The application of geophysics to gold exploration in South Africa

A.T. Roux
Union Corporation
Johannesburg, South Africa

reprinted from
Mining and Groundwater Geophysics/ 1967

The application of geophysics to gold exploration in South Africa

A.T. Roux

Union Corporation
Johannesburg, South Africa

Abstract. Practically all the gold and uranium produced by the Republic of South Africa is won from the auriferous conglomerates of the Witwatersrand System, and exploration is oriented towards locating areas underlain by these conglomerates (reefs).

The Witwatersrand Basin is filled by sedimentary and volcanic rocks up to a total thickness of 40 to 50 thousand feet. The Witwatersrand System with a lower division of predominantly argillaceous rocks, and an upper division of arenaceous rocks, comprises about one half the rocks filling the basin. The auriferous conglomerates occur in the Upper Witwatersrand. A thick succession of lavas and sediments of the Ventersdorp System lie both conformably and unconformably on the Witwatersrand, followed by the rocks of the Transvaal System. Karroo sediments cover these rocks over large areas.

The Upper Witwatersrand beds underlie an area of some 15,000 square miles in what is generally called the Main Witwatersrand Basin. An outlier, separated by structural deformation occurs 40 miles east of the main basin outcrop, whereas the outlier is entirely covered by younger rocks.

Highly magnetic shale horizons in the Lower Witwatersrand occur in fairly constant stratigraphic relation below the conglomerates over great distances and are mapped under cover by magnetic surveys. The density contrasts, between the light granites on which the basin lies, the heavy Lower Witwatersrand, the light Upper Witwatersrand and the heavy lavas and the great thicknesses of these groups, are the cause of substantial gravity anomalies.

Geophysics and sound geological reasoning have been responsible for locating three major extensions of the gold-bearing conglomerates of the Main Witwatersrand Basin under younger cover, and for the discovery of the outlier to the east of the main basin.

Resume. Le bassin du Witwatersrand est rempli d'une succession de roches sedimentaires et volcaniques qui atteint une epaisseur totale de quarante a cinquante mille pieds. Le systeme du Witwatersrand, qui se divise en une partie inferieure ou les roches argileuses predominent **et** une partie superieure a roches arenacees, comprend environ la moitie des roches qui remplissent le bassin. Une epaisse succession de laves et de sediments du systeme Ventersdorp reposent avec ou sand concordance sur le Witwatersrand et laisse ensuite la place aux dolomites, aux schistes et aux quartzites du Transvaal.

Une discordance marquee constitue un fondement plat aux sediments du Karroo qui recouvrent ces roches sur de grandes etendues. La zone d'interet economique est celle du Witwatersrand superieur ou se rencontrent des conglomarats auriferes. Du point de vue geophysique, le Witwatersrand inferieur a une grande importance a cause des horizons schisteux fortement magnetiques qui demeurent en relation stratigraphique assez constante au-dessous des conglomerats sur de grandes distances. Les contrastes de densite, particulierement entre les granites legers sous jacents au bassin, les roches denses du Witwatersrand inferieur, celles moins denses du Witwatersrand superieur de meme que les laves lourdes et les grandes epaisseurs de ces groupes sont les causes d'anomalies gravimetriques appreciables.

Les roches du Witwatersrand superieur sont sous jacentes a une region d'environ 15,000 milles canes qui fait partie de ce que l-on appelle generalement le bassin principal du Witwatersrand. En outre, une avant-butte de roches du Witwatersrand superieur, mais separee du bassin principal par une deformation structural, se trouve a 40 milles a l'Est du bassin principal. Environ le tiers seulement des couches du bassin principal du Witwatersrand affleure alors que l'avant-butte est entierement recouverte de roches plus recentes.

La geophysique a joue un grand role dans la localisation, dans le bassin principal et sous des roches plus recentes, de trois etendues considerables de conglomerats auriferes. C'est aux releves magnetiques au sot et aeroportes que nous devons la decouverte de l'avant-butte a l'Est du bassin principal.

The gold mines of the Republic of South Africa produce 73 per cent of the free world's gold. The annual production is more than 30 million ounces valued at over 1 billion dollars, with in addition, a uranium output valued at over 60 million dollars. Practically all the gold and uranium is won from the auriferous conglomerates of the Witwatersrand System, and only a very small 'amount of the gold is produced from rocks which do not belong to this system. It is therefore appropriate that the major effort in the exploration for gold in South Africa should be orientated towards locating areas underlain by gold-bearing conglomerates of the Witwatersrand System. Geophysics has an important role in this search and gravity and magnetic surveys together with sound geological reasoning have been responsible for the discovery of four important goldfields. These four fields, the West Wits Line, the Free State Goldfield, the Klerksdorp Goldfield and the Evander Goldfield today produce 80 per cent of the gold produced in the Republic.

History

Gold was discovered in 1886 on the Witwatersrand on the farm Langlaagte now a suburb of Johannesburg. The early prospectors had not previously encountered gold in conglomerates and it was thought that they were a form of quartz reef. The name `reef has stuck and all conglomerates likely to be gold bearing are called reefs and were given names such as the Main Reef, Bird Reef, Leader Reef, Basal Reef, Kimberley Reef, Vaal Reef, etc.

Before the turn of the century the whole outcrop area of 36 miles in extent from Boksburg in the east to Krugersdorp in the west was being actively mined and drilling had established that the reef extended to depth towards the south. The small workers had by then disappeared and mining was being carried out by companies.

To the east beyond Boksburg, the reef disappears beneath a cover of Karroo beds and still further east under the dolomite of the Transvaal System. This area, known as the East Rand' Basin,

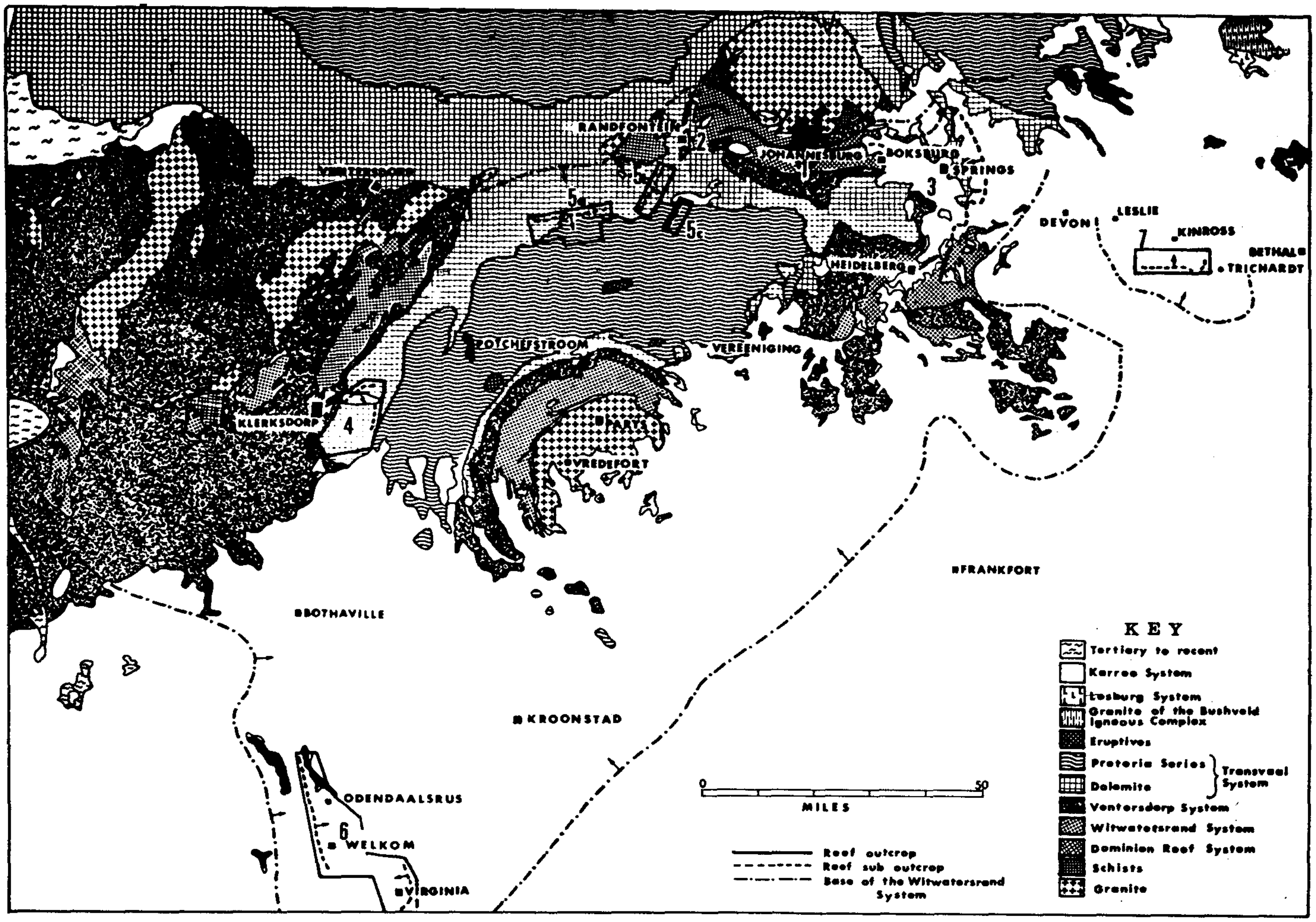


Figure 1. The geology of portion of the Transvaal and Urange Free State, Republic of South Africa, showing the extent of the Witwatersrand Basin and the location of the main gold-mining areas. 1. Central Witwatersrand or Central Rand. 2. West Rand. 3. East Rand and East Rand Basin. 4. Klerksdorp Goldfield. 5a, 5b and 5c West Wits Line. 6. Free State Goldfield. 7. Evander Goldfield on the Kinross Basin.

was prospected by drilling and because of good values and the flat dips the potential of the area was enormous. The East Rand Basin supported 26 mines at one time of which 10 are still operating. The average size of these mines (lease areas) is about 10 square miles.

One hundred miles southwest of Johannesburg near Klerksdorp gold had been discovered in 1886 only months after the discovery at Langlaagte. The Klerksdorp area did not prosper for long but when in 1932 South Africa went off the gold standard, exploration boomed, old mines were revived and new ones were started. By the 1930s gold mines were established on a 65-mile arc from north of Heidelberg in the southeast through Johannesburg to Randfontein in the west. There was a large gap of 80 miles between Randfontein and the Klerksdorp Goldfield. Along approximately half of this gap from Klerksdorp northwards only Lower Witwatersrand rocks were exposed. In the remaining half of the gap there were no outcrops of Witwatersrand rocks at all and if they did occur they were covered by the Transvaal dolomite and Pretoria series.

In 1930 Dr. R. Krahmann showed that the magnetic content of some of the Lower Witwatersrand shales made it possible to locate the position of these shale bands **hidden under a thick** cover, and to estimate strike and dip from the readings observed on a magnetometer. With a knowledge of the relationship of the reefs to the magnetic beds as observed from outcrops on the West Rand, it became possible to establish the more exact position, beneath the dolomite cover, of the Upper **Witwatersrand beds** within which the gold reefs occur. This had **been roughly established** some 30 years before by limited drilling. **Earlier** development of this field, the West Wits Line, had been prevented by technical difficulties encountered due to the enormous quantities of water contained in the overlying Transvaal dolomite.

Much thought had been given to the possibility of the Witwatersrand beds extending south from Klerksdorp into the province of the Orange Free State. Before 1900 a conglomerate was noticed on the farm Aandenk near Odendaalsrust. Although this conglomerate was barren and belonged to the Ventersdorp System which could be many thousands of feet thick, various parties from time to time insisted on reopening the workings and in 1933 a diamond drill hole was drilled down dip from the conglomerate outcrop and intersected lavas below the conglomerate. The chances of intersecting Witwatersrand beds were remote;

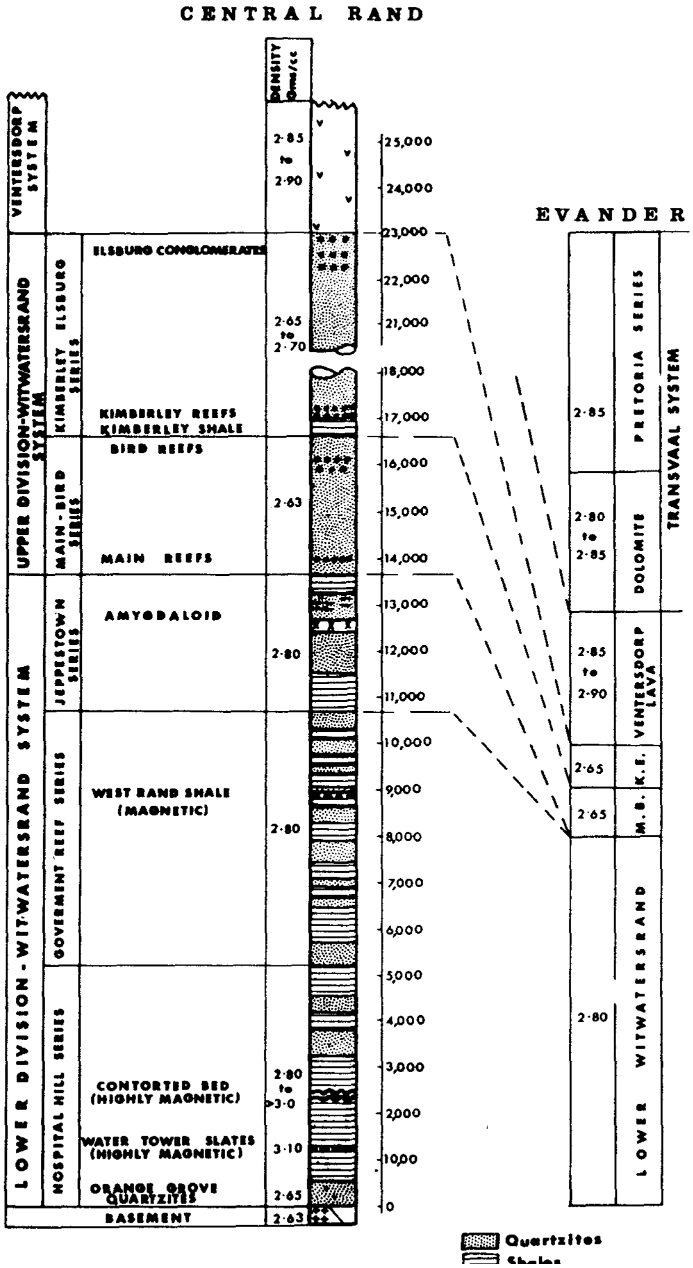


Figure 2. Diagrammatic stratigraphic column of the rocks of the Basement, Witwatersrand, Ventersdorp and Transvaal Systems in the Central Witwatersrand and Evander goldfields. The positions of the three major magnetic horizons are shown and the densities for the various suites of rocks indicated.

the nearest outcrop was 50 miles to the north. However, the hole was deepened and went out of lavas into Upper Witwatersrand rocks at 2721 feet! The hole was continued to 4046 feet but no pay values were encountered. This hole stopped some 400 feet above the Basal Reef, the `pay' reef of the Free State which was first discovered 5 years later in a borehole 20 miles away.

Huge areas were taken up in the Orange Free State and geophysical surveys were carried out using the magnetometer, the gravimeter and the torsion balance. The object of the gravity and torsion balance surveys was to locate the light Upper **Witwaters**rand rocks where the cover of heavy lavas was thin. Borehole S.H.1 on the farm St. Helena was sited on a gravity low to the east of a distinct zone of north-striking magnetic anomalies lying on a gravity high. Early in 1938 this borehole intersected a reef with erratic gold values. **Exploration proceeded and the first gold mine** in the Free State, Saint Helena Gold Mine, **was established on the** Basal Reef.

There was great activity around this area and by 1946 some 300 to 400 boreholes had been drilled in the Free State Goldfield which now supports eleven mines (Area 6, Figure 1).

In the 1930s a ground magnetic survey in the Kinross area revealed magnetic anomalies due to Lower Witwatersrand rocks. Twenty boreholes were drilled without discovering reef.

Structural difficulties in the area northeast of Klerksdorp suggested the use of geophysics to establish the nature of the ground below the iavas and dolomites. In 1947 BD. Maree located a gravity low on the farm Stilgontein. He suggested that this could be due to light Witwatersrand quartzites close to the surface beneath the dolmites. O. Weiss carried out a gravity survey on the farms Stffontein, Rietfontein and Hessie for the Strathmore group. Six boreholes sited on the gravity low all intersected the Vaal Reef conglomerate. The mines of Stilfontein, Buffelsfontein, Hartebeestfontein, Vaal Reefs, Zandpan and Western Reefs are now operating on this zone.

In 1948 the Oscar Weiss organisation flew the first airborne magnetometer survey for Union Corporation using a fluxgate magnetometer mounted inboard on a DC3 aircraft. Some 42,000 profile miles were flown on this survey. During 1948-1949 certain areas were detailed with airborne magnetometer for Union Corporation and other groups.

In 1949 interest was reawakened in the Kinross area by Union Corporation who carried out aerial magnetic, ground magnetic and gravity surveys in the area and after extensive drilling established the first mine, Winkelhaak Gold Mine, which started operating in 1956. This area, now known as the Evander Goldfield, supports four gold mines, Winkelhaak, Leslie, Bracken and Kinross.

At the present time there are 54 gold mines operating on Witwatersrand reefs. The most recent mines to be established are Kinross (1964) on the Evander Field and Kloof (1964) and Elsburg (1967) both in the West Wits area.

Location and geology

The location and extent of the Witwatersrand Basin is shown in Figure 1. The Witwatersrand Basin is filled by a thick succession of sedimentary and volcanic rocks up to a total thickness of 40 to 50 thousand feet. Rocks filling the basin belong to the Dominion Reef, Witwatersrand, Ventersdorp, Transvaal and Karroo Systems. The Witwatersrand System which is divided into a lower division of predominantly argillaceous rocks and an upper division of mainly arenaceous rocks, comprises about half the rocks filling the basin. A thick succession of lavas and sediments of the Ventersdorp System lies both conformably and unconformably on the Witwatersrand System and is followed by the dolomites, shales and quartzites of the Transvaal System. Closely associated with the Witwatersrand System at its base is the Dominion Reef System. Any one of these groups of rocks can lie on the basement of old granites or basement complex made up of

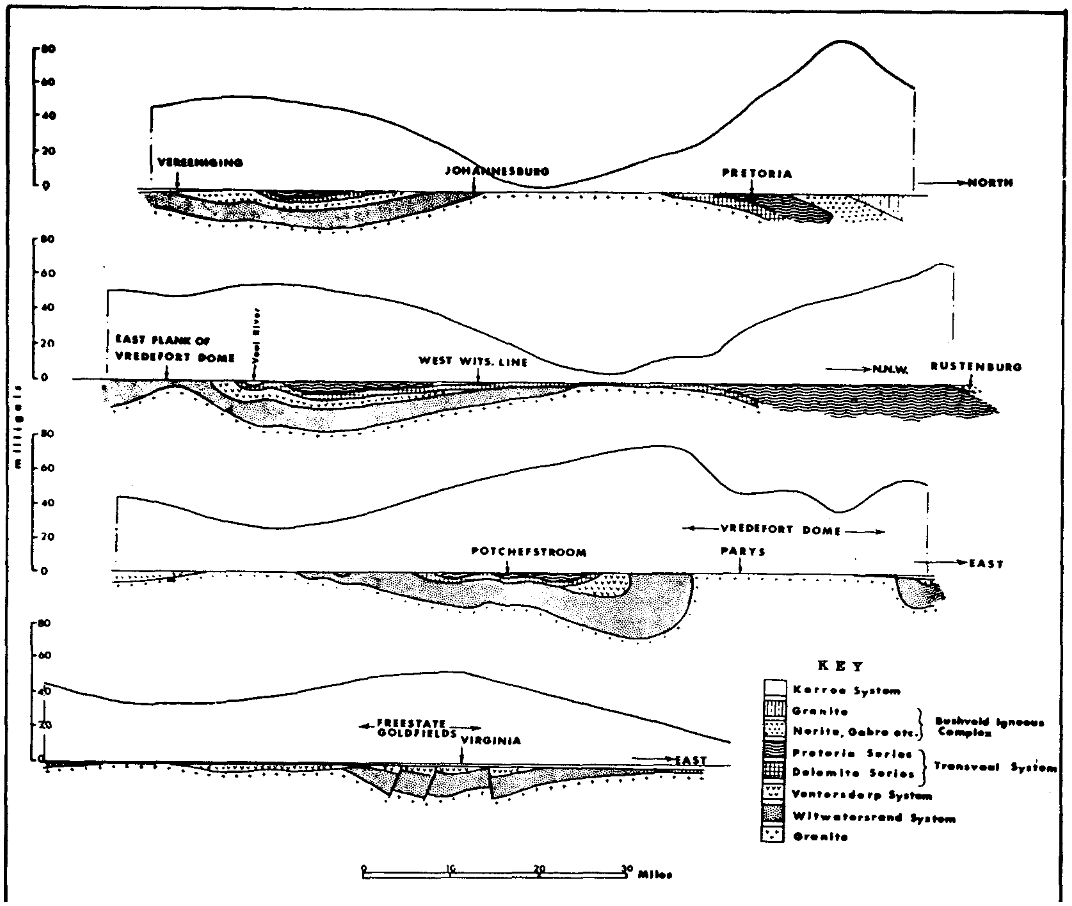


Figure 3. The Witwatersrand Basin. Geological sections and gravity profiles across the basin.

rocks of the Swaziland System or other pre-Witwatersrand rocks. A marked unconformity forms the comparatively flat floor of the Karroo sediments which overlie these rocks over a large area. The Karroo sediments were laid down in Carboniferous to Jurassic times whereas all the other rocks under discussion are Precambrian.

The Witwatersrand System is characterised by the remarkable persistence over great distances of even very thin beds. The zone of economic interest is the Upper Witwatersrand in which the gold-bearing conglomerates occur. Uranium is often associated with the gold in these conglomerates.

Only a small portion of the rocks contained in the Witwatersrand Basin is exposed at the surface, the remainder is concealed beneath a cover of younger rocks, notably by the Karroo sediments and the Transvaal dolomite. Of the 600 miles of strike length along the rim of the basin and on the flanks of the Vredefort dome only 180 miles of actual outcrop of Witwatersrand rocks occur. The Vredefort dome is a granite boss near the centre of the basin. The Witwatersrand and Ventersdorp beds around the boss have vertical to overturned dips.

The Upper Witwatersrand beds underlie an area of some 15,000 square miles in what is generally known as the Main Witwatersrand Basin or Rand Basin. The north-south axis of this basin (Upper Witwatersrand) is 180 miles long and the east-west axis is 80 miles long. In addition, an outlier of Upper Witwatersrand rocks, separated from the Main Basin by structural deformation occurs 40 miles to the east of the Main Basin: This outlier is known as the Kinross Basin and is entirely covered by younger rocks. The Evander Goldfield is on the Kinross Basin (Area 7, Figure 1).

Figure 2 summarises the stratigraphy of the Witwatersrand and Ventersdorp Systems and Figure 3 shows some typical sections across the basin. As mentioned, the Upper Witwatersrand contains the very important gold reefs. On the other hand, the Lower Witwatersrand is barren of gold except in a few isolated places but is of great importance in that the highly magnetic horizons of this division provide the means of detecting the system beneath thick cover. As with almost all the other horizons of the Witwatersrand System these magnetic beds are remarkably persistent over very large distances and remain in fairly constant stratigraphic relation below the conglomerates. Krahmann (1936) identified nine magnetic anomalies caused by magnetic shale bands on the West Rand. Of these he labelled five as major anomalies. However, it is now believed that possibly two of the major anomalies were the result of repetition due to faulting.

Geophysical exploration

Basic criteria. The gravity and magnetic methods have been used almost to the exclusion of all others in the exploration for Witwatersrand reefs. Both these methods are indirect in that neither locate the reefs themselves. This is in contrast to most methods of mining geophysics where the contrasting physical

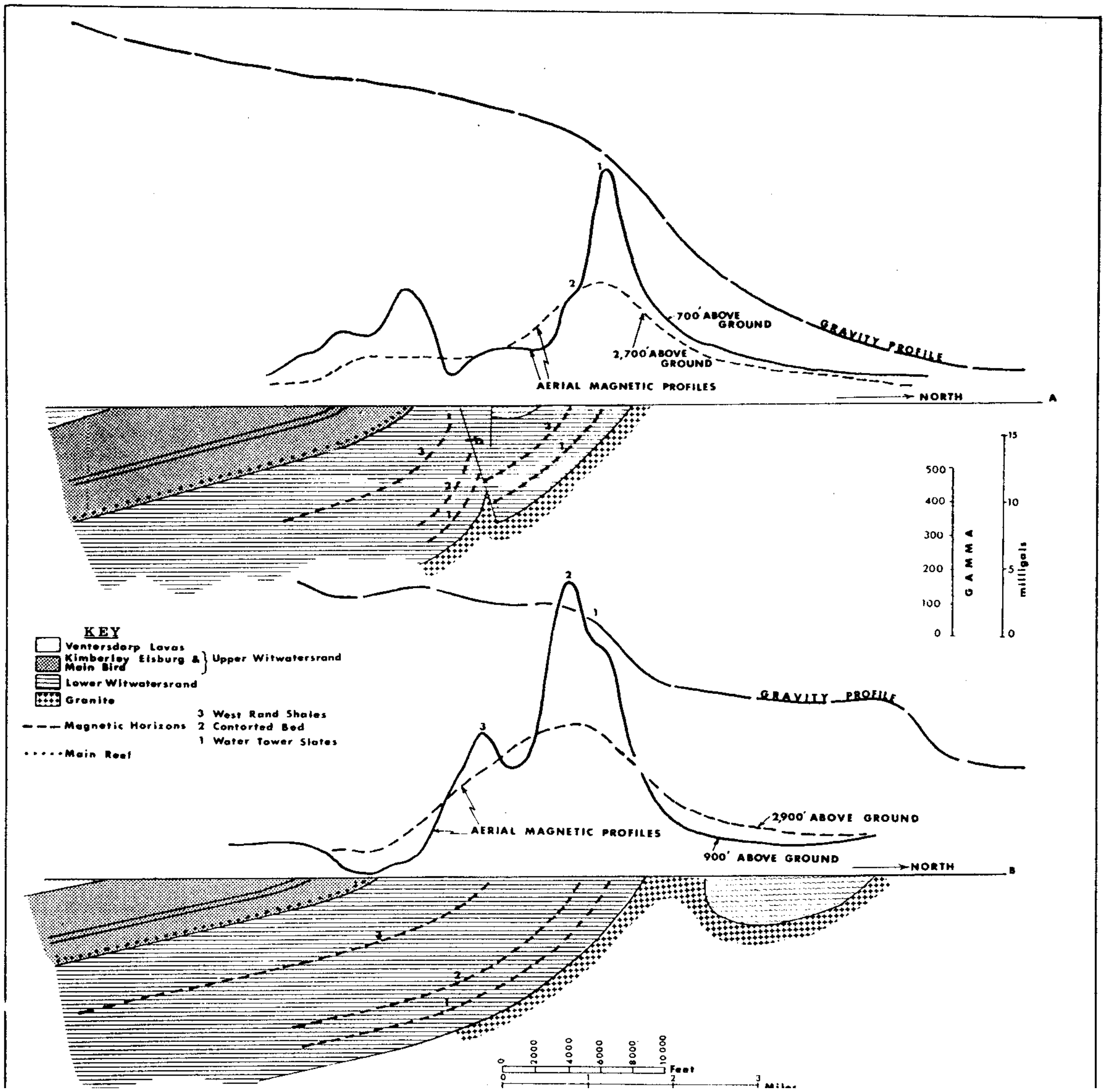


Figure 4. The Central Witwatersrand. Aerial magnetic profiles, gravity profiles and geological sections across southerly dipping Witwatersrand beds. A. Through the eastern suburbs of Johannesburg. B. Across the eastern edge of the outcrop area 11 miles east of Johannesburg.

properties of the ore and the surrounding rock provide the means of detecting the ore by gravity, electrical, magnetic or radioactive methods, or a marker horizon in close proximity to the ore is detected by one or other of these methods. Although the gold reefs are often radioactive and contain high percentages of pyrite, their presence can only be detected by radiation detectors under negligible cover or by electrical methods at comparatively shallow depth. This is of no interest to the prospector simply because the strike of the reefs is so extensive that if they do occur at shallow depth they must inevitably be outcropping close by and would have been followed in the normal course of mining or drilling. No geophysical or geochemical method is capable of indicating the presence of the gold in a hidden reef. The tenor of the gold is very low and the richest reef which may contain as much as 80 ounces per ton in places (Carbon Leader, West Wits Line) will only have a width of up to 2 inches. The percentage gold is never higher than 0.5 per cent. In the thicker reefs which may be several feet thick the gold content may be of the order of 10 dwt/ton or about 20 parts per million.

The gravity and magnetic methods only detect the formations of which the reefs or conglomerates form a very small part in a total thickness of up to 20,000 feet of rock. In fact, the magnetometer detects horizons which are several thousands of feet below the economic horizons and under favourable circumstances the gravimeter may detect the 5 to 10 thousand foot thick Upper Witwatersrand quartzites within which the conglomerates occur. The presence of gold-bearing conglomerates within these formations can only be established by drilling. Geophysically the problem is one of detecting formations and establishing structure and in this regard it is more akin to oil geophysics than mining geophysics.

Provided the grade is high enough, it is economically feasible to mine gold from reefs at great depths. Three gold mines are currently mining from depths in excess of 10,000 feet and one, Western Deep Levels on the West Wits Line, only starts mining on

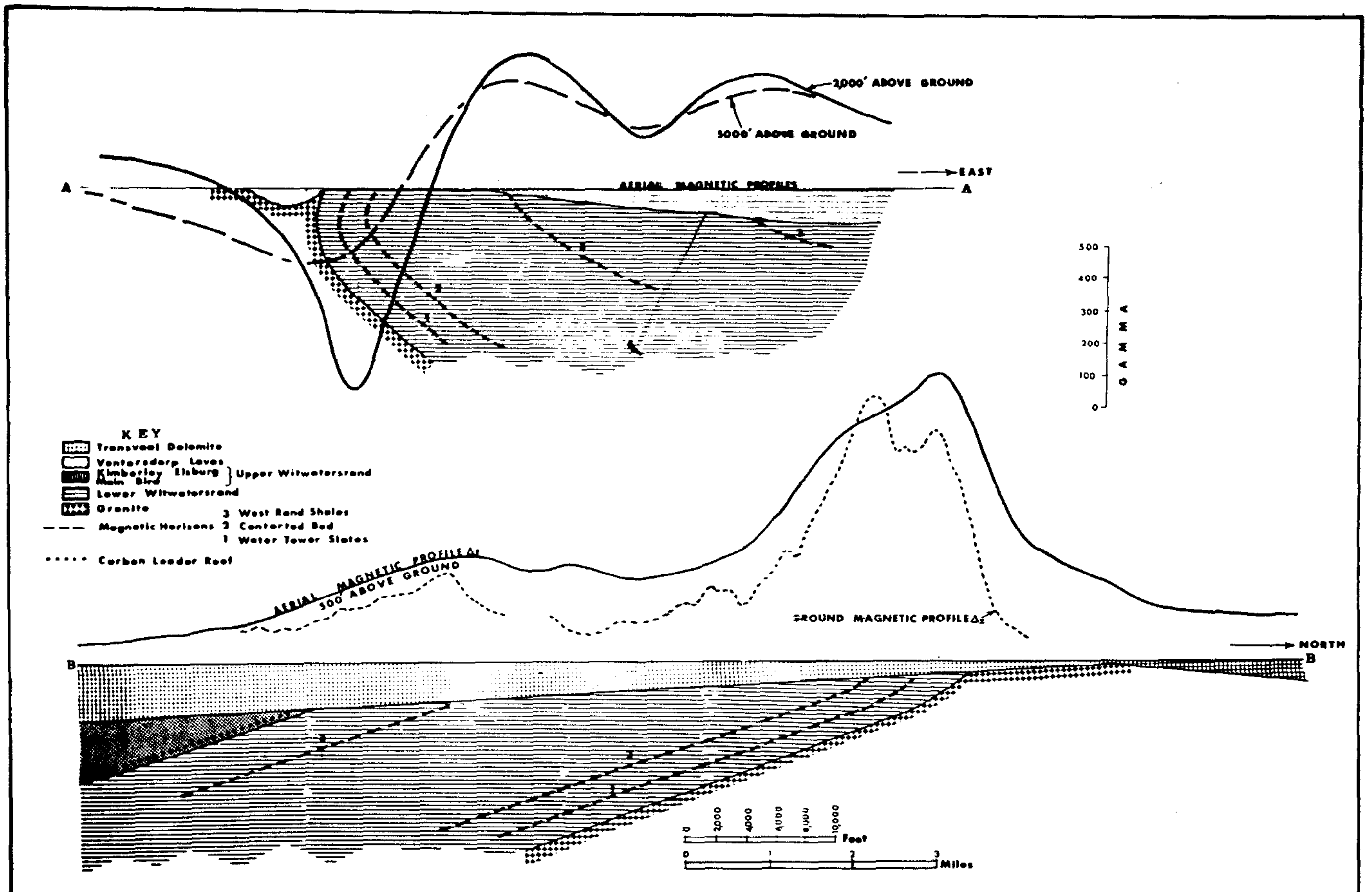


Figure 5. Magnetic profiles across the Witwatersrand System- A. Across overturned Lower Witwatersrand beds striking north northeast 12 miles south of Ventersdorp. B. Across the West Wits Line (Area 5a, Figure 1).

reef at 5200 feet. The shallowest mine in the Free State starts at 700 feet, the deepest at over 4000 feet. Therefore it is quite logical that extensions of the Witwatersrand System could be sought which are covered by several hundreds to several thousands of feet of younger rocks.

Magnetic method. Within the Lower Witwatersrand are several magnetic shales. The most important of these are the Watter tower slates, the Contorted bed, a highly contorted magnetite rich banded shale, and the West Rand shales. All three are sufficiently magnetic to be detected at depths of several thousand feet by moderately sensitive magnetometers. Figure 4 shows magnetic profiles flown at different heights over outcropping areas of the Central Rand. In Figure 4B the profile at 900 feet clearly shows the Water Tower slate (1), Contorted bed (2) and West Rand shale (3) anomalies. In Figure 4A the West Rand shale anomaly is not clearly defined, probably because of complicated faulting in this zone. The geological section is an oversimplification. At greater heights the Water Tower slates and Contorted bed anomalies merge completely to form one anomaly and the two effects are not resolved. In fact, if dips are steep and the distance below flight level approaches the separation of the magnetic beds all three anomalies become one anomaly (see aerial magnetic profile at 2900 feet above ground, Figure 4B).

Figure 2 shows the relative positions of these beds in the stratigraphic column. The lower one, the Water Tower slates, is some 1000 feet above the contact of the lowest member, the Orange Grove quartzites, with the basement. The position of this anomaly occurs therefore very close to the base of the Witwatersrand System and a magnetic map of an area underlain by Witwatersrand rocks will show an alignment of magnetic anomalies corresponding closely to the suboutcrop trace of the base of the system. Down dip further alignments of anomalies will correspond to the Contorted bed and to the West Rand shales. The polarity, shape and degree of resolution of these anomalies will depend on the magnetic nature of the beds, the strata dips and strikes and the depths below. observation level. The determination of dips from the magnetic anomalies is difficult largely because the two major anomalies are usually superimposed and the magnetism is remanent and its direction generally not known. It is usually not important to know the dips of the magnetic beds to any precision, because in the zone of economic interest the dips we'll be flatter, very often considerably flatter, than at the edge of the basin. Consequently the usually steep dips of the Water Tower slates and Contorted bed if determined from their anomalies would give an erroneous position of the Upper Witwatersrand beds and reef horizons. Strike faulting is commonplace throughout the Witwatersrand System and repetition of anomalies often occur down dip. Further, strike faulting within the Upper Witwatersrand beds in general will not be indicated by a magnetic anomaly as the magnetic beds are already too deep to indicate the presence of the fault, or if manifested, the anomaly would be so broad as to be worthless for positioning the fault from the magnetic map. Therefore as a consequence of strike faulting the position of the reef horizons could not be established with any degree of certainty even if the dips were established from the shape of the magnetic anomalies.

Up to this point it has been implied that the Lower Witwatersrand has a reasonably constant thickness, that the magnetic beds are continuous throughout and that they bear a fixed stratigraphic relationship to the conglomerate reefs in the Upper Witwatersrand. Although this appears to be true over large distances and is certainly true on the outcrop area of the Central Rand, there is sufficient evidence from boreholes and mining operations to show that the Upper Witwatersrand beds vary in thickness and there is every reason to believe that the Lower Witwatersrand beds behave similarly. The Upper Witwatersrand at the Evander Goldfield 70 miles east of Johannesburg has thinned to less than 3000 feet and the Lower Witwatersrand is evidently not more than 8000 feet thick. Unfortunately there is a very limited footage drilled into Lower Witwatersrand rocks simply because they occur below the economic horizons and therefore very little is known about these rocks outside the outcrop areas. The probable variation in thickness and relative position of the magnetic horizons relative to each other and the conglomerates adds further to the uncertainty of the position of the conglomerates relative to the anomalies of the magnetic map. It is possible that one or more of the major magnetic horizons could be entirely missing. From the foregoing it would appear that the interpretation of the magnetic map is largely empirical and the effectiveness of the interpretation depends on the available local knowledge of the structure. Even if a magnetic zone only indicates the possible presence of Witwatersrand rocks and the direction of their dips, progress has been made.

Depth determinations can be made on profiles using both the horizontal slope distance of the maximum slope, or Peters' method of the distance between tangents of the half maximum slope. These are subject to gross errors as they are influenced by the superposition of the two important anomalies and by adjacent interfering effects whether from deep seated or shallow causes. Standard profiles obtained by flying over known areas with various conditions of dip and strike are catalogued and compared with the profiles obtained on survey. A number of attempts have been made by the author's group to establish depth by flying at multiple levels. This is not really satisfactory unless the complete grid is flown at selected levels. The survey then becomes excessively costly.

Gravity method. The granite on which the Witwatersrand System generally rests has a density of 2:63 gm/cc. The rocks comprising the Lower Witwatersrand are shales, quartzites and intrusives with densities of 2.63 gm/cc for the quartzites, 2.8 to 3.85 gm/cc for the shales and slates and 2.8 to 3.0 gm/cc for the intrusives. The shales make up about 60 per cent, the quartzites 30 to 40 per cent and the intrusives '_' to 10 per cent. The mean density for the group varies between 2.75 and 2.83 gm/cc, thus making it denser than the granite by 0.1 '_' to 0.20 gm/cc. The total thickness of the formation can be as much as 20,000 feet and is probably nowhere less than 6000 feet, and thus represents a large relatively heavy mass compared with the granite. The Upper Witwatersrand is comprised predominantly of quartzites with some minor shale bands, conglomerates and intrusive sills. With the quartzites and conglomerates making up 90 per cent- of the Upper Witwatersrand rocks the mean density is 2.63 to 2.66 gm/cc. The thickness of the Upper Witwatersrand can vary from a **few thousand feet to 10** thousand feet and thus represents a light mass **compared with the** Lower Witwatersrand.

Lying both conformably and unconformably on the Witwatersrand System is the Ventersdorp System, comprised largely of great thicknesses of andesitic lavas of a density of 2.8 to 2.9 gm/cc, and usually lesser thicknesses of sediments predominantly quartzites and conglomerates. High up in the succession are porphyritic lavas with lower density than the andesitic lavas. The andesitic or basic lavas can be many thousands of feet thick and, contrasting in density by 0.2 to 0.3 gm/cc with the granite and the Witwatersrand quartzites, they form an appreciable heavy mass compared with the lighter rocks.

The Transvaal dolomite which can lie on any of the older formations has a density of 2.85 to 2.89 gm/cc and reaches a thickness of some 5000 feet. The Pretoria series, conformable with the Transvaal dolomite, has a mean density of around 2.85 to 2.90 gm/cc.

Because of these enormous thicknesses of material and the contrast in densities of around 0.15 to 0.3 gm/cc these formations produce appreciable gravity anomalies.

A Gravity Map of the Republic of South Africa with 10 milligal contours superimposed on the geology (scale 1:1,000,000) is published by the Geological Survey. An extensive network of stations was observed along roads at station intervals between 1 to 10 miles. This map used in conjunction with reconnaissance aerial magnetic surveys can form a useful starting point in exploration. The Witwatersrand Basin shows an anomalous gravity in excess of 40 milligals due to the heavy rocks of the Witwatersrand, Ventersdorp and Transvaal Systems filling the basin. High gravity is not confined to the Witwatersrand Basin only; deep basins of rocks belonging to the Ventersdorp, Transvaal and other systems where no Witwatersrand rocks are present also produce substantial gravity highs. The extensive occurrence of volcanic and intrusive rocks of the Bushveld igneous complex are the cause of the largest gravity anomalies in the country.

Figure 3 shows gravity profiles and geological sections derived from the gravity map of the Republic of South Africa and adequately illustrates the gravity effect caused by these formations.

The usefulness of the gravity method is twofold, first to establish the existence of a basin of predominantly heavy rocks beneath a cover of younger rocks, usually of Karroo age, and secondly to detail the structure within the basin. In particular changes of gradient and gravity lows can be indicative of the presence of the lighter Upper Witwatersrand quartzites sandwiched between the heavy Lower Witwatersrand and Ventersdorp rocks (Figures 6 and 7). Where heavy Ventersdorp lavas and Transvaal dolomite cover Witwatersrand formations gravity lows can occur where the Upper Witwatersrand quartzites are present below a shallow cover of these rocks (Figures 8 and 9).

The gravity and magnetic methods are complementary to each other. Magnetic anomalies can be due to other causes than the magnetic Lower Witwatersrand beds. If the magnetic anomalies occur on the edge of an extensive gravity high then the

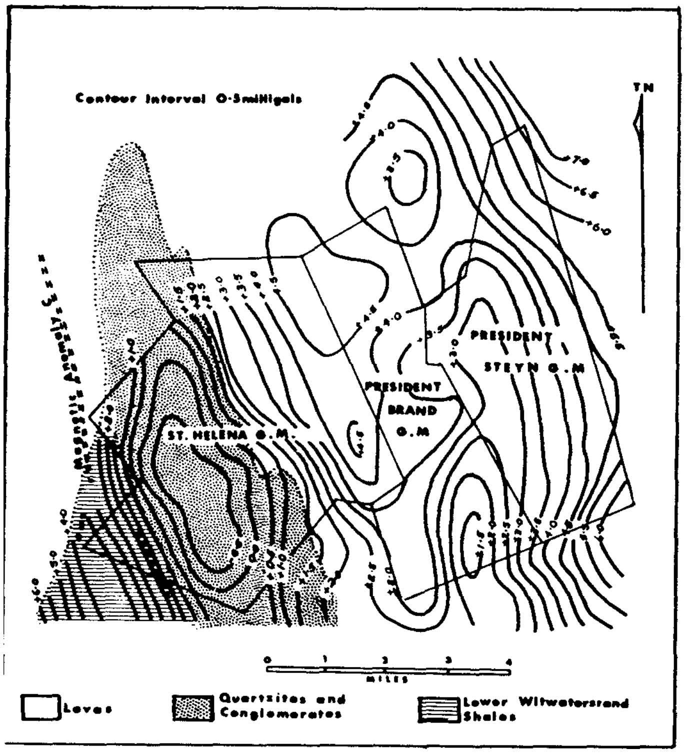


Figure 6. St. Helena. Gravity contours of portion of the Free State Goldfield and pre-Karroo geology showing the gravity low which lead to the discovery of the St. Helena Gold Mine.

chances that the magnetics are due to Lower Witwatersrand are greatly improved. Certain characteristics of magnetic anomalies based largely on type profiles over known areas strengthen the interpretation.

Although the initial interpretation of the magnetic map is largely empirical the geophysicist is able to make more specific deductions as to structure by comparing the data of the magnetic and gravity maps. A borehole site is selected on the basis of this interpretation and is sited to intersect reef. The reef may be some 6000 feet above the nearest magnetic horizon and if the dips of the formations are, say, 25 degrees the borehole site will be some 3 miles ahead of the peak of the anomaly and the chances therefore of intersecting reef in the first borehole are not high. Nevertheless useful stratigraphic information is obtained if the reef itself is not intersected and interpretation will be modified accordingly. This type of exploration is based entirely on geological theory with a thorough knowledge of local geology using the magnetic and gravity methods and the diamond drill to work out the details of the hidden structure. Continual collaboration between the geologist and geophysicist is absolutely essential.

Geophysical surveys

The West Wits Line. In the early 1900s boreholes drilled southwards from Randfontein intersected good gold values (Area 5b, Figure 1) and geological reasoning indicated that the Witwatersrand System must run somewhere beneath the dolomite towards the outcrop area southeast of Ventersdorp (Figure 1).

Dr. R. Krahmann (1936) demonstrated that the magnetic beds of the Lower Witwatersrand series **could be followed even under a** reasonably thick cover of the dolomite. A magnetic survey was conducted by Dr. Krahmann in collaboration with Dr. L. Reinecke for Goldfields of South Africa covering an area of 380 square miles involving over 100,000 observations on nearly 1500 miles of traverse. This was the first application of geophysics to the search for Witwatersrand reefs.

Borehole sites were selected by calculating the position of the reef from the position of the magnetic anomaly representing the highest magnetic horizon (the West Rand shales) after making certain assumptions as to dips of the dolomite and Witwatersrand beds and the thickness of the Witwatersrand beds between the highest magnetic horizon and the reef. These assumptions were based largely on outcrop and borehole information south of Randfontein.

A ground magnetic profile after Krahmann and an aerial magnetic profile across the West Wits Line is shown in Figure 5. These profiles show the three magnetic anomalies due to the Water Tower slates (A), the Contorted bed (B) and the West Rand shales (C).

Seven gold mines are producing in this area including the richest gold mine in the world, West Driefontein.

St Helena. The second geophysical success, that of St. Helena Gold Mine in the Free State was due to a combined application of geology, gravity and magnetics. A. Frost (Frost, *et al.*, 1946), Consulting Geologist for Union Corporation Limited, theorised that the normal succession of Witwatersrand and Ventersdorp rocks could occur somewhere in the Orange Free State at shallow depth accessible to mining. O. Weiss (Frost, *et al.*, 1946) suggested that if the Upper Witwatersrand quartzites occurred anywhere at shallow depth they would, by virtue of their thickness and their lower density (lava 2.85 gm/cc, quartzites 2.65 gm/cc), cause a detectable gravity low. The heavy Lower Witwatersrand rocks would be indicated by a gravity high with associated magnetic anomalies and the lavas by a gravity high with no magnetic anomalies.

Large areas in the Orange Free State were covered by the torsion balance and magnetometer and indicated that the lava cover was thick. Union Corporation Limited, in collaboration with Western Holdings Limited, then covered an area of ground held by Western Holdings which included the farm St. Helena.

Figure 6 shows gravity contours over a portion of the Free State Goldfield and Figure 7 shows a gravity and magnetic profile across St. Helena Gold Mine. The contours are according to Weiss and clearly show a closed gravity low of about 3 milligals. The gravity low occurs to the east of a zone of magnetic anomalies corresponding to anomalies A, B and C in Figure 7. These magnetic anomalies lie on a zone of high gravity. The interpretation was that the magnetic anomalies and the associated high gravity was due to Lower Witwatersrand rocks, that the gravity low was due to Upper Witwatersrand quartzites dipping eastwards, and that the increase of gravity east of the gravity low was caused by Ventersdorp lavas increasing in thickness to the east. Borehole S.H.1 was drilled about the middle of this low and after cutting through 991 feet of Karroo rocks, was drilled through 6081 feet of quartzites, where it intersected an auriferous reef. However, subsequent drilling showed that this hole was in the footwall of the Basal Reef but still in the Upper Witwatersrand division.

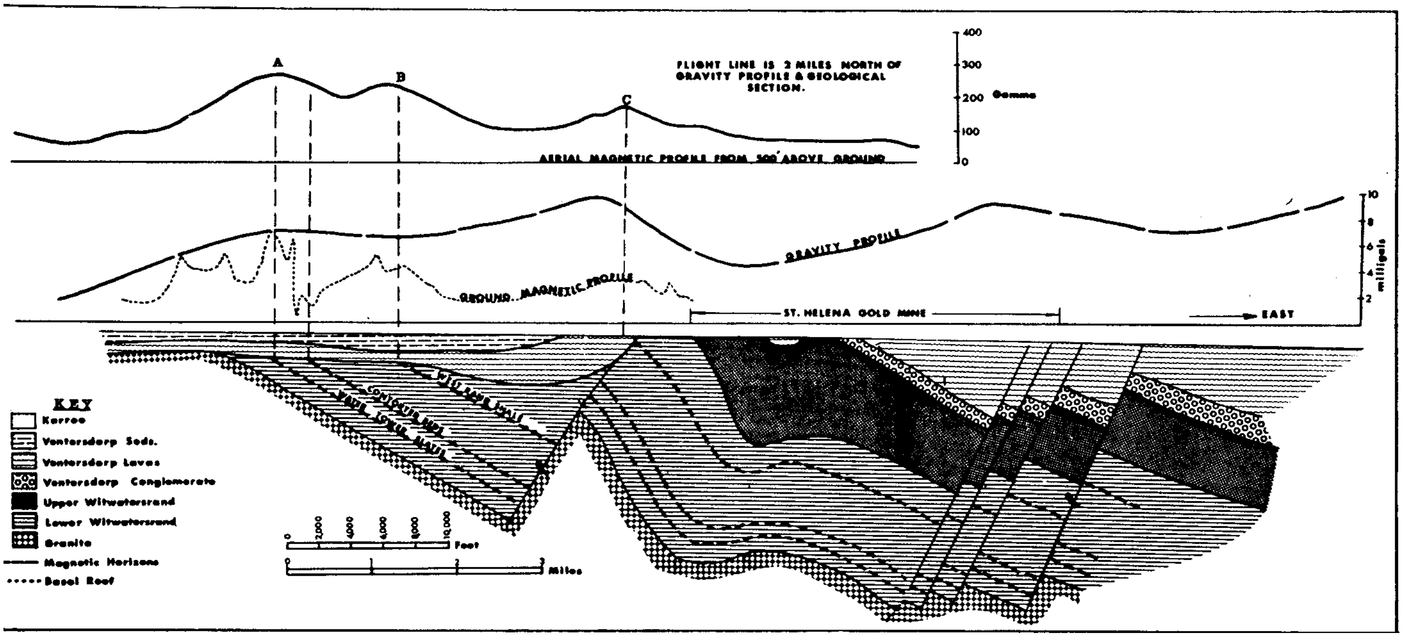


Figure 7. St. Helena. Gravity, ground magnetic and aerial magnetic profiles and geological section across St. Helena Gold Mine and environs.

A feature of the magnetics in this area is the way that the anomalies disappear on strike and reappear again. This is thought to be due to a deep lava trough which cuts across the strike of the anomalies, putting the magnetic beds at depth too deep to register at the surface. This trough is shown ahead and to the east of the anomalies in the section of Figure 7. Note the advantage of the aerial magnetic profile over the ground profile. Surface dolerite sills and dykes in the Karroo beds are the cause of the noisy results whereas these effects are largely eliminated from the air.

The geophysical interpretation is not as straightforward as this example may suggest it to be. From the extensive gravity work in the Free State Goldfield gravity lows can be found which are due not to Upper Witwatersrand quartzites, but to Ventersdorp sediments or in the one case to a deep Karroo trough (Karroo sandstone and shales have densities of 2.45 to 2.65 gm/cc). Likewise the best and most persistent magnetic anomalies which occur north of the Free State Goldfield suggest shallow magnetic beds, yet drilling down dip revealed deep lava in excess of 6000 feet. The explanation is that the magnetic beds are relatively shallow but that the dips are very steep and the Ventersdorp unconformity is such that the lavas deepen rapidly, cutting out the Upper Witwatersrand beds.

Stilfontein. Figure 8 shows the gravity contours (Weiss, 1951) of the Stilfontein area which lies some 10 miles northeast of Klerksdorp. The area of the gravity map lies wholly on dolomite and falls within the area No. 4 of Figure 1. To the west of the area are the outcrops of the Lower Witwatersrand System which dip eastwards. Early boreholes east of this outcrop in the dolomite area had stopped in Lower Witwatersrand rocks. The gravity low suggested that light Upper Witwatersrand quartzites could occur at shallow depth below the dolomite. Aerial magnetic data indicated that the gravity low area was magnetically flat, whereas to the north magnetic anomalies suggested the presence of Lower Witwatersrand rocks below the dolomite. Nine boreholes drilled into the gravity low intersected Upper Witwatersrand rocks at depths ranging from 1913 to 4039 feet. Six of these holes intersected the Vaal Reef. The sections in Figure 9 clearly illustrate the correlation between the gravity and the geology.

This area covered by the dolomite now has six operating gold mines. To the north of the area drilling and geophysical surveys have failed to indicate the presence of Upper Witwatersrand rocks beneath the dolomite. Steep faulting and folding is responsible

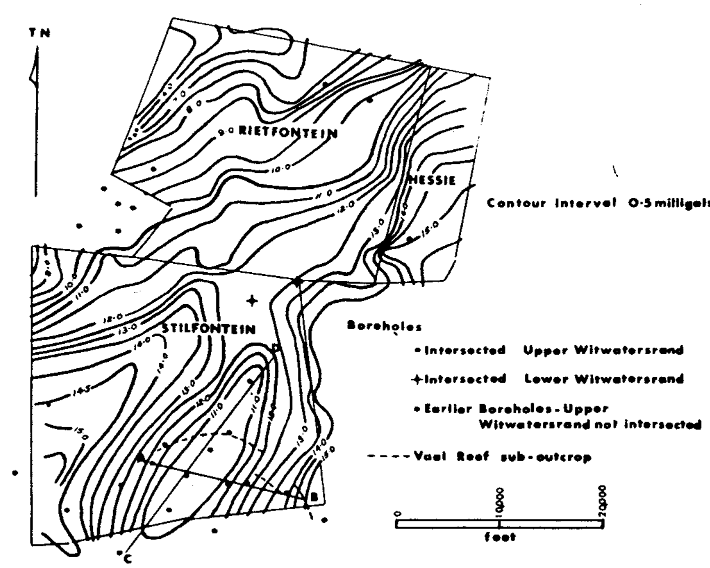


Figure 8. Stilfontein. Gravity contours on the farms Stilfontein, Hessie and Rietfontein showing the gravity low which led to the discovery of the Stilfontein Gold Mine in the Klerksdorp goldfield (Area 4, Figure 1).

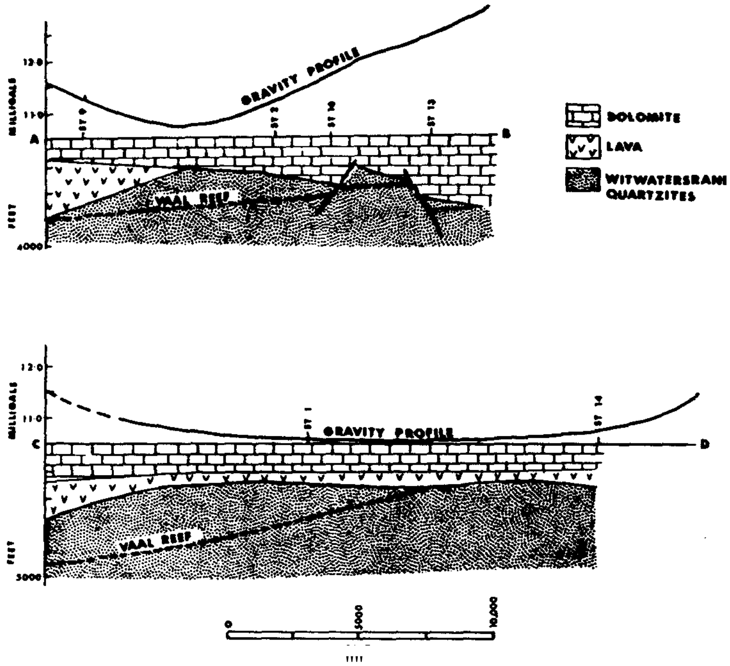


Figure 9. Stilfontein. Geological sections and gravity profiles on IinesAB and CD of Figure 8.

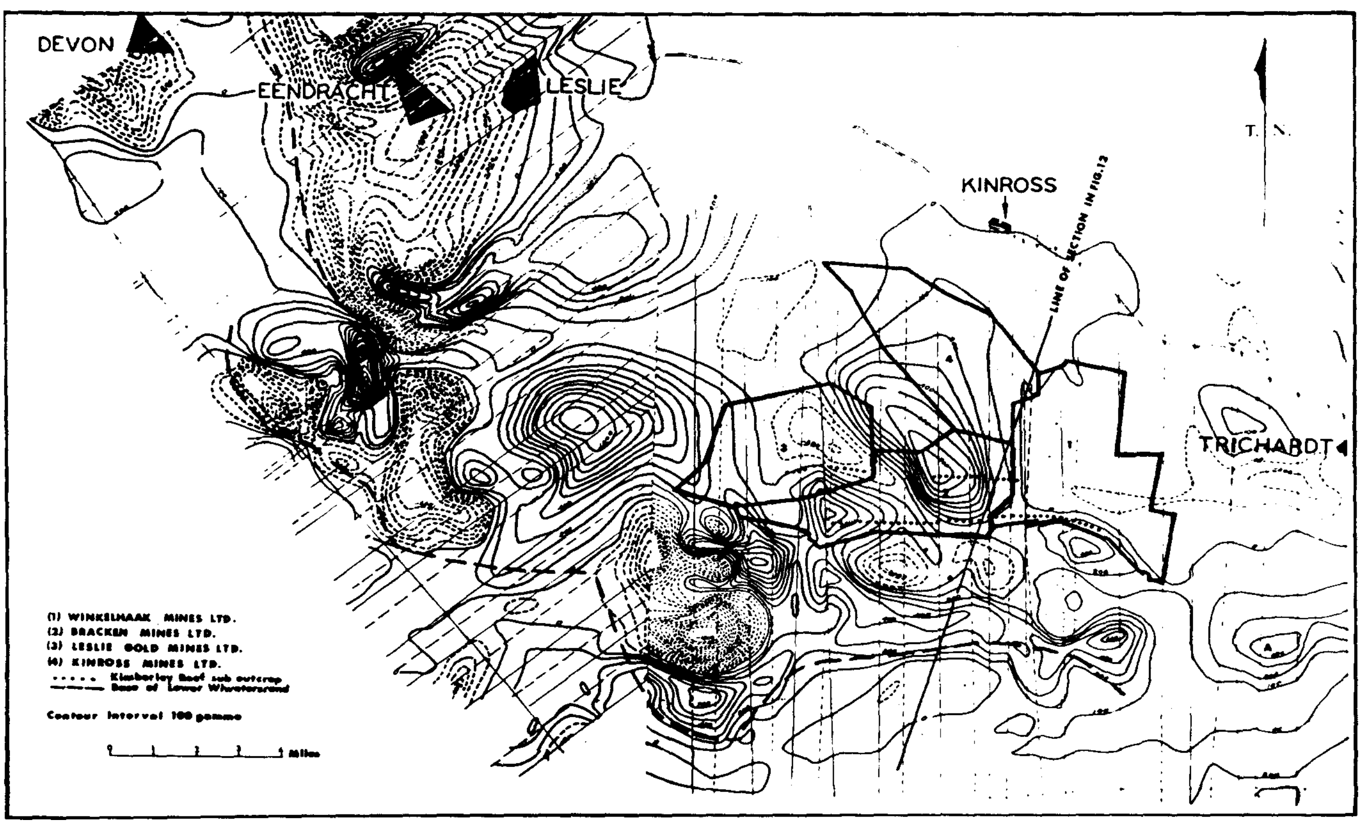
for bringing the Lower Witwatersrand rocks to suboutcrop apparently across the whole area of the dolomite. By the time the dolomite dips below the Pretoria series the dolomite is already 5000 feet thick and together with a varying thickness of Ventersdorp lavas the depth to reef would be considerable.

Geophysical case history: the discovery of the Evander Goldfield

The history of this field goes back to before 1933 when Lower Witwatersrand rocks were recognised in a borehole which was drilled to investigate gas emissions in the area (Area 7, Figure 1). In 1933 Fox started an investigation of the Far East Rand between Springs and Bethal (Fox, 1939). A ground magnetic survey involving 53,209 stations on 1240 miles of traverse was carried out in an area from north of Devon in the west, to near Trichardt in the east. This survey revealed magnetic anomalies forming a crescent striking south between Devon and Leslie and swinging to an easterly strike 10 miles south of Kinross. Fox postulated that these anomalies were due to Lower Witwatersrand beds. A vertical hole sited on the most intense of these anomalies near Leslie (20,000 gammas) intersected the highly magnetic Contorted bed of the Lower Witwatersrand below 477 feet of Karroo rocks (Fox, 1936).

The direction of the regional dip was interpreted as being inwards from the arc of magnetic anomalies, that is, northerly and easterly. Twenty boreholes were drilled in the area on the assumption that the Upper Witwatersrand beds would develop east and north from the magnetic anomaly arc. In not one of

Figure 10. The Evander Goldfield. Aerial magnetic contours



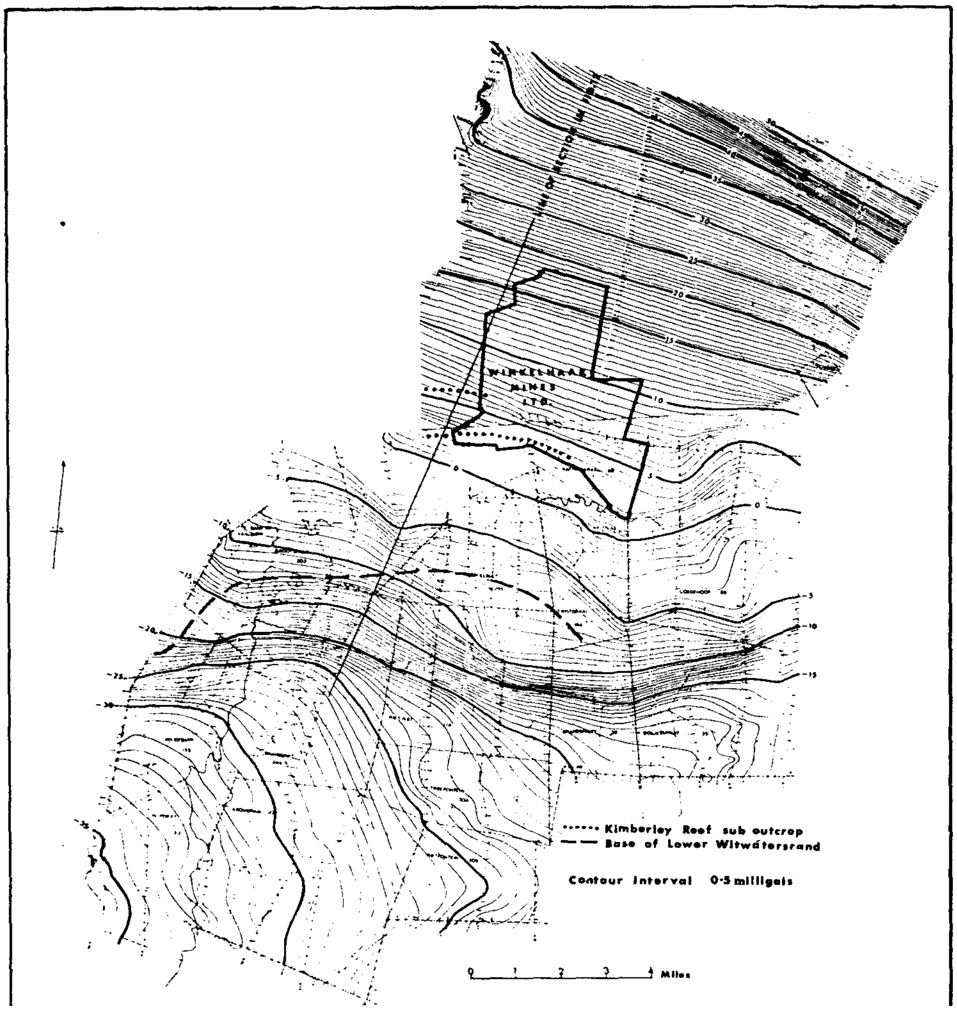


Figure 11. The Evander Goldfield. Gravity contours of portion of the Evander Goldfield.

these boreholes was the Main Reef or Kimberley Reef found or recognised. Exploration ceased in 1936.

Interest in the area remained dormant until 1948 when the Union Corporation started an investigation of the area. The area formed part of a regional airborne magnetic survey and during the course of this survey the area was covered by a wide-spaced grid at approximately 5-mile intervals. The results of this survey showed anomalies extending farther eastwards and indicated the magnetic relationship of this area to the known areas to the west. Although the magnetic anomalies pointed to northerly dips, it seemed more probable from geological considerations that the beds were dipping south and that they formed a part of the northern rim of the main basin displaced into the position indicated by the magnetic anomalies by faulting. On this basis a company, Capital Mining Areas, was formed and ground was taken under option on and to the south of the magnetic anomalies. Ground magnetometer and gravity surveys in this area indicated that the beds were in fact dipping north and ground was taken up to the north of the anomalies. This interpretation was based largely on the gravity survey (Figure 11) which showed an increase of gravity northwards with a steep gradient immediately south of the magnetic anomalies (Figure 12). The low gravity south of this steep gradient was virtually devoid of magnetic anomalies and was interpreted as being underlain by granite beneath the Karroo cover. The high gravity to the north was interpreted as being due to heavy rocks of the Witwatersrand System, lavas of the Ventersdorp System and Transvaal dolomite increasing in thickness beneath the cover of Karroo rocks. This interpretation was in accordance with a gravity profile through Johannesburg where the rocks of the various systems are exposed at surface (Figure 4).

A gravity traverse was run northwards along a road through Trichardt and showed a gravity peak of 90 milligals, 8 miles north of the town. This anomaly and the gradients over the Capital Mining Area were in excess of anything previously experienced in Witwatersrand basin studies and could only be accounted for by introducing both Pretoria beds and Bushveld igneous complex rocks all dipping north. The steep gradient in the area of interest was bothersome as it was difficult to remove to obtain residuals that would be sufficiently meaningful. At this stage -only the steeper gradient south of the magnetic anomalies could be used to establish the base of the Witwatersrand beds. (As it turned out later, this steep gradient occurred at the base of the schist below the Witwatersrand beds.)

There were a number of puzzling features about the magnetic anomalies particularly south of Trichardt (Anomaly A in Figure

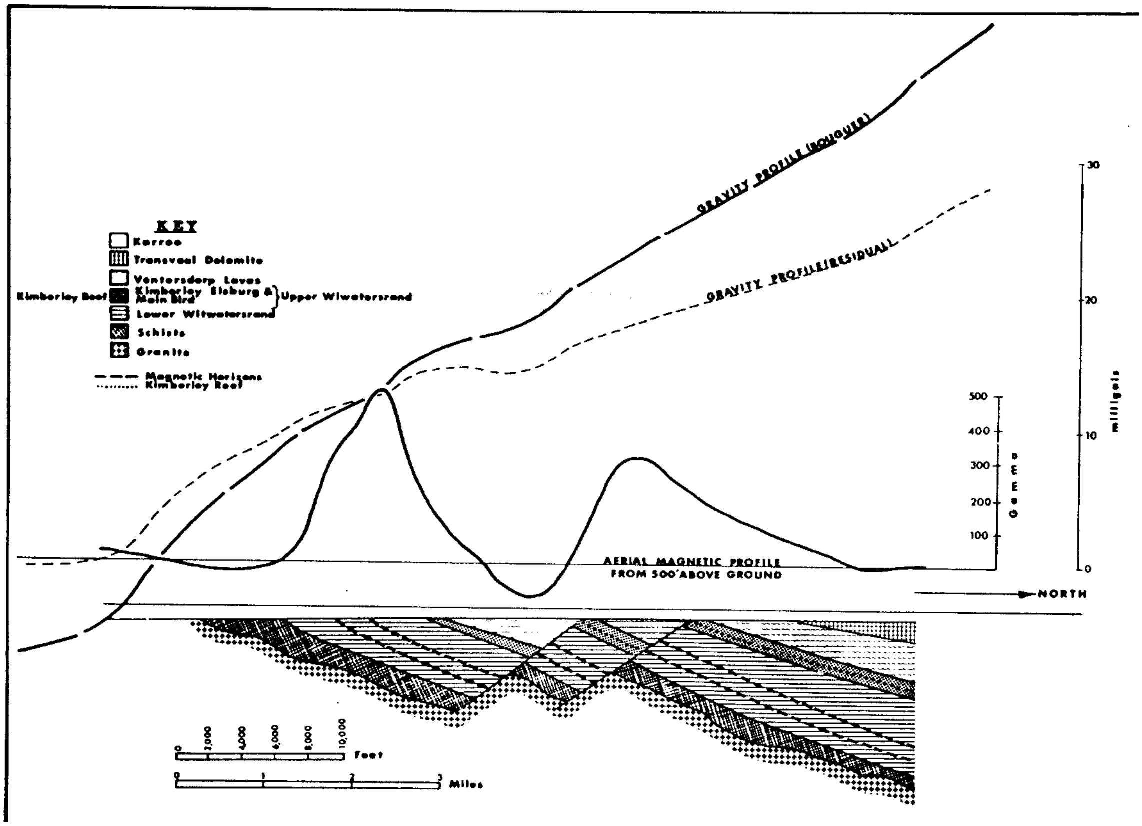


Figure 12. The Evander Goldfield. Gravity and aerial magnetic profiles and geological section on section line shown in Figures 11 and 12.

10). Here the magnetics showed only one anomaly and not the expected three anomalies of the Water Tower slates, Contorted bed and West Rand shales. To explain this a fault was postulated coinciding with the peak of the magnetic anomalies so that the northern side of the fault was downthrown and all three magnetic horizons butted up against this fault thus resulting in a single anomaly. On the basis of this interpretation a borehole, UC57, was sited immediately ahead of the anomaly peak in the hopes of intersecting Upper Witwatersrand beds.

This borehole commenced drilling in February 1950 and intersected Basement Schists below 695 feet of Karroo rocks. This was the first setback and forced a reassessment of the geophysical data. Although the schists in the borehole core were only slightly magnetic, it seemed possible that more highly magnetic schists could occur at greater depth and that the magnetic anomaly was in all probability due to schists. A second hole, UC60, was drilled 8000 feet north of the first and again intersected schists. It was then realised that drilling was in a structurally complicated area and a site for the third borehole was selected on the farm Winkelhaak some 7 1/2 miles northwest of the first hole. This borehole was the first success in that it established the existence of Upper Witwatersrand beds lying between Ventersdorp lavas at the top and Lower Witwatersrand beds at the bottom. A number of reef zones were intersected including the Kimberley Reef but the gold values were low. The drilling program was now concentrated on establishing the extensions of this reef on strike and down dip and to find values upon which a mine might be established.

In August 1952 six drills were in progress and ten holes had been completed of which seven had intersected the Kimberley Reef.

In March of 1952 after six boreholes had been completed a detailed aerial magnetic survey was flown over an area from Devon in the west to Breyten in the east. Two thousand profile miles were flown over an area of some 1300 square miles at 1/2-mile and 1-mile intervals.

Figure 10 shows the aerial magnetic contours of part of this survey over the area of the Evander Goldfield. The complexity of the pattern of the magnetic anomalies becomes apparent. The advantage of the aerial magnetics over ground magnetics in this area, apart from speed, was that the noisy background caused by surface dolerites of the Karroo System was eliminated.

By the time the results of the aerial magnetic survey were delivered, drilling had established that the Upper Witwatersrand System was considerably thinner than on the East Rand. There was also reason to believe that most of the Jeppestown Series was missing (Figure 2). This accounted for the fact that the Kimberley Reef suboutcrop was not as far down dip from the nearest magnetic anomaly as is usual on the East Rand, Central Rand and West Rand. Another unusual feature was that magnetic anomalies also occurred down dip from the reef suboutcrop. These anomalies were originally considered to be due to the West Rand shales before drilling proved this wrong. As drilling progressed it became evident that strike faulting occurred with upthrows on the north side resulting in the reef being brought back to suboutcrop. These faults were also responsible for bringing the magnetic horizons closer to the surface: To add to the complication of interpretation, a number of these faults have a particularly flat dip (Figure 12) and therefore the position of the magnetic anomaly depends on this angle, as well as on the usual angle of dip of the beds and the stratigraphic position of the magnetic horizon. All that could be said, was that strike faulting had caused repetition of the reef and the magnetic anomalies, and beyond that no more precise interpretation was attempted. From the end of 1952 until recently upward of 80 per cent of the boreholes were drilled for values and the remaining less than 20 per cent for structure. The close pattern of the drilling was such that geophysics could not substantially contribute to the evaluation of local structure. However, the reassessment of geophysical data as borehole information came to hand continued to guide the drilling in the wider exploration of the field.

Figure 12 shows the magnetic and gravity profiles with a generalised geological section. The dolomite, Ventersdorp lava, and Kimberley Elsburg and Main Bird Series quartzites are well established by drilling and except for a few minor faults this picture of the Kimberley Reef horizon is true. No closer drilling would substantially alter the section as shown. There are so few holes that have intersected Lower Witwatersrand beds that the section in the Lower Witwatersrand remains conjectural. However it becomes apparent that there are only two major magnetic horizons (probably the Water Tower slates and Contorted bed) and that the West Rand shales are probably absent. It is also apparent that the most northerly magnetic anomaly on this section is not due to a third magnetic horizon such as the West Rand shales but is caused by the lower magnetic horizons being brought closer to the surface on the north side of the flat dipping fault. A further point that these profiles bring to light is that the sharp increase of gravity south of the most southerly magnetic anomaly is apparently not caused by the Lower Witwatersrand-granite contact at this point, but is due to schists which underlie the Lower Witwatersrand rocks. The schists have the same mean density and from a gravity point of view form one unit with the Lower Witwatersrand.

As the rocks of the Main Bird and Kimberley Elsburg Series are considerably thinner than for other areas of the Witwatersrand Basin, they do not create a gravity low of the same order. Nevertheless there is a sufficient thickness of the quartzites to be the cause of anomalies of sufficient size to be diagnostic of faulting particularly where lavas are downthrown against these rocks. Difficulty arises when faulting as illustrated in the section occurs. The nature of the faulting is such that the effect of the light granite coming closer to the surface compensates for a wedge of heavy lava near the surface. Gravity lows caused by the uplift in the granite could be mistaken for lows due to quartzites. In spite of these difficulties, the gravimeter can be used to effect, particularly now that so much is known about the general and detailed structure and the thicknesses of the beds, particularly of the quartzites.

General

Experimental seismic surveys have been done both at St. Helena and on the East Rand in an effort to establish structures. These experiments proved expensive and slow and the records lacked resolution. High velocities in the Witwatersrand and Ventersdorp rocks resulted in loss of signal in the ground role because of short travel times. The state of the art has advanced enormously since these experiments were carried out some 17 years ago and it would seem feasible with modern techniques to produce a meaningful seismic section across faulted beds of the Witwatersrand System under a thick cover of Karroo rocks. Density contrasts of up to 0.2 gm/cc exist between the shales and quartzites and velocities vary from 16,000 ft/sec to 19,000 ft/sec. One of the problems would be multiple reflections from the many dolerite sills in the Karroo System. The cost of seismic surveys seems prohibitively high particularly when it is realised that one month's survey is the equivalent of nearly 10,000 feet of core drilling. Only drilling can establish the existence of a reef and once this has been done the drilling that follows is largely to establish the zones of payable reef during the course of which the structure is established. Circumstances nevertheless could arise where seismic surveys might be warranted

A brief mention of geophysical methods used down hole is appropriate here although these methods play no part in the exploration stage.

Radiometric logs (gamma logs) are taken down boreholes. Their use in detecting uranium-bearing reefs is of limited importance as the cores of all reefs are assayed for both gold and uranium. Simpson (1951; 1952) showed that certain beds and reefs of the Witwatersrand and Ventersdorp Systems could be correlated over long distances from the character of the radiometric logs.

Temperature surveys down boreholes have assisted in establishing the geothermal step (feet/' F) in various parts of the country. Deep level mining on the Witwatersrand is possible because of the high geothermal step (160-200 feet/°F) but a thick cover of Karroo beds can severely limit the depth to which ore can be economically mined. The geothermal step in the Karroo is 70-135 feet/° F.

Conclusions

Magnetic and gravity surveys have made a major contribution Towards the discovery of new goldfields and the extensions of existing goldfields. Falling into the first category are the Free State and the Evander goldfields and into the second, the West Wits Line and the northeastern portion of the Klerksdorp goldfield. Both gravity and magnetic surveys were employed in three of these programs whereas in the prospecting for the West Nits Line, gravity played no part. The major contribution to the discovery of the Stilfontein gold mine in the Klerksdorp area was made by gravity, and gravity played the more important role in the discovery of St. Helena in the Free State goldfields. Nevertheless if magnetic anomalies had not occurred up dip from the gravity lows the interpretation would not have been conclusive and certainly in the case of St. Helena the gravity low would probably not have been drilled.

The airborne magnetometer, because of its flexibility, speed of operation and freedom from noise caused by the dolerites of the Karroo System has greatly advanced the ease with which. magnetic surveys can be accomplished.

Gravity surveys are hampered by the need to acquire ground if the desired detail is to be achieved, and the tendency is to limit gravity surveys to public roads. This limitation does not apply to the airborne magnetometer.

It is becoming more difficult to find new goldfields. No new goldfields have been found since drilling proved the geophysical indications of the Evander Goldfield in 1951. Since then all new gold mines have been established on immediate extensions of existing gold-mining areas. The airborne magnetometer's last and only contribution as far as is known was towards the **discovery of the Evander Goldfield.** There have been some technical successes in locating Lower Witwatersrand beds but drilling has either failed to find the Upper Witwatersrand beds, or where they were present, no payable reefs were intersected.

The search goes on and gravity and magnetic surveys remain the only geophysical methods used. The advent of more sensitive magnetometers, magnetic gradiometers and digital processing in recent years is unlikely to make a major contribution to exploration in this field. No major breakthrough is foreseen whereby the auriferous reefs themselves can be directly detected.

The application of geophysics to establishing local structures in existing goldfields and during the opening up of new goldfields is an area in which little work has been done. A wider use of the gravimeter with more sophisticated treatment of the gravity data and the application of seismic methods call for further research.

Acknowledgments

The author wishes to thank Union Corporation Limited for permission to submit this paper. The co-operation of the geological staff of Union Corporation Limited, and in particular of Mr. Frost and Dr. Wiebols who read the proofs and made certain valuable suggestions, is gratefully acknowledged. In a review of this nature the author has had to draw partly from the work of others and in this regard credits must go to Drs. L. Reinecke and R. Krahmann, Messrs. A. Frost and O. Weiss, all pioneers in the application of geophysics to gold exploration in South Africa. Acknowledgment is made to the Geological Society of South Africa and the Canadian Institute of Mining and Metallurgy for permission to reproduce data previously published in the journals of these societies.

References

Borchers, R., and G.V. White, 1943. Preliminary contribution to the geology of the OdendaaIsrus goldfield. Trans. *Geol. Soc. S.A.* 46: 127-153.

Borchers, R., 1961. Exploration of the Witwatersrand System and its extensions. *Proc. Geol. Soc. S.A.* 64: 68-98. And 1964, The Geology of some ore deposits in South Africa: Johannesburg. *Geol. Soc. S.A.*

Bouwer, R.E., 1952. Measurement of borehole temperature **and the effect** of Geological Structure in the Nerksdorp and Orange Free State Areas. Trans. and Proc. *Geot Soc. S.A.* 55: 89-124.

Carte, A.E., 1954. Heat flow in the Transvaal and Orange Free **State.** Floc. Phys. Soc. B. 67: 664-672.

Carte, A.E., 1955. Thermal conductivity and mineral composition of some Transvaal rocks. *Am. J. Sci.* 253.

Coetzee, C.B., 1960. The geology of the Orange Free State **Goldfields.** Memoir 49, Geological Survey, Dept. Min., Rep. S.A.

Enslin, J.F., 1955. Some applications of geophysical prospecting in the Union of South Africa. *Geophysics.* 20: 886-912.

Fox, E.F., 1939. The geophysical and geological investigation of the Far East Rand. Trans. *Geol. Soc. S.A.* 42 : 83-122.

Frost, A., R.C. McIntyre, E.B. Papenfus, and O. Weiss, 1946. The discovery and prospecting of a potential goldfield near Odendaalrust in the Orange Free State, Union of South Africa. Trans. *Geol. Soc. S.A.* 49: 1-34.

Krahmann, R., 1936. The geophysical magnetometric investigations on the West Witwatersrand areas between Randfontein and Potchefstroom, Transvaal. Trans. *Geol. Soc.* S.A. 39: 1-44.

Mellor, E.T., 1917. The geology of the Witwatersrand, an explanation of the geological map of the Witwatersrand Goldfield. Geological Survey, Dept. Min., Union S.A.

Pelletier, R.A., 1937. Contributions to the geology of the Far West Rand. Trans. *Geol. Soc.* S.A. 40: 127-162.

Reinecke, L., and R. Krahmann, 1935. Magnetometric prospecting on the Witwatersrand. AIMS Meeting, New York Feb. 1935.

Simpson, D.1., 1951. Some results of radiometric logging in the boreholes of the Orange Free State Goldfields and neighbouring areas. Trans. and *Proc. Geol. Soc.* S.A. 54: 99-133.

Simpson, D.J., 1952. Correlation of the sediments of the Witwatersrand System in the West Witwatersrand, Klerksdorp and Orange Free State areas by radioactivity borehole logging. Trans. and Proc. *Geol. Soc.* S.A. 55: 89-124.

Smit, P.J., A.L. Hales, and D.I. Gough, 1962. The gravity survey of the Republic of South Africa. Geological Survey, Dept. Min., Rep. S.A.

Weiss, O., 1934. The application and limitations of geophysical prospecting methods in the Witwatersrand area. J. *Chem. Met. Min. Soc. S.A. 34.*

Weiss, O., D.J. Simpson, and G.L. Paver, 1936. Some magnetometric and gravimetric surveys in the Transvaal. Geological Survey, Dept. Min., Union S.A., Bull. 7.

Weiss, O., 1938. Temperature measurements with an electrical resistance thermometer in a deep borehole on the East Rand. *J. Chem. Met. Min.* Soc. S.A. 39.

Weiss, O., 1951. Contribution of geophysical surveys to the discovery of Stilfontein Gold Mine in South Africa. *Trans. AIMS* 190: 886-890.

Weiss, O., 1957. Geophysical surveys discover Stilfontein gold mine in South Africa. *Methods and Case Histories in Mining Geophysics.* 6th Coin. Min. and Met. Cong. Canada, 1957.

Geol. Soc. S.A., 1964. The geology of some ore deposits in South Africa. Johannesburg.