference is one of proportions). The conclusion is that (other) bodies of brecciated dolomite may be sporadic features of the disturbed dolomite which exists adjacent to the Bokkraal and the Vergenoegd Fault-zones.

VII. DISCUSSION AND EXPANSION OF RESULTS

A. Relation of Faults to the Deposits of Fluor-spar, Galena and Zinc-blende that are Classed as Types I and II.

The classification is that proposed on page 27. The following notes exclude consideration of the layered deposits of fluor-spar, which are classed as "Type III".

Willemse and others (1944) investigated the distribution of galena and zinc-blende thoroughly, and they plotted every deposit that was of possible consequence on a map on the scale of 1:100 000. (Except for the galena occurrence on Uitvlugt 275 JP. See Table 3). These authors included the positions of the pipe-like deposits and the breccia-type deposits, which commonly carry fluor-spar in addition to galena and zinc-blende. (Deposits of Type I). No new discoveries have been made, so it is apparent that the geographical plots of Willemse and others (1944, Plate XII) need not be amended, except for the addition of the very small deposit on Uitvlugt 275 JP.

The present writer was able to recognise the sites of some of the mineral deposits under the stereoscope, particularly the old mines, but on the photographs he was unable to recognise the exact location of most of the minor occurrences of galena. He was not able to visit most of the relevant localities in the field. In those instances where the site of a mineral deposit was not recognised on the photographs and the locality was not visited in the field, the location of each of the respective deposits was transferred accurately on to the completed photogeological maps by their comparison with the plot and the descriptions by Willemse and his co-authors (1944, pp.21 to 48, Plate XII).

Figures 4a and 4b, and particularly Figure 16, illustrate the result. If due credit is given to the southerly projection of the Vergenoegd Fault-zone into the dolomite terrain, as was discussed under the previous heading, and if the mineral-locations (excluding the deposits of layered fluor-spar) are evaluated in relation to the photogeological mapping and the supporting information, an outstanding set of facts emerge.

1. All the ore bodies and all the uneconomic deposits classified as Type I are confined to the Vergenoegd Fault-zone, where the dolomite host-rock has been deformed.

2. With the inclusion of the deposits mentioned above, no fewer than 21 out of the 22 deposits (see Figure 16) are localised on, or are adjacent to, the north-north-west-trending Vergenoegd and Bokkraal Fault-zones, and parallel lineaments. Worded differently, all but one of the 22 deposits that are classed as belonging to Type I or Type II, or are listed in Table 3, are coincident with the two major north-north-west-trending zones of faulting, or with recognisable lineaments which are parallel to them.

In the discussion of the last relationship, it is noted that fifteen of the deposits lie within or adjacent to the Bokkraal and Vergenoegd Fault-zones. The remaining six, all of which are occurrences of galena, are situated on the four farms Witrand 325 JP (one), Doornhoek 305 JP (three), Kafferskraal 306 JP (one), and Kuilfontein 324 JP (one).

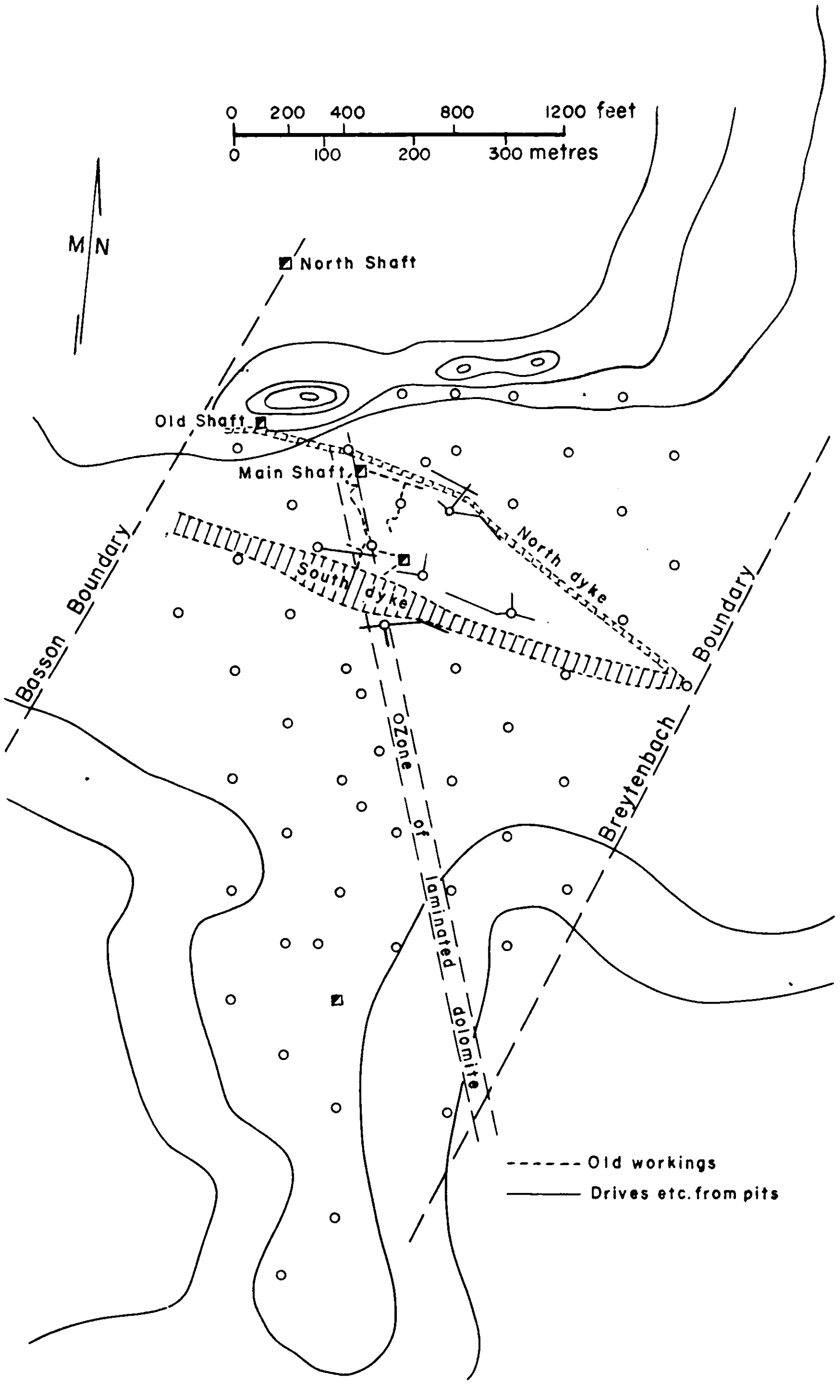
Of the occurrences of galena on Witrand and Doornhoek, among which is included the important but defunct Doornhoek Lead Mine, Willemse and others (1944, p.120) made the observation, which is very pertinent, that the four galena occurrences "lie along a line which trends more or less NNW-SSE". No faults, as such, were recognised on the aerial photographs in this general area, but strong fractures which strike north-north-west were noted on the relevant portion of Witrand 325 JP, and immediately to the south, on Wonderfontein 336 JP. Two of the occurrences of galena on Witrand are located very close to the fractures described above. The locations of the deposits on Doornhoek are reasonably coincident with the prolongation of the fractures, and the correspondence upholds the recognised association, particularly when the fact is related to the obvious alignment of the four deposits. It has been suggested already that the important slump-structures in the dolomite reflect tectonic "breaks" in the basement that were formed prior to the deposition of the sediments of the Transvaal System. It is conceivable that the en échelon off-set between the Strydfontein Trough and the Doornplaats Trough (See Fig.4b) reflects a pre-Transvaal cross-fault, which displaced the fundamental "break". The assumption would require a remarkably faithful spatial coincidence of the slump-structures with the original "break" in the basement. However, it is equally remarkable that the hypothetical cross-fault which would accord with the relative displacement of these two troughs, would strike roughly N20°W to N30°W and would coincide with the line of the galena deposits on Doornhoek and Witrand.

Concerning the ores of lead and vanadium on Kafferskraal 306 JP, Willemse and others (1944) provided a sketch-map in which was depicted a "zone of laminated dolomite" which trends in a north-north-west direction through the workings. Willemse quoted Justice as having ascribed the origin of this zone to minor thrusting prior to the intrusion of the dykes, the zone having formed the channelway for the mineralising solutions. (Willemse and others, 1944, p.31). Figure 17 illustrates the relevant relationship. It is significant that the relative ages of the fault and the dykes, as quoted by Willemse in regard to Kafferskraal, substantiate the association of the "laminated zone" with the family of lineaments which trend north-north-west, which have been shown to pre-date the period of dyke intrusion.

The galena occurrence on Kuilfontein 324 JP does not appear to conform with the general pattern in which there is an association with lineaments that are roughly parallel to the north-north-west direction. It is the only exception. At this locality no north-north-west lineaments were noted, either photogeologically, or in the literature. The Kuilfontein galena deposit is "small and of minor importance". (Willemse and others, 1944, p.30). Records of production of galena show that this was minimal. It is considered that in a statistical sense the lack of a demonstrable association with faults and or fractures which trend north-north-west is unimportant. The "odd-man out" does not negate the general validity of the recognised association between the mineral deposits of Types I and II and the north-north-west-striking faults and fractures.

In one sense, the abnormal location of the Kuilfontein deposit may be "the exception that proves the rule". Disregarding, for the present, the positive effect that physical breaks (channelways) in the recognised zones of faulting would have on the localisation of fluorine-rich and metal-rich solutions, it is obvious that a major effect of the faults is one of arching and contortion (and brecciation) of the dolomite. In other words the latter effects, in themselves, are potential "guides to ore". At Kuilfontein the geological structure is appropriate: Hammerbeck (1971, pp.1 and 8) recognised the existence of a monocline in the dolomite and he also noted folding in the "Pretoria shale". Figure 4b (in pocket) reveals that part of the monoclinal warp may be accounted for by a minor fault which has the downthrow on the north side.

The Kuilfontein deposit is situated very close to the southernmost of the two dykes that constitute the Twin-dyke Lineament. Perhaps the preferential tectonism (and permeability?) in this broad zone can be related to the origin of the Kuilfontein deposit. The absolute association of lead-ore with the Twin-dyke Lineament is not <u>necessarily</u> considered to be important, however, for the



after Willemse and others, 1944, fig 8

Fig. 17 SKETCH-MAP SHOWING THE ZONE OF SHEARING ("LAMINATED DOLOMITE") WHICH TRENDS IN A NNW DIRECTION THROUGH THE MINERALISED DOLOMITE ON KAFFERSKRAAL 306 JP statistics obviously prove that in a practical sense the major faults which trend north-north-west, and the linear zones that are parallel to them, are all-important. They are the specific guides to ore deposits of Types I and II and they are the major controls as well. Therefore the adherence of the "freak" deposit on Kuilfontein to a structural model (one structural model, namely arches and folds in the dolomite), which is encountered most commonly within the major zones of faulting, in a sense merely tends to prove the general validity of the recognition of the fault-zones as the major controlling features of these deposits.

B. Deposits of Layered Fluor-spar (Type III) in Relation to the Photogeological Detail

No general or useful association, or relationship, could be recognised between photogeological detail and the very numerous fluor-spar deposits of Type III (See Figs. 4a and 4b). When compared with the very positive associations just described, this fact was, initially, surprising.

On Zendelingspost 300 JP, fluor-spar of Type III is exposed in the core of an obvious chert-capped anticlinal fold, adjacent to the visible trace of the Vergenoegd Fault. (See also Fig.15). On Knoflookfontein 310 JP, a similar type of ore has been mined, and the location of these few scattered deposits is between the twin dykes, that is, in coincidence with the major Twin-dyke Lineament. These deposits on Zendelingspost and Knoflookfontein represent the distal extremities of the distribution of the layered deposits of fluor-spar, and the immediate suggestion is that their existence could be attributed to a direct association with the lineaments. This is not so, for on more careful and comprehensive examination of the data, it becomes obvious that the overwhelming majority of the individual ore-grade (and other) occurrences of fluor-spar of Type III are scattered at random throughout the area in which they are found. In fact, the photogeological mapping, which accentuates lineaments, indicates that on this scale no useful or constant relationship exists between individual local lineaments and these deposits.

The problem of the photogeological recognition of local stratigraphic details in the dolomite has been noted. If the major local control of the individual deposits, or the group as a whole, is a stratigraphic one, then this would explain why the photogeological information is not definitive. In fact, Button (1973c, p.21) has noted that the fluor-spar is confined to the mixed zone (See Fig.6). The observed coincidence of the distal deposits of fluor-spar ore of Type III, and the lineaments mentioned, may be a function of the (fortuitous?) preservation, in these localities, of the sediments that belong to the mixed zone, more than of any other association or relationship. It might be possible to argue that the preservation of the mixed zone could be an indirect manifestation of the lineaments - for example the Vergenoegd Fault-zone. The implication is superfluous, however, for in the present context the conclusion must still be the same as that noted in the first paragraph. It should be noted that this negative conclusion stems from information derived from within the confines of the study-area. On a much broader scale, the regional interrelation of the locus of fluor-spar mineralisation south of Zeerust with a grid of linear geographical zones in which the rocks are enriched with fluorine; and with the tectonic and structural zones with which these zones correspond; is highly instructive, and this subject is expanded later.

C. Regional Interrelation of the Mineralised Zones of Faulting and Fracturing

The significant sets of lineaments in the study-area, namely, the two sets which trend, respectively, roughly east-north-east and roughly north-north-west, are so dominant that it was concluded that they resulted from fundamental tectonic stresses that existed over a very wide region. They were probably impressed throughout a long span of time, and total constancy in the tectonic processes, and the related effects, would almost certainly not apply. It is therefore appropriate in the present discussion of regional relationships, to disregard minor deviations of the strike of certain individual lineaments and local groups of lineaments from the average trends of the recognised sets of lineaments.

The linear zones of the Bokkraal and Vergenoegd Faults are included, in a tectonic sense, with the very prominent and strongly silicified fractures which strike roughly N20°W to N30°W in the dolomite. It is considered that they are both an integral part of the regional, north-north-west tectonic direction. It is worth noting that although the fractures are commonly silicified, the planes of the major faults are not. This fact suggests that a long period must have elapsed between the formation of the fractures, their subsequent silicification, and the later generation of the important faults. An appropriate model is provided by the "Koppies continental arch" (Pretorius, 1974, Fig.2). The arch is a fundamental tectonic unit of the Kaapvaal craton. Its relationships and effects have been described by Hunter (1974b, pp.298 and 322) and it is apparent that, as a tectonic entity, it was operative continuously from a time prior to the deposition of the Transvaal System to some time after the deposition of the Waterberg System.

The tectonic arch is responsible for the curvature of the axes of the Transvaal and the Waterberg basins: the curvature is seen when these entities are traced from the Cape Province into the Transvaal, and the study-area falls well within the zone of influence of the arch - in fact very close to the axis (See Fig.1).

The writer considers that the gentle upward-flexing of the superincumbent strata that was caused by the arch, would have been attended by tensional stresses that were directed in the horizontal plane at right angles to the axis of the arch. These stresses generated fractures parallel to the axis of the arch and it is to this circumstance that the set of early fractures, which in part compose the north-north-west tectonic direction in the study-area, is ascribed. Later fractures which are also included in this general tectonic direction, in particular the two major faults, have a strike which is rotated a few degrees in the clockwise direction from the average direction of strike of the set of fractures that was formed earlier. This can be explained by presuming that, with the passage of time, the axis of the arch was rotated a few degrees in a clockwise direction, thus affecting the strike of the attendant tensional zones along its flanks in a corresponding manner.

A considerable period of time would have been necessary for the progressive, albeit minor, rotation of the axis of such a fundamental tectonic feature as the continental arch. The hypothesis demands that the Bokkraal and Vergenoegd Fault-zones, and the associated fractures, must be considerably younger than the early, silicified set of fractures. These major zones of faulting are, in fact, very nearly the same age as the Bushveld Complex. The following are the relevant facts.

It has been noted that the Vergenoegd Fault-zone, as recognised photo-geologically, lies exactly on the south-south-easterly prolongation of a large fault. It is significant that the identical situation exists in respect of the Bokkraal Fault-zone. A major fault can be traced on the existing geological map of the Republic (scale 1:1 000 000) from the vicinity of the Goudini carbonatite (80 kilometres from Bokkraal) in a south-south-easterly direction, through the Bushveld norite and the Magaliesberg sediments, into the Daspoort sediments - from which point the trace of the fault can be followed on the map by the linearity of the Marico River - to join the Bokkraal Fault-zone. The Bokkraal and Vergenoegd Faults, as mapped, are thus the southernmost portions of two very major, continuous, and parallel faults which have not been fully traced previously (Compare Figs. 5, 14 and 16).

Hall (1932, pp.203 to 207), in the discussion of the "Structural Design" of the Bushveld Complex, included the portions of the above faults which were recognised at the time, with other faults which he classed as "floor adjustments" in the periphery of the Complex. (See Hall, 1932, Fig.14). They were the avenues by which the supporting floor gave way under the great pressure created by the emplacement of the Bushveld magma. The Bokkraal and Vergenoegd Faults which localise most of the deposits of economic minerals of Types I and II in the study-area are thus linear zones of adjustment of the floor of the Bushveld Complex. They are but two of a number of similar, parallel, faults which project into the dolomite in the Transvaal basin. These faults were doubtless controlled and limited in their direction of strike to a pre-determined direction on account of the over-all tectonic influence of the Koppies continental arch. It is significant that the mechanism of formation of the faults (that is, essentially a "gravity-effect") is in full accord with the facts that were noted when the local displacements were discussed in detail.

D. Fluor-spar Deposits in the Transvaal, and the Regional Setting of the Layered Deposits of Fluor-spar south of Zeerust.

On the realisation that the major, mineralised faults in the study-area are related, physically and spatially, to a family of widespread, regional geological lineaments in the Transvaal, namely, the north-north-west-trending zones of structural adjustment of the floor of the Bushveld Complex, an attempt was made to determine whether any comparable regional relationships exist in respect of the deposits of layered fluor-spar (Type III). Accordingly, the locations of all the occurrences of fluor-spar that are recorded in the Transvaal were plotted on a map in relation to the geology, and the available details on the nature of the deposits were tabulated. (See Fig.18, and Table 6). The resultant conclusions are highly significant and they stem directly from the regional scale of thinking that is induced by the photogeological approach.

Briefly the following are the significant relationships that were recognised.

1. All the deposits of fluor-spar that are known to exist in the Transvaal (and those near Hlabisa in northern Zululand) are confined within the bounds of a number of major, linear geographical zones that are up

TABLE 6.- Condensed Descriptions of Fluor-spar Deposits in the Transvaal and Northern Zululand (Hlabisa)

Note 1. Descriptive data, highly condensed, is after Crocker (1972, and 1974), except numbers 68 and 69.

2. Many small and economically unimportant fluor-spar occurrences are included. The larger deposits have been underlined and mines (past and present) have been noted.

3. Genetic grouping of the deposits, on the basis of field observations and geochemical data, is according to the classification by Crocker (1974), which, in a modified form, is apposite for the present purpose.

Group 1. Considered to be of pegmatitic origin, and deposits are possibly related to the last stages of crystallisation of the Bushveld granites. Characterised by a high rare-earth content and by a dominance of yttrium over the light lanthanides.

Group 2. Considered to be typical of the transition from pegmatitic to high-temperature granitic hydrothermal deposits (Bushveld granites). Characterised by a rare-earth profile similar to that of Group 1, but at a reduced level. There is a detectable enrichment of Nd over La and Ce, whilst Y is greatly enriched over the light lanthanides.

Group 3. Medium-to low-temperature hydrothermal deposits with evidence to suggest that some fluorite in this group may still be precipitating at the present time from very low-temperature thermal waters. Deposits are generally of the vein type and are characterised by low rare-earth contents, especially of the light lanthanides. Y is still the dominant rare earth and there is a trend towards enrichment of La and Ce over Nd, as in Group 1. The trace-profile is similar to that of Groups 1 and 2 and the deposits in all three groups are probably of the same origin, except that some deposits included in Group 3 were deposited from non-magmatic sources, i.e. from thermal waters of meteoric origin.

Group 4. Fluor-spar deposits associated with alkaline intrusions, with metasomatic and or pegmatitic affinities. The rare-earth geochemistry reflects the relative enrichment of La and Ce earths over Y, which is characteristic of this group.

Group 5. Hydrothermal vein-deposits associated with the alkaline intrusions noted in Group 4. Rare-earth profiles show a trend similar to that which characterises Group 4, but the trend is expressed at a reduced level.

Group 6. Pneumatolytic and or pegmatitic deposits characterised by accessory fluorite and other minerals, with significant amounts of cassiterite. The rare-earth geochemistry is not known.

Farm and District	Abbreviated description and genetic grouping
1. Blokspruit 157 JQ Warmbaths	Fluor-spar in sporadic vugs in vertical to flat-lying hematite-quartz veins in Bushveld granite. Group 2.
2. Buffelsfontein 347 KR Potgietersrust (Buffalo Fluor-spar Mine)	Fluor-spar as replacement layers subparallel to relict bedding of a coarse-grained leptite which occurs as a large xenolith in Bushveld granite also as joint-fillings in the granite. The most important fluor-spar mine in South Africa. Group 1.
3. Buffelskloof 514 KR Potgietersrust	No data available
4. Buffelskloof 52 JQ Rustenburg	Fluor-spar veins in joint and breccia zones in red syenite of the Pilanesberg Complex. Group 5.
5. Cyferfontein 434 KR Warmbaths	Fluor-spar with quartz, as veins striking east-west in Bushveld granite Group 3.
6. De Mond van Blokspruit 158 JQ Brits	As 1 above Group 2.
7. Doornhoek 91 JQ Rustenburg	Vein and breccia-fill deposits of fluor-spar in syenites and foyaite pegmatites associated with the Pilanesberg Complex. Group 5.
8. Eerste Geluk 512 KR Potgietersrust	Fluor-spar reported. No data available, but probably in Bushveld granite or Rooiberg felsite Group 3?
9. Enkeldoorn 217 KR Bronkhorstspruit	Very minor amounts of fluorite in large cassiterite-bearing quartz-veins in Bushveld granite of Bobbejaankop type. Group 3.
10. Goudini 30 JP Marico	Fluor-spar associated with Goudini carbonatite i.e. sövite dykes containing interstitial fluorite. Minor amounts fluor-spar in narrow veins. Groups 4 and 5.
11. Glenover 391 LQ Waterberg	Fluor-spar associated with Glenover carbonatite. Occurs as accessory in carbonatite dykelets and in fissure-fill dykes and veins. Also small veins in beforsite. Groups 4 and 5

Farm and District	Abbreviated description and genetic grouping
12. Grobbelaars Hoek 462 LR Potgietersrust	Vein of botryoidal-type fluor-spar, with much quartz, in Bushveld granite near contact with overlying felsite. <u>Group 3</u>.
13. Groenvley 224 KR Potgietersrust	Fluorite as an accessory to pneumatolitic or pegmatitic cassiterite in Bobbejaankop Granite. <u>Group 6</u>.
14. Haakdoornfontein 532 KQ Warmbaths	Fluor-spar as narrow veins filling open spaces and breccia in a post-Karroo fault in Bushveld granite (Group 3). Also in fracture veins in the trachyte of the Roodeplaat Complex and in breccia on the same fault, on Rietdal 555KQ farther west. <u>Groups 5 and 3</u>.
15. Hartbeestpoort 522 KQ Warmbaths	Large fissure vein carrying fluor-spar in Magaliesberg quartzite near the contact with intrusive Bushveld granite Also described as an anastomosing network of veins which occupy a system of east-north-east-trending fractures and small faults in the quartzite, immediately above the granite. Some faults displace the granite. <u>Group 3.</u>
16. Hartebeestvley 510 KQ Warmbaths	Botryoidal fluor-spar in post-Karroo fracture-zones in quartzites of the Pretoria Series. As 15. <u>Group 3</u>.
17. Houtenbek 194 JR Groblersdal	Minor fluor-spar associated with uneconomic molybdenite and monazite in quartz veins in Bushveld granite. Also in flat-lying vugs and lenses which follow local lines of jointing. <u>Group 2</u>.
18. Kaffirsdraai 513 LQ Waterberg	Vein of botryoidal fluor-spar up to 2 metres in width in an open joint in Waterberg sandstone which overlies granite close to a major east-west fault. <u>Group 3</u>.
19. Kenkelbos 152 JQ Rustenburg	As for 1 above. <u>Group 2</u>.
20. Klipdraai 559 KQ Warmbaths	As for 14 above <u>Group 3</u>.
21. Knoppieskraal 537 KQ Warmbaths	As for 16 above. <u>Group 3</u>.

Farm and District	Abbreviated description and genetic grouping
22. Kromdraai 560 KQ Warmbaths	As for 14 above. Group 3.
23. Kromdraai 209 JR Bronkhorstspruit (Vergenoeg Fluor-spar Mine)	Very strong fluor-spar impregnation and replacement of hematitic tuff and agglomerate in Rooiberg felsite. Major ore body, presumably related to the intrusion of Bushveld granite. Situated at a major volcanic centre. Main Vergenoeg body represents a choked vent(?). Group 1(?)
24. Kruidfontein 139 JQ Rustenburg	Fluor-spar in meta-sövite and meta-beforsite as a finely crystallised metasomatic constituent, and in vein form. Groups 4 and 5.
25. Kwaggafontein 520 KQ Warmbaths	Fluor-spar in narrow veins in Rooiberg felsite. Also in waste sorted from copper and tin prospects. Similar to Morgenzon (see 31) Group 3.
26. Ledig 93 JQ Rustenburg	As for 7 above. Fluor-spar and apatite in foyaite host-rock. Group 4.
27. Leeuwfontein 50 JQ Rustenburg	As for 4 above. Group 5.
28. Leeuwfontein 299 JR Pretoria	Fluor-spar as disseminations and breccia cement in red soda-syenite intrusion. Also fracture-fill veins of fluor-spar in both the intruded quartzite and the syenite. Group 4.
29. Leeuwpoort 554 KQ Warmbaths	Quartz-hematite vein with large vug of white fluor-spar. As for 1, 6 and 19 above. Group 2.
30. Maroelesfontein 602 KR Waterberg	Botryoidal fluor-spar in the large post-Karroo "Warmbaths fault". Probably deposited from cooling thermal waters. Mineralisation took place later than the brecciation. Group 3.
31. Morgenzon 533 KQ Warmbaths (Thompson Fluor-spar Mine)	Botryoidal fluor-spar cementing breccia in three vertical fracture-zones, or veins, in Rooiberg felsite. Veins strike east-north-east. Group 3.
32. Nooitgedacht 49 JQ Rustenburg	As for 4 above. (Once mined unsuccessfully). Barite is present as an important accessory. Group 5.

EXPLANATION OF SYMBOLS

• 22	Fluor-spar occurrence or minor deposit		numbers correspond with those in Table 6 in text
◉ 6	Significant fluor-spar deposit, includes mines		
●	Tin-fields	A Potgietersrus B Olifants C Elands D Rooiberg E Nylstroom F Moloto	after Hunter, 1973 c, fig. 4
+	Fluorine content of ground water in excess of 6 p.p.m (From Ockerse, 1944, Map)		
★	Locus of fenitisation near Buhrmannsdrif. Refer to Appendix A		
— —	Illustrative limits of recognised zones of enrichment with flourine		
◊, ▽	Kimberlite, diatreme		

GEOLOGICAL EXPLANATION

	——	Major fault	
	R	Recent deposits	
200 m.y.	K	Undifferentiated Karroo System	
1300-1400 m.y.	AS2	Alkalic and carbonatitic igneous complexes (C = carbonatite)	
	W	Waterberg System	
1450 m.y.	G, gy	Granitic and granophyric rocks	Bushveld Complex
	AN3	Basic and ultrabasic rocks	
2000 m.y.	F	Rooiberg felsite	
2000 m.y.	AS1	Palabora Complex and related intrusions	
2000 m.y.	AG4	Metamorphic and ultrametamorphic rocks of the Limpopo Mobile Belt	
	T3	Pretoria Series	Transvaal System
	T2	Dolomite Series	
	T1	Largely Black Reef Series, where delineated	
2300 m.y.	V	Basic and acid volcanics of the Ventersdorp System	
>2300 m.y.	GW	Pre-Ventersdorp rocks; undifferentiated	
2900 m.y.	AN2	Usushwana Complex and other basic intrusives	
3200-3300 m.y.	S	"Greenstone Belts" of the Swaziland System	

Note: Diagrammatic curvature of the Murchison Zone partially compensates for minor lateral-dislocation and mis-alignment brought about by more recent faults.

Fig 18. LINEAR ZONES IN THE TRANSVAAL THAT ARE ENRICHED WITH FLUORINE

Farm and District	Abbreviated description and genetic grouping
33. Rietfontein 446 JR Bronkhorstspruit	Fluor-spar reported. Probably an accessory to minor tin mineralisation but no data are available. Group 3.
34. Rietfontein 536 KQ Warmbaths	As for 31 above. Same fissure-zone. Group 3.
35. Rhenosterhoekspruit 466 KQ Warmbaths	Fluor-spar is present as veins in a fracture-zone in Rooiberg felsite close to a fault, also as disseminations in a large hematite-quartz body. Group 2.
36. Roodeplaat 293 JR Pretoria	As 49; also minor fluor-spar veins, and disseminations in a trachytic breccia. Groups 4 and 5.
37. Roodepoort 222 KR Potgietersrust	As for 13 above. Group 6.
38. Ruighoek 169 JP Rustenburg	Fluor-spar float reported. Interpreted as possibly a large vein of fluor-spar within rocks belonging to the Pilanesberg Complex. Group 5.
39. Ruigtepoort 162 JQ Warmbaths (Ruigtepoort, Goudkoppies or Gilspar Mine. Defunct)	Similar to 1, 6 and 19 above. Large fluor-spar deposit in the form of an oval-shaped replacement body in the upper portion of a granite cupola, floored by fresh granite. The ore body consists of chloritised granite with large amounts of specular hematite, quartz, and fluor-spar as large masses and finer clumps. ("Essentially quartz-hematite-fluorite ore bodies floored by fresh granite.") Important previous source of fluor-spar. Group 2.
40. Saulspoort 38 JQ Rustenburg	As for 7 above. Group 5.
41. Schaapkraal 170 JP Rustenburg	Fluor-spar in veins a few centimetres thick in decomposed alkaline rocks of the Pilanesberg Complex. Group 5.
42. Slipfontein 551 KQ Warmbaths (Slipfontein or "Big Ben" Mine. Relatively important past producer)	Flat-lying body of quartz-hematite with large masses of fluor-spar, probably replacing the hematite, in Bushveld granite. Body previously considered to be a circular vein surrounding a plug-like quartz - hematite body, e.g. Kent and others, 1943, p30. Group 2.

Farm and District	Abbreviated description and genetic grouping
43. Solomons Temple 230 KR Potgietersrust	As for 13 above. Group 6.
44. Stavoren 676 KS Potgietersrust	As for 13 above. Group 6.
45. Tooyskraal 531 KQ Warmbaths (Previous producer; veins mined to 20 metres)	Fluor-spar in large vugs in a zone of quartz and hematite in Bushveld granite, similar to deposits 39 and 42 above. Group 2. Also siliceous fluor-spar veins in Bushveld granite. Group 3.
46. Valschfontein 33 JS	Fluor-spar as the vein filling in three sub-parallel east-west fissures in Bushveld granite, in association with minor barite and dominant quartz. Group 3.
47. Vischgat 520 KR	Significant occurrence of fluor-spar on a fault-plane in Smelterskop sediments overlying and intruded by the Bushveld granite. Fluor-spar in a flat-lying fracture-lode and in faults near the contact between granite and felsite. Group 3.
48. Vogelstruisnek 173 JP Rustenburg	As 7 above. Group 5.
49. Walmannsthal 278 JR Pretoria	Significant irregular body of fluor-spar and apatite in trachyte of the Roodeplaat Complex. Genetic similarity to the Wydhoek type of ore body. Considered to be a pipe-like pegmatitic body. Group 4.
50. Welgelegen 246 KR Potgietersrust	As 13 and 43 above, but also fluor-spar in a fracture-zone in felsite overlying mineralised Bobbejaankop Granite. Also as Vischgat above. (Stockworks?) Group 3.
51. Welgevonden 232 KR Potgietersrust	As 13 and 43 above. Group 6. Also type similar to Morgenzon, No.31. Group 3.
52. Witwal 523 KQ Warmbaths	Minor fluorite as an accessory to cassiterite on a fault plane in a roof-pendant of Pretoria sediments in Bushveld granite. Group 3.
53. Wydhoek 92 JQ Rustenburg (Defunct mine)	Unique deposit in form of "ring-dyke" in alkali rocks of Pilanesberg Complex. Small foyaite plug 80 metres in diameter intrudes effusive lavas and tuffs. Coarse fluorite-apatite-aegerine ore mantled the apical part of the plug and decreased in thickness down flanks. Group 4.

Farm and District	Abbreviated description and genetic grouping
54. Zaaiplaats 223 KR Potgietersrust	As 13 above. Group 6.
55. Zeekoegat 296 JR Pretoria	Fine-grained fluor-spar resulting from metasomatic replacement, in bands parallel to the bedding, of a limestone member in the uppermost quartzites of the Pretoria Series. Possibly ascribable to the nearby intrusion of the Leeuwfontein Complex. Group 4.
56. Zwartkloof 470 KR Warmbaths	Major deposit of three fluor-spar ore bodies in subparallel fissures or breccia zones in Rooiberg felsite, in a zone of thrust-faulting and wrench-faulting. Group 1. Also a body of specular hematite and quartz with fluor-spar. Group 2.
57. Zusterstroom 447 JR Bronkhorstspruit	Fluor-spar reported from a fracture zone trending east-north-east in Bushveld granite, but not verified. Group 3.
58. Rietfontein 460 KQ Warmbaths	Minor fluor-spar in Rooiberg felsite. No data available; presumably in fissures and joints. Group 3.
59. Doornfontein 498 KQ Rustenburg	Fluor-spar in granite. No data available.
60. Nooitgedacht 22 JQ Warmbaths	Fluor-spar reported in a small gash-vein in dolomite, presumably related genetically to the adjacent Kruidfontein Complex and the Kruidfontein volcano. No other details available.
61. Roodepoort 467 KR Warmbaths	Fluor-spar and ankerite in a fault-zone? No details available.
62. Witfontein 430 KR Warmbaths	Impregnation and replacement of tuffaceous felsite below a shale horizon in the Rooiberg felsite, in association with subordinate amounts of cassiterite. Group 2?
63. Leeuwbosch 129 KQ Thabazimbi	Accessory fluor-spar with galena in dolomite adjacent to a satellite outcrop of the Bushveld granite. Group ?
64. Naauwpoort 208 JR Bronkhorstspruit	Extension of the fluor-spar deposit noted in 23 above. Group 1.
65. Paalkraal 556 KQ Warmbaths	Record only. No data available.

Farm and District	Abbreviated description and genetic grouping
66. Driefontein 553 KQ Warmbaths	Record only. No data available.
67. Haakdoornfontein 119 JR Pretoria	Fluor-spar in fracture veins in trachyte of the Roodeplaat Complex. Group 4?
68. Near Hlabisa in Zululand (Kwa-zulu); numerous farms.	Fluor-spar occurs with quartz in major true fissure-veins in Archaean granite, Table Mountain sandstone, and in Dwyka (Karroo) sediments. A major mineralised belt, approximately 19 kilometres by 10 kilometres in extent. Group 3?
69. Zeerust Area; Numerous mineralised localities on many farms.	Major fluor-spar region, extensively exploited. Fluor-spar occurs in dolomite in structurally localised, irregular bodies of breccia, "breccia pipes" and zones of gash-veining, together with zinc-blende and galena. Also as important, widespread, high- to low-grade disseminations in dolomite in concordant zones just below the Giant Chert which caps the dolomite. No genetic grouping available.

to 30 kilometres wide and up to 650 kilometres long. These geographical zones are associated in the pattern of quasi-orthogonal rectilinear sets.

2. The average trends of the linear zones are, respectively, either east-north-east or north-north-west, that is, parallel to the average directions of strike of the important sets of lineaments that were recognised in the study-area south of Zeerust. The immediate implication is that the linear geographical zones are not fortuitous and that they may bear some relationship to the structural and tectonic framework of the study-area.

3. There is a distinct concentration of deposits of fluor-spar within one of the linear geographical zones that trends in the east-north-east direction. This zone encloses the prolongation of the axis of the Murchison mountain range and it was therefore named the "Murchison Zone".

4. The large locus of concentrated but varied deposits of fluor-spar that exists south of Zeerust is situated within the Murchison Zone. This implies that although the major local associations of the layered deposits of fluor-spar of Type III are stratigraphic,there is a fundamental reason for their existence in that particular localised area which is common to the other deposits of fluor-spar within the Murchison Zone, (and to the deposits within the other linear zones of enrichment with fluorine).

5. In respect of igneous intrusions in the Bushveld the following relationships were recognised.

    a. Every alkalic intrusive complex, carbonatitic complex, and kimberlite that exists within the geographical confines of the Bushveld Complex, as represented on the current geological map of South Africa on the scale of 1:1 000 000, is situated within the recognised fluor-spar-rich linear zones, or close to major faults which are parallel to them, for example, the Goudini carbonatite.

    b. There is an almost total restriction of the locations of the known tin-bearing granites in the Bushveld, as reflected by the locations of deposits of cassiterite, to the geographical confines of the fluor-spar-rich zones.

c. Many of the respective intrusive bodies are associated with deposits of fluor-spar.

6. All but one of the sites of peak-concentration of fluorine in ground water, as determined by Ockerse (1944, map), are situated within the recognised geographical zones, and the fact tends to provide confirmation of the relative enrichment with fluorine of the rocks within these zones.

On considering the above, and on particular contemplation of the information given under Item 2, it became apparent that at least two of the linear zones which are enriched with fluorine are demonstrably <u>co-axial with major litho-tectonic elements in the crystalline basement</u>. These are the Murchison Zone, which incorporates the Murchison Greenstone Belt of Archaean age; and the Grobbelaars Hoek-Hlabisa Zone, which is co-axial with the Lower Proterozoic Usushwana Complex. Moreover, it was noted that the fluorine-enriched alkalic intrusions which led Shand (1923) to recognise the tectonic affiliations of the "Franspoort line" north-east of Pretoria, are clearly localised in one of the linear zones which trends in the north-north-west direction. (For this reason the zone was named the "Franspoort Zone").

The last-mentioned facts suggest very strongly that a relationship may exist between the fluorine-enriched linear zones, as recognised, and major tectonic and lithological elements on the craton. The relationship is, in fact, a fundamental one, and the matter is discussed next.

E. Tectonic Affiliations of the Linear Fluorine-rich Zones, and some Implications

1. The Zones which trend in the East-north-east Direction

a. <u>The Murchison Zone</u>.- In 1914 Hall (p.63) wrote of the Murchison region, "It seems ... that the Archaean complex of the low country was affected by repeated systems of earth movements which occurred at widely different periods, and all followed more or less the same general direction". These repeated "earth movements" define a dominant tectonic direction that was east-north-east, and it controlled, and is clearly displayed by, the axis of the major folding in the Murchison Greenstone Belt. The tectonic direction was therefore referred to by Hall (1932, p.454) as the "Murchison Direction". Subsequent investigators,

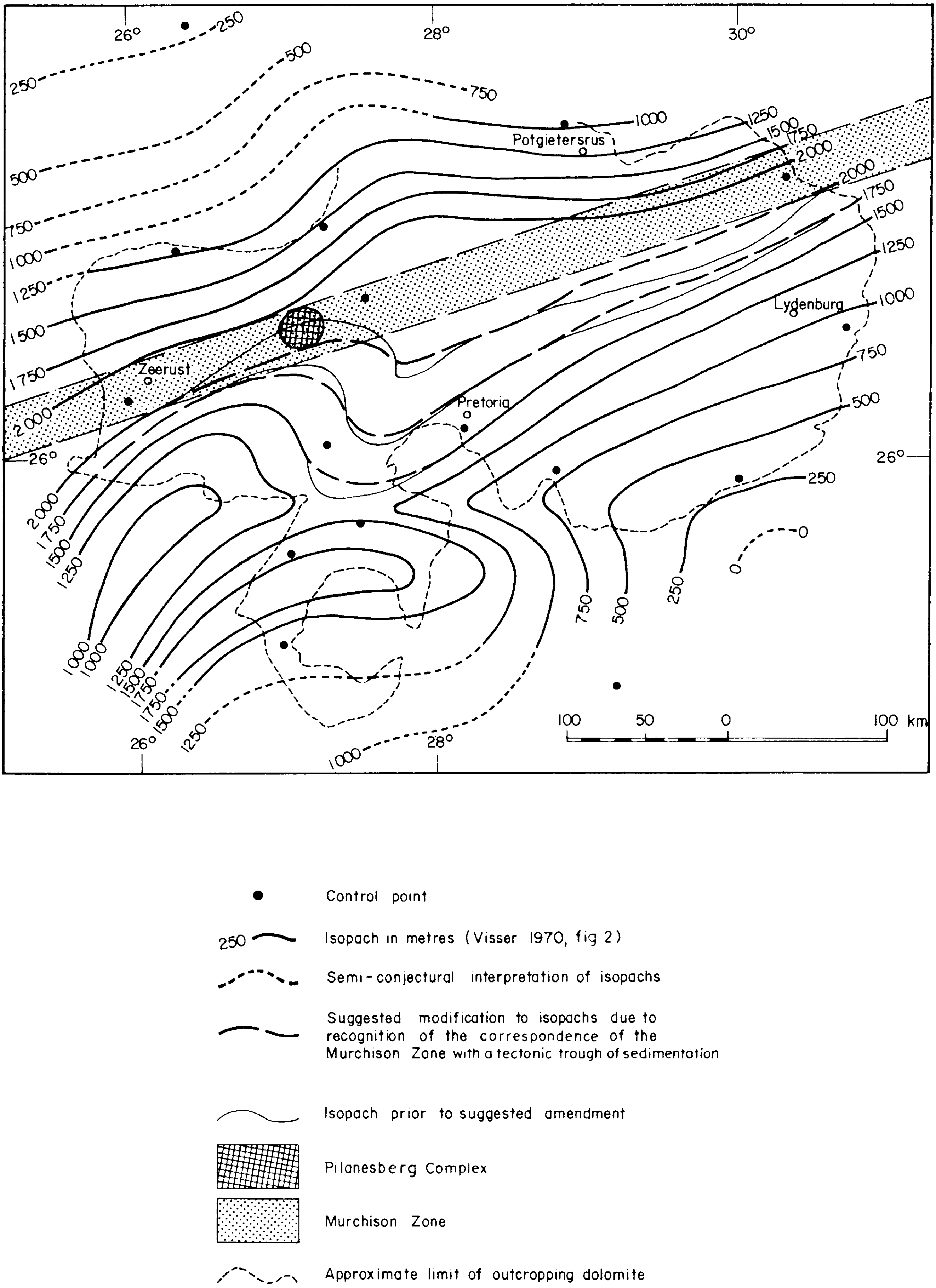


Fig. 19 ISOPACHS OF THE DOLOMITE SERIES (after Visser, 1970, fig. 2) IN RELATION TO THE MURCHISON ZONE OF ENRICHMENT WITH FLOURINE

for example Van Eeden and others (1939), Brandt and Le Roex (1945), Kent (1957), and Schwellnus and others (1962), were unanimous in their recognition of the structural imprint of the Murchison (tectonic) direction.

Hall (1932, p.206) recognised that intense folding of the Proterozoic dolomite and the banded ironstones in the Mhlapitsi fold-belt in the north-eastern portion of the Transvaal basin was evidence for renewed tectonism within a narrow belt that coincides with the axis of the Murchison Greenstone Belt, that is, a tectonic axis that coincides geographically with the Murchison zone of enrichment with fluorine. The work of Bastin (1968) provides confirmatory evidence of the structural effects that are related to the rejuvenation of this particular tectonic lineament, although Bastin's own appreciation of the relationship appears to have not been deep. However, it is the work done by Button (1973a, 1973b and 1973c) that elucidates most fully the fundamental affiliation of the Murchison Zone in the Eastern Transvaal with a coincident linear zone of continuous tectonism.

Button (1973c, p.14) summarised his findings on the tectonic controls of the Transvaal basin. He remarked on the tectonic behavior of Archaean greenstone belts during sedimentation, and noted that some greenstone belts (the Barberton for example) had no noticeable effect on sedimentation and behaved in a fashion similar to the surrounding granitic areas. However, he concluded in effect, that the "Murchison Schist Belt" was a tectonically anomalous zone, and that it represents a "deep-seated crustal inhomogeneity ... (possibly extending down to below the rigid levels of the crust)". It was the site of the Selati Trough, where a sedimentary pile accumulated that was many times thicker than in the surrounding areas. In two papers Button (1973a and 1973b) documented explicitly the controlling influence that this tectonic trough of sedimentation exerted on the stratigraphy and the sedimentation of the Lower Proterozoic sediments in the north-eastern extremity of the Transvaal basin. He showed that the Selati Trough was the response of sedimentation to a dominant, linear tectonic belt in the floor of the Transvaal basin that was intermittently active for a period of geologic time which probably exceeds 1 billion years (Button, 1973a, p.24).

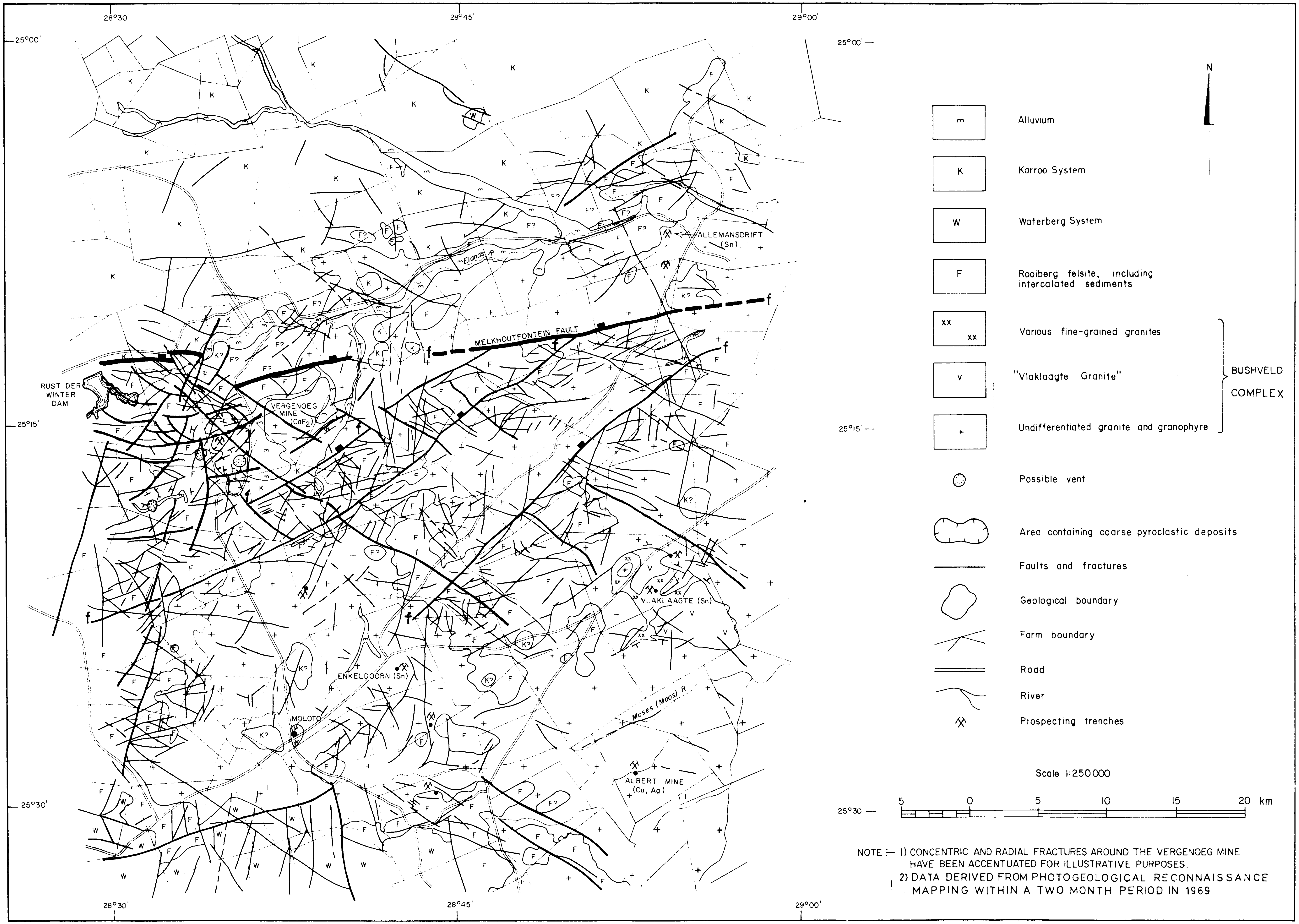
It is notable that the axis of the Selati Trough in the north-eastern Transvaal is coincident with the axis of the geographical zone of enrichment with fluorine that is the Murchison Zone. (Compare Fig.18 with Button, 1973b, Fig.3)

There is a very significant thickening of the sediments in the Selati Trough when a comparison is made with those on its flanks. Figure 19 (after

Visser 1970) suggests strongly that the thickening of sediments in the Selati Trough, as noted by Button, is but a relatively local expression of the much more significant general thickening of the Dolomite Series that takes place in coincidence with a very major axis of sedimentation which traverses across the entire Transvaal basin in the east-north-east direction. It is reasonable to conclude, by analogy with the Selati Trough, that this major axis of sedimentation, in which the isopachs of the Dolomite Series exceed 2000 metres, is also a tectonic axis. Thus, it is quite in order to deduce from the aforegoing that the fluorine-rich Murchison Zone, as recognised, coincides with an ancient tectonic axis that was rejuvenated at intervals throughout a vast period of geologic time.

b. The Glenover-Grobbelaars Hoek Zone.- This zone takes account of the locations of the Glenover carbonatite and the deposits of fluor-spar on Kaffirsdraai 513 LQ and Grobbelaars Hoek 462 LR, and it is significant that it is aligned closely with the southern flank of the Limpopo Mobile Belt. The existence of major transcurrent faults within the Belt, and the continuous tectonic instability of the belt from the early Precambrian until the present, has been noted already (page 8). Thus, although the continuation of the zone east of Grobbelaars Hoek is conjectural, there is little hesitancy in recognising the geographical correspondence of the carbonatite and the fluor-spar deposits with a major linear tectonic zone of considerable longevity.

c. The Soutpan-Spitskop Zone.- The tectonic affiliation of the Soutpan-Spitskop Zone is not easily seen on reference to the literature because relevant information is scant. Figure 20 is, however, relevant. It illustrates the condensed results of a photogeological survey that was conducted by the writer in 1969. (Wilson, 1969a). The main geological feature in the area (2600 square kilometres) is a very major fault-scarp which has over 200 metres of relief, relative to the low country on the north side. The direction of strike of this fault is a few degrees north of east and it is considered that this direction, when it is taken in a regional context, is close enough to the trend of the Murchison direction (with which the trend of the Limpopo Mobile Belt also corresponds) to be related to one and the same fundamental set of east-north-east trending lineaments. Note that the Vergenoegd Fluor-spar Mine (number 23 in Table 6) is situated very close to the focus of very marked radial and concentric fractures, in which vents have been recognised tentatively. The ore consists of mineralised coarse and fine pyroclastic breccia (Wagner, 1928, pp.42 to 55) and it is obvious that the mine is located within a major volcanic centre. There can be little doubt that the large Melkoutfontein Fault was the



NOTE :– 1) CONCENTRIC AND RADIAL FRACTURES AROUND THE VERGENOEG MINE HAVE BEEN ACCENTUATED FOR ILLUSTRATIVE PURPOSES.
2) DATA DERIVED FROM PHOTOGEOLOGICAL RECONNAISSANCE MAPPING WITHIN A TWO MONTH PERIOD IN 1969

Fig. 20 FRACTURE PATTERN AROUND THE VERGENOEG FLUOR-SPAR MINE, RUST DER WINTER major control of the volcanicity, so even in this example the tectonic affiliation of the fluorine-enriched geographical zone is manifest.

2. The Zones which trend in the North-north-west Direction

The north-north-west-trending zones which are enriched with fluorine (see Fig.18) are parallel to, and include, the Franspoort line of Shand (1923). In substantiation of the previous indication that the fluorine-rich linear zones are related to fundamental tectonic lineaments, it is particularly relevant that Shand stressed (1923, p.97) that whether the Franspoort line is viewed as a fault or a fold it has a "peculiar tectonic significance ... [and it is] ..., a line of weakness in the older rocks of the Bushveld Igneous Complex and its floor". It is a colloboratory fact that the Grobbelaars Hoek-Hlabisa Zone also corresponds with another fundamental tectonic element in the craton. This zone is co-axial with the linear Usushwana Complex, and Hunter (1970, in Hunter, 1974b) has noted that this complex was emplaced in a major graben which trends north-north-west.

Data which relate specifically to the zone which trends in the north-north-west direction through Phalaborwa are scant, and its recognition is somewhat tentative. However, following the relationships that were recognised under Items 5a and 6 on page 76, it is considered that there is sufficient justification for the recognition of this zone, following the recognition of the others that are depicted in Figure 18. The trend of the zone is appropriate to the facts of the discussion,and it is relevant that the deposits of phlogopite and vermiculite in the Palabora Complex, which amount to "many million tons" (Mineral Resources of the Union of South Africa, 1959 Edn., p.562) very probably represent a very considerable store of fluorine. Certainly, Deer, Howie and Zussman (1967, p.44) note that fluorine is common in natural phlogopites, in significant amounts, the highest recorded content of fluorine being 6,74 per cent, by weight. In tabulating this figure amongst numerous others, Wedepohl (1969, Tables 9-D-1 to 9-D-4) tends to show that phlogopite is particularly favoured as a repository for fluorine. In fact Deer, Howie and Zussman (1967, p.50) observe that the formation of phlogopite in many areas of thermal metamorphism is the actual result of fluorine metasomatism. Thus, there seems to be little valid reason to doubt that the amount of fluorine within the mass of phlogopitic rock associated with the intrusive (alkalic and carbonatitic) Palabora Complex does correspond with a major repository of this element. It is concluded that the recognition of the zone is fully warranted.

It is significant that the north-north-west tectonic trends that were noted in the preceding paragraphs are very probably related to the Koppies continental arch in the same way as are the linear zones of adjustment of the floor of the Bushveld Complex that have been noted already. The tectonic longevity of the arch and its tectonic effects at different times have also been noted, and the information tends to confirm that all three of the fluorine-rich zones may be related to fundamental tectonic lineaments, although, on present information the lithostructural effect is seen clearly in only two of the zones.

3. Implications of the Observations

It is considered, notwithstanding the lack of clear evidence of the association in every case, that it is reasonable to draw the general conclusion that follows, namely, that all of the recognised narrow zones in which the rocks have been enriched with fluorine coincide with fundamental tectonic lineaments that have suffered tectonic reactivation in greater or lesser degree, throughout long periods of time. The constancy of the relationship is explained below.

Fluorine is the most chemically reactive of all the elements. (Encyclopaedia Brittanica, 15th Edn., 1973, Vol.4, p.199). Fluorine thus has the geochemical property that once it is mobilised from its host-mineral, or host-rock, it is fixed very rapidly in its new environment. Of the rock-forming minerals noted by Deer, Howie and Zussman (1967), only topaz and fluorite have fluorine as an essential constituent in the formula. The other fluorine-bearing minerals are accessory minerals, but fluorine is a common element, nevertheless, and can exist in significant amounts in ubiquitous rock-forming minerals, particularly micas and amphiboles, as an amorphous replacement in the lattice in the OH-position. (Wedepohl, 1969, p.9-D-1). Thus the tendency towards the very rapid fixation of fluorine in any new environment is accommodated by the abundance of potentially favourable sites of replacement by fluorine of the (OH) ion in common minerals. Therefore a primitive pattern, as noted above, in which the crustal rocks were enriched with fluorine in narrow linear (tectonic) zones, could manifest itself throughout time, and would result in the linear distribution of deposits of fluorine-enriched minerals, including fluor-spar in particular, which are of vastly different ages, and which suffered various modes of formation.

Owing to the very limited solubility of fluor-spar, once the fluorine that was present in any area had been precipitated as CaF_2, the distribution of deposits of fluor-spar would mirror the zones or areas in which the rocks were enriched with fluorine. Moreover the ages of these deposits would indicate the time-range during which the enrichment of the rocks with fluorine was manifest.

Recognition of these relationships explains a fact that is a feature of the information that is contained in Table 6 and Figure 18; that is, that within the individual "zones", the relative ages of the various fluor-spar deposits differ greatly. As a whole, the ages vary from at least 1950 m.y. (emplacement of the Bushveld Complex), to post-Waterberg, to Pilanesberg age (1250 m.y.), then to post-Karroo (less than 125 m.y.?). In fact, in some deposits fluorite may still be precipitating (see Crocker, 1972, pp.7 and 9).

Thus, the time-span during which every fluor-spar deposit in the Transvaal is seen to have conformed with the zones plotted in Figure 18 is very great. In the preceding discussion these zones were shown to coincide with long-lived megatectonic lineaments. The geochemical aspects cannot, in themselves, explain the initial regular association of fluor-spar with these lineaments, and the relationship cannot be ascribed to fortuity. It is concluded that there must be a genetic link.

The contention receives independent verification from Scheglov (1969), whose findings may be paraphrased as follows.

> Fluorite deposits constitute a specific group of hypogene ores which are controlled by zones of "self-activation" and prolonged tectonism. They are confined most closely to zones of regional fractures and prolonged regional faulting, which are particularly explicit in regions where old crystalline rocks are exposed on the surface. Fluorite deposits are reliable indicators of tectonomagmatic activity and their presence in regions where no other signs of tectonomagmatic activity have been detected can be used as an indicator of its probability, and of the possible existence of deposits that are characteristic of tectonomagmatic zones.

Figure 18 shows that it is a fact that virtually every deposit of cassiterite in the Bushveld is constrained in its location by the recognised geographical zones which may now be equated with fluorine-rich tectonic zones. So are the carbonatites and kimberlites - a particular association that was noted by Scheglov. It is obvious that future exploration in the Transvaal, and in the Bushveld Complex in particular, should take into careful account the existence, the locations and the implications of the fluorine-rich linear zones. In this sense the otherwise puzzling observation by Crocker (1974, p.7) is now understandable. It is as follows, and it relates to the Bushveld Complex.

"Of note is the complete lack of fluorite and other mineralisation in the two largest areas of granite, namely that forming the eastern lobe known as the Sekukuni area, and that forming the western lobe between Roodeplaat and the Pilanesberg".

The reason, now apparent, is that these barren areas mostly lie between the fluorine-rich tectonic belts that have been the subject of the preceding pages.

F. Thoughts on the Origin of the Deposits of Galena, Zinc-blende and Fluor-spar in the Dolomite Series near Zeerust.

Most early investigators considered only the various mineral deposits of Types I and II. Traditionally, these deposits, which are epigenetic, have been ascribed to an igneous source represented by the acid phase of the Bushveld Complex. These conclusions were based on popular and convenient supposition at the time, not on facts, or on any close geographical association of Bushveld granite and the ore deposits.

Only Kupferburger (1928), and Simpson (1965), considered the layered deposits of fluor-spar in addition to the ore-types mentioned above. They were apparently satisfied to ascribe all the various fluor-spar, lead,and zinc ores, including the layered deposits of fluor-spar (that is, deposits of Types I, II and III), to the same ultimate source; namely, to a speculative intrusion of Bushveld granite, or to "some intrusion such as the alkaline intrusives of Secucuniland, the Franspoort line, and the Pilanesberg". (Kupferburger, 1928,p.51).

Hammerbeck (1970) broke with tradition on two accounts; firstly, in proposing a sedimentary origin for the layered fluor-spar ore, and secondly, by proposing simultaneously (in substance) that the genesis of all the deposits of fluor-spar, and lead and zinc minerals in the dolomite was not necessarily the same. In effect, this meant that two different modes of origin, and two different times of mineralisation would have to be considered when the problem of the genesis of the deposits of Types I and II, and Type III, respectively, was considered in the future.

The matter is complex and there is great scope for the postulation of various combinations of ore-forming processes and sources. However, a vital point which has not been considered previously, is the newly-recognised fact that near Zeerust all the fluor-spar, and the deposits of lead and zinc minerals are localised, in a regional sense, on the west-south-western extremity of the Murchison Zone. In particular, the intimate spatial relationship that exists on the regional scale between the deposits of the economic minerals and the fundamental tectonic lineament that underpins the entire zone of enrichment with fluorine, must obviously be taken into account in future models of ore-formation in the dolomite in the Western Transvaal. Moreover, the fact that the tectonic lineament which underlies the Murchison Zone had a very pronounced influence on the pattern, and the character, of sedimentation of the dolomitic strata (see Fig.19), taken together with the fact that sedimentary ore-forming processes have been credited relatively recently to be vitally important in the development of some base-metal (and other) ore-bodies, necessitates that both these aspects be examined in relation to the Zeerust area. In the following pages the writer examines aspects of these matters and he attempts to weld them to produce a reasonable and cohesive picture of ore-formation in the Zeerust area.

1. Factors which Relate to Epigenetic Ore in the Zeerust Area

The layered fluor-spar deposits of Type III have, in the past, been ascribed to epigenetic agencies and, latterly, to synsedimentary agencies. The remaining ore-types, namely the stratabound lead ore, as on Doornhoek 305 JP, Rhenosterhoek 343 JP, and Bokkraal 344 JP (see Table 3), and the mineralised breccia-type and pipe-like bodies listed in Table 2, clearly are epigenetic - and this fact stands irrespective of the source or the nature of the mineralising solutions. As no research has been done anywhere which could throw light on the nature and the temperature of the ore-forming solutions, it is equally possible to ascribe the mineralisation to hot igneous emanations, (whether from alkalic or acidic source-rocks), or to cool, mineralised ground-water, or to any other hypothetical source which may appear to be reasonable.

Since, at the present stage, there are no factors which limit speculation as to the nature and the source of the epigenetic ore-forming solutions, the most important consideration must be one that is factual, namely, that the ores in question are confined to structurally disturbed linear zones in the dolomite, particularly major faults.

The above fact was demonstrated earlier in the text and the disclosures indicate that the mineralised pipes on Buffelshoek 301 JP and Witkop 302 JP are specifically included in the relationship. These pipes are the type-(ore) deposits which correspond to the "ore-circles" and the "circles" that were noted by earlier writers. The passage of time has proved that only two of the numerous "circles" that were discovered were ever found to be mineralised. On the assumption that the identical expression of the recognised circles on the surface reflects a causative and a structural similarity, it becomes apparent that the mere generation of these brecciated structures is not, in itself, an inviolable associate, or a direct cause, of mineralisation. Obviously, mineralisation was dependent on more than just the formation of a brecciated pipe-like body in the dolomite,and a more fundamental process must be involved. Apart from the mineralised pipes or "ore-circles", there is an obvious association between other bodies of breccia in the dolomite, and ore. (See Table 2). Like the mineralised breccia-pipes it is unlikely that the mere formation of a body of breccia (by whatever means) was the overriding cause of the mineralisation process in these bodies.

The very marked degree of folding and distortion of the dolomite in and adjacent to the major zones of faulting which control the geographic location of the more important bodies of ore of the types under consideration, has been discussed at some length. It is considered here that it is tectonic breccia which owes its origin to the disruption of the dolomite alongside the recognised zones of faulting, that was normally favoured as a locus of mineralisation. The selectivity, it is presumed, is because the recognised lineaments were also responsible for the transmission and the accumulation of the mineral-rich solutions.

Evidence has been presented which indicates that intense brecciation took place within the apices of some folds in the dolomite, for example, adjacent to the Bokkraal Fault on Rhenosterfontein 343 JP. It is instructive that a sample of the brecciated dolomite on analysis gave a value of 1330 ppm Zn. Of more than 230 rock-samples and soil-samples that were taken by the writer from sites in which ore minerals are not known to exist, this was the highest value of zinc that was recorded. Figures 4a and 15 illustrate that arching and contortion is also an integral part of the Vergenoegd Fault-zone. Reference to Figures 7 to 10 make it clear that there is a definite tendency for some of the so-called "breccia-type" or "pipe-like" deposits to be present as ellipsoidal, arched zones which "dip away" beneath unbrecciated dolomite, for example the deposits on Oog Van Malmani 333 JP, and Kaalplaats 330 JP. Figure 15 indicates that the lastmentioned deposit almost certainly formed in the crestal portion of a fold-structure. Table 2 records the effects of shaly "cap rock" in limiting the brecciation and the mineralisation in certain bodies. This further substantiates the conclusion that the (mineralised) breccia was a function of the competence of the enclosing rock, and the competence was presumably brought into effect during folding which attended the formation of the fault along which the deposits are aligned. It should be noted that Kupferburger (1928, p.51) concluded that the fluor-spar deposit on Oog Van Malmani 333 JP was "probably due to replacement laterally along the crest of a shallow dome-fold in the dolomite overlain by impervious layers".

In summary, as far as the deposits of Type I and Type II are concerned, the major zones of faulting, and fractures that are parallel to them, are of paramount importance. They caused disruption of the dolomite, and consequent brecciation - the latter, on occasion, clearly took place within the crestal portions of folds which themselves resulted from the stresses that were related to the faulting - and they also acted as the important channelways for the mineralising solutions. If this conclusion is correct then any other bodies of breccia which were not produced by the tectonic distortion of the dolomite (as discussed), could still suffer mineralisation provided they coincide (fortuitously) with the zone of influence of one of the relevant tectonic lineaments.

The conclusion is that the breccia-pipes on Buffelshoek 301 JP and Witkop 302 JP were mineralised only because they are located, by chance, within the Vergenoegd Fault-zone. The implication is that the co-existence of the breccia and the ore-solutions was of more significance, in these cases, than the fact that the breccia was formed by "spot-solution" at depth, and by slumping. In turn, this implies that any significant mineralisation of any other form of "dissolution collapse breccia" (Callahan, 1965) as mentioned on page 42, would still be dependent on the access of mineralising fluids by channelways within the laterally restricted fault-zones.

Exceptional flows of ground-water take place within the zones of influence of the Vergenoegd and Bokkraal Faults. (See Hall, 1910, pp.10 to 15). One is encouraged to speculate that this fact may be related to the deposition of ore-minerals, but the subject is beyond the scope of this thesis.

It may be seen that, on present knowledge, the epigenetic factors that are relevant to this study provide information which relates only to the preferred sites of deposition of the ore-minerals. The actual origin of the lead, zinc and fluorine in the deposits is more relevant to the following section.

2. Synsedimentary Ore-genesis in Relation to the Murchison Zone

The formation of ores of base-metal sulphides, and other minerals, by natural sedimentary process has been advocated for a very long time by some American, Japanese and European schools of thought, in regard to the genesis of the ore deposits of the Mississippi Valley-type, the Kuroko-type and the Kupferschiefer-type, respectively. (For example, see Siebenthal, 1915, pp.69 to 77). Only in the last two decades has the matter received concentrated attention and widespread credibility - largely as a result of the latter-day "pioneering" of Australian and other geologists (for example, King, 1965; and Stanton, 1955, 1960, 1961, 1966 and 1972).

A very large amount of geological information, and a voluminous literature, that is of relevance to the precipitation of base-metal sulphides within sedimentary accumulations that incorporate limestone, dolomite and or carbonaceous shale, has been summarised and presented expertly by Stanton (1972). The synthesis, together with specific recent contributions in regard to major bodies of sedimentary lead and zinc ore in Australia, for example at Mount Isa (Croxford, 1964, and personal communication), Lady Loretta (Cox, personal communication) and McArthur River (Cotton, 1965, Croxford, 1968, and Croxford and Jephcott, 1972), together with general research on a broad front, for example by Vine and Tourtelot (1970), Wedepohl (1964, in Wedepohl, 1969), and the Baas Becking Geobiological Laboratory in Canberra (personal communication), has proved conclusively the possibility of the sedimentary accumulation of a wide variety of economic minerals in particular sedimentary environments. The reason for the disclosures on pages 24 to 26 now becomes apparent: it is a fact that the palaeoenvironment in which the Dolomite Series was laid down is analagous, in many respects, with "model" environments which are favourable for the stratiform accumulation of ore or proto-ore of (sulphides of) lead and zinc.

Moreover, it is now acknowledged widely that an euxinic environment, like that which may exist within a linear, tectonic basin (for example, the Selati Trough) may be particularly favourable in respect of the sedimentary concentration of base-metal sulphides, like galena and sphalerite, in appropriate types of rock. One example is the huge lead, zinc, and copper ore body in calcareous black shale within Proterozoic rocks at Mount Isa in north-western Queensland, Australia. The ore-bearing strata are found within a sedimentary trough which corresponds with a tectonic megalineament (see Carter, Brooks and Walker, 1961, Fig.4, Fig.5D, and p.52; Bennett, 1965, map opposite p.274; and Wilson, 1972). Another is the McArthur River ore body in the Northern Territory of Australia. (Lambert and Scott, 1973).

The ore body near the McArthur River is particularly instructive and it is discussed in more detail below.

The McArthur River deposit (also known as the H.Y.C. deposit), contains ore-grade concentrations of galena and sphalerite. It occurs within a discontinuous belt of Proterozoic sediments that stretches from the north-western part of Queensland to the north-eastern part of the Northern Territory. This is an important lead, zinc and silver province which includes the similar deposits at Mount Isa and Hilton, and a number of smaller deposits of stratiform ores (in the sense of Stanton, 1972, p.541) of lead and zinc. The McArthur ore body is very large (over 200 million tonnes of ore). It has not been deformed structurally, or metamorphosed to any significant extent. Geochemical and geological data support a syngenetic origin for the ore. From the work reported by Croxford (1968), Croxford and Jephcott (1972) and Lambert (personal communication), there is little doubt that the ore deposit formed by the syngenetic (or early diagenetic) addition of metals and sulphur to the host-rocks, which were mineralised preferentially in restricted, subsiding, euxinic basins of deposition. These basins, which contain the ore, lie within the zone of the megalineament that coincides with the tectonically active Emu Fault. They are restricted to the easternmost, tectonically deepened, portion of a much larger, elongated, basin of carbonate sedimentation. (Compare Fig.19).

Metalliferous solutions are thought to have ascended in the zone of the Emu Fault. The fault was active during sedimentation and it delineates the eastern edge of the Proterozoic trough. The metalliferous solutions were trapped in favourable (tectonic) depressions in a shallow sea, and the corresponding sedimentary processes are now represented by the thickest sequences of black shales. Some of the related dolomites are stromatolitic. It appears that igneous activity, manifested as potash-rich beds of tuff in the sediments, was directly responsible for the availability of metalliferous solutions.

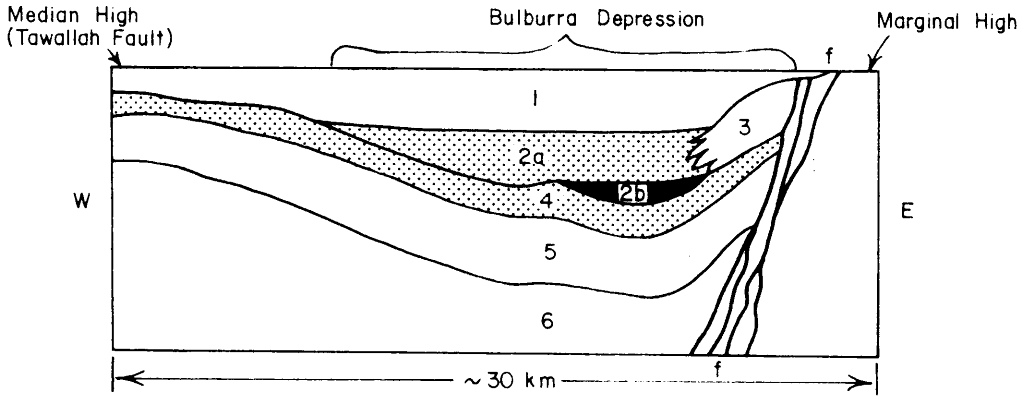
Lambert and Scott (1973) concluded from their studies, which involved a considerable amount of geochemistry, that the highest potential for the development of ore deposits of lead and zinc of McArthur type, exists within shallow, marine sedimentary sequences which contain high-potash, pyritic black shales that display major, widely dispersed Zn, Pb, As and Hg anomalies, bands of vitric tuff, and ferroan dolomites. The basal parts of the thickest sequences of black shales have the best potential, especially those which are located proximal to major faults. These manifested themselves in the tectonic deepening of the euxinic basins during sedimentation.

When the information, above, is compared with that given by Button (1973a and 1973b) and by Brandt and Le Roex (1945), there are seen to be definite similarities between the tectonic framework, and to a significant but lesser extent the lithologic framework, of the Bulburra Depression (within which the McArthur deposit is localised), and the Selati Trough (See Fig.21). The tectonic control of sedimentation within both zones of crustal weakness is wholly comparable. The Middle Proterozoic succession of carbonates, shales, siltstones and arenites at McArthur is the same, in a general fashion, as that which is found in the dolomitic strata, and in the underlying Wolkberg strata, in the Eastern Transvaal. The main discrepancy is the excessive preponderance of arenaceous strata within the formations that constitute the Wolkberg Formation (Wolkberg Group of Button, 1973a) below the Black Reef Quartzite. Even so, it is clear that the Anlage and Mametjas Members (following the nomenclature of Button, 1973a) are comparable directly with the ore-bearing Barney Creek Formation in the Bulburra Depression. On entering the Selati Trough, they thicken, respectively, from 100 metres to 500 metres, and from 130 metres to 400 metres, and they consist almost entirely of carbonaceous shales, tuffaceous mudstones, sandy dolomites, and dolomitic argillites. The transition zone at the base of the "Malmani Dolomite" (Button, 1973b) contains iron- and manganese-rich dolomite, a significant proportion of pyritic strata, and universal carbonaceous mudstone and shale. Its thickness increases considerably in the Selati Trough and it exceeds 200 metres. The transition zone is, likewise, comparable directly with the ore-bearing beds in the McArthur area.

All in all, the disclosures by Lambert and Scott (1973), when they are taken in conjunction with the strongly tuffaceous nature of the comparable sedimentary succession in the Selati Trough, makes it quite clear that these latter sediments exist in full accord with what has been concluded to be a geological environment that is highly favourable in respect of the development of stratiform deposits of lead and zinc ore.

On considering the Dolomite Series in the Zeerust area, after the appreciation of the aforegoing, it is apparent that here, too, there has been a tectonic deepening of the basin, and a thickening of the sediments, in coincidence with the

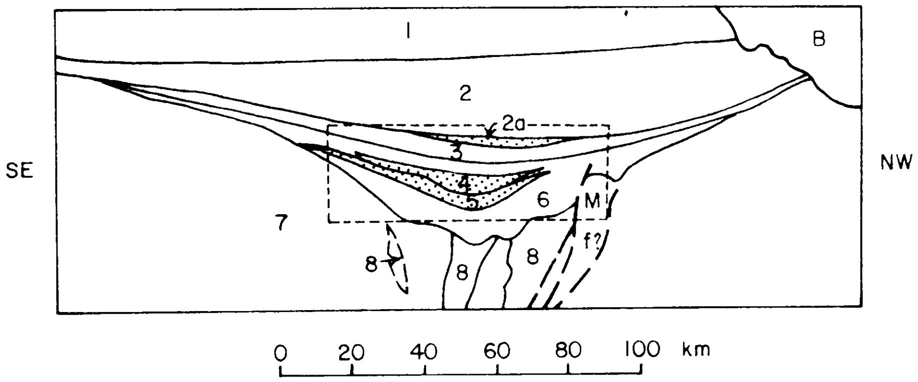
(a) Diagrammatic cross-section across the Bulburra Depression, McArthur River, N.T., Australia. (After Lambert and Scott 1973)



1. Reward Dolomite
2a. H.Y.C. Pyritic Shale
2b. McArthur Zn-Pb Ore-deposit
3 Cooley Dolomite
4. W-fold Shale
5. Teena and Emmerugga Dolomites
6. Underlying dolomites, siltstones, sandstones and cherts

(b) Diagrammatic cross-section across the Selati Trough, N.E. Transvaal, South Africa. (After Button 1973 a, fig. 6, and Plates I and II)

(Faults postulated by present author)



1. Pretoria Group
2. Olifants River Group. 2a = Transition beds
3. Black Reef Quartzite
4 Mametjas Member } Wolkberg Group
5. Anlage Member
6. Undifferentiated Wolkberg Group
7. Basement Granite
8. Greenstone remnants (Murchison Greenstone Belt)
M = Georges Valley Mesa
B = Basic intrusive rocks (Bushveld Complex)

NOTE: 1. Additional lithological data is given in the text (p.89) and in the papers noted above.
2. Note the smaller scale of diagram (b) and the almost exact equivalence, tectonically, and scale-wise, of the area indicated in diagram (a).
3. Ornamented areas represent black shales.

Fig.21 SCHEMATIC COMPARISON OF THE BULBURRA DEPRESSION AND SELATI TROUGH

Murchison Zone. This fact becomes clear on evaluation of Visser's isopach map of the Dolomite Series in the Transvaal. (Fig.19). However, no very thick succession of arenaceous strata developed, as they did in the Wolkberg Formation in the Selati Trough itself, some hundreds of kilometres to the east-north-east. It is apparent that the relative thickening was brought about by the deposition of calcareous (and argillaceous) strata and, by comparison, the fact obviously tends to enhance the theoretical potential for the synsedimentary concentration of ore and proto-ore of lead and zinc in this area.

It is clear that the potential for ore-grade deposits of syngenetic lead and zinc sulphides within the stratigraphic zones mentioned above, should not be disregarded. (The potential is well worth the testing). However, it is in relation to the "Source Bed Concept" of Knight (1957) that the aforegoing can presently be related more definitely to the epigenetic deposits of galena and zinc-blende in the Zeerust area. Clearly, even if all the theoretical factors are not favourable, there may still have been a tendency towards the deposition of smaller amounts of sulphides(?) of lead and zinc in shaly horizons in the Dolomite Series, particularly in and near the tectonic trough which coincides with the Murchison Zone.

In the Dolomite Series, beds of black carbonaceous shale are generally thin and totally subordinate, so their efficacy as source-beds (or ore horizons) could be contended. However, even very thin horizons of the appropriate type of sediments can be enriched significantly with metals. For example, Wedepohl (1971, p.268) indicated that the "Kupferschiefer" has an average content of zinc in excess of 0,3 per cent, throughout an area that exceeds 30 000 square kilometres, although the average thickness of the bed is only 0,3 to 0,5 metres.

The discussion will now centre on fluor-spar.

Early laboratory investigation of CaF_2 lead to the belief that it could not precipitate inorganically as a sedimentary deposit (Wedepohl, 1969). According to the same writer, however, (1969, p.9-k-6), it has been proved since by Russian investigators, that the precipitation of fluorite in carbonate-rocks is possible under certain conditions; for example, when fresh river-water flows into the fluorine-rich saline basin. Strakhov (1970, pp.503 to 505) makes the following observation, which is very pertinent in relation to the Zeerust area, where the deposits of layered fluor-spar occur near the top of the dolomite. "Fluorine forms an independent solid phase in saline deposits. It has a low solubility and therefore accumulates in sediments at relatively low salinites, reaching its maximum in dolomites, in deposits forming at the end of the carbonate stage".

Details given by Rankama and Sahama (1949, p.763) and Schulz (1964) also prove the ability of fluorite to be concentrated as a natural sedimentary accumulation in appropriate environments. The prime factors appear to be the concentration of fluorine in alkaline, saline, marine environments from which dolomitic strata are being deposited. In these environments the physical and chemical changes which take place after the influx of fresh water can lead to oversaturation with CaF_2, and precipitation of fluorite. (Wedepohl, 1969, p.9-K-8). Truswell and Eriksson (1975), in respect of a comparable environment, concluded that the same agent, namely meteoric water, was responsible for the precipitation of silica, leading to the formation of chert. It is, therefore, perhaps more than coincidence that the deposits of layered fluor-spar near Zeerust, which have been suggested already to be primary sedimentary deposits (Hammerbeck, 1971), are situated below the Giant Chert, and close to it. Crockett postulated that the formation of the Giant Chert was the result of contributions of silica to the dolomite sea by way of silica-rich streams of gas that emanated from recognised sites of solfataric vents on the tectonically-active margins of basins in south-eastern Botswana (Crockett, 1972, p.282). Crockett suggested that the gas-streaming continued at least until the time of deposition of the Giant Chert "which may have been formed following a particularly strong discharge". The active tectonic zones that are supposed to have controlled the gas-streaming are aligned markedly parallel to the Limpopo Mobile Belt and to the Murchison direction (Crockett, 1971b, Fig.4). It seems plausible that the tectonic activity that must have been ultimately responsible for the strong discharge of silica-rich gases in south-eastern Botswana towards the end of the period of carbonate sedimentation, would have had a concomitant manifestation within the unstable tectonic zone (that coincides with the Murchison Zone) that existed only 100 kilometres to the south. From what has gone before it is likely that any similar emanations of gas, or any leakage of volatiles upwards, would have been relatively rich in fluorine (in addition to silica). This state of affairs could have led to the local oversaturation of the sea-water with CaF_2, and the resultant precipitation of fluorite (at a site within the Murchison Zone that is represented now by the locus of the deposits of layered fluor-spar) immediately prior to the period during which silica became saturated, and was precipitated to form what is now Giant Chert.

3. Conclusion

From the comparative models that were discussed in this section, it is reasonable to conclude that lead and zinc (as sulphides?), and fluorine (as fluorite), did form primary sedimentary accumulates within the Dolomite Series, and that this took place, particularly, in a linear tectonic zone that coincides with the sedimentary axis of the Dolomite Series in the Transvaal basin. This tectonic zone is now defined on the surface by the fluorine-enriched Murchison Zone. It is concluded that the layered fluor-spar ore of Type III represents a primary fluoriferous sediment; whereas the lead and zinc minerals, and the fluor-spar, in the deposits of Types I and II, were derived from the primary sedimentary accumulations by processes of solution, transportation, concentration and precipitation. The dependence of the epigenetic deposits (Tables 2 and 3, or Fig.16), on structural zones that were generated soon after the emplacement of the Bushveld Complex leads to the conclusion that the processes just mentioned probably took place in response to heat-effects that were related to the metamorphic aureole of the Complex.

The observations and the deductions in the preceding pages make the picture of ore-formation in the study-area relatively cohesive and complete. The recognition of two different primary sources (that is, sedimentary and igneous) for the different deposits of fluor-spar is not (any longer) necessary - nor can the evidence justify a recourse to a hypothetical igneous body which could be taken to account arbitrarily for all three ore-minerals, in all three types of deposits.

VII. SUMMARY AND CONCLUSIONS

An area of approximately 4300 square kilometres south of Zeerust was mapped photogeologically to determine the major controls of the deposits of galena, zinc-blende and fluor-spar which exist within the Dolomite Series of the Transvaal System.

Three types of ore-occurrence were recognised. Deposits of Type I contain variable proportions of galena, zinc-blende and fluor-spar in bodies of brecciated dolomite; two of these ore bodies are regular and are shaped like pipes, the others are not. Deposits of Type II have the form of irregular masses and nodules of galena, with subordinate amounts of the other minerals, in concordant zones in the dolomite in close proximity of the disconformable terriginous sediments of the overlying Pretoria Series. The deposits of Type III are fluor-spar deposits in which the fluor-spar exists in the form of grains, blebs, and layered disseminations within concordant stratigraphic zones,or layers, closely below the horizon of the Giant Chert which caps the dolomite in the study-area.

The existing records do not interrelate the various modes of occurrence of the three ore minerals adequately because the literature is compartmentalised artificially on the basis of particular ore-minerals. Clarification of the history of mining revealed that in certain individual ore deposits of Type I different ore-minerals were exploited at different times and, in addition, similar ore bodies on adjacent farms were mined simultaneously for different minerals.

The deposits of Types I and II are clearly of epigenetic origin and they are similar to important type-deposits in the Mississippi Valley. The comparison was one of the factors which motivated the photogeological study but the comparison is misleading. In the study-area the corresponding ore bodies are (or were) very small, and they justified only primitive, intermittent, exploitation before their reserves of ore were exhausted.

The fluor-spar deposits of Type III represent enormous resources of fluor-spar, stated to represent half the world's known reserves of this commodity. These layered deposits possess a number of features which resemble those of the fluor-spar deposits in Illinois and Kentucky.

Academic studies have been lacking, but the geology has been mapped on the ground on numerous occasions. No philosophy of the major controls of the mineralisation eventuated from the earlier work, nor did previous workers provide firm data to support their suppositions, opinions or prognostications. Abstract hypotheses on the structural control of the ore deposits in the study-area were commonly linked with the supposition that the source of the ore-minerals was a hidden igneous intrusion.

Finite limitations of the photogeological mapping, for example the problem of the recognition and identification on the photographs of bodies of chert _in situ_, were partly overcome by the use of photographs on the scales of both 1:20 000 and 1:50 000. The photogeological overview was, however, of distinct advantage and, complemented by diligent stereoscopic annotation of the photographs, it allowed the recognition and the interrelation of a multitude of lineaments, and some distinct trends of lineaments, within the study-area.

In the study-area two sets of lineaments are important. Their average trends are, respectively, approximately north-north-west, and approximately east-north-east.

The lineaments which strike approximately north-north-west comprise the older set. They were imprinted during two different periods, or stages, but in response to the one fundamental pattern of stress in the craton. In the first stage, large fractures formed in the dolomite _prior_ to the emplacement of the Bushveld Complex, and in places they were silicified and formed large veins of quartz. Much later, in the second stage of the imprint of the north-north-west tectonic trend, two major zones of faulting formed _as a consequence of_ the emplacement of the Bushveld Complex. The two zones of faulting, namely, the Bokkraal Fault-zone and the Vergenoegd Fault-zone, were recognised for the first time as a result of the photogeological approach to the mapping. The average direction of strike of the two fault-zones is slightly west of north and it is rotated clockwise a few degrees from the average direction of strike of the numerous major (silicified) fractures that formed earlier.

The stress-pattern which controlled the development of the abovementioned fractures and faults was a function of tensional stresses which attended the development of the Koppies continental arch, a fundamental tectonic feature of the craton. The axial zone of the arch is situated immediately beyond the western boundary of the study-area. The axis is aligned in the approximate north-north-west direction and, at the times of their respective inceptions, the respective directions of strike of both the major fractures and the faults corresponded with the direction of the axis of the arch. The inconsiderable divergence between the average strike of the major fractures and the average strike of the zones of faulting is believed to be a function of the slight angular migration of the axis of the arch in the clockwise direction, through a period of time.

The second of the important sets of lineaments in the study-area, namely that which has an average trend in the east-north-east direction, comprises fractures that were accentuated by the intrusion of basic dykes. Two of the dykes are long, parallel, and obvious under the stereoscope (although dykes seldom crop out and are not readily appreciated in the field), and they constitute what was named the "Twin-dyke Lineament". Local evidence, in the form of palaeoerosion of the dolomite, unusual basic intrusions, and a possible major "break" in the basement, led to the conclusion that this lineament coincides with, and is related to, a preferentially active tectonic zone.

It was shown, and it was concluded, that the Bokkraal and the Vergenoegd Fault-zones, and fractures which are parallel to them, exercise the dominant control on the localisation of the epigenetic mineral deposits of Types I and II.

1. All the ore bodies of Type I are confined within the zone of structural influence of the Vergenoegd Fault.

2. Including the deposits of Type II and a number of other occurrences of galena in the dolomite which have no economic significance, but are important in the statistical sense, 22 out of the 23 deposits that are documented from the study-area have a direct spatial relationship with faults and fractures that belong to the set of lineaments which trends in the general north-north-west direction.

In relation to the fluor-spar deposits of Type III the major local control of the mineralisation was stratigraphic and there exists no direct relationship between individual deposits and <u>local</u> lineaments.

The two sets of lineaments in the study-area were evaluated in their broader regional context by reference to the literature. The following were the conclusions.

1. The set which follows the approximate north-north-west direction, and which reflects the effects of the Koppies continental arch, is also related to the well-known tectonic lineament that is named the "Franspoort line". Of more direct relevance, the Bokkraal and Vergenoegd Faults are but two of a number of parallel and related "zones of adjustment" of the floor of the Bushveld Complex.

2. The set of lineaments which follows the approximate east-north-east direction reflects the well-known Murchison tectonic direction, (which is also displayed by the long-lived Limpopo Mobile Belt), and the Twin-dyke Lineament corresponds with the line of prolongation of the axis of the Murchison Greenstone Belt.

The plotting on a geological map of the locations of all the known deposits of fluor-spar in the Transvaal revealed the fact that all the fluor-spar deposits, and the highest values of fluorine in ground-water, are confined within narrow, linear geographical zones. These zones are up to 650 kilometres long and up to 30 kilometres wide, and they form a sparse but definite quasi-orthogonal grid. The linear zones trend east-north-east and north-north-west: that is, they are parallel to the trends of the important sets of lineaments in the study-area, and they are also parallel to the well-known Murchison and Franspoort tectonic directions.

The zones of enrichment with fluorine also constrain the locations and the distribution of all the known alkalic complexes, carbonatites, kimberlites, and tin-bearing granites in the Transvaal.

Following reference to the literature and to the results of previous photogeological mapping in the Moloto-Rust de Winter area, it was concluded, as a general premise, that all of the fluorine-rich linear zones, as recognised, are coincident with fundamental, long-lived, tectonic lineaments in the Transvaal. (The manifestation of the tectonic instability in these zones of enrichment with fluorine is most apparent in relation to the <u>Murchison Zone</u>. This zone is co-axial with the Murchison Greenstone Belt and it was shown to coincide with, and reflect, a linear tectonic zone of continuous instability for a period that probably exceeds 1 billion years.)

A major, tectonically deepened sedimentary trough defines the axis of sedimentation of the Dolomite Series in the Transvaal Basin. The conditions of sedimentation in the trough were highly favourable in regard to the accumulation in the sedimentary rocks of fluorite, and sulphides of lead and zinc, in the form of primary sedimentary precipitates. In its geographic location, the axis of the trough of sedimentation coincides exactly with the Murchison Zone, and the entire area of mineralised dolomite south of Zeerust is situated within this zone. The relationship was concluded to be of genetic significance and, unlike previous hypothesis on the origin of the ore-minerals in the study-area, it has a factual basis.

The following conclusions were finally drawn with respect to the origin of the deposits of fluor-spar, galena, and zinc-blende in the dolomite south of Zeerust.

1. The epigenetic mineral deposits of Types I and II owe their origins to the precipitation of the ore-minerals from solutions that derived their contents of lead and zinc and fluorine from sedimentary "source beds". The latter were enriched with the above elements, preferentially, within a tectonic trough of sedimentation that reflects the Murchison tectonic lineament and is mirrored on the surface by the Murchison zone of enrichment of rocks and ground-water with fluorine.

2. The layered deposits of fluor-spar of Type III are sedimentary deposits. Their main local controls are stratigraphic, but in the regional sense the main controlling factor is the primitive, fluorine-rich Murchison tectonic lineament with which they and their host-rocks coincide. The deposits of Type III are, in all probability, the source-beds from which was derived the epigenetic fluorite in the other two types of deposits.

3. The mobilisation of the elements from the sedimentary source-beds probably took place as a function of the effects of intrusion of the Bushveld Complex, but contrary to the opinions of previous workers, the Bushveld granite is not believed to have been the source of any of the ore.

4. The major zones of faulting acted as the important channelways for the epigenetic ore solutions.

5. The deposits of Type I resulted from the mineralisation of bodies of breccia in the dolomite that exist within the zone of structural disturbance of the Vergenoegd Fault. Most of the mineralised bodies of breccia developed in the crestal portions of fold-structures in the dolomite and they are of tectonic origin. Two of a number of pipe-like bodies of

(slump-) breccia that were formed by "spot-solution" of the dolomite in depth, were mineralised only because they existed, fortuitously, within the zone of influence of the Vergenoegd Fault.

Long narrow, linear, slump-structures, up to 25 kilometres long and up to 0,5 kilometres wide, exist in the dolomite south of Zeerust. They were recognised for the first time during the stereoscopic reconnaissance which preceded detailed photogeological mapping. In the field they are inconspicuous, and in the past they were overlooked completely. Recent workers have been attracted by the linear magnetic anomaly with which they are associated. Identical structures in similar lithological and mineralogical settings in the United States of America carry ore. The mineral potential of these major linear slump features in the study-area is high and they should be investigated thoroughly.

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Figure 14 is reproduced with the permission of the Director of the Geological Survey, Pretoria. Various members of the staff of the Geological Survey co-operated in the provision of information by discussion or by correspondence, particularly Mr. I.T. Crocker. Early in 1975 Dr. J.E.J. Martini of the Geological Survey discussed with the writer aspects of his recent research on fluor-spar south of Zeerust. At that time the first draft of the writer's thesis was complete and it was a condition of the discussion that the writer would make no reference to this work until it was published by Dr. Martini. To the present (August 1975) none of the results of Dr. Martini's research have been made public, but it is relevant that many of Martini's interim conclusions differ significantly from those drawn by the writer.

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APPENDICES

APPENDIX A. ANCILLARY OBSERVATIONS AND COMMENTS

A. Possible Fenitisation West of Slurry

Hammerbeck (1967) described a deposit of sericite that is found beside a fault within layered tuffs, which he correlated with the Soetlief Formation of the Dominion Reef System, on Benadeplaats 93 JO, approximately 1,6 kilometres north of the hamlet of Buhrmannsdrif. (See Fig.4a). The co-ordinates are given as $25^{0}48'$E and $25^{0}48'$S and they identify a locality west of the base of the Black Reef Series, in a position which is close to the axis of the Twin-dyke Lineament if the latter is extended to the west-south-west.

Of particular interest is the fact that the sericite is accompanied by nepheline, "needles of aegerine-augite" and calcite. Sericite is exposed in two large excavations approximately 0,8 kilometres apart, and immediately to the north of them is a fault which strikes east-north-east and is marked by a silicified breccia.

The deposit was ascribed to the selective replacement of tuff by sericite, following active circulation of ground-water, and possible hydrothermal action next to the fault. No thought was given to the origin of the nepheline and the aegerine-augite.

Hammerbeck apparently did no mapping. Little attention was paid to weaker effects of alteration, whether sericitic or alkalic. The fact that the two excavations are 0,8 kilometres apart indicates that intense sericitisation is relatively widespread, and it may be assumed from the details given, that a lower intensity of sericitic and alkalic alteration exists over an even wider area. The present writer's hypothesis, on the basis of the observations by Hammerbeck, and following previous discussion about the tectonic controls of carbonatites and alkalic complexes in the Transvaal is that this alteration on Benadeplaats 93 JO is a form of fenitisation; that is, it is a metasomatic affect that is related to a hidden body of carbonatitic or alkalic rock that was intruded within the tectonic megalineament that corresponds with the Murchison Zone.

If the hypothesis is correct, one may ask why the visible effects of the fenitisation process are (on first appearance) subdued to the extent that they have not been recognised previously in relation to what they represent. One explanation may concern the nature of the lithotypes that surround, and overlie, the hypothetical intrusion. Specific information on the lithotypes that constitute the host-rocks for the altered tuffs is not available from Hammerbeck's record. The photogeological mapping did not distinguish between rocks of the Ventersdorp and Dominion Reef Systems, nor was any particular attempt made to do so, because the occurrence of sericite and alkalic minerals was not known to the writer at the time of the original work. The Dolomite Series was, in any event, accorded prime interest and the locality was not visited in the field.

It is probable that the sericitised pyroclastic rocks are actually interstratified within the Ventersdorp System, which is composed largely of basic volcanic rocks*. The significance is that the alkalic body would have intruded rocks that are dominantly basic. The general basicity of the over-all environment is confirmed by Hall and Humphrey (1910, p.43) who recorded the fact that from Ramathlabama Spruit to Rooigrond "the area is covered by basic igneous rocks of various types". The importance of the observation is that ninety per cent of all known carbonatites have been emplaced in an environment of granite and gneiss, and the result is that effects of fenitisation that have been documented in overwhelming relation to acid rocks, are commonly accepted as "normal". On the other hand, fenitisation is not documented well in relation to basic rocks (Ferguson, personal communication; Ferguson and Currie, 1972; and Verwoerd, 1967, p.144 and pp.269 to 270) and it is reasonable to expect that effects of the metasomatic process may exist in these rocks, although they may not be the same as the "normal" effects.

While traversing in the field during the investigation of photogeological features, an epidotised vesicular rock was located in float on Grootvallei 94 JO, 0,8 kilometres south of Buhrmannsdrif siding. Hall and Humphrey (1910, p.44) make reference to what is obviously the identical metasomatised lava on "Buhrmansdrift No.105".

Five things are significant here.

1. Within a much larger area (of basic Venterdorp rocks) that was mapped by Hall and Humphrey (1910) the epidotisation of basic lavas was recorded only in the <u>one</u> locality - and the occurrence was unique to the extent that it warranted a particular description.

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* The distinction between the Dominion Reef System and the younger Ventersdorp System in this region is contentious. (See Crockett, 1971a, pp.18 to 21; and Haughton, 1969, p.118). It is believed that the layered tuffs, in which the sericitic alteration is strongest, were classified incorrectly by Hammerbeck with the group of acid rocks that are older than the Ventersdorp System. (see particularly Crockett, 1971a, p.18).

2. Epidote is known very well as a metamorphic product of igneous and sedimentary rocks in lime-rich environments (Ford, 1958, p.622). The lime could, conceivably, be derived from the host-rocks — or from a carbonatite.

3. There is a coincidence of the localities in which the minerals sericite, nepheline, aegerine-augite, and epidote are found.

4. The locus of the effects of alteration lies within the Murchison Zone, as mentioned previously.

5. The locus of the effects of alteration coincides with a strong magnetic lineament that is associated with the linear slump-structures, and the "breaks" in the basement that are related to them, which were discussed on page 54 (See Fig.14).

The sericite, the nepheline, and the aegerine-augite have already been ascribed to fenitisation processes, so it is reasonable to consider the epidote in the same light. Verwoerd (1967, p.264) disregards epidote as a mineral within fenites, although Heinrich (1966, p.81) notes its development in fenitised amphibolites near the carbonatite at Iron Hill, Colorado. At present the writer's unproved contention is that, in the future, epidote will be proved to be a normal effect of the fenitisation of basic rocks under certain conditions. Therefore when the locality is studied more closely the possible lack of relationships which are characteristic of fenites in acid rocks should not detract from the distinct likelihood that there is a hidden alkalic intrusion in the basic rocks near Buhrmannsdrif.

What has been said, in effect, is that the epidote was not recognised as an effect of fenitisation because no evidence had been noted to support the intrusion of an alkalic body (or any other). It is pertinent that in areas elsewhere, the aegerine found as a coating on joints in granitic rocks was recognised as a mild effect of fenitisation only because the existence of a carbonatite had been proved (for example, the Dorowa Complex, Rhodesia; and Iron Hill, Colorado, see Heinrich, 1966).

The disposition of the hypotheticalintrusion is speculative. The composition is, of course, entirely unknown, but obvious possibilities are alkalic, carbonatitic and kimberlitic rocks. Figure 14 tends to indicate that there are no magnetic data which confirm the existence of a discrete plug-like intrusion, although the scale of the air-borne reconnaissance survey, and the marked magnetic response of the basic lavas, do not allow definite statements to be made in this connection. The coincidence of the zone of alteration with the very strong magnetic lineament that coincides with the Strydfontein Trough, and other troughs that were described, (see also Fig.14), raises the strong possibility that they are related to one another. The evidence was taken to indicate that the magnetic lineament is a function of a "break" in the basement, and that the "break" existed prior to the deposition of the Dolomite Series. Accordingly, it is quite possible that the hypothetical intrusion was also intruded before the time of commencement of the deposition of the Transvaal sediments. (The influence of the Murchison tectonic direction was, of course, in existence at that time, and the fortuitous coincidence of both the anomalous "break" in the basement and the tectonic lineament that corresponds with the Murchison Zone was, possibly, a factor which controlled the location of the intrusion). There is no information which shows, or even suggests, that there has been any metamorphism of the dolomite, which is exposed barely 3 kilometres east of the centre of fenitisation, that could be related to the body that brought about the very strong, widespread metasomatic effects in the Ventersdorp lava. The negative evidence tends to uphold the suggestion that the fenitisation took place before the deposition of the Transvaal System. The corollary is that the hypothetical alkalic body should not be viewed as a possible direct source of the epigenetic fluor-spar in the deposits south of Zeerust.

This thesis is based on photogeological mapping and regional geological concepts. It is significant that a new dimension was added to the isolated description of a deposit of "sericite" solely because of the application of a totally different scale of thinking that is a consequence of the photogeological overview.

B. The Relationship between Deposits of Fluor-spar and Deposits of Cassiterite in the Bushveld

1. General

It is generally believed that tin is commonly transported in the form of its highly volatile compounds, tin tetrafluoride, and tin tetrachloride (Hesp, personal communication). It is also recognised that deposits of cassiterite are in places found in relatively distinct linear zones, or belts (For example, see Wright, 1970; Schuiling, 1967; and Hosking, 1970; see also Hunter, 1973, p.60). Thus, the association of deposits of cassiterite with fluor-spar, and with tectonic megalineaments, is well known - but it is considered by the writer to be unusual, and remarkable, that a combination of the two associations is displayed so directly as they are in the Bushveld, and so well. (As far as the writer is aware there is no worthy comparison).

Scheglov (1969) attributed "tectonomagmatic activity" and "self-activation" to linear tectonic zones that are characterised by an enrichment with fluorine, and the direct linear, spatial relationship that exists in the Bushveld between deposits of fluor-spar and deposits of cassiterite, clearly upholds the genetic association of the two minerals. When the directness of this association is considered in relation to the discrete, long, linear zones in which fluorine is enriched throughout the Transvaal, it is possible to discuss Scheglov's observation in specific terms, and the implications have a bearing on the future exploration for cassiterite in the Bushveld.

The evidence and the facts that were marshalled led to the conclusion that the tectonic lineaments in the Transvaal which now correspond with fluorine-enriched linear zones on the surface, were extant at a very early time, that is, in the Archaean. There are also grounds for believing that one of the characteristic features of these tectonic lineaments in the craton (according to Scheglov, 1969), namely an enrichment with fluorine, was also manifested at a very early stage.

Hammerbeck (1970) provided specific facts to support the possibility that the layered deposits of fluor-spar of Type III are of sedimentary origin, and Button (1973c) confirmed the possibility, by noting that these deposits are restricted to a definite lithostratigraphic zone in the dolomite (mixed zone). Therefore, including the information that has already been presented in this report, the evidence indicates that the tectonic megalineaments were enriched with fluorine prior to, and during, the early Proterozoic. The sedentary geochemical nature of fluorine (in geographical terms) has been noted, and a combination of the two observations leads to the general conclusion that the Transvaal System in the Transvaal was actually deposited on a basement that incorporated linear tectonic zones in which the rocks were significantly enriched with fluorine.

2. The Role of Fluorine

Various processes have been held responsible for the origin of magmas from which stanniferous granites were generated, among them, commonly, the anatexis of pre-existing crustal rocks which contained tin-bearing minerals. (For example, Hosking, 1970, Fig.24). In particular, after a considerable amount of research, the origin of the various granites in the Bushveld Complex was related to the same general process (Lenthall, 1972, pp.29 and 32). Button suggested that the Bushveld granites owe their existence to the partial melting of the basement granites below the Transvaal System following the depression of the crust by the overburden of sediments, which exceeded 11 kilometres (Button, 1973c, p.19). From what was noted above, the crustal rocks which suffered anatexis would have been relatively rich in fluorine in places and in this connection it is important to note a significant property of fluorine: that is, fluorine behaves as a flux. For example, according to Wedepohl (1969), Wyllie and Tuttle (1961), who investigated the system "granite - H_2O - HF", showed that the addition of even a small percentage of HF produces a marked depression of the melting temperature of the rock, and further additions of HF produces similar, but smaller, effects.

It follows, that when the physical and the chemical conditions of a mass of buried rock approach anatectic proportions, those masses which contain fluor-spar, or minerals which act as hosts to fluorine, will be melted preferentially, and easily mobilised.

3. The Role of Volatiles

The role of volatiles in the transport and the concentration of tin in late-stage magmatic differentiates, for example, by the process of "volatile stripping" (Lenthall, 1972, p.34) is commonly acknowledged. Much less often is the concept of "volatiles" qualified by specific reference to particular agents, and, as far as the writer is aware, little definite information is available regarding the probable identity of the main agent of transport of the tin in particular situations. The Bushveld Complex represents one environment where it at least seems reasonable to predict that fluorine was the main transporting agent in the volatile-rich "melts"; that is, in what might be termed "fluorine-fluxed anatectic magmas". In the Complex the tin-bearing granite is the Bobbejaankop Granite, and, clearly, all Bobbejaankop Granite which is known to contain cassiterite is confined to the fluorine-rich linear zones, as recognised. (Fig.18). The Bobbejaankop Granite represents a highly fractionated, volatile-rich magma. It is postulated by the writer that the tin-bearing granite has a dual dependence on the role of fluorine; firstly in relation to its genesis by low-temperature anatexis, and secondly, in relation to the volatility and the transport and the concentration of the tin. If this is accepted, then the spatial relationship that exists between the deposits of fluor-spar and the tin-bearing granite in the Bushveld has a very deep, fundamental, genetic basis, that is much more significant than might have been realised previously.

Lenthall (1970, 1971, 1972) undertook what was probably the most detailed and comprehensive study of the acid rocks of the Bushveld Complex, although owing to his tragic, untimely death, no final summary was given. Lenthall believed in the derivation of the Bushveld granite by the partial fusion of pre-existing granitic crust. Through progressive reasoning (Lenthall, 1972, pp.32 to 34) he concluded, as a main consideration, that it is impossible that the Bobbejaankop Granite was derived at any considerable depth and thereafter brought close to the surface. The basic foundation of his reasoning was that the onset of fusion of the granitic material took place under "normal geothermal conditions". On his accepting the necessity, in his view, for a low partial-pressure (due to water) on the granitic material, he envisaged, and in fact concluded, that "the fusion of the material which constitutes the Bushveld granite occurred at a depth of between 30 and 35 km when the ambient temperature rose to between 900^{o}C and 950^{o}C". He also concluded that "the Bushveld granite magma must have had an extremely low volatile content for it to have risen through the great distances indicated". (That is, indicated on the basis of his reasoning that only a very hot and "dry" magma could have ascended through the vertical distance that he envisaged, without recrossing "the [normal] melting curve", and solidifying at depth).

Lenthall seemed to have not been aware of the very definite linear spatial relationship that exists on the regional scale between deposits of fluor-spar and deposits of cassiterite in the Bushveld Complex, and he completely overlooked the role that would have been filled by fluorine in the lowering of the melting-point during anatexis of the crustal rocks. Normal geothermal conditions might have applied, as he specifically assumed, but universal, normal, conditions of <u>melting</u>, which he assumed tacitly to have existed, almost certainly did <u>not</u>.

It is envisaged that the tin-bearing Bobbejaankop Granite is the result of anatexis of crustal rocks in loci which were particularly enriched with fluorine, and that this anatexis took place at depths that were considerably less than Lenthall suggested: moreover, the resultant magma was comparatively cool, and was particularly enriched in the volatile fluorides.

Lenthall's research, when it is eventually published in full, may, and should, have a significant influence on future research projects which are related to the Bushveld granite. However, the significance of the above is that, in relation to the genesis and the emplacement of the tin-bearing Bobbejaankop

Granite, Lenthall's basic premise, and therefore his conclusions, are, potentially, grossly invalid; and as far as other Bushveld granite is concerned, the error may be one of degree.

4. "Path-finders" in Exploration Geochemistry

One problem in the exploration for primary deposits of cassiterite is the determination of which granites are potentially tin-bearing, and which are not. The solution is not simple; to date no clear-cut mineralogical or chemical distinctions have been defined which can be used to differentiate mineralised granites from barren granites. (See Hunter and Lenthall, 1971, p.3). Hunter (1973, pp.57 to 59) reviewed the problem, which has focused particularly on the trace-element geochemistry of the rocks and their contained minerals. The reviews are a tacit diction of the fact that, although many and varied attempts to distinguish barren granites from tin-bearing granites have been based on the role played by volatile-stripping in the concentration of the various trace-elements, the volatiles themselves have generally been overlooked as potential avenues for the recognition of tin-bearing granites. It has been commonplace for researchers to resort to statistics of relatively complicated interrelationships between selected trace-elements, with little meaningful result as far as the exploration for deposits of cassiterite is concerned. On occasion, the research embodied the involved and intricate separation of fractions of selected minerals from granitic rocks, and their analysis for ranges of trace-elements: by this step the earlier and simpler, but also unrewarding, analyses of the "whole-rock" for selected trace elements was superseded.

Recently, analyses of rocks for their contents of chlorine and fluorine have yielded some results which can be correlated with the existence of economic elements in the rocks (see Stollery and others, 1971; Kesler, Van Loon and Moore, 1973; Kesler, Van Loon and Bateson, 1973). Hunter (1973, p.59) also records that Tausen and others (1968) found that mineralised granites from eastern Siberia contain four to five times as much F, (and Nb and Ta) than un-mineralised granites. Thus there is evidence which suggests that the "volatiles" or the "transporting agents" may, in fact, be of as much use as path-finder elements in the search for tin-bearing granites as the trace-elements themselves. It seems likely that in circumstances in which it is possible to suggest, or predict, the identity of the main transporting agent, (for example, fluorine, in the Bushveld Complex) the step of using that element as a path-finder in geochemical exploration is justified.

The writer, however, cannot see the sense of restricting the attempted recognition of path-finders to one of the groups (that is, to trace-elements or to "transporters"). Obviously, both are interdependent. In the example of the Bobbejaankop Granite, and other granites in the Bushveld, it is not unreasonable to suggest that useful relationships between the values of tin and the other trace-elements may be recognisable only after due note is also taken of the content of fluorine in the rock, or in the selected mineral-fraction, or in both. For example, within a tin-bearing granite, the existence of biotite with a low content of Sn may possibly be due to the fact that much of the tin that was originally in the biotite was "stripped" by volatiles and was concentrated elsewhere, in deposits of cassiterite. Alternatively, an unmineralised granite may have a high content of trace-elements (for example Sn in biotite), which, although it is of superficial interest, may be irrelevant - simply because no transportation and concentration of the elements could have taken place owing to the lack of volatile fraction. In other words, the distribution and the concentration of trace-elements in a rock or in a mineral-fraction may be meaningless in relation to the effective recognition of tin-bearing granites, unless the data are related to the existence and the role of the transporting agent.

The conclusion is that in the Bushveld Complex, geochemical research and geochemical exploration that is related to tin-bearing granites, should in the future take serious account of the distribution, the concentration, the influences, and the effects, of fluorine - on all scales of the evaluation.

C. Analysis of Fractures in the Acid Rocks of the Bushveld Complex

On considering the expanded results of the photogeological mapping near Zeerust in conjunction with the information derived from the earlier photogeological investigation of the area which contains deposits of cassiterite and fluor-spar east of Rust der Winter, 60 km north-east of Pretoria (Fig.20), there was clear evidence to support the following points as a working hypothesis for future selective exploration in the Bushveld Complex.

1. The distribution of deposits of fluor-spar is related directly to two sets of tectonic megalineaments, which in places include structural components that are expressed clearly on the surface as linear entities, for example, fold belts, grabens, and dykes, faults, and fractures.

2. Some individual deposits of fluor-spar are related to distinctive patterns of fractures and faults that are easy to recognise. (For example, the ore body at the Vergenoegd Mine, on Kromdraai 209 JR, Rust der Winter; see Fig.20).

3. The recognised megalineaments control the distribution of the numerous alkalic complexes, and the carbonatites, that are known to exist in the Bushveld and its surroundings, they localise the distribution of those kimberlites that are known to be present in and near the Bushveld Complex, and they restrict the locations of tin-rich acid intrusions within the Complex itself.

Although Hall (1932), and others, had remarked on fundamental "directions" or "lines" in the context of the structural framework of the Bushveld Complex, and in relation to the intrusive alkalic complexes, there is no record of any appreciation, prior to the execution of the work described in this report, of the role played by lineaments in the control of various forms of mineralisation in the Bushveld Complex. The writer had been associated indirectly with the regional analysis of fractures as an aid during exploration (A.O.C. Technical Services, 1970) and the relationships that were recognised in the Bushveld made it obvious that the analysis of fractures could be applied fruitfully during the exploration for minerals in the Bushveld Complex.

Accordingly, on the following premise,

> "There seems to have been a lack of appreciation of the fact that the basement trends, e.g. Murchison Line, appear to have been rejuvenated ... and ... imprinted in the rocks of the Bushveld Complex, and were capable of exerting a localising and causative influence on later geological episodes, e.g. intrusion, extrusion and associated mineralisation",

the writer, in June 1970, made the following proposals to a consortium of mining companies on behalf of R.F. Loxton, Hunting and Associates.

1. "A detailed and comprehensive fracture-analysis of the granitic areas of the Bushveld Igneous Complex [should] be undertaken ... in an attempt to recognise foci of sub-surface igneous intrusion, or volcanic disturbance, which are considered to be foci of potential fluor-spar/tin (and other mineral) associations.

2. "[The] fracture-analysis [should] be based on detailed photogeological annotation of lineaments, at a photographic scale greater than approximately 1:40 000, followed by

   (a) empirical examination and analysis of the compiled annotation, and

   (b) computerised statistical analysis of lineations [lineaments].

3. "... selected target areas [should] be studied ...by means of detailed photogeological mapping ... to confirm the mineralisation potential of the focal areas in terms of minor structures, trap rocks, host-rocks, etc., prior to recommendation regarding localised exploration procedures".

The proposal was accepted without delay, and the work was executed in respect of an area that exceeds 25 000 square kilometres. (See Fig.22). (R.F. Loxton, Hunting and Associates, 1971). Over 80 000 lineaments were annotated under the stereoscope, including fractures, faults, dykes and joints. They were catalogued and co-ordinated in a digital, computer-compatible, format. Figure 23 is a highly-reduced reproduction of the entire "field of fractures", which facilitates the comprehension of the project.

The analysis of the fractures (or, stated correctly, the analysis of their traces on the surface) was not without its logistic problems, which included the development of sophisticated computer programs. Although the practical details are not relevant, the application and the outcome of the fracture-trace analysis <u>are</u> relevant because the photogeological results that were described in the earlier sections, after they were expanded by "regional thinking", were the prime vindication of the proposal and its acceptance.

It is instructive that subsequent research by others has confirmed amply the validity of what was, at the time of its formulation, an original and a unique exploration philosophy - in so far as it related to the Bushveld Complex. Thus, the work by Visser (1970); Button (1973a and 1973b); and by Minnitt, Button and Kable (1973), subsequently allowed a more complete appreciation of certain tectonic and lithostratigraphic characteristics of (one of) the recognised megalineaments. (This resulted in an expansion of the exploration philosophy to include stratiform (sedimentary) deposits of metal ores). Pretorius (personal communication, 1974) concluded, on the basis of "certain

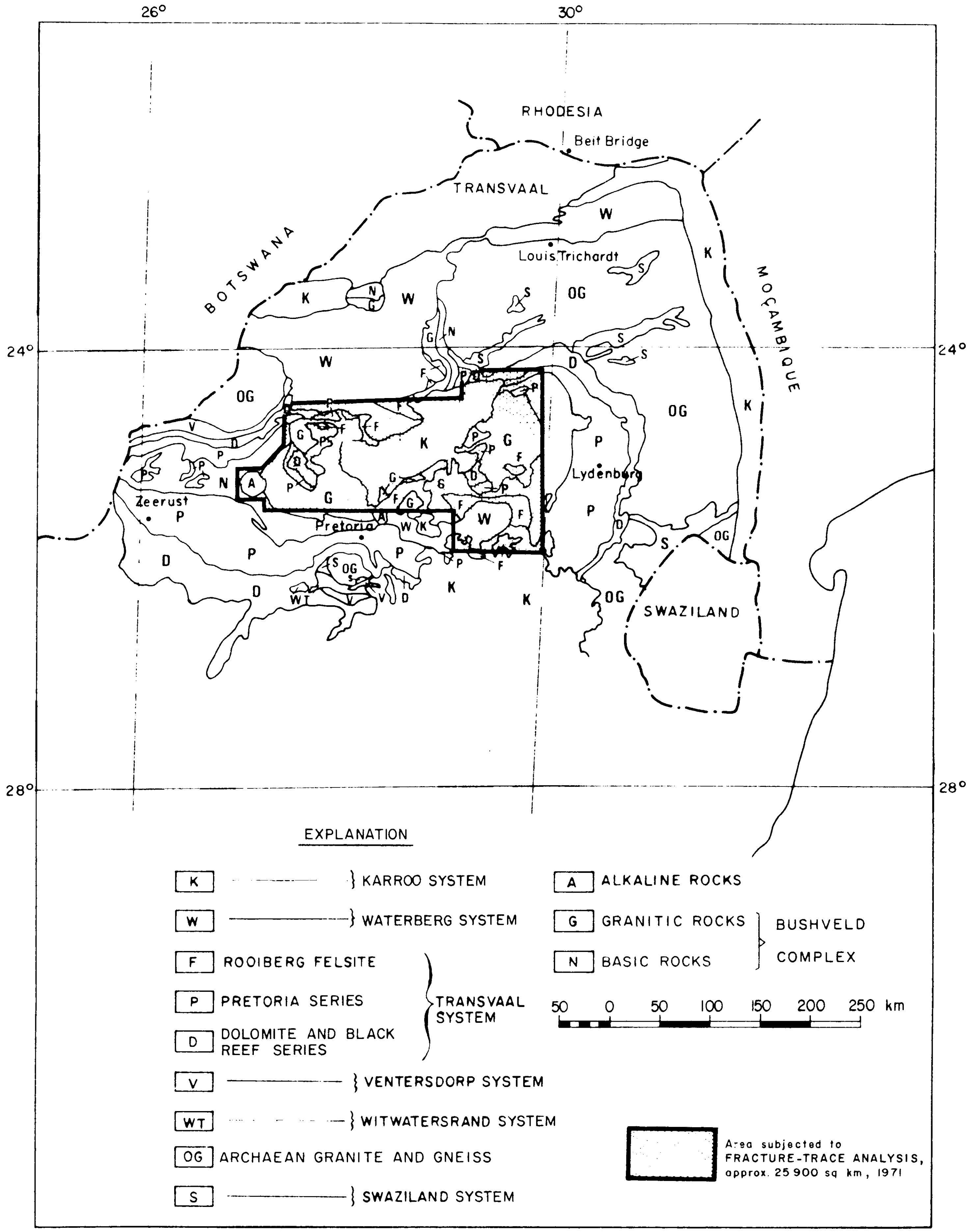
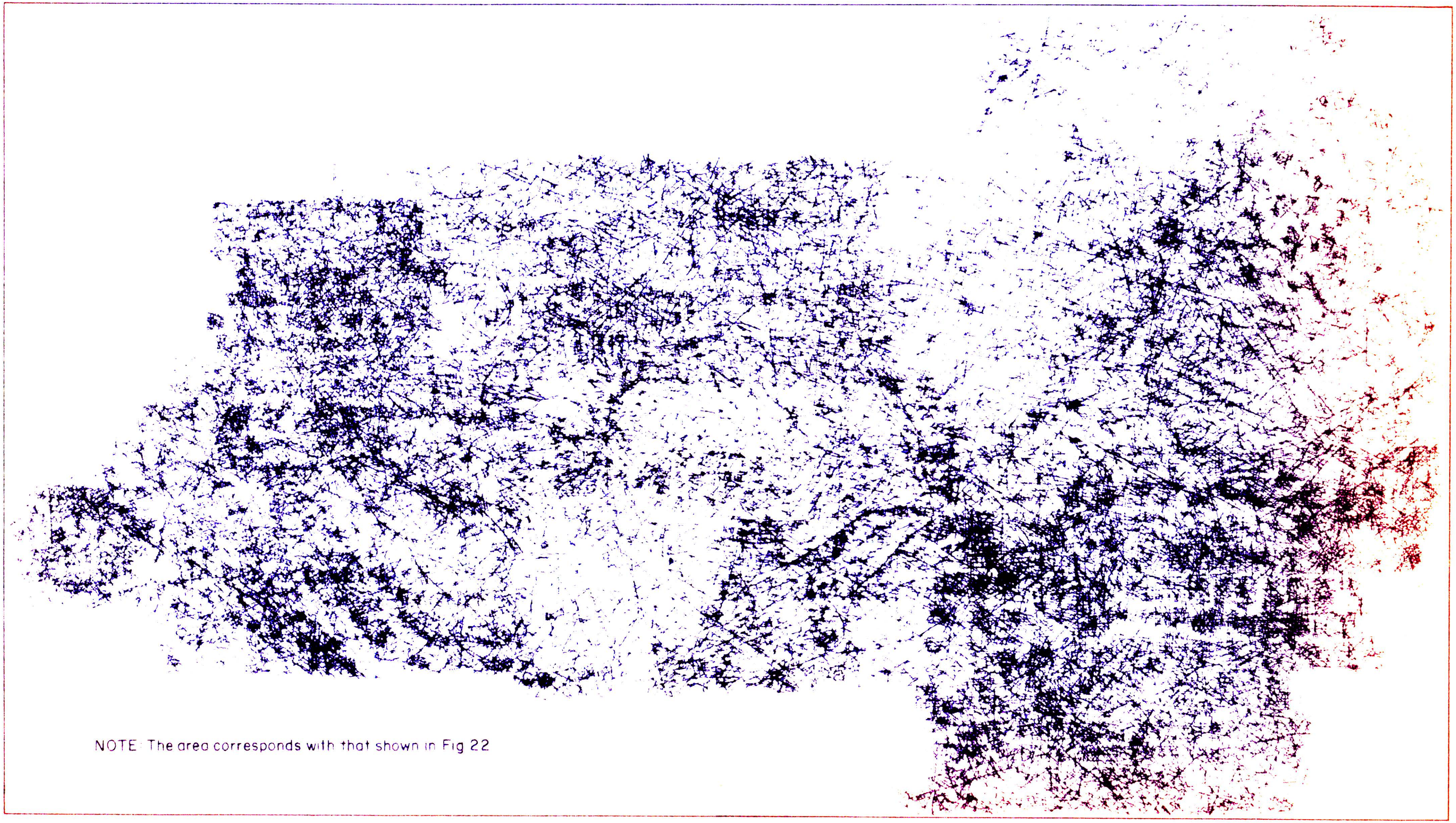


Fig. 22 AREA SUBJECTED TO FRACTURE-TRACE ANALYSIS IN THE ACID ROCKS OF THE BUSHVELD COMPLEX



NOTE: The area corresponds with that shown in Fig 22

Fig. 23 MAP OF "TOTAL FIELD OF FRACTURES" WHICH WAS PRODUCED PHOTOGEOLOGICALLY FOR FRACTURE-TRACE ANALYSIS IN THE ACID ROCKS OF THE BUSHVELD COMPLEX

(After R.F. Loxton, Hunting and Associates, 1971, unpublished) fundamental geophysical data", particularly gravity, (taking only that part of his communiqué which is of direct relevance to the tectonic trends that were considered by the writer) that the trends "control the Bushveld Complex, kimberlites, carbonatites, and a host of other igneous bodies". This independent conclusion, based on data that are entirely different from those which were considered by the writer, provides a full substantiation of the relationships that were recognised. It should be noted that Pretorius' studies encompassed a subcontinental area. His results incorporate other tectonic trends within the southern part of Africa. With regard to the two sets of megalineaments that were recognised by photogeological means to be of importance in the Transvaal, Pretorius' data indicate that they form part of two supreme sets of tectonic lineaments, the trends of which he has termed the "Vaal" and the "Orange". The Vaal trend incorporates the Murchison tectonic direction, and the Orange trend incorporates the Franspoort line and the zones of tectonic adjustment of the floor of the Bushveld Complex that are parallel to it.

The specific results of the fracture-trace analysis in the acid rocks of the Bushveld Complex have not been made public. As far as is known, no ore deposit was found, but according to Parsons (personal communication), a carbonatite was discovered in the eastern portion of the Complex. (By this time the writer was in Australia). Technical aspects of the analysis of the lineaments have been discussed by Pretorius and Partridge (1974) who, in describing the follow-up of "angular atypicality anomalies", record the following information.

> "In a brief field examination of certain of these [anomalous] areas, the locations of ten features were visited. Of these, five proved to be of intrusive or extrusive origin, one was eliminated and four were soil-covered. Of the five confirmed in the field three were associated with mineralisation that could be identified in the hand specimen".

Thus, the practical results substantiate the basic validity of the exploration strategy, and both reflect favourably on the concepts that have been propounded in this report.

APPENDIX B. REGIONAL FRACTURE-TRACE ANALYSIS

The analysis of the traces of fractures ("fracture-trace analysis") whether this is undertaken empirically or statistically, is not designed to be a direct, "short-cut" method of finding bodies of ore, nor is it intended that it is represented here in this light. The analysis is a means of facilitating the definition and the recognition of patterns of fracturing within a region which, when taken in conjunction with the known geology, can be used to recognise other areas of similar geological characteristics on the basis of comparable fracture patterns in those areas. Ideally, and in comparable circumstances, it is possible to relate the patterns of fracturing that exist around mines or geological entities in the one area, to fracture patterns in the second area, which are then potentially associated with similar geological features and(or) mineral deposits. When it is used in virgin areas where little is known of the effects of mineralisation, or when aspects of mineralisation are played down on purpose, fracture-trace analysis for the indication of areas which possess the best mineral potential is based on theoretical concepts, and on logical considerations.

The recognition of the fracture-traces is most commonly undertaken on aerial photographs, or on satellite images.

The empirical analysis of the fracture-traces involves both the visual and the mental evaluation of a map of the "total field of fractures", in relation to the geology, effects of mineralisation, and other relevant information. The empirical analysis is subjective, and it normally encompasses the simple recognition, and the evaluation, of major zones and major trend of fractures, the intersections of zones of fractures, variations in the patterns made by the fractures, and the recognition of type-patterns: for example, radial, concentric, and conjugate. The density and the distribution of the fractures are also appraised. The empirical analysis of fracture-traces usually results in the deeper understanding of geological relationships, and it generates new ideas regarding areas which, on comparative or theoretical grounds, warrant most attention during further exploration. In short, areas are selected for follow-up study.

Whenever the step is appropriate the empirical analysis of fracture-traces should be followed by their statistical analysis. Because of the vast amount of data that require statistical treatment during the quantitative analysis of fracture-traces, this form of analysis is necessarily computerised. In the computerised analysis of the traces of fractures a second, subjective, evaluation of the data is delayed until these data have been treated statistically, and until they are displayed in the form of contour-maps, histograms, rose diagrams, polynomial trend surfaces, and other optional maps. For the statistical evaluation of the total field of fractures, that is, the fracture-map of the entire area of study, the map is divided into cells of equal size. The dimensions of the cells are arbitrary and variable, and they depend on logistic considerations. The parameters of the fractures in each cell are then digitised and encoded, and their statistical evaluation is based on special computer programs.

Empirical (subjective) analysis of fracture-traces can be undertaken without the formal statistical treatment of the fracture-data, but the quantitative or statistical analysis of fractures can not be independent of the subjective evaluation of the resultant computer-generated maps of the statistical data; in other words , the computer generates results that have to be compared with other factual, theoretical, or hypothetical data, before any realistic geological interpretation of the results is possible.

The print-outs which are generated by the computer are, in fact, maps of selected statistical parameters of the fractures in the study-area. These parameters are normally presented in the form of contours, or as pictorial printouts, for example, rose diagrams. The pictorial representations correspond geographically to the centres of the selected cells. Most of the relevant computer programs are concerned with the routine statistical analysis of factual data, for example, the analysis of the density of the fractures throughout the area. (The number of fractures per cell, or the total length of all fractures in each cell, or the total number of fractures longer or shorter than "x" kilometres per cell, are common statistical classifications). The depiction of more involved statistical data, for example the number of "fracture-intersections" per cell, or the "number of intersections of projected fractures" per cell is also possible. Some programs can define the statistical characteristics of the actual patterns of fracturing around selected geological features, for example, a granitic intrusion, or a dome, or a volcanic vent, or a fold, and they can be used (ideally) to define similar features in other areas where the comparison is justified. Other programs enable the recognition of specified patterns of fractures which can then be related, on hypothetical grounds, to geological features of potential interest, for example, a radial pattern in relation to an intruded plug.

In common practice, the fracture data are statistically analysed, classified, and manipulated in the computer until the patterns in one or more of the many optional displays (for example, contours which depict trend-surfaces, or contours of the densities of "fracture-intersections" in each cell) appear to have some particular relevance on the basis of the known geology: or preferably, characteristic features in relation to the known deposits of minerals. The aim is that similar relationships will be recognised elsewhere within the study-region, and will be found to be the result of similar causes. One has, however, to take into account the fact that not all the existing fractures are annotated, or even recognised, on the aerial photographs. Similar patterns on the computer print-outs, whether they are displayed by fractures, or by contours, or by other means, therefore do not necessarily indicate similar causative influences. Hence there is the need for common sense, and for maximum access to geological information.

The last stipulation dictates that fracture-trace analysis should never be conducted in total isolation. It is relevant that a wealth of potentially important concepts and ideas generally results from both the simple, empirical, analysis of fracture-traces, and from the sophisticated computerised, statistical analysis of fracture-traces. This is true to the extent that it is vitally important that the data which are of potential importance are distinguishable from unimportant data. The selection is aided by reference to the geology and the literature, and by the re-examination of the photographs under the stereoscope. It is at this stage, at the latest, that a photogeological study of at least the areas of immediate relevance is essential. Areas of apparent potential, as gauged on the basis of fracture-trace anomalies, may be of the order of tens, or hundreds, of square kilometres in extent, and they can be most conveniently appraised at first, and perhaps eliminated from further consideration, by photogeological means.

APPENDIX C. PRINCIPLES AND CONCEPTS IN PHOTOGEOLOGICAL MAPPING

Basically, photogeology entails the study and the geological interpretation of photographic images. The veracity and the content of any photogeological map depends directly on the ability of the individual concerned to recognise, evaluate, record, and interpret the significant elements and interrelationships within individual images (mostly viewed under the stereoscope), and to interrelate the information derived from work in the field with the sum of the information from all the stereoscopic images. Interpretative ability is partly inherent in the photogeologist concerned, and it is improved only by his own personal experience. This interpretative ability can be evaluated only in the form in which it is manifested during photogeological mapping, namely, by the annotation of detail on the photographs. The annotation of photogeological detail therefore reflects a process of continual observation, interpretation and decision-making during the stereoscopic study of the aerial photographs, and it is the most important element in photogeological mapping.

There are two sides to photogeological annotation; the practical, and the conceptual.

A. Practical aspects of Annotation

The practical side of photogeological annotation concerns aspects of suitable stereoscopic equipment, adequate lighting, routine and system in the office, technique, standard procedures, and precision, accuracy and neatness (for example, "annotation" instead of "obliteration"). Also relevant are practical procedures which are applied when, for example, attributes and features of the bed-rock are determined by particular stress on the geomorphic component in the stereo-image. These include the application of pseudoscopic vision, and the use of special techniques during the delineation of overburden. On a general front the practical basis of "getting and keeping one's eye in", and the formal or informal compartmentalisation of the image during final detailed annotation, are also relevant. In general, these practical aspects of annotation have been called "tricks of the trade". They can be learned by anyone, but in reality they are of very little importance because during photogeological mapping the crucial element is actually the mental one of "decision-making". Therefore, when the quality of the "decision-making" is taken into account, the conceptual principles that are mentioned below are of far greater significance than the practical aspects of annotation.

B. Conceptual Principles in Annotation

1. The Fallacy of Distinctive "Signatures"

Tutors of photogeology commonly tend to overstress the importance of the individual elements of the photographic image. The tendency is always to relate the photographic response of particular rock-types, or geological features, to the absolute elements of tone, texture, internal pattern, size, shape, and distribution, and to definitive patterns in the drainage. Unfortunately, definitive elements in the photographic image are commonly lacking during normal photogeological mapping: they exist only in ideal circumstances and in areas where the bedrock is exposed, and the general acceptance of their individual importance is to be deplored. During normal photogeological mapping, the stereoscopically-exaggerated three-dimensional image of the topography is the most important criterion in the mapping of the bedrock. This criterion is commonly followed closely in importance by the characteristics of the natural vegetation. Although the elements of tone and texture influence the appreciation of the vegetation to a considerable extent, there is no doubt that, as characteristic and direct indicators of the geology, the individual elements (including colour and hue when applicable) are of considerably less importance than is commonly appreciated by many earth-scientists.

2. The Importance of the Whole Stereo-image, and the Importance of Significant Relative Differences

On becoming familiar with both large and small photogeological projects, it is obvious that key-responses, or "signatures", of rocks and geological features are encountered rarely. In most circumstances geological photo-interpretation involves the intense mental appraisal of all the elements, and all the relationships, in the whole stereoscopic image. Of prime consideration and importance is the recognition of meaningful relative differences in the combined response of all the photo-elements, and in the factors to which they are related (for example, relief and cultural effects). Undue reliance on any one element, or factor, will lead to interpretations of the geology which are incorrect.

The folly in attempting photogeological mapping on the basis of individual keys or photo-elements is obvious on the minimal amount of reflection. For example, an horizon of shale which traverses an area would, in common practice, be identified by numerous criteria which change constantly. The following criteria are given merely as illustrative possibilities, and each of them, if they exist, would be viewed in the context of all the associated photographic responses within the whole image, and the surrounding images, before the significance was assigned to them.

(a) relatively dense or coarse vegetation, or both in different locations; or, perhaps, a lack of trees

(b) a linear, topographic "low", or a gentle, rounded ridge

(c) the linear arrangement of cultivated fields, or the preferential clearing of bush

(d) differences in tone and texture relative to the adjacent rocks

(e) the formation of sharp ridges only where the unit is crossed by fractures (a fact which may indicate the silicification of an horizon which is relatively non-resistant, and which might be composed of shale)

(f) the control of linear drainage

(g) stratification

(h) the refraction or deflection of intruded dykes

Similarly, an inconspicuous fault-plane may be manifest only if attention is given to the mass-response, and the appraisal, of the following "unrelated" features of the stereoscopic image;

(a) a few quartz "blows", or, in the field, a few angular pebbles of vein-quartz

(b) an escarpment that is not explained

(c) a linear ridge, or a depression

(d) a linear boundary between adjacent land-patterns

(e) the linearity, or the deflection, of channels of drainage

(f) a natural arrangement of trees, or bush, which is linear

(g) springs, windmills, seepages, or damp patches on the ground

(h) large individual trees that are left standing in cultivated lands

(i) contrasting directions of strike on either side of a vague lineament

Thus, photogeology is concerned with three-dimensional interrelationships and with relative differences, and not with the identification of bedrock by means of any one or two photographic elements. It may be said that the competent photogeologist is one who continually recognises the most significant of the meaningful, relative differences, which vary continually.

3. The Importance of Geological Orientation, and Field-work

Photogeological studies should not be executed in isolation for the same reason that geophysical and geochemical studies are seldom conducted voluntarily without regard to the known geology; that is, the value and the results of the interpretation are related to, and hinge upon, previous knowledge of the geology - no matter how scant this may be. Field-work should be viewed as an essential part of every program of photogeological mapping.

In the previous section, the importance of the whole stereoscopic image in the recognition of relative differences (which vary continually) has been stressed. It is important to realise that it is only those details which correspond to relative differences which appear to be meaningful in the eyes and the experience of the photo-interpreter that are annotated, and are later interpreted in their over-all context.

Every stereo-image comprises a wealth of photographic detail which embodies responses to a host of factors, of which geology is but one; for example, climatic, hydrological, agricultural, vegetational, pedological, geomorphological and cultural. The selection and appraisal of photographic detail which relates directly or indirectly to the geology, and the disregard for detail which appears to be inconsequential, is a vital part of interpretative procedure, and, as inferred above, it is facilitated greatly by access to existing geological (and other) information. At some time prior to the final stereoscopic annotation of the photographs the photogeologist has to have a mental picture of, at least, the "geological possibilities" within the region; or better still, intimate knowledge of the geology of the area.

Reference to existing geological maps and literature is invaluable, but during detailed annotation other factors - such as agricultural, cultural or hydrological - are always taken into consideration. Cultural effects have a very significant manifestation on the photo-image even in undeveloped regions. It is essential that these are accorded the full significance and the interpretation they deserve. For example, during photogeological interpretation on a peneplaned island in Indonesia, the value of the recognition that patterns of deforestation commonly display trends which are parallel to the stratification in the buried, decomposed, bedrock, is a very important interpretative factor. These patterns of deforestation are meaningful only when it is understood that the bullocks which pull the carts which remove the cut timber find it more difficult to pull the laden carts over the very slight undulations which represent the expression of buried strike-ridges, than to pull them along tracks which are parallel to the trend of the undulations. In the field, and under the stereoscope, the undulations are so minor that they would normally be overlooked. It may be seen, even from the one example, that it is essential that a multi-faceted "feel" for the area is developed.

The previous remarks apply particularly to terrain in which the bedrock is exposed very poorly, that is, to areas in which geological data that are based on work in the field are distinctly limited, and of dubious authenticity, and in which intense stereoscopic study is required in order to obtain results. For example, the mental processes that are involved in the appraisal of a stereo-image of an area of tropical jungle in which the bedrock is not exposed, but is known to be related to an isoclinally-folded, homogeneous, sedimentary sequence, will be distinctly different, and will yield different results, (even with the same image) relative to the results of the appraisal of the bedrock as highly cleaved and sheared igneous or volcanic rock. Naturally, in areas in which the bedrock is exposed reasonably well, even the briefest of monoscopic scans of the photographs will provide a mental picture of the "type of geology" that exists, and the information obviously places constraints on the interpretation of ambiguous photographic details. Ideally, the final results should provide a full, sensible and reasonable geological picture; in absolute terms, and in relation to the stereo-images and the geological possibilities that were conceived. Preconceptions of the geology, however, should not be taken too far.

4. The Concept of "Inward Projection" or "Convergence of Evidence"

Because photogeological annotation (micro-interpretation) seldom depends on individual characteristic elements of the photographic or stereoscopic response, and because preconception plays a large part in the mental evaluation of the image, it is quite possible that information which is subtle, yet potentially significant, may be overlooked during the phase of general annotation under the stereoscope. However, once further data become available which indicate, or dictate, that certain geological conditions could exist in a particular area, it is commonly possible to locate and to define that stereo-detail (that is, those subtle or minute entities and differences) which, under the circumstances, can be related confidently to the geology. This is so, even although the detail may not have been accorded any significance, and may not even have been noticed, during diligent study. This implies that the subtleties and the minute changes in the photographic image can be so vast in number, and so broad in scope, that it becomes impossible to accord to each change the different condition it represents, even if the time allows. Only that detail which is obviously, or potentially, of geological significance is recorded; unless, for example, a condition or a relationship which was recognised in adjacent areas can be projected into or through the area in question. A good example is that of a dyke, or a fault, or a geological contact, which, after easy recognition on certain photographs, may be traced by means of very vague stereo-detail through areas in which the feature was not recognised initially, because the corresponding relative differences in tone, geomorphic response, texture, and other elements were not noted, or were not recognised to be meaningful.

The ability to project photogeological detail from the surrounding region into the area of interest is fairly common. The potential to do so always exists, and it is a prerequisite for optimum photogeological results that the photographic coverage includes suitable, broad, fringe-areas. This is particularly true in relatively small areas in which the exposure of the bedrock is limited, and in which the scale of photography is relatively large; that is, 1:12 000 to 1:25 000. In these circumstances it may be difficult to recognise the significance of certain features, for example sand-filled valleys; whereas wider coverage (and access to photography on a smaller scale) could well suggest that the former are related to extensions of faults, or joints, or argillaceous strata, or dykes; to quote but a few possibilities.

5. Vague Information, and Detail which is of Potential Significance

Stereoscopic details which are not meaningful at first, sometimes become meaningful on the re-appraisal of the results of the photogeology after they have been compiled in the form of a rough map; or after work in the field, or after geological detail has been projected into the area. The vague details therefore become meaningful after the broadening of one's concept of the geological conditions that really apply to the area that is under study. Commonly, tonal, textural or other detail is noticed in passing, but because it does not appear to be meaningful on the first appraisal it is not annotated. Later it is found that this information is related, directly, to new and important information; for example, anomalous, isolated, flat areas (remnant river channels), and small areas in which the distribution of scattered large bushes is regular and anomalous (jointed inliers of dolomite, surrounded by a thick layer of chert rubble). For this reason the annotation (by remark only, if necessary) of data which may be informative, is warranted. The annotation may obviate a total re-study of all the relevant photographs.

6. The Concept of Routine Re-annotation

Because photogeological annotation and interpretation is based on subjective information, and because the initial compilation of a map greatly expands the scope for accurate interpretation of the photographs (even if the map is incomplete and disjointed), it is essential that a second phase of annotation is viewed as a routine part of photogeological mapping. Commonly a third, and rarely, a fourth complete stereoscopic re-appraisal of the photographs is justified, particularly in regional studies (for example, regional stratigraphic correlations). In regional investigations the initial and the second studies may be oriented towards the definition, understanding and mapping of local detail, that is, print-by-print; and this is separate from the stereoscopic mental evaluation of this detail on a regional basis, during which relevant mental images retained from the entire region are used as comparative yardsticks. The re-annotation of the photographs is therefore designed to progressively provide improved approximations to the final requirement, and the process is deliberate. It is particularly valid in relation to extensive studies which involve many photographs.

7. The Concept of "Saturation Annotation"

This concept is related to the intense study (saturation study) of all the available types and scales of photographs, in relation to all relevant sources of geological information, in order to arrive at as much geological detail as possible. In practice, annotation to saturation is applied in areas which are poorly exposed, or inaccessible, and in which the proved mineral potential is sufficiently encouraging to warrant intense and time-consuming photogeological study.

The photographic expression of a single geological feature or a geological relationship varies, often markedly, from one photograph to another. The expression depends on the factors of scale, sun-angle, season, print-contrast, and the quality of the processing. During saturation annotation full use is made of the variability in the geological expression of features or relationships, from one set of photographs to the next. By means of constant cross-reference between corresponding prints it is possible to detect an amount of detail which would not be gleaned from any one set of photographs alone.

Although the intensity of study, and the time that is required for the achievement of saturation, normally militates against the full use of the method in general photogeological mapping for exploration, in problematical areas where photogeological relationships are obscure it is natural to resort to a modification of the principle. In these circumstances all available photographs are studied without saturation necessarily being reached during annotation.

8. "Building a Picture"

This aspect is partially a facet of that mentioned under 3 above, but it is of sufficient importance as a mental concept in its own right to warrant separate mention.

Where the bedrock is exposed, or where the patterns of rock-distribution and geological structure are obvious, the concept is already passively assimilated by the photogeologist, since the over-all geological "picture" is clear. However, in areas in which the bedrock is exposed very poorly, particularly if the bedrock is contorted strongly, and the areas of outcrop are small and spaced widely, the annotation of isolated photogeological detail is not wholly appropriate because, by this method, the detail emerges but not the over-all picture. The error is a very common one. It is necessary for the photogeologist to strive consciously for the recognition of the general picture, particularly where folded strata are involved, by consciously adapting his method of study, and his technique of annotation, to produce the broad picture as the first requirement. Thereafter, progressively more detail may be annotated, and the detail must serve to confirm the broader picture if it was deduced correctly.

9. "Going the Extra Mile"

Anyone can annotate aerial photographs physically, and every geologist will be able to derive some photogeological information from even the most difficult areas. So the duty and, indeed, the value of the skilled photogeologist lies in the observation, recognition and interpretation of significant photographic detail (relative differences) which would normally not be recognised by individuals who possess lesser stereoscopic experience. This mandatory stipulation, apart from prescribing a large amount of previous field-work in relation to the stereoscopic study of aerial photographs, also prescribes that the actual stereoscopic study of the photographs must be undertaken as a conscious and a fully-fledged study in its own right; this allows the necessary time and the mental continuity for intense, diligent, and laborious study of the photographs. "Going the extra mile" may make all the difference to the outcome of an exploration program, whether this applies to a particularly canny field-geologist, a geophysicist, or a photogeologist: it is unlikely that "dabblers" will produce the important extra results. In photogeology, particularly, in which the simplicity of the tools and the technique are commonly confused with the apparent simplicity of obtaining adequate results, the adage of the "extra mile" should not be forgotten. From the above it is apparent that the photo-interpreter must be allowed time for the continuity of his effort and his mental processes, without the imposition of interruptions and other distractions.

10. The Conceptual Aspect of the Compilation of Photogeological Detail

"Compilation" is the practical means by which the geological annotation on the photographs is made into the form of a map. The map provides a suitable, cohesive, base from which selected geological data can be extracted. The compilation may incorporate all, or only some, of the annotated details, and the choice depends on the requirements of the photogeological study.

In the most narrow, immature appraisal, compilation can be considered to entail the mere preparation of a map from the photogeological data. When so appraised, for example, by the average field-geologist, the viewer tends to conceive the map as a geological map and he evaluates it solely in relation to the results of mapping in the field, although the specifications, the practical aims, the results, and the scope of the two programs, are not the same. It is common that the viewer lacks an understanding of the advantages and the limitations of photogeology. The step of compilation should be viewed - particularly in regional studies - as an avenue towards the gaining of a synoptic view of the geology - that is, a much wider perspective that is based on the possibilities inherent in the relatively detailed study of large areas when they are viewed from a relatively great height. This overview introduces a range of geological and allied phenomena which can not be recognised during operations in the field and this fact has been demonstrated adequately in the text of the present report. The compilation phase itself, although the end-result is a photogeological map, is more than just "map preparation"; it is the avenue to the recognition of geological relationships that would otherwise not be detected.

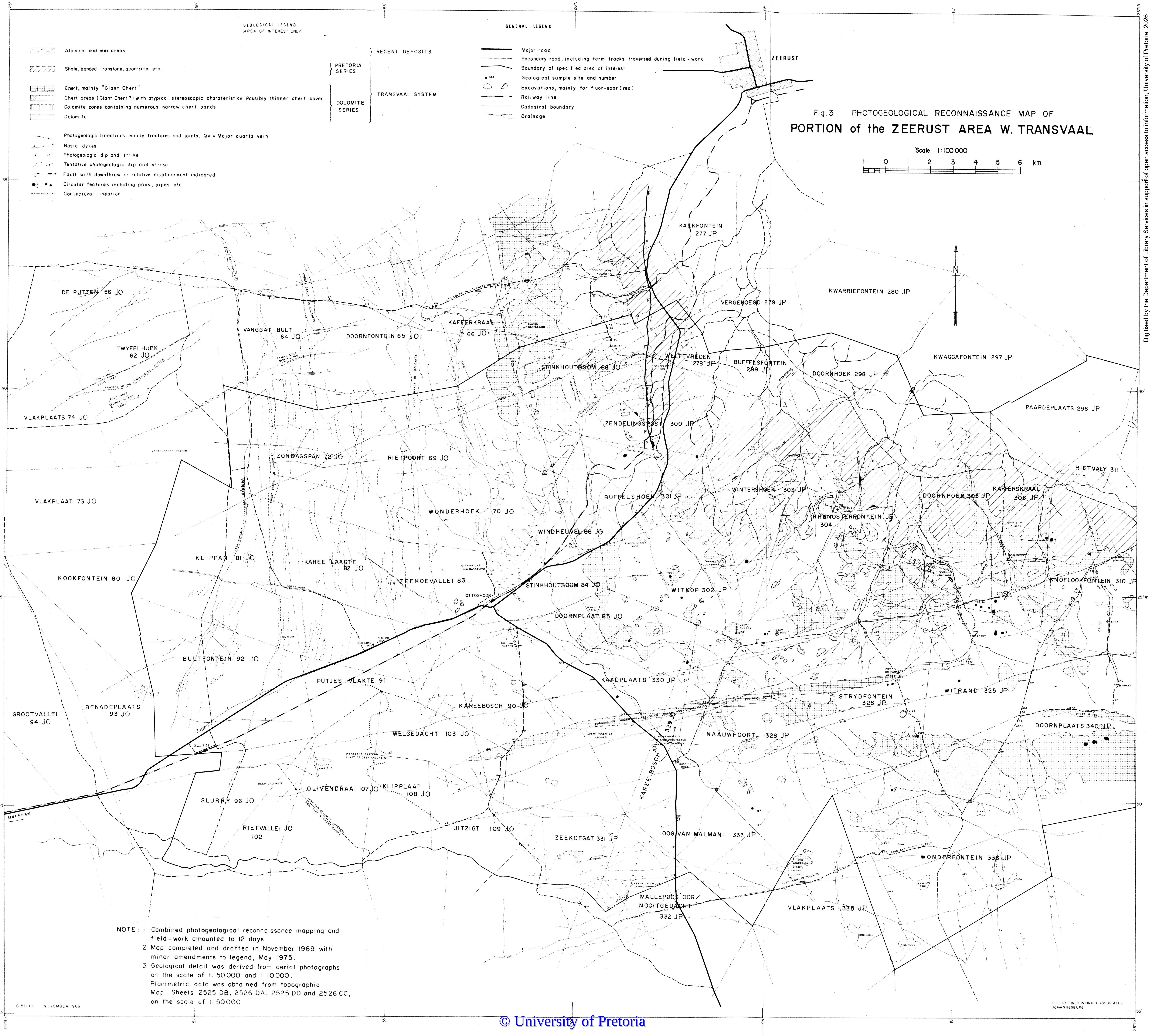


Fig. 3 PHOTOGEOLOGICAL RECONNAISSANCE MAP OF

PORTION of the ZEERUST AREA W. TRANSVAAL

NOTE: 1 Combined photogeological reconnaissance-mapping and field-work amounted to 12 days.

2 Map completed and drafted in November 1969 with minor amendments to legend, May 1975.

3 Geological detail was derived from aerial photographs on the scale of 1:50 000 and 1:10 000. Planimetric data was obtained from topographic Map Sheets 2525 DB, 2526 DA, 2525 DD and 2526 CC, on the scale of 1:50 000

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R.F. LOXTON, HUNTING & ASSOCIATES
JOHANNESBURG

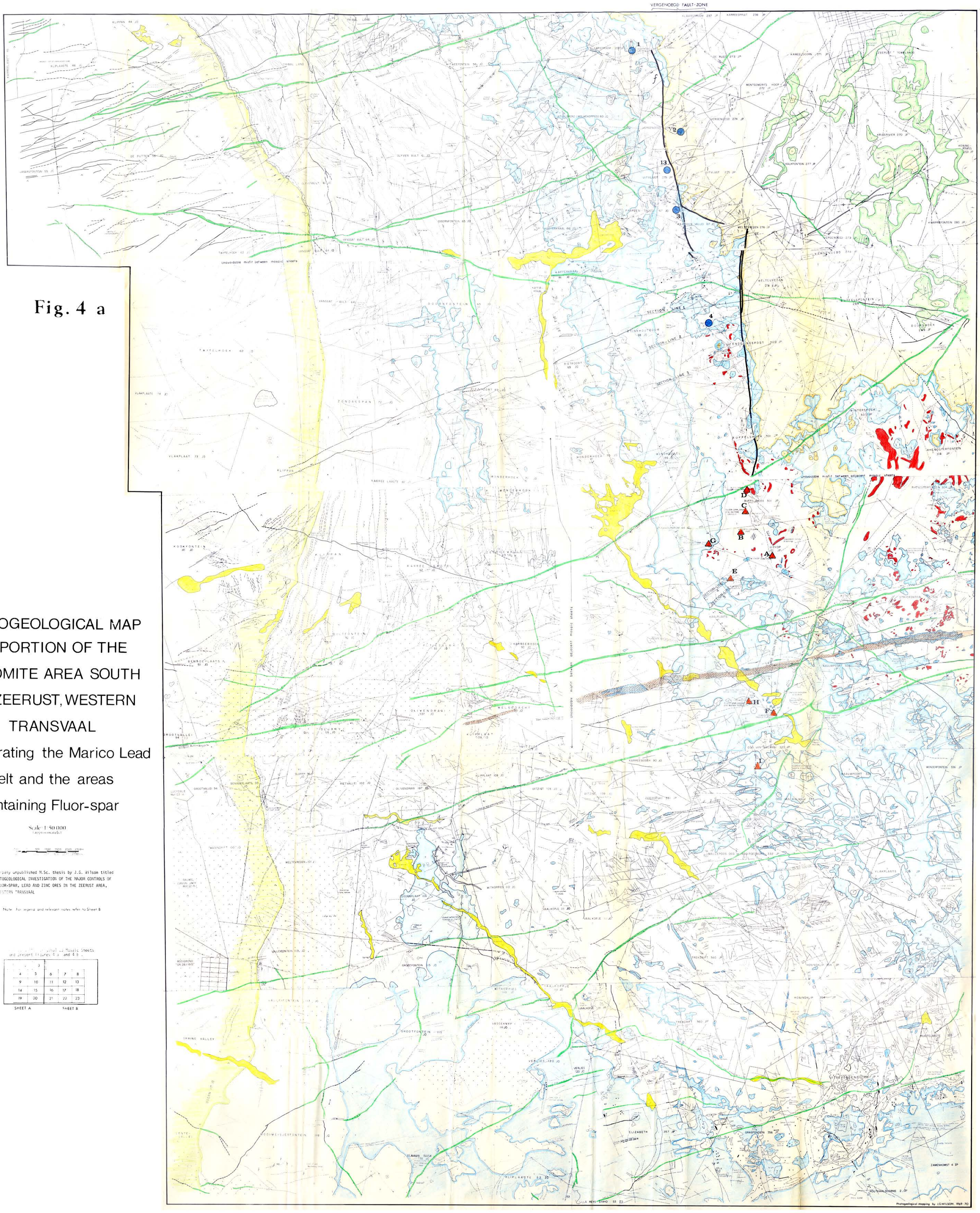

Fig. 4 a

PHOTOGEOLOGICAL MAP
OF PORTION OF THE
DOLOMITE AREA SOUTH
OF ZEERUST, WESTERN
TRANSVAAL

Incorporating the Marico Lead
Belt and the areas
containing Fluor-spar

Scale 1:50 000
(approximately)

To accompany unpublished M.Sc. thesis by J.G. Wilson titled
A PHOTOGEOLOGICAL INVESTIGATION OF THE MAJOR CONTROLS OF
FLUOR-SPAR, LEAD AND ZINC ORES IN THE ZEERUST AREA,
WESTERN TRANSVAAL

Note: For legend and relevant notes refer to Sheet B

Original 23 Mosaic Sheets
and present figures 4 a and 4 b.

PHOTOGEOLOGICAL MAP OF PORTION OF THE DOLOMITE AREA SOUTH OF ZEERUST, WESTERN TRANSVAAL

Incorporating the Marico Lead Belt and the areas containing Fluor-spar

Scale : 1:50 000
(approximately)

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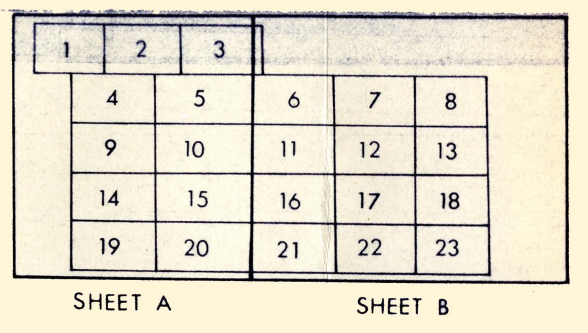
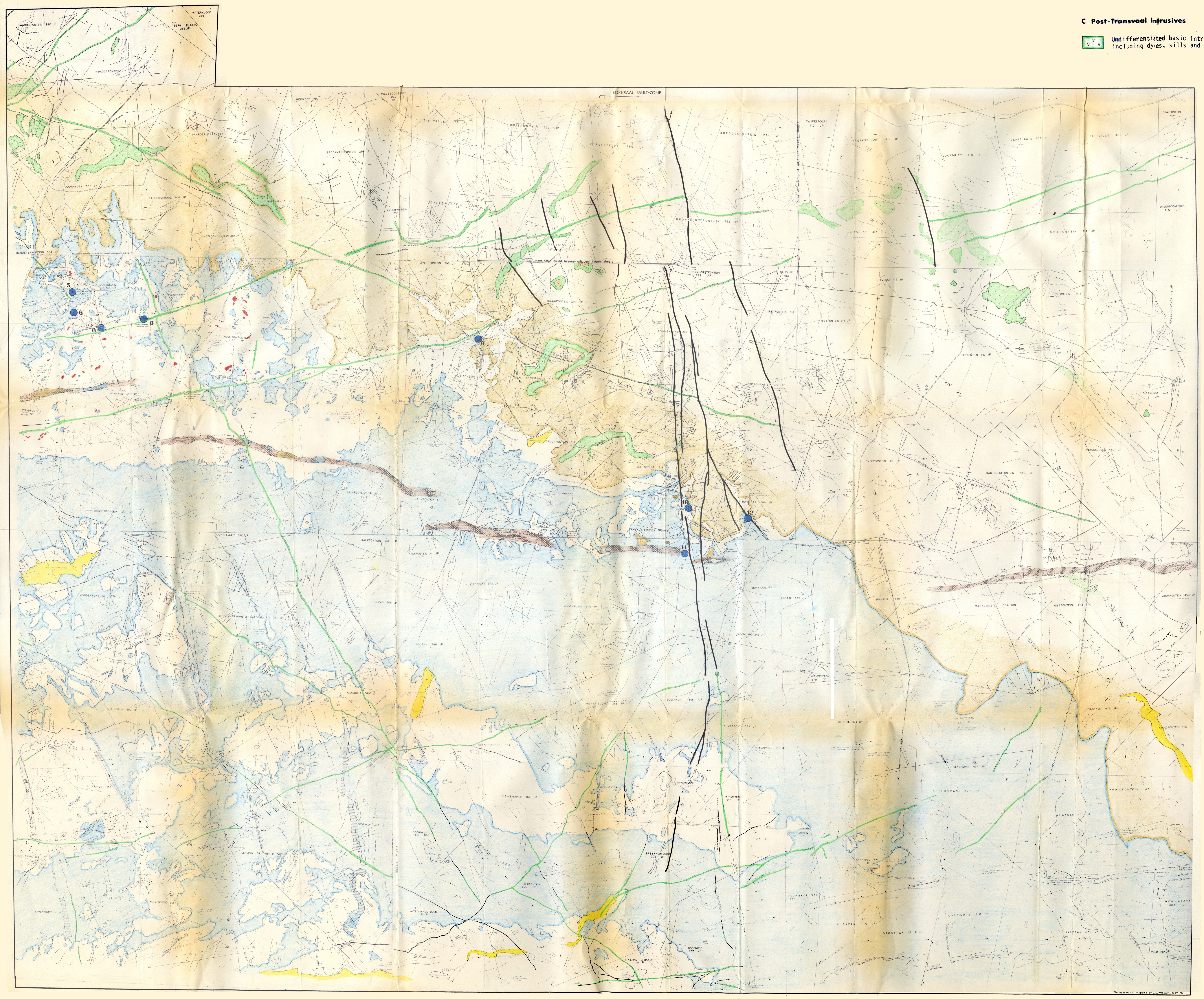
WESTERN TRANSVAAL

Fig. 4 b

KEY DIAGRAM.- Original 23 Mosaic Sheets
and present Figures 4 a and 4 b .





Photogeological Mapping by J.G. WILSON, 1969-70

EXPLANATION

B Geological

AGE RELATIONSHIPS

⁚	Thick undifferentiated soil, masking geology		RECENT DEPOSITS	TERTIARY TO RECENT	
~	Alluvium				
·	Surface-limestone (Calcrete)				
K	Thick sandy soil	Wind-blown sand or thick residual soil on Karroo sediments	UNDIFFERENTIATED KARROO SYSTEM or recent deposits	CARBONIFEROUS PERMIAN?	max. 250 m.y.
P	Chert Breccia, banded cherty ironstone, quartzite, shale	Pretoria Series	TRANSVAAL SYSTEM	PROTEROZOIC	>1950 m.y.
C	Massive banded chert (Giant Chert). Includes Chert Breccia and recent chert rubble where distinction is not possible	Dolomite Series			
D	Dolomitic limestone with intercalated thin cherty and shaly horizons				
⁙	Thin basal quartzite and overlying shale	Black Reef Series			
A	Amygdaloidal andesitic lava, acid lava, and sediments		VENTERSDORP SYSTEM		>2100 m.y.

C Post-Transvaal Intrusives

V V V	Undifferentiated basic intrusive rocks, including dykes, sills and irregular bodies	1290 m.y. to <200 m.y. ?

A General

Site and number of rock sample	• 156
Route taken during the checking of photogeological data in the field	→
Railway	┼
Primary and secondary roads	═
Farm boundary	—
River or stream	~
Excavation for road material	G
General mining or prospecting activity, past and present	• ⚒
Long, deep trench	•—•
Small trench	•
Excavation for alluvial diamonds	D
Deepest excavations	•
Excavation for surface-limestone or "vlei-limestone"	⚒ L
Excavation for manganese ore	⚒ Mn
"Breccia type" and "pipe-like" bodies containing fluor-spar, galena and zinc-blende	▲ A - H
Other galena deposits, including old mines	● 1 - 12
Kaffirskraal Vanadium Mine (defunct)	• V
Unspecified mineral-excavation or mine. Mostly fluor-spar	▬
Quartz-vein, with prospecting trench or shaft, or old gold mine	QV • ⚒
Topographic hump or ridge	▨
Linear slump-zone	▨
Vague photogeological boundary; topographical or tonal boundary; geological projection	– –
Geological boundary	~
Bedding plane	- - -
Horizontal strata	+
Vertical dip or contact	┼
Direction of strike and dip of bedding plane	┬
Locally contorted strata	≈
Fracture, joint, or similar lineament	—
Fault and indistinct fault, showing downthrow and directions of relative displacement	⇆
Major fault	—
Prominent trend of local lineaments, e.g. joints	↔
Strong general jointing	J
Depression: less distinct than sink-hole or slumping	d
Sink-hole: i.e. deeper depression, or steep-sided hole	s
Possible pipe-like body in dolomite. Potentially mineralised with Pb, Zn, (Cu) and CaF_2	○ Pipe
Dyke	—
Fold axis	— + —

Refer also to Fig. 16 in text of thesis

Note:
1. Photogeology based on stereoscopic annotation of black and white contact-prints of vertical aerial photographs on the scale of 1:20 000.
2. Compilation of photogeological data was on to transparent overlays of twenty-three separate mosaic sheets on the scale of the contact-prints.
3. The present map represents a "best-fit" compilation of the photographic reductions of the original twenty-three map sheets.
4. Circumstances dictating the mismatching of internal detail, including that corresponding to boundaries of original mosaic sheets, are noted in Sections I C and VI A of the accompanying text.
5. The area mapped is approximately 4300 sq km and original map sheets were draughted in the period July to September 1970.
6. Field-work was unavoidably restricted to three weeks.
7. Users of this map are warned to familiarise themselves with the relative advantages and disadvantages of basic photogeological mapping and basic field mapping prior to evaluation of the present results. Section VI A of the accompanying thesis, and the Appendix, are relevant.