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Gamma ray fluorescence for in situ evaluation of ore in Witwatersrand gold mines

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the measuring speed relates the measurement time of an effective amount of rock to the measurement precision, and that these parameters can be manipulated at will to suit the precision requirement.

The tests showed that with the right instrument the overall measuring speed could be at least increased to ten times the chipping speed under most situations.

In these tests the instrument was measuring in fixed positions. It is possible to measure a large number of discrete samples in this way to obtain a precise average. The sampling statistics of many discrete samples measured to high precision are, however, poorer than those of a large number of practically independent small samples such as would result from the continuous examination of a face by flourescence scanning for the same total measuring time. Scanning of a face to obtain an average value, when the gold is very heterogeneously distributed, is likely to yield a far better estimate of the true value of the face than chip sampling at a few fixed positions. This is so in spite of the fact that the total volume of rock "sampled" may be less in the case of fluorescence measurement by scanning than in the case of chip sampling. It may be noted that scanning may actually take more time than chip sampling, but it is contended that the value of a chosen sampling strategy cannot be judged on the time taken for sampling any more than it can be judged on the weight of sample taken. The only criterion is whether the results of sampling enable better mining decisions to be taken, so as to increase the overall profitability of mining. Whether scanning would in

fact permit an improved sampling strategy to be developed, still had to be tested, and indications were that this looked very promising.

Another important advantage of the fluoresence method was experienced, namely, that spot or area values are immediately available and that this could be of great assistance in locating and tracing invisible gold bands, thus making possible improved sampling strategies.

It was concluded that the first underground tests of the gamma-ray fluorescence technique had proved the feasibility of the technique for ore valuation at the present ore pay limit in a location where sampling was by no means easy, and that improved equipment was required to conduct further tests.

14.2 First-prototype results from Marievale Gold Mine

The fluorescence measurements experiment at Marievale gold mine was designed to determine the reproducibility of measurements when all the sources of error were taken into account. The relative magnitudes of the different types of error were investigated to confirm that there were no unacceptably large errors.

On block No.25, thirty contiguous samples were marked off and scanned 28 times over a period of a month. The results are given in Table 14.3. The mean value of all the measurements was 359 cm.g/t, but the "zero" value of the instrument drifted continuously and was therefore measured frequently. Interpolation of these "zero" mesurements for the 28 scans gave a mean zero offset of 148cm.g/t so that the average gold value was 211cm.g/t. The 30x28 measurements

TABLE 14.3 FLUORESCENCE MEASUREMENTS WITH FIRST PORTABLE PROTOTYPE ON 30 STOPE FACE SAMPLES AT MARIEVALE. Units cm g/t.

Sample No.

Scan No.

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	$\bar{x}_i$	$S(x_i)$
1	340	270	400	20	-320	430	530	570	510	490	270	470	510	-170	400	260	670	270	120	220	390	830	410	700	-90	290	280	700	349	267
2	710		620	950	1360	550	350	150	140	530	1010	-140		0	1980	1000	550	950	730	590	410	530	220	450	660	900	1140	490	1020		678	442
3		60	600	620	-240	370	440	-120	190	860	-80	100	590	910	-530	-50	-100	580	870	1270	790	-10	-50	790	-60	270	330	740	350		286	394
4	-800	-70	200	940	-190	1020	-350		90	250	140	670	710	190	-140	700	250	-190	420	590	260	370	670	200		10	710	860	1540	910		374	451
5	300	-400	590		0	910	250	290	-90	1200	-580	810	550	160	910	820	140	760	1070	450	400	520	120	-280	730	200	850	1170	600		444	459
6	120	-670	820	810	970	600	800	-340	-70	950	650	940		10	450	-110	620		10	910	980	670	800	510	-170	420	470	1101	130	850		427	452
7	820	190	850	400	540	740	-210	190	950	150	420	490	210	240	530	740	750	1901	100	820	790	860	590	730	500	1070		1901	010		498	335
8	490	870	500	1070	-110	660	-750	-230	480	-10	590	960	-10	1040	100	130	670	150	610	1180	790	-110	470		70	860	620	960	490		584	444
9	-310		0	50	-300	100	720	-190	470	1290	100	590		20	280	110	240	550	1300	400	220	-60	430	-90	190	710	870	200	510	400		273	3[illegible]
10	-170	720	500	400		80	110	100		90	90	150	740	-40	1700	1060	-410	730	840	770		10	-20	530	-560	200	790	700	810	650	790		253	3[illegible]
11	-550	-120	700	1010		70	-420	-80	-140	560	240	-410	-720		20	470	820	750	720	-110	-140	660	840		20	810	910	210	750	250	210		173	389
12	470	170	810	540	870	890	160	-690	910	-90	-10	170	130	-70	-80	-30	770	700	620	-410		80	720	-10	800	-420	-50	1070	-200		215	426
13	-80	710		10	540	840	870	980	50	140	470	1010	560	400	880		50	740	740	840	590	-60		80	810	-350	370	730	420	610	250		360	387
14	-200	700	-470	260		90		90	880	160	-150	-470	910	840	190	940	-80	500	500	-80		40	890	450	730	200	810		90	740	750	380		227	337
15	-70	450	720	940	220	630	190	-570	140	750	1800	1080	730	750		-10	610	610	770		-10	490	560	100	870	520	-140	1190	880	1090		418	401
16		-10	700		70	610	870	640	-170		-70	860	680	700	-370	240	830	890	860	1160		080	260	460	560	570	560		50	410	210	480	670		485	349
17		280	790	500	1000	790		70	980	760	850	420	850	1080		110	250	470	870	810		110	-310	770	1000	850	1800	1170	1260	350	530	430		543	385
18	-110		20	980		-30	960	640	690		-20		-70	1300	1080	-280	520	760	100	560	850	480	840	910	700	130	520	-400	670	1270	950	840		453	446
19		180		-60	850		-70	770		-80	-110	-370	820	740	490	410	980	620	280	820	640	670	170	620	720	810	740	580	840	1080	1340		497	400
20		-70	780		-30	800	580	900	-340	-270	550		70	280	460	500	1410		-270	740		-70	-630	740	640	670	800	870	-130	150	650	1330	1270		392	524
21		-40	-150	680	-240		40	470	1200		90	870	620	620	810	190	780	800	720	-280	670	800	-200	-130		40	210	100	880		30	630	900		356	418
22	-410		770	630	-360	490		-40		60	720	-250	170	780	-100		40	-270	990	450	510	770	550	480		-60	390	120		60	840		1070	980		244	418
23	-610		360	830	760	260	810	160		-10	170		1010	1820	560	-410	600		90		90	700	870	520	740		-20	820	140		-40	820	180	210	540		356	412
24		140	110	270	630	520	100	-570	-570	710		70	160	500	-100	230	560	-280	530	700	420	150	230		-80	-190	460		-70	730	650		-40		187	339
25	260	240	-790	270	-780	420	240		-70	610	440	-110	470	770	800	670	970		670	400	150	230		-80	-190	460		-70	730	650		-40		364	473
26		30	500	130	-770	500	770		-70		80	580	-130	-720	420	590	930		40	910	140	080	670	410	-200	-280	-200	-250		-50	180	360	830		198	354
27	210		130	-260	150	200		20		80	860	-140		-30	890	600		-60	720	260	870	270	470	400	690	440	-280		50	250	920	640	-330	1050		210	390
28		170	460	130		-40	960	310	-200		-10	870	2900	2880	290	740	250	-490	320	560		-60	950	280	980	-490	930	280		-80	210	540	950		387	681
29		170	710	-480	1040		-90	290		-40		-10	650	750	780	560	-190	740		950	410	960		0	-470	1300	700	310	560	420		90	-190	650	230		307	431
30	820		470		60	160		30		-60		0	-360	470	690	100	940	950	-240	910	-100	690		-20	670	750	160	740	740	210	450	450	550	300		355	366
																													$\bar{x}$	359	409
																													$S(\bar{x}_i)$	[illegible]	$S(\bar{x}_i)$
$\bar{x}_j$	97	265	312	368	333	390	104	-18	425	845	582	371	220	466	276	389	500	345	410	424	407	298	317	354	374	432	649	654	$\bar{x}$	359	150
$S(x_j)$	268	366	733	466	454	344	421	741	446	315	659	[illegible]	330	389	790	296	268	749	394	380	324	431	372	385	336	392	299	394	$S(x_j)$	337	$S(x_j)$

Interpolated blank values

-40	160	215	125	-71	-74	-85	-85	-146	-140	-133	355	355	257	230	706	333	100	85	245	360	240	190	210	230	80	380	380		149	

were analysed to obtain an indication of the distribution of gold at the sampling site, of the overall geometrical effect and of the instrument calibration stability over a period of a month. Four types of standard deviations were calculated: S_c the theoretical counting standard deviation, S_g the overall geometrical standard deviation for an individual measurement, S_d the instrumental drift standard deviation for successive measurements, and S_{Au} the inherent gold standard deviation in the group of thirty samples. These are set out in Table 14.3 where the subscripts i and j for a measured value $x_{i,j}$ refer to the sample number and successive measurement number respectively, i.e. to the ith row and j^{th} column in Table 14.3.

Every individual measurement is subject to a counting error, S_c, and a geometrical error, S_g, analogous to assaying and sampling errors in chip sampling. When the same sample is scanned repeatedly over many days the observed standard deviation includes the instrumental drift S_d from scan to scan, as in equations 14.1 and 14.4 in Table 14.4. The short-term (0,5 hour) drift for a scan of thirty samples was assumed to be insignificant. The observed standard deviation of many samples in a scan thus includes only the gold distribution, S_{Au}, as in equations 14.2 and 14.3. The theoretical counting standard deviation for individual measurement, S_c, is determined by the background count preset in the instrument, and is given in equation 14.5, from which S_g, S_d and S_{Au} may be calculated, with the results given in equations 14.6 to 14.8.

These values show that the geometrical error was

Table 14.4
Calculation of the variances in the determination of gold concentrations at Marievale

$$\overline{s^2(x_i)} = s_c^2 + s_g^2 + s_d^2 = (409 \text{ cm g/t})^2 \quad 14.1$$

$$s^2(\bar{x}_i) = (s_c^2 + s_g^2)/28 + s_{Au}^2 = (113 \text{ cm g/t})^2 \quad 14.2$$

$$\overline{s^2(x_j)} = s_c^2 + s_g^2 + s_{Au}^2 = (397 \text{ cm g/t})^2 \quad 14.3$$

$$s^2(\bar{x}_j) = (s_c^2 + s_g^2)/30 + s_d^2 = (150 \text{ cm g/t})^2 \quad 14.4$$

$$s_c = 10\sqrt{1\,000 \times 4/3} = 365 \text{ cm g/t} \quad 14.5.$$

$$\therefore s_g = 129 \text{ cm g/t} \quad 14.6$$

$$s_d = 132 \text{ cm g/t} \quad 14.7$$

$$\text{and } s_{Au} = 88 \text{ cm g/t} \quad 14.8$$

considerably smaller than the counting error and thus had only a small effect on the measurement error. The combined errors $s_c^2 + s_g^2$ can be expected to decrease as the number of fixed-time measurements in an average increases, or as the measurement time increases, as shown in Figure 14.3. Drift for successive scans in the first prototype dominated the measurement error for measurement times exceeding three minutes, as can be seen from equation 14.4. The drift s_d = 132 cm.g/t for successive scans was of the same order of magnitude as the overall gold value (211 cm.g/t) at this site, making it difficult to get reproducible scan averages. For routine valuation, instrument drift should be less than 5% of the current pay-limit value of the ore (approximately 500cm.g/t), without requiring daily adjustment of the instrument. Some of the large drifts observed with the first portable prototype could have been the result of the

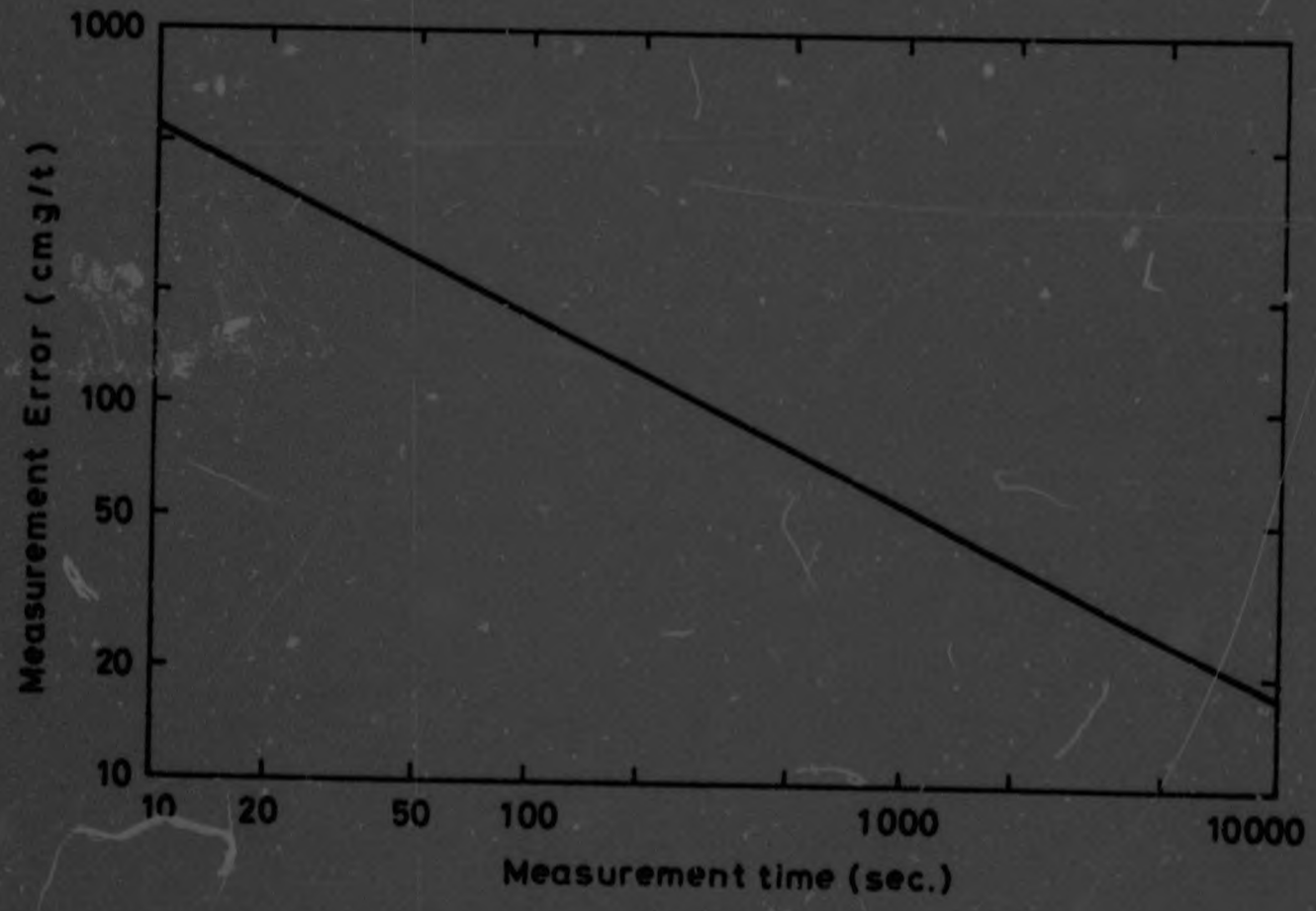

Figure 4.3 Prototype 1 Measurement Error $(S_c^2 + S_g^2)^{1/2}$

instrument "ZERO" fault. A five-fold improvement in stability was sought in the design of the second prototype.

14.2.1 Minimum length of stope face for quantitative estimation of the gold content at Marievale Gold Mine

The most important valuation decisions are required when ore values are marginal. In the following it is assumed that the pay limit is 500cm.g/t and that a valuation precision of 50cm.g/t (10% of the pay-limit) may be considered a satisfactory requirement for quantitative estimation. At this site, a coefficient-of-variation for the gold of $CV_{Au} = S_{Au}/\text{mean} = 88/211 = 0,42$ was found for 15cm wide x 2,5cm deep samples. Assuming a constant CV_{Au} this would indicate a gold variation of $S_{Au} = 0,42 \times 500 = 210$cm.g/t at the pay-limit for 15cm wide samples and a variation of $S_{Au} = 50$cm.g/t for $(210/50)^2 \times 15\text{cm} = 2,6$m of stope face.

It would, however, not be practical to estimate the gold content of the ore with a negligibly small error, as this would be too time consuming. In scanning trials underground, no difficulty was experienced in tracing the reef at scanning rates of up to about three metres per minute, while maintaining the probe between 2,5 and 6,5cm from the face. The geometrical error S_g may thus be assumed to be independent of rate and to depend only on the total measurement time as shown in Figure 14.3. Adding a measurement error $(S_c^2 + S_g^2)^{0,5}$ to S_{Au} increases, by a factor equal to the variance ratio, $(S_c^2 + S_g^2 + S_{Au}^2)/S_{Au}^2$, the minimum face length required to reach a precision of 50cm.g/t in the estimate of the gold value. The results of

such a calculation are shown in Figure 14.4. From this figure a stope face length of about 10m measured in about half an hour appears a practical minimum length for quantitative estimation of marginal grades. "Quantitative", in this context, means a valuation precision of 50cm.g/t, and if less precision is desired, the length of face required for the estimation of the gold content would be reduced accordingly. For instance, a precision of the order of 100cm.g/t could be achieved in about 2,5m and 6min scan time, and a precision of 25cm.g/t in about 40m and 100min scan time.

14.3 Results obtained with the first prototype at Blyvooruitzicht Gold Mine

Two experiments were conducted at Blyvooruitzicht with the first portable prototype. One experiment was designed to determine the extent to which fluorescence sampling of the face could yield an estimate of the bulk content of the gold in the reef. The other experiment was designed to confirm, by correlation of the results with those of chip-sampling, that the gold analyser could be used to measure quantitatively. The results of measurements are given in Table 14.5.

Of the 64 batches (4m face x 0,5m on blast) of blocks 1E to 8E mined in the experimental stope, 41 batch faces were scanned with the fluorescence analyser to a precision of about 75cm.g/t (1 standard deviation). The averages of the values measured with the fluorescence analyser were compared with the bulk batch values for reef to the east, (see Figure 14.2), and for reef to the west of the face, and the

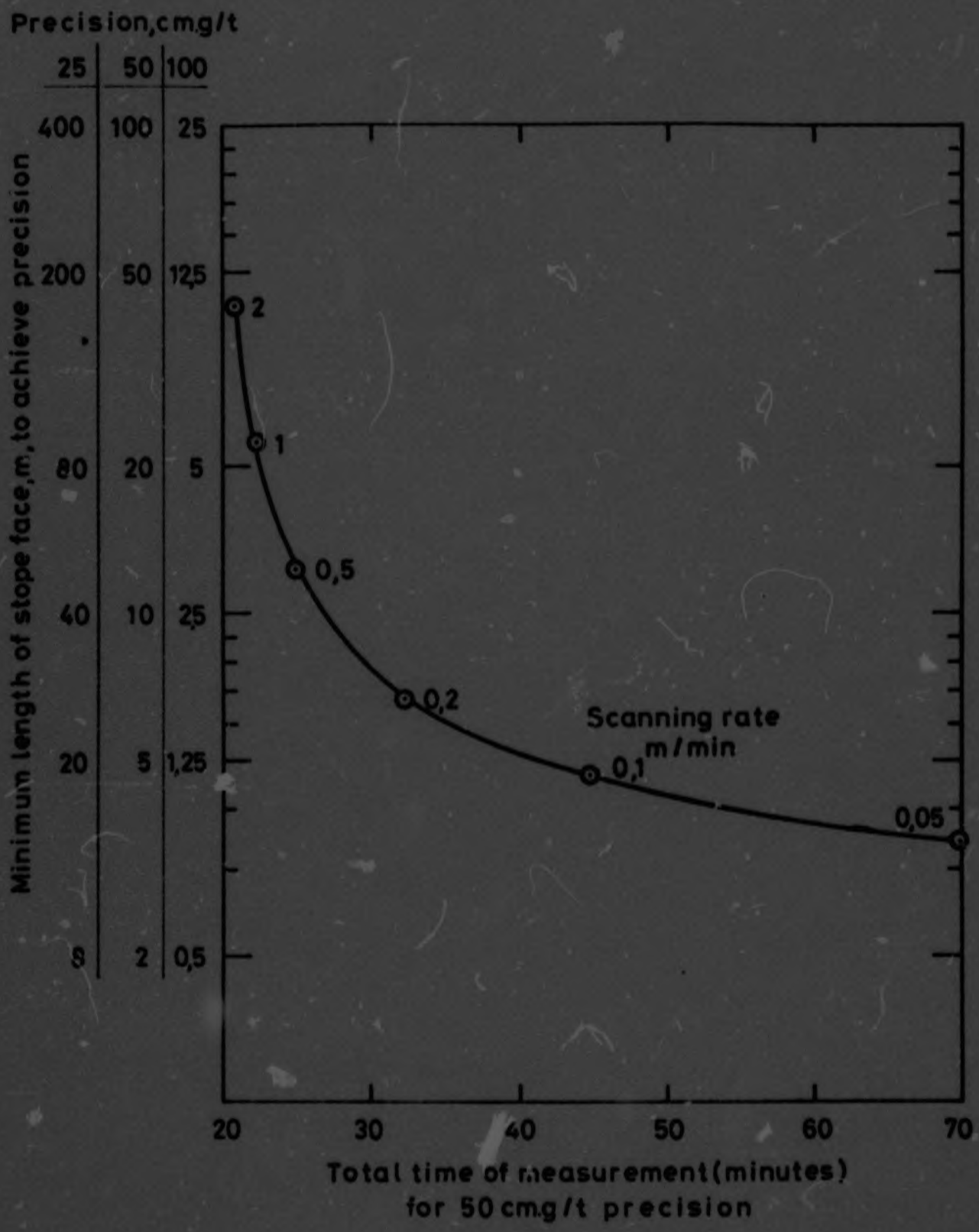

Figure 14.4 Length of face to be scanned at Marievale using Prototype 1, to achieve the given precision in the given time

TABLE 14.5

BATCH MEASUREMENTS AT BLYVOORUITZICHT

Units cm g/t

3a Bulk batch values.

Block No.	Batch No.							
	1	2	3	4	5	6	7	8
1W	2064	1638	1403	1486	727	651		667
1E	1338	1274	1634	1233	1082	1604	1726	1621
2E	545	1328	1762	1438	728	953	1431	2865
3E	1654	1865	1764	1618	2130	1381	1517	2847
4E	2265	2407	2318	1695	1138	1087	1103	1132
5E	851	895	1101	1200	1307	1618	1453	2417
6E	1318	1647	1566	1520	1312	1321	1421	1303
7E	950	1275	1450	1152	2016	1891	1910	1699
8E	1095	1584	2225					

3b Face values by fluorescence measurement.

Block No.	Batch No.							
	1	2	3	4	5	6	7	8
1W								
1E	735	1105	885	1135	1040		1165	1000
2E	1260	690	765	1720	1080			
3E	1253				1850	2330	2670	
4E	2370	2920	2740		1080	1291	1680	
5E	1180	1820	1710	1490	2210		1660	2340
6E	2395	2820	1590	1520				1350
7E	1365		1720		1230		2170	1530
8E	730		2860					

3c Face values by chip sampling.

Block No.	Batch No.	
	1	5
1W	576	938
1E	1142	1515
2E	1956	893
3E	2053	1981
4E	1956	1197
5E	979	1384
6E	2142	1683
7E	1368	1624
8E	1717	

correlattion coefficents found (r = 0,54 and r = 1,48 with 40 degrees of freedom) had a probability of about 0,1% of coming from random values. This very high level of significance of the correlation coefficient supports the hypothesis that the fluorescence method can be used for quantitative measurement of the gold content of the ore. The fairly low value of the correlation coefficient shows merely that the gold content varied considerably within a batch while the fluorescence sample (4m face x 2,5cm deep) represents only 5% of the batch. High variability at this site is shown by the values in Figure 14.6, and the semivariogram in Figure 14.7, of 128 consecutive batches of ore. A striking periodicity of the values every 18 batches, or 9m, is apparent from the variogram. Instrument drift as well as insufficient operator expertise in tracing unmarked reef could also have introduced variation into the measurements.

The face of every fourth batch of the 64 batches was chip-sampled contiguously. The average for the 4m faces, when compared with the bulk batch values for the ore to the east and to the west of the face, gave correlation coefficients (r = 0,47 and 0,70 with 14 degrees of freedom) having probabilities between 7% and 0,1% of coming from random values. This is not significantly different from the result obtained with the fluorescence analyser.

The results of chip-sample and fluorescence measurements on six faces (15cm wide) were compared. The measurements are given in Table 14.6. For six faces the correlation of results of fluorescence and chip-sample measurements for

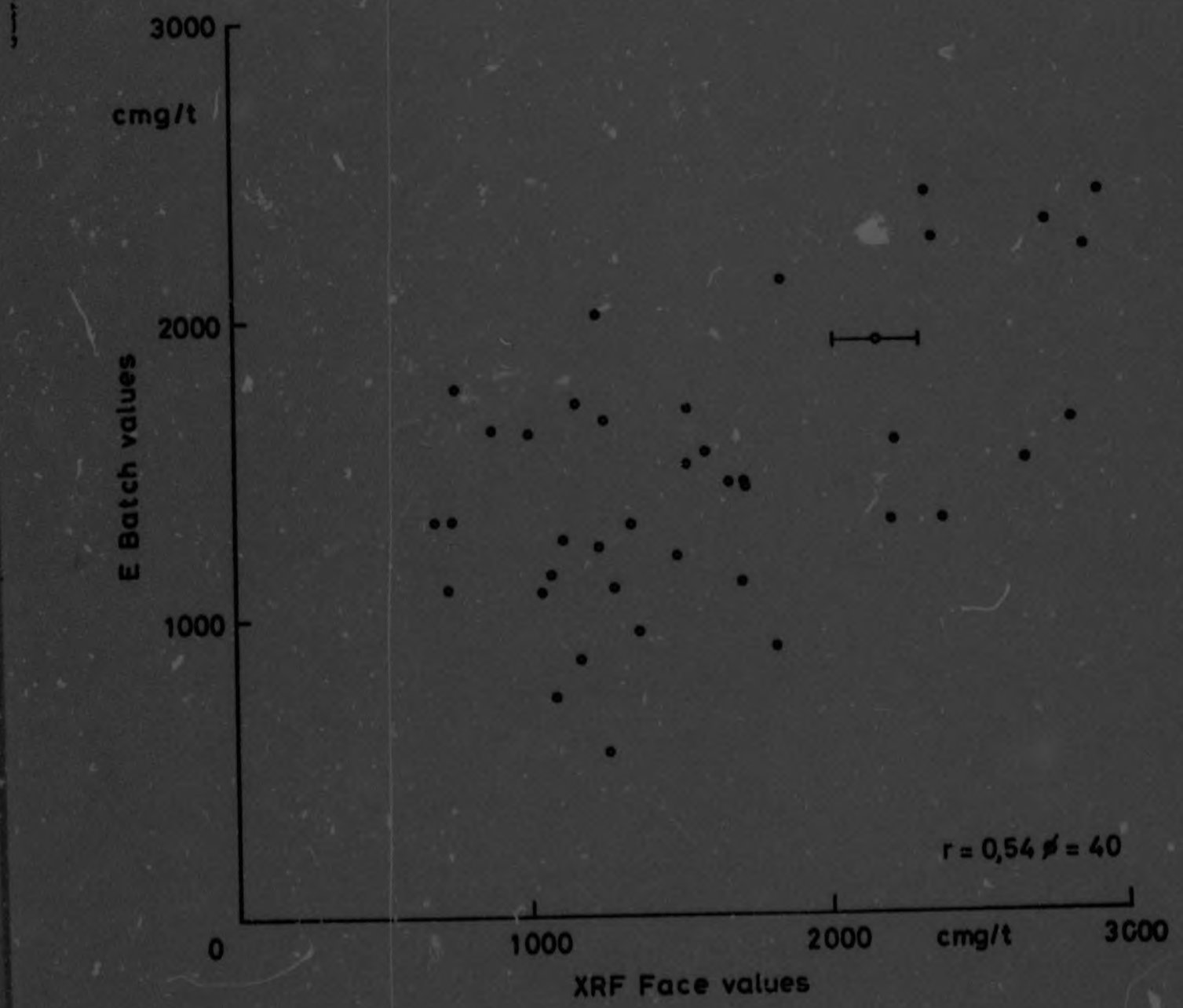

Figure 4.5 Comparison of batch and X-ray fluorescence estimates at Blyvooruitzicht. Error bar shows standard deviation of fluorescence estimate. Error of batch estimate unknown.

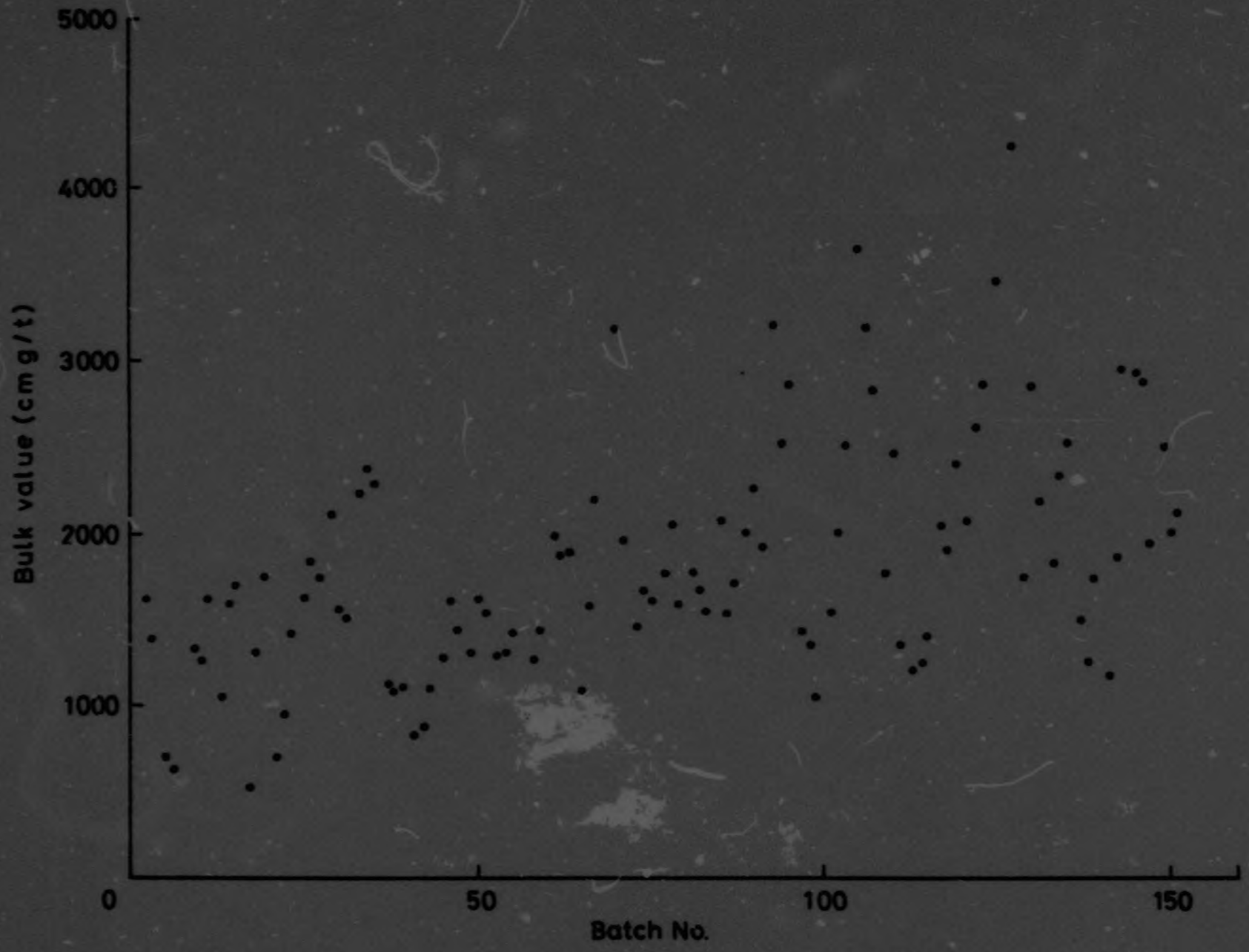

Figure 14.6 Bulk values of 152 batches at Blyvooruitzicht, in consecutive batch number

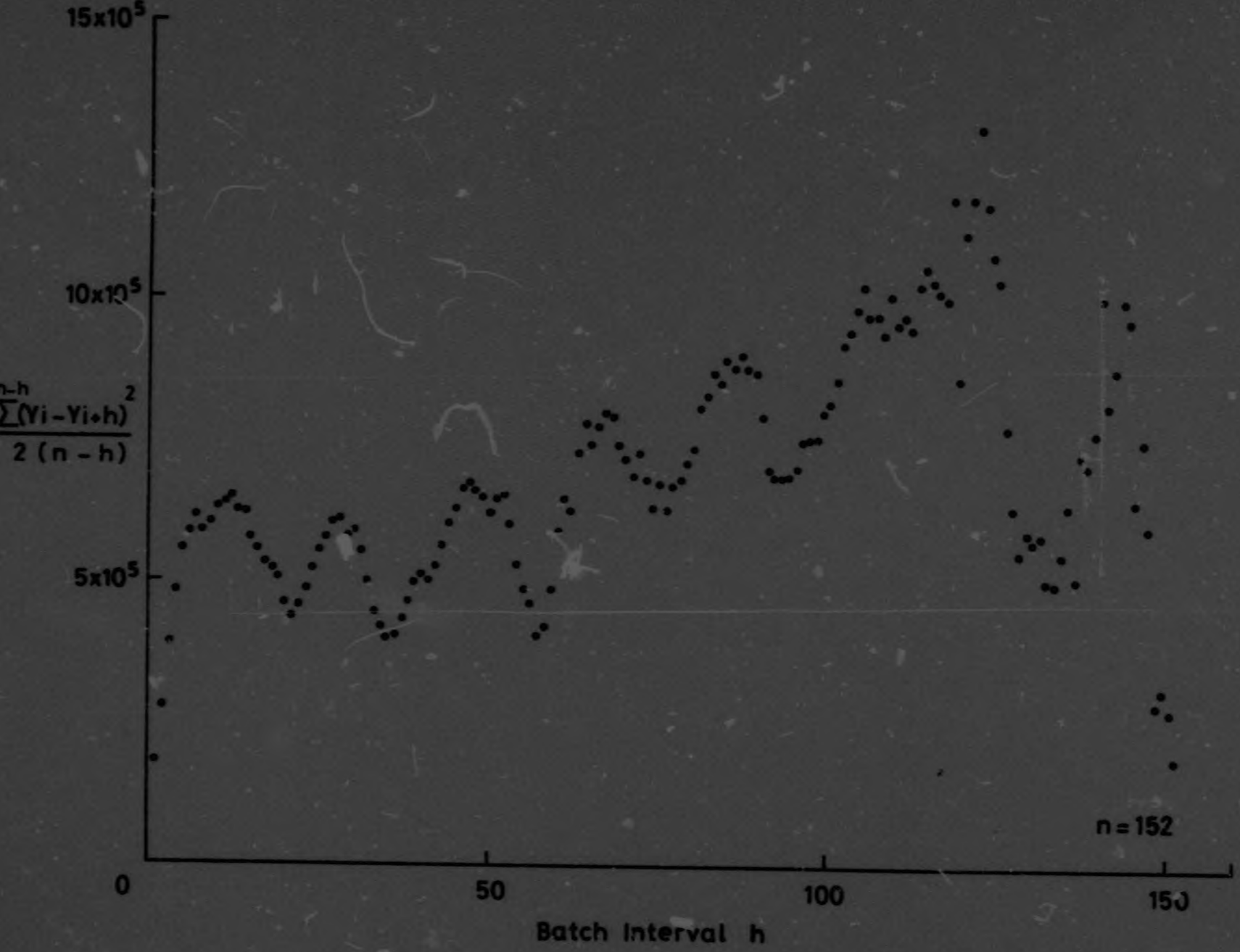

Figure 4.7 Variogram of 152 consecutive batch values at Blyvooruitzicht

TABLE 14.6. Prototype 1 fluorescence-(XRF) and chip values and their correlation coefficients at Blyvooruitzicht.

SAMPLE NO.	BLOCK AND BATCH NO.											
	3EB5		4EB5		4E NORTH		5EB1		6E SOUTH		7EB1	
	XRF	CHIP	XRF	CHIP	XRF	CHIP	XRF	CHIP	XRF	CHIP	XRF	CHIP
1					3170	2368	2220	1741			780	1343
2					270	747	1830	1709			1340	1322
3					1820	932	370	952			1180	560
4					1580	1561	1280	1578			770	840
5					1640	1355	1130	1195			590	378
					2720	1212	1300	1726			260	619
					2250	858	810	1340			940	663
					4210	1432	890	719			2540	766
					2900	2956	920	619			1030	1210
10					4470	4535	230	671	2020	1946	1450	1726
					5010	3139	640	722	2280	2561	1550	1322
					8210	6756	250	261	930	1083	2180	1873
			890	932	5400	3048	210	484	1100	1524	520	1248
			920	1120	3000	2093	960	604	1590	2277	2520	1707
15			590	1138	2500	2298	2110	766	2350	2277	1580	2228
			1010	876	6340	2093	1110	1909	1090	2764	2100	932
			1260	1304	3010	2919	2790	2020	990	971	1890	3397
	1150	1414	1500	2313	2970	2020	1240	1276	1530	2350	5940	3778
	1190	3905	1030	784	1680	812	170	1008	940	1083	4760	1781
20	2320	1928	210	766	-330	1389	180	1120	880	368	3150	1909
	1890	2515	-130	290	1280	1260	910	1340	6440	3727	5050	2846
	-30	952	710	217	1170	1649	210	376	1210	1442	3460	3268
	150	803	990	319	1610	2444	750	772	2010	4700	3050	1285
	1060	1047	2120	1909	3210	3690	850	1285			1380	1175
25	1210	1083	2000	1871	1250	1138	540	334			1100	1027
	1780	2094	1270	2313	100	988	240	254			2000	1597
	1030	1474	390	766	1590	914	530	174			2320	1744
	1000	1570	670	803	990	1138	770	432				
					3850	1800	350	503				
30					2560	1782						
					1190	1386						
	r=0,49		r=0,71		r=0,76		r=0,73		r=0,60		r=0,70	

Overall r = 0,73

individual samples gave correlation coefficients (r = 0,5 to 0,8 with 10 and 30 degrees of freedom) having probabilities 4% to <0,01% of arising from random values, with an overall coefficient for the 123 samples (r = 0,73 and 127 degrees of freedom) having a probability <<0,01% of arising from random values. This very high level of significance of the correlation coefficient leaves little doubt regarding the validity of the fluorescence method for quantitative measurement.

In the batch comparisons the correlation coefficients were fairly low because only 5% of a very variable gold distribution was sampled. In the comparison of results obtained by the fluorescence analyser and chip-sampling methods the coefficients were fairly low partly because counting and geometrical errors were permitted to be relatively large and partly because the shapes and sizes of the samples used in the two methods were different.

14.3.1 Results using the second prototype at Blyvooruitzicht Gold Mine

An attempt was made to determine the correlation between batch and chip values using the second prototype portable analyser. However, too few batch faces could be measured to permit a meaningful statistical evaluation to be made of the correlation between fluorescence and batch results.

On four faces of block 14E, corresponding individual fluorescence measurements and chip-samples were taken; the results are given in Table 14.7. The four correlation coefficients (r = 0,71; 0,73; 0,64; 0,69) calculated for the sets of data given in Table 14.7 all have a probability

TABLE 14.7 Proto 2 Fluorescence and chip values(cmg/t)

SAMPLE NO.

BLOCK AND BATCH NO.

	14E SOUTH		14EB5		14E NORTH		15EB1	
	XRF	CHIP	XRF	CHIP	XRF	CHIP	XRF	CHIP
1	560	159	-1770	1891	2580	2460	540	971
2	1300	513	1660	1781	1910	1248	490	1625
3	2140	1414	5720	4425	300	1138	430	729
4	3680	2368	3000	2552	600	971	770	393
5	1280	268	580	971	1950	1065	640	699
6	(6750)	638	510	437	2700	2130	-410	722
7	1930	1763	440	459	6650	4094	510	1324
8	810	451	720	246	5140	4370	-90	546
9	3470	2001	1480	2745	1580	3617	2170	568
10	1540	1506	2350	2460	2360	6150	1290	840
11	790	714	1600	1561	750	1340	1610	3029
12	1760	404	3140	1450	990	480	620	5205
13	4960	3522	1710	2736	-140	876	1180	3286
14	1620	1873	3810	4691	-230	144	11980	8391
15	3080	4186	1780	3837	-180	42	3960	3231
16	3490	2020	1820	2580	360	126	360	72
17	290	368	4060	5178	(70	8354)	90	57
18	1380	1506	1250	2700	-360	342	4870	2020
19	4800	1487	-430	320	710	614	-280	130
20	2520	1065	500	503	2340	9620	160	790
21			760	568	2810	1909	2400	1450
22			250	1120	1520	8703	1770	1377
23			1180	2773	1620	3745	3290	8622
24			1170	3415	9770	20233	4230	4406
25			520	2111	(10760)	3801	780	1726
26							750	2607
27					5900	2938	1640	2306
28					1730	2625	2000	1083
29							1540	876
30					1390	952	1310	971
31							1430	1047
32					2260	1561	2620	1597
33							2310	1212

Correlation coefficient:

r=0,71 r=0,73 r=0,64 r=0,69

TABLE 14.7 Proto 2 Fluorescence and chip values(cmg/t)

SAMPLE NO.

	BLOCK AND BATCH NO							
	14E SOUTH		14EB5		14E NORTH		15EB1	
	XRF	CHIP	XRF	CHIP	XRF	CHIP	XRF	CHIP
1	560	159	-1770	1891	2580	2460	540	971
2	1300	513	1660	1781	1910	1248	490	1625
3	2140	1414	5720	4425	300	1138	430	729
4	3680	2368	3000	2552	600	971	770	393
5	1280	268	580	971	1950	1065	640	699
6	(6750)	638	510	437	2700	2130	-410	722
7	1930	1763	440	459	6650	4094	510	1324
8	810	451	720	246	5140	4370	-90	540
9	3470	2001	1480	2745	1580	3617	2170	568
10	1540	1506	2350	2460	2360	6150	1290	840
11	790	714	1600	1561	750	1340	1610	3029
12	1760	404	3140	1450	990	480	620	5205
13	4960	3522	1710	2736	-140	876	1180	3286
14	1620	1873	3810	4691	-230	144	11980	8391
15	3080	4186	1780	3837	-180	42	3960	3231
16	3490	2020	1820	2680	360	126	360	72
17	290	368	4060	5178	(70	8354)	90	57
18	1380	1506	1250	2700	-360	342	4870	2020
19	4800	1487	-430	320	710	614	-280	130
20	2520	1065	500	503	2340	9620	160	790
21			760	568	2810	1909	2400	1450
22			250	1120	1520	8703	1770	1377
23			1180	2773	1620	3745	3290	8622
24			1170	3415	9770	20233	4230	4406
25			520	2111	(10760)	3801	790	1726
26							750	2607
27					5900	2938	1640	2306
28					1730	2625	2000	1083
29							1540	876
30					1390	952	1310	971
31							1430	1047
32					2260	1561	2620	1597
33							2310	1212

Correlation coefficient:

r=0,71 r=0,73 r=0,64 r=0,69

below 0,1% of arising from random values and the significance of the correlation of the combined data is still far higher. This finding adds further support to the hypothesis that the flluorescence method can be used quantitatively.

In addition, an experiment was conducted to determine the reproducibility of measurements using the second prototype, and to test for the effects of possible differences in technique between one operator and another. The experiment was undertaken on the north face of block No.11 in the experimental stope. Nineteen samples 15cm wide by 10cm high were marked off on a narrow reef and were measured 14 times in succession by two operators. The values obtained are shown in Table 14.8.

The instrument had been calibrated to give, for individual measurements (approximately 40s) a counting standard-deviation, S_c, of 425cm.g/t. Both operators obtained identical within-sample measurement variances of $(S_c^2 + S_g^2) = (445\text{cm.g/t})^2$. The value of the geometrical standard-deviation, S_g, of 132cm.g/t was not unexpected in view of the uneven nature of the rock face scanned. Both operators were thus capable of performing measurements within counting statistics. The means (of 14 measurements) of the 19 samples had a highly significant correllation for the two operators ($r = 0,97$; 18 degrees of freedom) with a probability of less than 0,01% of coming from random values. The high correlation coefficent shows the good reproducibility of the method at an average ore value of 939cm.g/t, that is, at about twice the pay limit. The 8%

TABLE14.8 Prototype 2 fluorescence measurements on 19 samples of Blyvooruitzicht. Units cm g/t.

OPERATOR A.

Sample No	Measurement No. 1	2	3	4	5	6	7	8	9	10
1	1420	1130	230	2170	950	1000	1600	1150	1180	-160
2	450	270	30	770	500	700	820	150	220	360
3	1000	830	60	270	870	150	1090	220	890	1020
4	-100	-280	300	1130	-440	1140	500	110	340	450
5	460	520	710	300	-420	570	600	-490	540	-590
6	-420	470	320	-160	200	-320	-40	110	-220	630
7	-360	-110	460	-660	580	-640	-480	-20	700	250
8	970	970	40	650	140	950	110	780	210	630
9	960	900	800	1130	-220	1020	390	430	840	1000
10	1260	1320	1230	540	1000	1070	940	1130	1540	1830
11	3390	3020	3430	2880	2730	2500	3018	3820	2530	2630
12	2710	2650	2400	2140	2130	22[illegible]	1920	1380	2000	1850
13	1810	390	1270	1310	1880	181[illegible]	1810	1080	540	1020
14	2770	1630	1050	1550	1440	1700	190	1360	1770	1820
15	860	660	1090	820	1490	1210	950	1190	730	1110
16	1910	1330	2390	1630	1270	870	2000	1440	1950	1730
17	1680	1060	1910	630	1010	710	240	430	2310	360
18	270	800	870	1410	558	820	1380	1140	860	390
19	-90	130	660	410	830	340	490	680	290	540

OPERATOR B.

	Measurement No. 11	12	13	14	15	16	17	18
1	1228	770	1240	1300	1150	1390	920	540
2	1330	1470	780	30	320	-430	720	250
3	690	540	960	1040	730	420	720	780
4	850	730	-70	160	1260	360	250	860
5	60	660	820	590	720	-630	-300	1300
6	810	310	310	390	30	-330	-630	-230
7	110	-90	-20	-60	550	-220	-210	570
8	-170	60	950	360	310	-110	500	610
9	1040	200	440	480	-300	270	500	-220
10	1830	1030	920	1300	1150	1040	860	970
11	3910	3270	3180	2660	3900	3160	2880	3460
12	2350	2340	1320	1350	2450	2730	2660	2380
13	1450	810	960	1400	740	590	1680	1230
14	1900	1590	1560	720	1370	960	780	1320
15	1640	1210	1100	1180	1520	680	1240	1180
16	1620	1450	1420	7050	1590	1360	1720	2250
17	1630	1130	540	820	1210	1780	1140	70
18	750	1410	720	1280	950	780	1350	1040
19	1050	850	720	280	-560	710	610	-360

TABLE 14.8(Continued)

OPERATOR B. (Continued)

Sample No.	Measurement No.									
	19	20	21	22	23	24	25	26	27	28
1	1360	1360	590	300	850	700	1010	1010	1500	440
2	780	1030	1180	810	240	410	-110	230	250	0
3	610	780	1080	-560	760	510	540	250	310	1630
4	220	1620	60	640	720	1100	520	240	320	500
5	30	530	470	-700	1010	610	810	210	470	50
6	-180	310	-170	40	130	-640	-590	80	-290	280
7	470	-1160	220	-300	-490	-460	-410	-220	130	-400
8	590	460	210	630	500	570	-420	780	960	-120
9	1180	610	200	-220	490	1000	480	30	490	-60
10	800	1180	820	350	1290	1220	-120	720	980	640
11	2620	4290	2550	3620	2840	2310	3190	3500	3280	2330
12	2320	1500	2360	2100	1950	2620	1580	1950	1490	2360
13	1590	480	1930	1040	1640	510	1390	470	910	830
14	2030	1110	830	1760	1100	1440	860	1120	2120	1210
15	1090	1730	940	1840	1250	1290	1850	760	1650	530
16	1940	1610	1260	2590	1640	1450	1560	1480	1620	1770
17	1620	740	610	1410	1280	1120	1210	1350	1500	1820
18	460	1630	1270	1000	1250	1270	910	200	820	1230
19	350	570	-20	-130	-200	330	130	260	-220	-90

	A		B		A and B	
	i=1 to 14		i=15 to 28		i=1 to 28	
	$\bar{x}_i$	S_{x_i}	$\bar{x}_i$	S_{x_i}	$\bar{x}_i$	S_{x_i}
1	1086	559	937	385	1011	477
2	563	446	406	450	484	447
3	688	368	611	481	650	422
4	344	493	619	451	482	484
5	309	475	327	589	318	525
6	170	364	-156	319	7	375
7	-24	424	-138	481	-81	448
8	475	411	391	381	433	391
9	672	392	318	448	495	451
10	1149	308	850	377	999	370
11	3140	556	3138	589	3139	562
12	2059	455	2175	424	2117	435
13	1253	481	1074	502	1163	491
14	1504	593	1286	426	1395	518
15	1089	273	1254	428	1171	362
16	1647	391	1703	354	1675	367
17	1033	632	1204	473	1119	554
18	904	373	1010	373	957	370
19	513	310	99	386	306	403
Means	977	437	900	438	939	445
$S_{\bar{x}_i}$	746		812		774	

difference between the total average values found by the two operators falls within acceptable statistical limits and does not indicate a real bias between these two operators.

14.3.2 Minimum length of stope face at Blyvooruitzicht Mine for quantitative estimation of the gold value

Following the same line of thought as in section 14.2.1, an estimate of the minimum length of stope face required for quantitative valuation may be obtained from the gold distribution S_{Au} found at this site. The variation in sample means was found to be :

$$S^2(x_i) = (S_c^2 + S_g^2)/28 + S_{Au}^2 = (773cm.g/t)^2$$
$$= (445)^2/28 + S_{Au}^2$$

giving S_{Au} = 768cm.g/t at a mean gold value of 939cm.g/t and $CV_{Au} = S_{Au}/mean = 768/939 = 0,82$

Therefore at marginal grades of 500cm.g/t, the value of S_{Au} for 15cm wide x 2,5cm deep samples would be 409cm.g/t, and a valuation precision of S_{Au} = 50cm.g/t would require a measurement of $(409/50)^2$ x 15cm = 10m stope face.

The addition of the measurement error (of the second prototype) $(S_c^2 + S_g^2)^{0,5}$ leads to the minimum stope face length and measurement times shown in Figure 14.8, from which it appears that for the more variable gold distribution at Blyvooruitzicht a stope face length of the order of 330m measured in about 1,5 hours seems to be a practical minimum length of marginal grade for quantitative estimation of gold values.

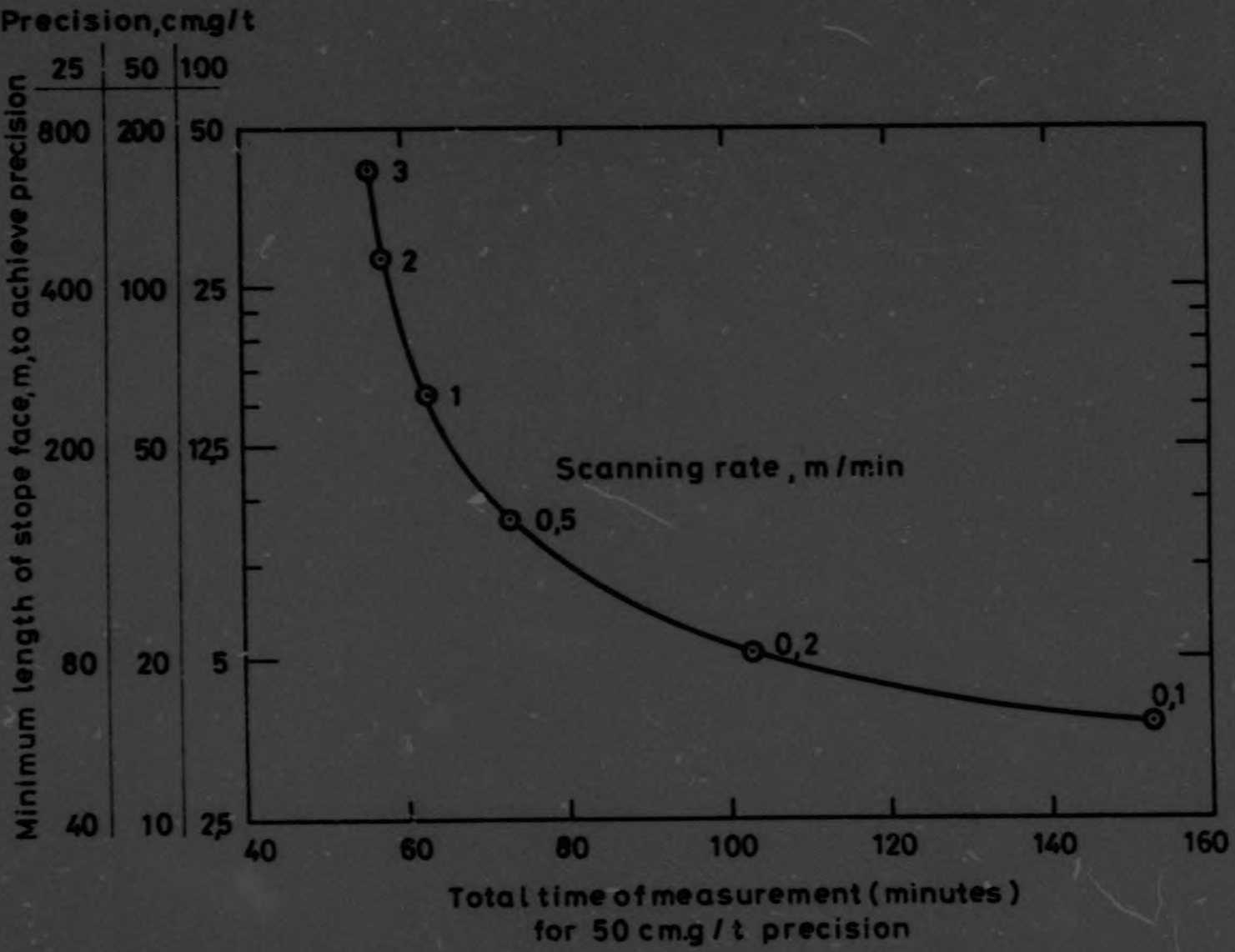

Figure 4.8 Length of face to be scanned at Blyvooruitzicht using Prototype 2, to achieve the given precision in the given time.

15 CONCLUSIONS

The need for improvements in the precision of ore valuation in the gold mining industry has been recognized widely. It has been realized that the conventional method of evaluation by chip sampling and fire assay would allow only a significant improvement in the precision if many more sampling teams were employed, and this would greatly escalate ore valuation costs. Methods of *in situ* instrumental ore evaluation, amenable to scanning greater amounts of exposed rock face, were thus sought.

A number of potential instrumental methods had undergone provisional investigation and of these the gamma ray fluorescence method seemed the most promising. The problems of measuring trace concentrations in situ presented a great challenge. At the outset it was not certain whether gamma ray fluorescence spectrometry could be developed into an economical method of evaluation, but it seemed that with optimization of all the measurement parameters, this goal should be within reach of the available technology.

Many aspects of the method were investigated from fundamental principles to allow quantitative assessment both of the parameters and of the interrelation of the parameters, so that the method as a whole could be optimized for the evaluation of Witwatersrand gold ores to serve as an ore valuation tool and to assist in the identification of geological strata. Quantitative formulation of measurement

parameters made possible the calculation of the maximum improvements available for certain parameters and the trade-off with others. For example, a single-channel pulse-height analyser scheme was optimised so that measurement times therewith would be only a few percent longer than the best possible times with a multichannel scheme, which would have placed greater demands on battery power.

Parallel with the derivation of optimum measurement parameters went the development of laboratory-type instrume[illegible] followed by the development of portable instruments in collaboration with ORTEC INC., the field testing of instruments and continual appraisal of the method.

Some of the instrumental parameters implemented in the third prototype analyzer still fall short of the calculated optimum values because the manufacturer, for some of the sub-units, preferred to rely on familiar or proven technology. For example, a monostable-based timing system to define the amplifier pulse peak position, for the purpose of pileup rejection, was developed by the author, but the instrument manufacturer preferred to use a more familiar amplitude peak detector for which the trailing edge pileup parameter β cannot be optimised to the same degree, and relevant in situ measuring times with the latter system are thus slightly longer. As the gold analyser is going into commercial production some of the sub-units, for which significant improvement is possible, are being redesigned.

The many fluorescence measurement values obtained to date at experimental underground sites with the prototype

instruments, were in all instances found to have a highly significant correlation with those obtained from the same locations by chip or bulk sampling and fire assay.

At the completion of this thesis three units of the third prototype version of the portable gold analyser are being deployed in normal working stopes to derive optimum measurement procedures for ore valuation. Gamma ray fluorescence results from more than 1000 man hours of operation have shown high reproducibility and predictable valuation precision (Davies et al., 1979). True to expectation, at a number of locations it has been possible to show with the fluorescence instrument that mining was following the wrong horizon.

The possibility of simultaneous measurement of uranium and gold with an instrument of this type, and the need in several mines for combined ore valuation of these metals has generated a demand for the addition to the instrument of an analysing channel for uranium. This may mean the rapid evolution of a second generation of commercial instruments, which may be brought closer to the optima which have been identified in this thesis.

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