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Radiometric determination *in situ* of the face grades in Witwatersrand gold and uranium mines

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SYNOPSIS

A prototype collimated radiometric face scanner was tested in the Harmony Gold Mine.

The results obtained during the pilot study indicate that *in situ* radiometric uranium assays are statistically indistinguishable from those obtained conventionally from channel chip samples. In addition, the study demonstrated that reasonably reliable gold estimates can be deduced from the radiometric measurements, by use of the ratio of gold to uranium within a mine.

The instrumentation, calibration procedures, and background determination are described briefly.

SAMEVATTING

'n Prototipe gekollimeerde radiometriese frontaftaster is in die Harmony-goudmyn aan toetse onderwerp.

Die resultate wat uit die aanvoorstudie voortspruit, dui daarop dat *in situ* radiometriese uraanwaardes statisties onwaarneembaar verskil met dié verkry uit konvensionele kanaalafslaanmonsters. Hierbenewens toon die studie aan dat redelik betroubare goudskattings uit die radiometriese opnames verkry kan word, deur middel van die goud/uraanverhouding binne 'n myn.

Die instrumentasie, kalibrasietegnieke en agtergrondbepalings word kortliks omskryf.

Introduction

The South African gold- and uranium-mining industry has a need for a compact, portable instrument that can be used for rapid underground assaying at the stope face. Currently, mine evaluation relies almost entirely on 'fire' and chemical assays of channel chip samples—a slow, labour-intensive operation that is prone to large statistical errors related to the relatively small, unrepresentative samples involved. Slight variations in channel width and depth may exert a marked influence on the assay results, leading to closely spaced channels that return vastly different grades. In view of this and the erratic nature of the mineralization along a reef, it is not surprising that assay values frequently fail to correspond to the actual metal concentration in the oreblock mined.

Scientists at NUCOR favoured, as a specific alternative for uranium, the use of *in situ* radiometric assaying techniques, which utilize samples of much larger volume. Initial investigation[1] by Corner[1] at the West Rand Consolidated Mine pav[ed] the way for a more comprehensive study conducted at the experimental site of the Chamber of Mines Research Organization at Blyvooruitzicht Gold Mine. Fig. 1 presents a summary of the results obtained with a differential face scanner. Further research by Smit *et al.*[2] showed that collimated detectors should, in theory, be equally acceptable for the special sedimentological conditions prevailing in the Witwatersrand goldfields. Hence, a preliminary investigation of the *in situ* radiometric assaying of uranium by use of a collimated scintillometer was launched in the Harmony Mine (Rand Mines Group) near Virginia, Orange Free State.

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However, an instrument capable of analysing only for uranium would be of limited use in most Witwatersrand mines, unless a collateral gold detector were also available. Prototype gold analysers based on a gamma fluorescence technique have been under development for some years. Using such instruments, scientists at the Chamber of Mines Research Organization[3,4] have obtained accurate results on narrow reefs, and have indicated that the simultaneous measurement of uranium is also feasible through the detection of lead, one of uranium's daughter nuclides. Similarly, an indirect measure of the grade of the gold face could be obtained from radiometric uranium assays if a suitable gold/uranium ratio could be established.

Sedimentological studies conducted by Smith and Minter[5] in the Klerksdorp and Welkom goldfields demonstrated the placer origin of gold and uranium, both acting as heavy minerals, which are concentrated physically by hydraulic sorting processes during transport and deposition. Provenance-controlled grain-size limitations and interference effects linked to the density, shape, and surface area of grains may significantly alter gold/uranium ratios on a regional scale, and may also produce non-linear correlations. However, Smith and Minter showed that, at least on the local scale, a significant and predictable correlation exists between the two components. This is certainly true at the Harmony Mine. The investigation was thus extended to include the indirect assaying of gold by gamma scintillometry. Unfortunately, very little information pertaining to the variation in gold/uranium ratios over the entire Witwatersrand Basin have been published. For an assessment of the general applicability of indirect gold assaying, further studies are essential.

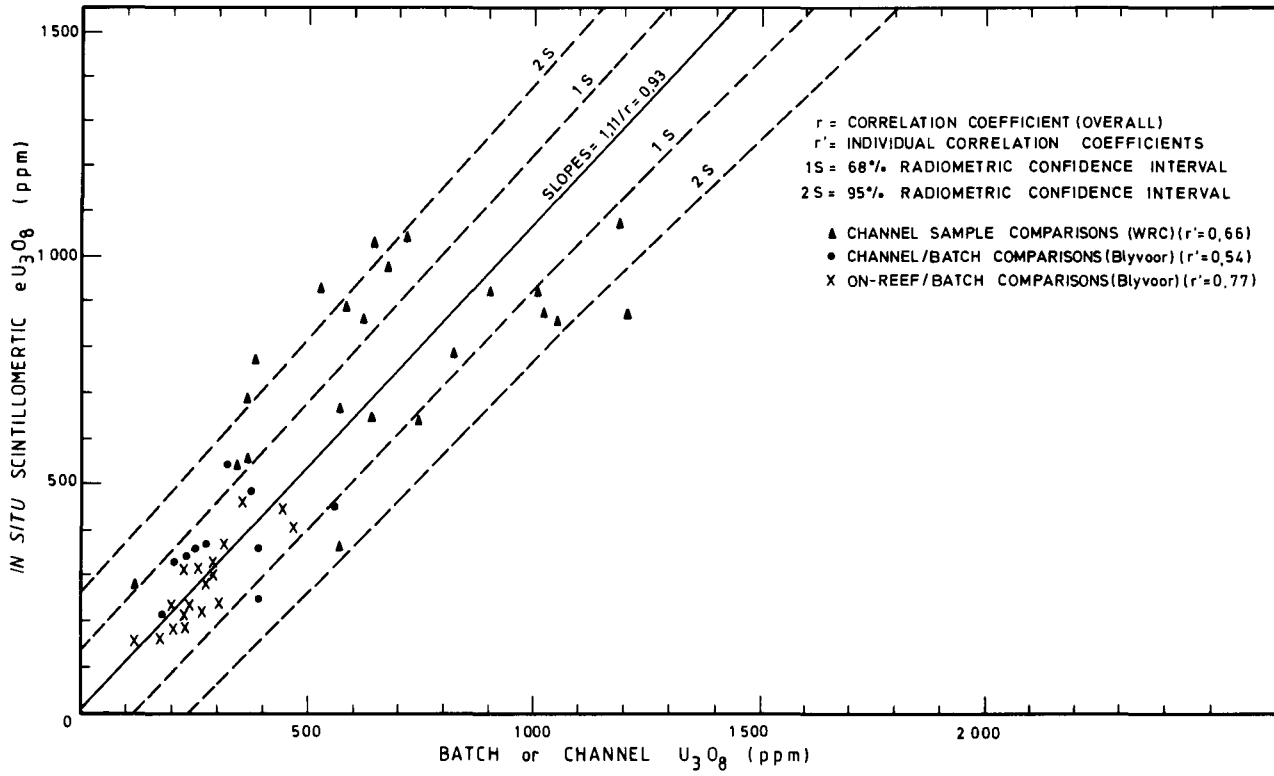


Fig.1—Comparison between *in situ* radiometric U_3O_8 and corresponding batch values or channel-sample assays of U_3O_8 content using a differential face scanner

Instrumentation

The principles on which the design of the prototype collimated radiometric face scanner was based have been outlined elsewhere[2,6]. In gamma scintillometry, uranium is detected indirectly by measurement of the natural gamma radiation emitted by one of its daughter products, namely ^{214}Bi, which is characterized by a complex gamma spectrum containing a number of prominent photopeaks. Nuclides in the thorium decay series, notably ^{208}Tl, may contribute significantly towards the measured spectrum and are usually removed by spectral stripping. However, if the thorium is of low tenor, which is generally true in the Witwatersrand sediments[2], reliable uranium assays can be obtained by measurement of the entire gamma spectrum or any one of the characteristic ^{214}Bi photopeaks.

Gamma particles are detected essentially by absorption processes in scintillating crystals, such as thallium-activated sodium iodide, which show an exponential increase in detection efficiency towards the low-energy portion of the spectrum. Unwanted stray radiation, originating from broken ore and nearby reef exposures, must be screened from the crystal by the use of high-density shields made of lead or tungsten. The gamma absorption efficiency of heavy metals is also biased towards low-energy radiation. Thus, if low-energy gamma radiation alone is to be measured, a compromise can be made between adequate shielding and high counting rates, requiring large crystals, while the instrument will still be reasonably light in weight. It should be noted that a collimated detector was chosen merely on logistical considerations, and that a differential screening technique is equally acceptable.

A prototype collimated face scanner was supplied by Chemtron (Pty) Ltd, of Potchefstroom, South Africa. The instrument comprises a sealed NaI(Tl) detector crystal with a thickness of 50 mm and a diameter of 25 mm, which is surrounded by a 10 mm thick lead collimator that extends 10 mm to the front and 30 mm to the rear of the crystal (Fig. 2). The crystal–photomultiplier assembly is coupled to an amplifier and single-channel pulse-height analyser, incorporating high-voltage supply to the crystal, controls, and LED displays. Controls include an on/off switch with stand-by mode, selectable count intervals of 20, 40, and 80 seconds, background and count mode selector, and a separate start/reset trigger on the pistol grip. The window threshold of the pulse-height analyser was preset to 0,52 MeV, with a window width of 0,20 MeV centred on the 0,61 MeV ^{214}Bi photopeak. Background values were stored as negative counts to which the counter was reset upon triggering, facilitating automatic background corrections. All the printed circuit boards were sprayed with a waterproof resin to prevent the build-up of moisture as a result of the high humidities prevailing underground. In addition, the instrument housing complied with the South African standards for fiery mines. The instrument is powered by internal rechargeable batteries, and weighs less than 5 kg. It is expected to sell at approximately R4000.

Calibration

Normal calibration procedures applicable to surface scintillometers assume a constant source–detector geometry and essentially infinite sample volumes[7].

Fig. 2—The prototype collimated face scanner in use in the harsh underground environment

This is clearly far removed from a shielded detector operating on reefs of varying thicknesses in restricted underground workings. In addition to the calibration factor, which relates count rates to uranium grades, the effective sample volume of a shielded radiometric instrument has to be determined. This is accomplished through the construction of a suite of uranium-enriched concrete reefs at least 1 m in length and 350 mm in depth, and with a width varying from approximately 50 mm to 1 m. Care should be taken to ensure that all the simulated reefs exhibit essentially the same gamma activity. These are embedded in barren concrete or sand at 1 m intervals. A graph of the maximum count rate registered on each successive reef versus the reef thickness yields a hyperbolic curve from which the diameter of the effective sample volume can be obtained; this is conveniently taken as the thickness corresponding to the attainment of 90 per cent of the count rate measured on an essentially infinite calibration pad of similar activity. The effective sampling diameter of the Chemtron prototype amounted to 400 mm when held against the reef. Because 0,6 MeV gamma rays will penetrate through quartzite for more than 200 mm, it is clear that the radiometric sampling volume is much larger than that of a conventional chip sample.

A knowledge of the uranium grade in the simulated reefs permits the determination of calibration constants related to specific reef thicknesses. The area under the curve obtained when the detector is moved in small steps (50 mm) across each simulated reef is divided by the reef thickness. The quotient is subsequently divided into the uranium grade of the reef to calculate a K-factor applicable to mineralized zones of similar thickness. The Chemtron face scanner was calibrated in this way by the use of concrete standards constructed by Cantello and La Grange[8], and of the standard pads available at Pelindaba.

Background

Some compromise in the amount of shielding is necessary to minimize the weight of the collimator. Although a 10 mm lead shield is considered sufficient to cope with spurious side effects due to poor face geometry[2], some high-energy gamma rays emitted by ^{214}Bi residing outside the effective sample volume may still be detected.

Unwanted radiation that penetrates the shield is removed by the subtraction of a suitable background count at each measuring station. In confined working spaces, the background count rate is assessed when the open end of the collimator is plugged with a 10 mm lead disk while the instrument is pointed towards the reef. Within large excavations, it is sufficient for the instrument to be moved approximately 1 m away from the reef while the open collimator is pointed parallel to the stope face in both directions, thus giving an average background correction.

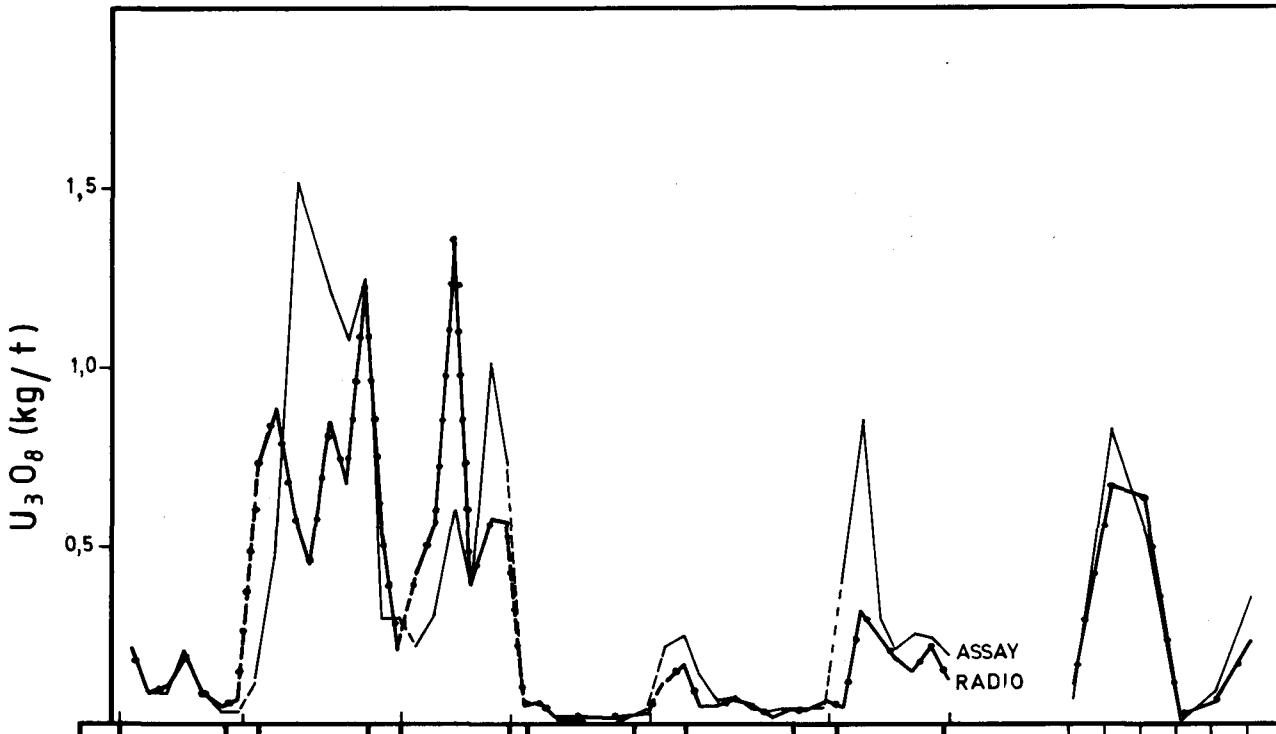
Test Site

Preliminary tests were conducted on the Basal and Leader Reefs of the Harmony Mine. Both reefs are very thick, extremely erratic, and contain conglomerate lenses that pinch and swell over short distances. In some places the mineralization is concentrated in narrow zones within the conglomerate. However, the same stope may display evenly distributed grades over the full width of the conglomerate lens. In spite of a fair local correlation on a stope scale, the ratios of gold (expressed in grams per ton) to uranium (expressed in kilograms per ton) are highly variable, ranging from 20 to 200 over the entire mining area. Fortunately, the staff of the mining-evaluation section at Harmony have maintained meticulous records of the variation in the ratio within each reef horizon. Smooth, regular contours of the ratio have been plotted on stope maps, on which all the values of interest are readily accessible.

Ten stopes, including six on the Basal Reef, were assayed radiometrically before channel chip samples were taken at the same locality. On each stope, between six and ten sample channels, spaced 6 m apart, were divided into 50 mm intervals between the hanging walls and the footwalls. By use of the open-collimator technique already described, a single background reading was obtained for every channel measured. At a sampling time of 20 seconds, the sample locations were gamma-probed, the background count being subtracted automatically. Then, channel samples were collected according to normal mine procedures, in which the maximum channel length per sample is 150 mm over mineralized zones. Lithological changes may result in shorter channel lengths constituting a sample. All the samples thus obtained are collectively referred to as a channel. Thus, individual samples within a channel were not directly related to single count measurements. It was realized from the outset that the comparison between radiometric and chemical values would be meaningful only over the full width of the channel, and would hence require a statistical approach.

Test Results

The channel chip samples were subjected to conventional analysis in the chemical laboratory on the mine. Uranium, expressed in kilograms of U_3O_8 per ton, was determined by X-ray-fluorescence spectrometry, while gold was assayed by wet-chemical methods in grams per ton. As individual samples within a channel were not directly related to the radiometric sample points, the weighted averages of both elements in the channel sample were calculated for every channel. All the data, including the weighted channel assay averages, are il-



DISTANCE	STOPE 1		STOPE 2		STOPE 3		STOPE 4		STOPE 5		STOPE 6	
	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO
0	0,22	0,20	0,12	0,71	0,23	0,42	0,08	0,04	0,23	0,11	0,46	0,04
6	0,09	0,07	0,48	0,87	0,31	0,55	0,07	0,05	0,26	0,16	0,88	0,31
12	0,09	0,09	1,53	0,58	0,61	1,34	0,02	0,004	0,15	0,04	0,32	0,25
18	0,21	0,17	1,38	0,43	0,40	0,37	0,02	0,01	0,08	0,04	0,23	0,16
24	0,09	0,07	1,21	0,73	1,03	0,56	0,01	0,01	0,09	0,06	0,27	0,14
30	0,04	0,03	1,09	0,66	0,74	0,55	0,01	0,004	0,06	0,05	0,26	0,21
36	0,04	0,05	1,25	1,22			0,02	-	0,05	0,01	0,21	0,12
42			0,31	0,52			0,03	0,01	0,06	0,03		
48			0,31	0,19			0,05	0,02	0,06	0,03		
54									0,06	0,06		
$\bar{x}$	0,11	0,16	0,85	0,66	0,55	0,63	0,03	0,02	0,12	0,06	0,38	0,23
s	0,07	0,06	0,54	0,29	0,30	0,63	0,03	0,02	0,08	0,04	0,24	0,10

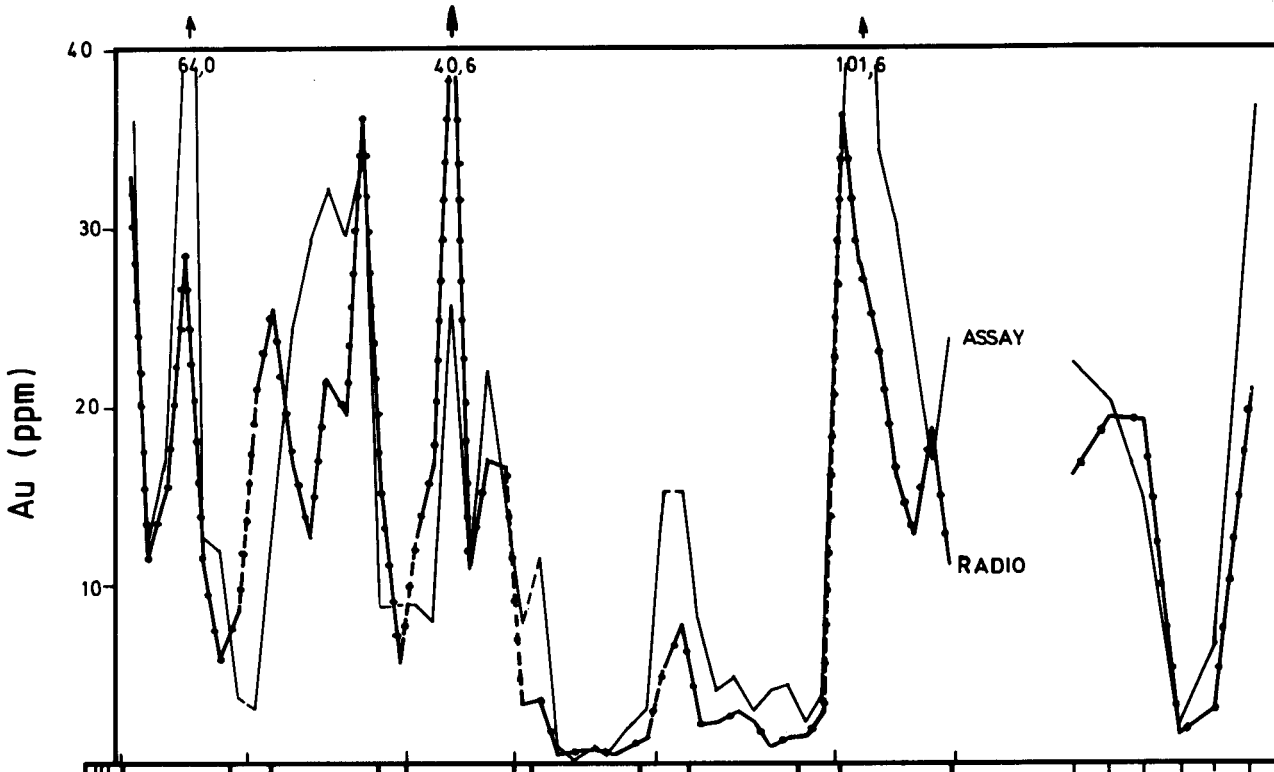
Fig. 3—Graphical illustration showing the close correspondence between the radiometric and the chemical values for uranium in the Basal Reef. *Assay* in this and all the other diagrams refers to weighted chemical averages, whereas *Radio* refers to radiometrically predicted averages

lustrated in Figs. 3 to 6. Tabled assay values of the ten stopes are listed directly below the pertinent sections of the graphs. Data points on adjacent stopes have been interconnected by broken lines. For each stope, an average assay value (x) and standard deviation (s) about the mean were obtained for comparison with the radiometrically predicted values.

Radiometric uranium values were calculated by a reversal of the calibration procedure. The area under the curve for gamma count rate versus distance using a 50 mm probe interval is divided by the thickness of the reef zone and then multiplied by the instrument calibration constant applicable to the specific reef. Radiometric uranium values of individual channels, as well as averages and standard deviations for the ten stopes, are included in Figs. 3 and 5. Radiometrically predicted gold values were obtained by simple multiplication of the radiometric value for uranium by the gold/uranium ratio interpolated from the contour lines on the stope maps. These values, as well as the stope statistics, are displayed in Figs. 4 and 6.

The validity of the ratio adopted to convert radiometric uranium values into gold was checked by division of the chemical averages of the ten stopes. A comparison of the two ratio sets yielded a correlation coefficient of $r = 0,99$. However, a graphical comparison between the weighted chemical gold and uranium averages of individual channel samples (Fig. 7) displays a clear bi-modal distribution that is not reef-related. Stopes 1 and 6 on the Basal Reef form a separate group, with a good internal correlation ($r = 0,87$) between gold and uranium. The remaining eight stopes scatter around a different regression line with $r = 0,92$, but the overall correlation is mediocre, with $r = 0,56$.

Nevertheless, a scrutiny of Figs. 4 and 6 reveals that, apart from two highly incongruent samples, the radiometric gold contents of stopes 1 and 6 agree closely



DISTANCE	STOPE 1		STOPE 2		STOPE 3		STOPE 4		STOPE 5		STOPE 6	
	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO
0	35,95	32,68	3,08	21,00	8,94	12,64	7,80	3,19	15,30	5,14	38,10	36,45
6	12,14	11,53	13,72	25,51	7,93	16,77	11,50	3,39	15,29	7,62	101,63	27,80
12	17,19	15,08	24,34	16,99	25,25	40,60	0,82	0,30	7,94	1,93	34,35	23,05
18	64,02	28,17	29,40	12,53	11,02	11,25	0,33	0,45	4,10	2,12	30,21	16,14
24	12,52	11,12	32,21	21,58	22,19	17,02	0,76	0,72	4,85	2,63	23,47	12,77
30	11,94	5,78	29,55	19,36	14,57	16,63	0,62	0,31	2,82	2,27	17,45	18,88
36	3,59	8,54	34,33	35,97			0,18	-	4,08	0,66	23,87	10,94
42			8,69	15,38			2,18	0,73	4,38	1,34		
48			8,59	5,59			3,18	1,34	2,25	1,45		
54									4,02	2,79		
$\bar{X}$	22,48	16,13	20,43	19,32	14,98	19,15	2,04	1,37	6,60	2,80	36,97	20,86
S	20,85	10,25	11,91	8,51	7,20	10,78	3,98	1,40	4,78	2,90	29,48	9,00

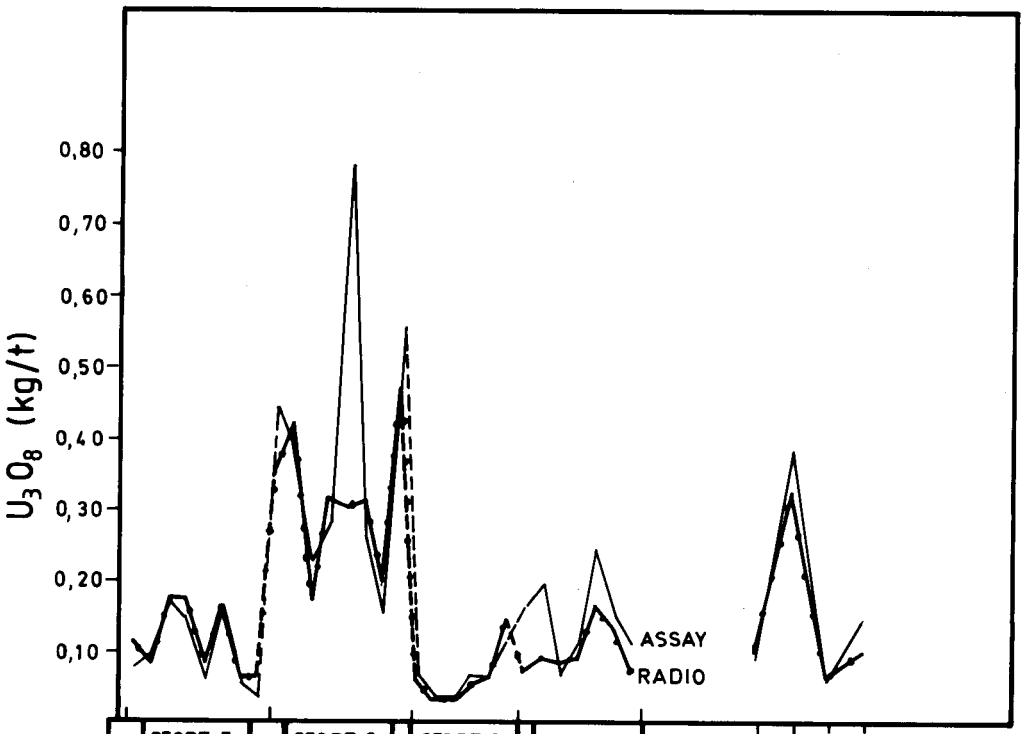
Fig. 4—Graphical illustration depicting the sympathetic relationship between the chemical and the indirectly predicted radiometric values for gold in the Basal Reef

with the chemical assays.

Comprehensive statistical analysis of the data tabled in Figs. 3 to 6 has not been attempted, although some general comments can be made. From the tables and Fig. 8 it is apparent that the correlation between the assay and the radiometric values for uranium is generally very good. If linearity is assumed, the overall correlation coefficient between individual channels (r) is 0,72, with a regression line $y = 0,07 + 0,92\,x$. Paired values collected on the Leader Reef appear to correlate better ($r = 0,83$) than those from the Basal Reef ($r = 0,70$). The marked discrepancy evident on stope 2 is attributed to a known post-depositional erosion channel, while other misfits are usually limited to single channel samples such as on stopes 3, 6, and 8. These inconsistencies are probably due to nugget effects and to the large differences in sample volumes utilized in the two methods under consideration. When the stope averages are compared, the disparity in sample dimensions becomes less critical, yielding excellent agreement ($r = 0,96$) between the two methods.

The accuracy with which the gold content could be predicted radiometrically exceeded all expectations. A linear comparison (Fig. 9) between the individual weighted channel assays and the predicted gold, including the discrepant channels on stopes 1 and 6, yields a correlation coefficient of $r = 0,74$, with a regression line of $y = 1,17 + 1,19\,x$. However, here the correlation among paired values is insensitive to the reef horizon from which they were obtained, with $r = 0,73$ on the Leader Reef as opposed to $r = 0,69$ on the Basal Reef. When the stope averages are compared, a remarkable correlation coefficient of 0,90 is determined.

Statistical inference provides an alternative method of relating the assay values to the radiometrically predicted gold and uranium through simple hypothesis testing[9]. To conduct the test, the overall radiometric and chemical



DISTANCE	STOPE 7		STOPE 8		STOPE 9		STOPE 10	
	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO	ASSAY	RADIO
0	0,07	0,11	0,44	0,35	0,04	0,36	0,16	0,07
6	0,09	0,08	0,38	0,42	0,03	0,33	0,19	0,09
12	0,16	0,17	0,22	0,17	0,03	0,03	0,06	0,08
18	0,14	0,17	0,28	0,31	0,06	0,05	0,11	0,09
24	0,05	0,08	0,78	0,30	0,06	0,06	0,24	0,16
30	0,11	0,10	0,26	0,31	0,11	0,14	0,15	0,13
36	0,05	0,06	0,15	0,19			0,11	0,07
42	0,03	0,06	0,55	0,47				
48								
54								
$\bar{X}$	0,09	0,10	0,38	0,32	0,06	0,06	0,15	0,10
S	0,05	0,04	0,21	0,10	0,03	0,04	0,06	0,03

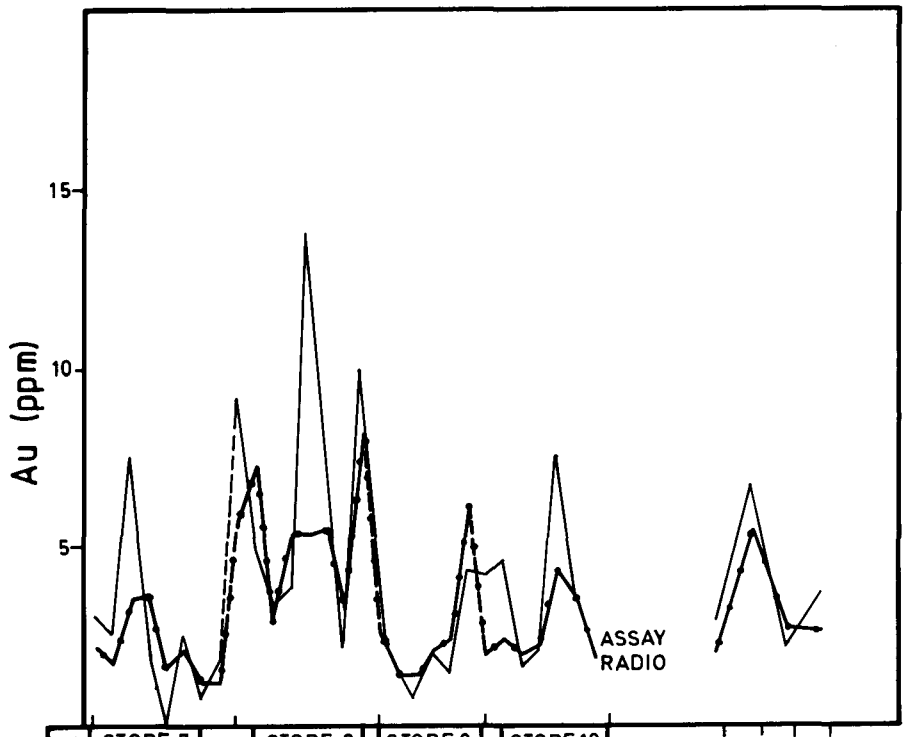
Fig. 5—Graphical illustration showing the close correspondence between the radiometric and the chemical values for uranium in the Leader Reef

mean values obtained from the 77 channel-sample locations, together with their standard deviations, were calculated and are presented in Table IA. By use of the Student's *t*-distribution, the null hypothesis, stating equivalence between the chemical and the radiometric mean values, was tested against the two-sided alternative that the average values are different.

If a 10 per cent confidence level and different sample variances within the two populations are assumed, the data obtained thus far indicate that there is no statistical difference between the means of the two methods.

Although simple tests of hypothesis do not discriminate between the gold mean values listed in Table IA, intuition suggests that the radiometric technique may be under-estimating the gold content of the reef. Stopes 1 and 6 were previously noted as displaying a peculiar relationship between the gold and uranium distributions. This aspect was not investigated further, but it probably relates to facies variations in the proximal region of the Basal Reef. The work of Smith and Minter[5] has revealed that gold is often related exponentially to uranium, which implies that high gold values are not necessarily accompanied by a similar increase in uranium concentrations. When considered as a separate group, stopes 1 and 6 confirm this view, with a chemically analysed mean gold value of 29,72 (s = 25,66), which appears significantly higher than the estimated radiometric mean of 18,50 (s = 9,59). The exclusion of the two anomalous channel samples reduces the assay mean value to 24,19 (s = 15,78). It should be noted, however, that the null hypothesis as previously defined will still be accepted in both cases.

Statistics obtained from the remaining eight stopes, summarized in Table IB, are self-evident. In contrast to the chemical mean values, which require a substantial labour force and a turnaround time measured in days,



DISTANCE	STOPE 7 ASSAY	STOPE 7 RADIO	STOPE 8 ASSAY	STOPE 8 RADIO	STOPE 9 ASSAY	STOPE 9 RADIO	STOPE 10 ASSAY	STOPE 10 RADIO
0	3,16	2,18	9,34	6,14	3,04	2,67	4,26	1,93
6	2,63	1,69	5,27	7,29	1,70	1,47	4,62	2,41
12	7,70	3,52	3,41	2,96	0,85	1,47	1,66	1,98
18	1,95	3,56	3,93	5,35	2,01	2,02	2,13	2,27
24	0 17	1,57	13,83	5,31	1,58	2,46	7,70	4,34
30	2,62	2,06	6,42	5,43	4,37	6,15	3,64	3,52
36	0,85	1,19	2,34	3,27			2,29	1,95
42	1,90	1,14	10,00	8,20				
48								
54								
$\bar{X}$	2,96	2,11	6,82	5,49	2,26	2,70	3,76	2,63
S	2,20	0,95	3,93	1,79	1,26	1,75	2,07	0,94

Fig. 6—Graphical illustration depicting the sympathetic relationship between the chemical and the indirectly predicted radiometric values for gold in the Leader Reef

TABLE I
STATISTICS USED IN THE TEST OF HYPOTHESIS

Constituent	Value	A. All channels* Assay	A. All channels* Radio	B. Without channels 1 and 6† Assay	B. Without channels 1 and 6† Radio
U_3O_8	$\bar{x}$	0,27	0,23	0,28	0,24
	s	0,34	0,27	0,36	0,29
Au	$\bar{x}$	11,68	8,97	7,67	6,82
	s	15,61	9,77	8,41	8,49

* The values for all 77 channels were used
† The values for 63 channels were used, omitting stopes 1 and 6 on the Basal Reef

the radiometric estimates in Table I were realized underground, essentially in minutes, by a single operator.

Conclusions

The advantages offered by *in situ* radiometric assaying for uranium in Witwatersrand gold and uranium mines have never been questioned by those who appreciate that the incongruence between individual radiometric and chemical samples is related to variations in sample size. However, the absence of a rapid technique for the *in situ* determination of gold has severely hampered the acceptance of radiometric instruments. The results reported in this pilot study indicate that reliable uranium assays can be obtained from gamma measurements. In addition, there is the possibility that fairly accurate gold estimates can be realized if the ratio of gold to uranium within a reef in a particular mine is known.

Although radiometric techniques may never replace

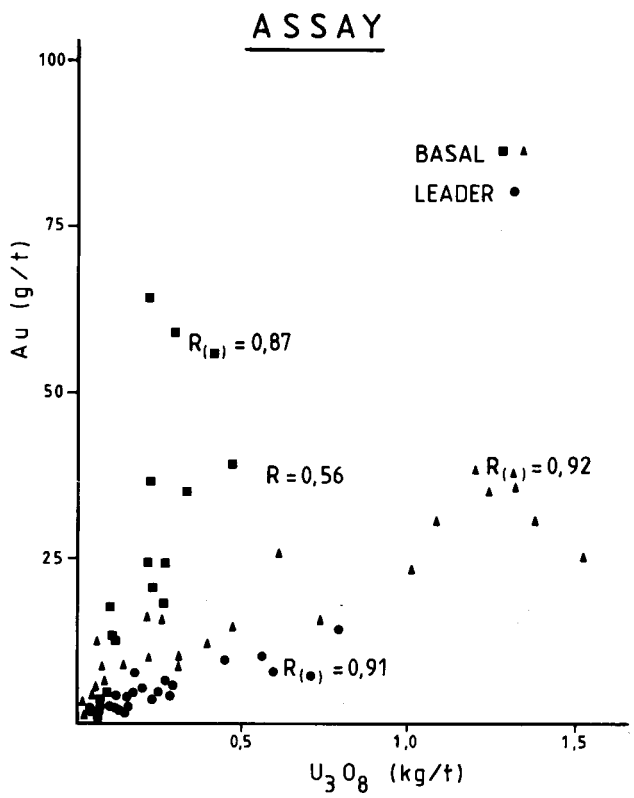


Fig. 7—Linear comparison between the weighted chemical channel averages for gold versus those for uranium. The samples obtained from stopes 1 and 6 on the Basal Reef are depicted by squares

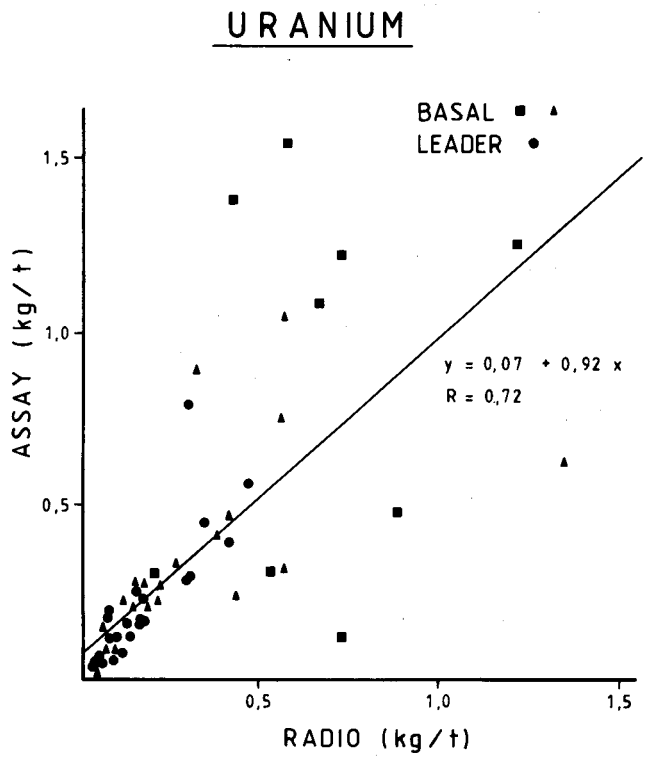


Fig. 8—Linear comparison between the radiometric and the weighted chemical channel averages for uranium. The squares represent data obtained from a post-depositional erosion channel on stope 2

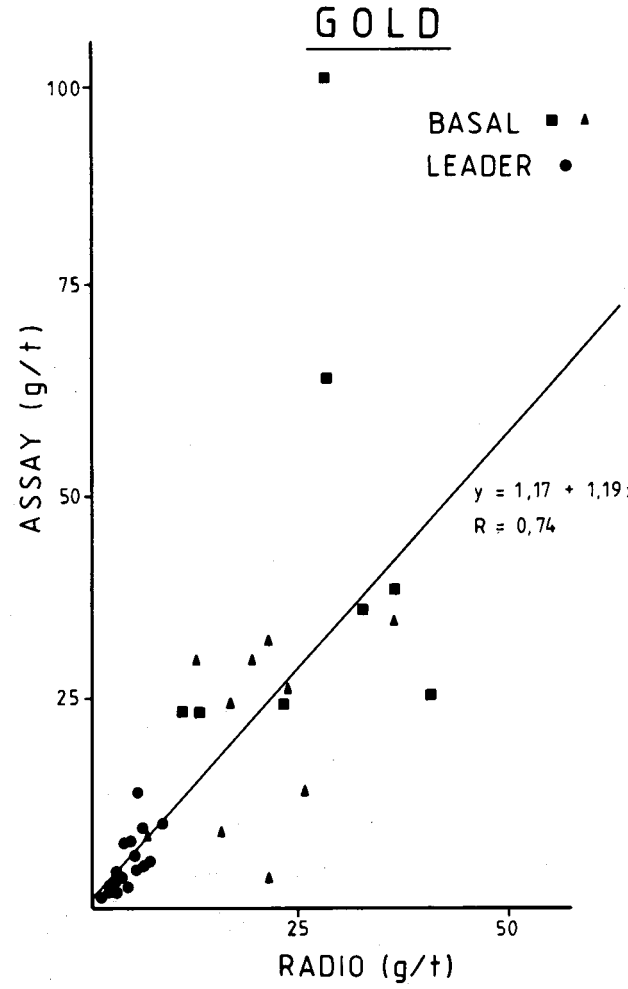


Fig. 9—Linear comparison between the weighted chemical channel averages versus the indirectly predicted radiometric values for gold. The squares represent data obtained from a post-depositional erosion channel on stope 2

channel samples entirely, they certainly offer exciting possibilities as rapid, one-man production tools.

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Light metals

- Thermomechanical treatment (e.g. hot forming, recovery, recrystallization). Corrosion, surfaces, and surface treatment. New light-metal alloys (e.g. alloys for elevated temperatures, PM-alloys, materials for lightweight designs, composite materials).

In the fields of manufacturing and processing, the main topics include:

- Bayer process

which can be given in German or English. The preliminary title and key words of expected content, covering about 10 lines, should be submitted before the end of April 1986 to the Secretariat of the 8th ILMT, c/o Prof. Dr. F. Jeglitsch, Institut für Metallkunde und Werkstoffprüfung, Montanuniversität, A-8700 Leoben, Austria.

Metallurgy and materials science

The Metallurgical Society of the Canadian Institute of Mining and Metallurgy is to hold its 25th Annual Conference of Metallurgists in Toronto from 17th to 21st August, 1986. Multiple sessions will update metallurgists and materials scientists with the latest scientific and technical developments.

The September 1985 issue of the *CIM Bulletin* gives complete details of the technical programme, including three international symposia on nickel metallurgy, zinc–aluminium (ZA) casting alloys, and inclusions and residuals in steels. General sessions will include topics of special interest in basic sciences, corrosion, historical metallurgy, hydrometallurgy, iron and steel, materials engineering, mineral science and metallography, and nonferrous pyrometallurgy.

Anyone interested in presenting a paper should submit an abstract of 100 words by 15th January, 1986, to

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