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THE NOBLE-METAL CONTENT OF ORE IN THE LEVACK WEST AND LITTLE STOBIE MINES, ONTARIO

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ABSTRACT

A nickel sulfide fire-assay preconcentration procedure has been adapted to the determination of Rh, Pd, Pt, Ir, Os, Ru and Au in ores and host rocks by instrumental neutron activation. This procedure, suitable for large samples, corrects for their inhomogeneity. At the Levack West mine (North Range of the Sudbury Nickel Irruptive) a major difference is noted between the samples of two ore zones: in the Levack-breccia ore the Cu-rich stringers are enriched in Pd, Pt and Cu, and depleted in Os, Ru, Ir, Rh and Ni, with respect to the granitic breccia ores of the Main ore zone. The Little Stobie mine (South Range) consists of two orebodies: #1 parallel to the Irruptive–footwall contact and #2 projecting dyke-like into the footwall. More Rh, Pd, Ir, Os and Ru is found in #2 than in #1. The Cu and Ni values are not significantly different for these two orebodies, which result from the injection of two separate pulses of ore-bearing magmatic material, with only slightly different histories of equilibration with the Irruptive magma. The Cu-rich footwall stringers are also enriched in Pd, Pt and Au relative to the main #1 orebody with which they are associated. The overall level of Pd, Pt and Au is higher at Little Stobie than in the Main ore zone at Levack West, from which we infer that at Levack West, the Pd, Pt and Au associated with the Cu-rich stringers were derived from the Main ore zone, possibly by thermal diffusion. *R*-mode factor analyses show that Ir, Os, Ru and Rh, spatially, or genetically, or both, behave as a group associated with Ni mineralization, whereas Pd, Pt and Au, to a much lesser extent, however, are associated with Cu mineralization.

SOMMAIRE

Nous avons adapté une méthode appliquée en docimasie des sulfures de nickel, avant concentration, à la détermination, par activation neutronique, de Rh, Pt, Ir, Os, Ru et Au dans le minerai et la roche hôte. Cette méthode, qui permet d'utiliser de gros échantillons, corrige donc leur manque d'homogénéité. A la mine Levack Ouest (flanc nord de l'intrusion de Sudbury), on note une grande différence entre les échantillons de deux zones minéralisées: dans la brèche Levack, les filonnets cuprifères sont enrichis en Pd, Pt et Au, et appauvris en Os, Ru, Ir, Rh et Ni, par rapport à la brèche granitique de la zone minéralisée principale. A la mine de Little Stobie (flanc sud), on distingue deux gîtes distincts: No 1 qui longe le contact entre le massif intrusif et l'éponte inférieure et No 2 qui, tel un dyke, pénètre cette éponte. On trouve plus de Rh, Pd, Ir, Os et Ru dans le No 2 que dans le No 1. Les teneurs en Cu et Ni ne diffèrent pas beaucoup entre les deux gîtes, lesquels résultent de l'injection de fluide magmatique minéralisateur en deux stades distincts, mais ne diffèrent guère quant à leur équilibration avec le magma de l'intrusion. Les filonnets cuprifères sont, eux aussi, enrichis en Pd, Pt et Au par rapport au reste du gîte No 1. La teneur globale en Pd, Pt et Au est plus élevée à Little Stobie que dans la zone minéralisée principale de Levack Ouest, d'où la conclusion que ces trois métaux nobles dans les filonnets cuprifères de Levack Ouest proviennent de la zone minéralisée principale, peut-être par diffusion thermale. Des analyses factorielles de mode *R* montrent que Ir, Os, Ru et Rh, tant spatialement que génétiquement, se comportent comme groupe associé à la minéralisation en Ni, tandis que Pd, Pt et Au sont, de façon beaucoup moindre, associés à la minéralisation en Cu.

(Traduit par la Rédaction)

INTRODUCTION

Few data exist on the platinum-group-element and gold contents of the Cu–Ni ore deposits associated with the Sudbury Irruptive. The first published information on the PGE content of the Sudbury ores was that of Hawley *et al.* (1951), Hawley & Rimsaite (1953) and Hawley (1962). More detailed studies were conducted by Keays & Crocket (1970) and Chyi & Crocket (1976) on mineral separates, mainly from the Strathcona mine, a North-Range deposit. Platinum-group-element mineralogical studies have been carried out on selected Sud-

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bury deposits and have been summarized by Cabri & Laflamme (1976).

The lack of data is mainly a function of the ppb levels of noble-metal concentration in the ores, combined with the lack of sensitivity of most of the currently accepted analytical techniques, the inhomogeneity of the noble metals in ores, and the very high cost of analysis. A nickel sulfide fire-assay preconcentration combined with an instrumental neutron-activation analysis method has been described by Hoffman (1978) and Hoffman *et al.* (1978). This method provides for the rapid, accurate, inexpensive analysis of all the platinum-group elements and gold.

Analytical technique

Thirty-three and thirty-nine samples were collected from the Levack West and Little Stobie mines, respectively, so that they would be characteristic of the major ore types within each mine. Each individual sample was in effect a composite of a number of samples of a particular ore type from a certain section of the mine. Because the samples analyzed are representative of different ore types and because these have different PGE concentrations, an unweighted average of the analyses is *not* representative of the grade of the mine studied.

Up to 50 g portions of the crushed and ground (95% -100 mesh pulp, taken at least in duplicate, were run through a fire-assay preconcentration procedure originally described by Robért *et al.* (1971) with modifications described by Hoffman (1978). The crushed fire-assay button was dissolved in hot, concentrated HCl and the solution was filtered. The residue retained on the filter paper contained virtually all the PGE and Au.

These filter papers were irradiated serially for 5 minutes at a flux of 1.0×10^{11} n $cm^{-2}s^{-1}$ in the SLOWPOKE II reactor at the University of Toronto. The samples were allowed to decay for 1 minute and were counted with a high-resolution Ge(Li) detector for 200 seconds for ^{104m}Rh and ^{109m}Pd radio-isotopes. Up to 40 samples, ore standard, internal standards and flux monitors were then irradiated for 16 hours (at a flux of 1.0×10^{11} n $cm^{-2}s^{-1}$). The samples were allowed to decay for four hours and were recounted for ^{109}Pd if Pd was not observed in the previous counting. The samples were allowed to decay further for a week and were counted for 700–5000 seconds for ^{192}Ir, ^{191}Os, ^{103}Ru, ^{198}Au and ^{199}Au (for Pt content) on a high-resolution Ge(Li) detector. Sample activities were corrected for decay and were compared to standards of known concentration. Comparison of results obtained by this method to published values on the PTC noble-metal standard is given in Hoffman *et al.* (1978). Detection limits are 0.1 ppb for Ir and Au, 1 ppb for Rh, 2 ppb for Os, 3 ppb for Ru, and 5 ppb for Pt and Pd, as determined by extrapolation of the count rates to their lowest significant values at two standard deviations.

GEOLOGY OF THE LEVACK WEST MINE

The Levack West mine occurs at the western limit of an extensively mineralized, 9.7 km long segment of the North Range of the Sudbury Irruptive. There has been no published description of the geology of this mine; however, the geological environment is similar to that of the Strathcona mine (4.8 km to the northeast) described in detail by Naldrett & Kullerud (1967) and Cowen (1968).

Figure 1 is a generalized cross-section of the Levack West mine showing sample locations. The ores are related to a suite of sulfide- and inclusion-rich sublayer norites and leucocratic breccias that lie between the hanging-wall rocks composed of basal mafic and felsic norites of the main Sudbury Irruptive, and the brecciated granodiorite, granodiorite gneiss and migmatites of the footwall known as the Levack complex. The main sublayer phase is a granite breccia and a subordinate phase is sublayer norite or xenolithic norite. The granite breccia is a metamorphic- to subigneous-textured granodioritic rock that hosts a heterogeneous population of footwall inclusions and xenoliths and a variable proportion of blebby to massive Cu–Ni–Fe sulfides. The xenoliths in these rocks are mainly gabbro and gabbro hornfels; however, 'exotic' pyroxenitic to peridotitic types also occur, similar in nature to those found at the Little Stobie mine. The sublayer norite is a fine-grained two-pyroxene gabbro. The Levack breccia, occurring in the footwall beyond the granite breccia, is an unusual rock with a cataclastic matrix containing fragments of footwall rocks of all sizes. It seems to be earlier than the granite breccia.

The orebody at Levack West can be subdivided into two main zones: the *Main ore zone* consists of mineralized granite breccia that occupies an embayment in the footwall. The ore may be massive, composed of pyrrhotite, pentlandite and chalcopyrite, or may be of a disseminated variety. The latter ore type contains very finely disseminated mineralization,

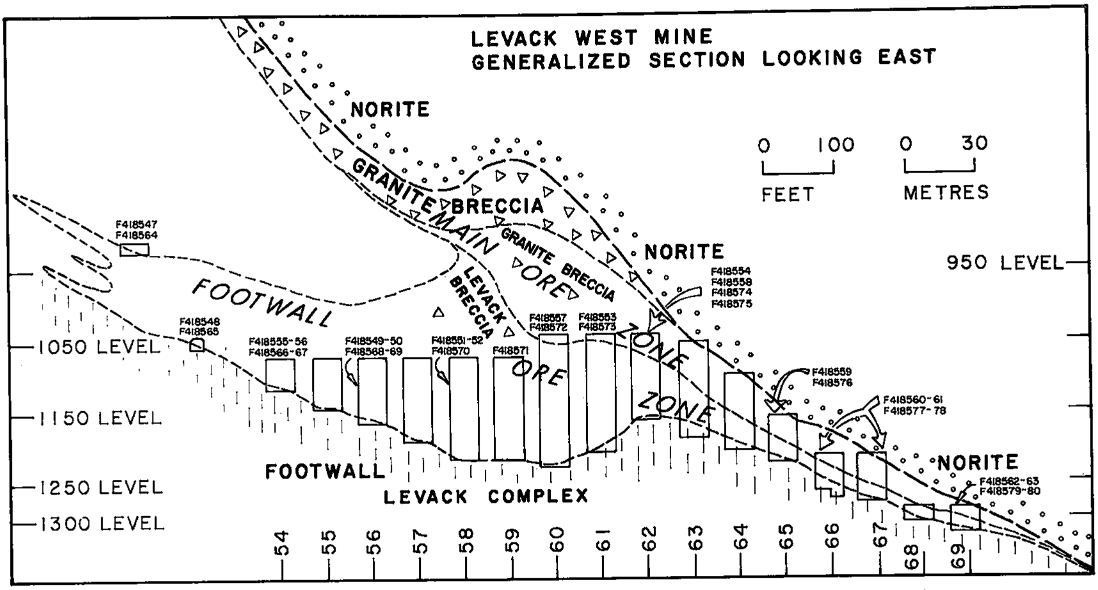

FIG. 1. Generalized section of the Levack West mine. The top of the stopes shown on this section represent the elevation of the indicated samples.

with the sulfide possibly having a fragmental texture (E.F. Pattison, pers. comm., 1978). The Ni:Cu ratio over most of the Main ore zone is about 5:2 (J. Guse, pers. comm., 1978) but may vary locally. This ore zone grades into the *Footwall ore zone,* which consists of massive chalcopyrite, millerite, pyrrhotite and pentlandite filling fractures in a Levack breccia body. These veins vary in width from about 1 mm to about 2 m thick. Some of the wider veins may show pyrrhotite bands parallel to the sides of the veins. The larger veins parallel the NE trend of the overlying main ore zone and dip steeply to the SE. Samples from this zone can be divided into three types: (1) massive sulfide stringers in Levack breccia, (2) atypical Cu-rich stringer ore, and (3) disseminated ore. The latter two types of ore are not believed to be significant volumetrically. Breccia rocks from a few tens of metres below the ore zone very closely resemble the Levack breccia rocks in the ore zone both chemically and mineralogically. The grain size does increase, however, as the ore zone is approached. The granite breccia from the Main ore zone is also very similar to the Levack breccia chemically but seems to have been at least partially melted (E.F. Pattison, pers. comm., 1978) and is now coarser grained than the Levack breccia. The Footwall ore zone seems equivalent to the 'deep-zone ore' at the Strathcona mina described by Naldrett & Kullerud (1967). Evidence of classical hydrothermal activity is lacking at Levack West. All the rocks from this mine are relatively unaltered from the hanging wall to the base of the Footwall ore zone and continuing below the ore zone (E.F. Pattison, pers. comm., 1978). The Levack West mine does not have any equivalent to the disseminated sulfide zone in the overlying hanging-wall norite which Naldrett & Kullerud (1967) report for the Strathcona mine.

Platinum-group-element, gold, major and trace-element contents as determined by us are shown in Table 1. They have been recalculated to the level expected in 100% massive sulfides by using an α factor listed in Table 1 for each sample; this was determined by converting the % Ni in the sample to wt. % pentlandite, the % Cu to wt. % chalcopyrite and by calculating the remaining sulfur in the sample (by subtracting the sulfur involved in each of these conversions from the total sulfur) as wt. % monoclinic pyrrhotite. The total wt. % sulfides thus calculated was then divided into 100 to give the α factor. This factor is used to multiply the noble metal values and other metal values in Table 1 to give the values for 100% sulfide. Averages of these values for each of the different ore types as recognized in this study are given in Table 2.

There is an obvious major difference between the concentration of some of the precious metals of the Levack-breccia ore zone (exclud-

TABLE 1. PLATINUM-GROUP ELEMENT, Au, Cu, Ni, Fe, Co, S, Zn and Pb CONTENT OF LEVACK WEST MINE SAMPLES

SAMPLE	Rh ppb	Pd ppb	Pt ppb	Ir ppb	Os ppb	Ru ppb	Au ppb	Cu wt.%	Ni wt.%	Fe wt.%	Co wt.%	S wt.%	Zn ppm	Pb ppm	α Factor	Description
F418547	<1 (2)	63±6 (2)[+]	37±5 (3)	0.1±1 (3)	<2 (3)	<3 (3)	28±3 (2)*	0.23	0.03	3.6	0.002	0.3	94	70		F.W.
F418548	<1 (2)	351±4 (2)	510±50 (2)	0.1±0 (2)	<2 (2)	<3 (2)	190±50 (2)	0.50	0.13	4.9	0.003	0.5	158	90		F.W.
F418549	<1 (2)	117±1 (2)	59±8 (2)	0.1±0 (2)	<2 (2)	<3 (2)	39±3 (2)	1.84	0.15	13.9	0.004	2.2	2352	25		F.W.
F418550	<1 (2)	220±30 (2)	178±1 (2)	0.2±0 (2)	<2 (2)	<3 (2)	150±30 (2)	0.41	0.08	6.0	0.003	0.7	90	89		F.W.
F418551	<1 (2)	107±2 (2)	98±5 (2)	0.1±0 (2)	<2 (2)	<3 (2)	60±10 (2)	0.31	0.06	2.9	0.002	0.5	52	76		F.W.
F418552	1±0 (2)	50±10 (2)	40±1 (2)	0.2±0 (2)	<2 (2)	<3 (2)	36±1 (2)*	0.22	0.12	5.7	0.005	0.9	56	23		F.W.
F418553	7±0 (2)	440±20 (2)	126±4 (2)	2±0 (2)	2±1 (2)	<3 (2)	50±20 (2)	1.12	0.34	8.7	0.009	3.2	145	32		D.S. in G.B.
F418554	<1 (2)	37±0 (2)	48±1 (2)	0.2±0 (2)	<2 (2)	<3 (2)	3±0 (2)	0.10	0.12	4.5	0.004	0.9	54	12		D.S. in G.B.
F418555	<1 (2)	204±1 (2)	109±2 (2)	0.1±0 (2)	<2 (2)	<3 (2)	300±50 (2)	0.48	0.11	5.0	0.004	0.5	98	125		D.S. in L.B.
F418556	<1 (2)	94±8 (2)	106±6 (2)	0.1±0 (2)	<2 (2)	<3 (2)	17±0 (2)	0.26	0.08	4.8	0.003	0.6	63	41		D.S. in L.B.
F418557	24±2 (2)	217±5 (2)	280±10 (2)	10±0 (2)	5±1 (2)	14±1 (2)	43±4 (2)	0.73	0.89	11.0	0.019	5.7	195	85	6.10	D.S. in L.B.
F418558	49±4 (2)	100±20 (2)	100±20 (2)	16±4 (2)	7±1 (2)	20±4 (2)	14±1 (2)	0.43	0.84	12.4	0.027	5.4	53	20	6.99	D.S. in G.B.
F418559	9±0 (2)	60±10 (2)	34±3 (2)	5±1 (2)	2±0 (2)	5±0 (2)	7±0 (2)	0.43	1.16	18.0	0.042	9.2	129	15	4.13	D.S. in G.B.
F418560	36±0 (2)	200±20 (2)	190±30 (2)	9±1 (2)	3±0 (2)	10±1 (2)	24±2 (2)	0.46	0.78	11.0	0.023	5.1	82	40	7.36	D.S. in G.B.
F418561	62±6 (2)	309±7 (2)	500±100 (3)	18±3 (3)	6±1 (3)	18±2 (3)	70±30 (2)*	1.48	0.92	16.2	0.056	8.6	133	36	3.98	D.S. in G.B.
F418562	32±2 (2)	320±10 (2)	327±4 (2)	8±1 (2)	4±1 (2)	6±0 (2)	30±1 (2)	0.83	1.06	15.8	0.032	7.0	105	33	5.37	D.S. in G.B.
F418563	11±1 (2)	155±4 (2)	125±7 (2)	3±0 (2)	2±1 (2)	3±0 (2)	60±10 (2)	0.49	0.42	8.5	0.013	3.0		20		D.S. in G.B.
F418564	<10 (2)	3800±70 (2)	2100±200 (2)	<0.1 (2)	<2 (2)	<3 (2)	300±100 (2)*	24.00	2.60	35.0	0.027	33.1	4347	267	1.07	Atypical Cu-str.
F418565	<10 (2)	10600±300 (2)	8000±1000 (2)	0.6±3 (2)	<2 (2)	<3 (2)	4000±400 (2)	32.70	0.68	29.4	0.004	31.9	2516	502	1.03	Atypical Cu-str.
F418566	<10 (3)	6300±900 (3)	2400±300 (3)	0.2±1 (3)	<2 (3)	<3 (3)	130±20 (3)	22.60	4.90	34.6	0.028	33.8	3631	232	1.05	Atypical Cu-str.in L.B.
F418567	3±2 (3)	2100±300 (3)	1500±100 (3)	0.2±1 (3)	3±1 (3)	<3 (3)	63±7 (3)	7.21	5.05	43.7	0.071	29.8	711	20	1.24	MSSV.sulf.str.in L.B.
F418568	<10 (2)	2000±100 (2)	630±40 (2)	0.2±1 (2)	<2 (2)	<3 (2)	70±10 (2)	26.20	1.63	33.4	0.023	33.3	3397	30	1.07	Atypical Cu-str.in L.B.
F418569	17±4 (2)	970±30 (2)	980±30 (2)	3±0 (2)	3±1 (2)	<3 (2)	33±2 (2)	2.86	4.70	50.6	0.088	32.0	407	30	1.18	MSSV.sulf.str.in L.B.
F418570	20±4 (2)	740±20 (2)	950±20 (2)	3±0 (2)	5±1 (2)	<3 (2)	33±6 (2)	5.94	4.23	50.8	0.083	32.5	414	31	1.15	MSSV.sulf.str.in L.B.
F418571	56±6 (2)	670±70 (2)	700±100 (2)	12±1 (2)	6±1 (2)	11±3 (2)	60±30 (2)	2.38	4.94	50.5	0.133	30.7	212	30	1.23	MSSV.sulf.str.in L.B.
F418572	224±3 (2)	730±20 (2)	710±20 (2)	90±1 (2)	34±1 (2)	121±8 (2)	36±2 (2)	1.61	5.36	49.6	0.125	32.4	143	35	1.17	MSSV.sulf. in G.B.
F418573	121±4 (2)	530±60 (2)	630±20 (2)	31±1 (2)	13±1 (2)	26±1 (2)	30±10 (2)	2.09	4.98	52.2	0.127	31.5	265	40	1.20	MSSV.sulf. in G.B.
F418574	500±10 (2)	297±5 (2)	510±30 (2)	172±4 (2)	67±7 (2)	220±1 (2)	19±6 (2)	0.77	5.08	49.8	0.156	31.9	104	38	1.19	MSSV.sulf. in G.B.
F418575	303±4 (2)	500±30 (2)	720±20 (2)	80±2 (2)	35±1 (2)	76±6 (2)	80±40 (2)	1.45	5.20	48.8	0.142	31.4	97	33	1.20	MSSV.sulf. in G.B.
F418576	11±1 (2)	217±8 (2)	203±4 (2)	3±0 (2)	<2 (2)	<3 (2)	12±0 (2)	0.58	3.80	48.2	0.108	27.6	70	15	1.38	MSSV.sulf. in G.B.
F418577	195±4 (2)	790±10 (2)	1020±30 (2)	54±1 (2)	24±2 (2)	60±20 (2)	140±20 (2)	2.17	5.06	50.4	0.127	31.1		40	1.21	MSSV.sulf. in G.B.
F418578	263±2 (2)	940±40 (2)	1340±50 (2)	65±1 (2)	30±1 (2)	66±5 (2)	30±10 (2)	0.85	5.61	49.3	0.131	32.3	123	22	1.17	MSSV.sulf. in G.B.
F418579	129±1 (2)	793±9 (2)	1010±10 (2)	25±0 (2)	12±1 (2)	29±2 (2)	50±20 (2)	1.18	5.25	50.3	0.135	32.1	78	18	1.18	MSSV.sulf. in G.B.
F418580	267±8 (2)	1290±60 (2)	1174±4 (2)	4±0 (2)	4±0 (2)	5±0 (2)	40±30 (2)	1.04	5.52	50.3	0.123	32.6	136	17	1.16	MSSV.sulf. in G.B.

[+] 1 σ standard deviation. Number of analyses is in parenthesis below each PGE analysis. The α factor will be used to convert samples with greater than 2 wt. % S to 100% sulfide in Table 2.

* Indicates sample which contained erratic analysis for either gold or platinum. The erratic value was omitted on calculating means and S.D. (A value was considered erratic if it varied from the other analyses for that element by more than 200 percent.)

Cu, Ni, Co, Fe were analysed by Inco Metals Company, by atomic absorption using $HCl-HNO_3-HF-HClO_4$ digestion. S was analysed by Inco Metals Company using Leco combustion methods.

Zn, Pb were analyzed by S. Gentleman of University of Toronto, using atomic-absorption techniques.

F.W. = Footwall rocks
D.S. in G.B. = Disseminated sulfide in granite breccia
D.S. in L.B. = Disseminated sulfide in Levack breccia
MSSV.sulf.str. in L.B. = Massive sulfide stringers in Levack breccia
MSSV.sulf. in G.B. = Massive sulfide in granite breccia
Atypical Cu-str. in L.B. = Atypical Cu-stringer ore in Levack breccia

ing the atypical very Cu-rich samples) and the granite breccia (Main) ore zone (Table 2). The Levack breccia ore zone is significantly (95% confidence limits) depleted in Rh (4.3x), Ir (3.6x), Os (2.6x) and Ru (3.3x), whereas Pt and Pd are not significantly different. The Ni content in massive sulfides of the two zones is the same, whereas the Cu content of the Levack breccia zone is slightly higher than the granite breccia ore zone (5.3 *versus* 3.2 wt. % Cu). The atypical Cu-rich Levack breccia stringer ore is even more depleted in Os, Ir, Ru and Rh than the normal Levack breccia ore and in addition is enriched in Pt and Pd with respect to the granite-breccia ore zone. Cu is, of course, very enriched in the atypical Levack breccia ore, whereas Ni is depleted with respect to both the granite-breccia ore and the normal Levack-breccia ore. Considering the granite-breccia (Main) ore zone, the PGE con-

TABLE 2. CONCENTRATION OF THE PGE, Au, Cu and Ni IN THE SULFIDE MELT FOR THE VARIOUS ORE TYPES AT THE LEVACK WEST MINE

ORE TYPE		Rh	Pd	Pt	Ir	Os	Ru	Au	Cu	Ni	n
		ppb							wt.%		
Disseminated sulfide in granite breccia	$\bar{x}$	182	1763	1269	54	21	63	304	5.4	5.0	7
	SD	109	1552	623	32	14	43	282	3.7	0.9	
Massive sulfide in granite breccia	$\bar{x}$	265	802	964	69	29	80	59	1.6	6.1	9
	SD	162	377	405	63	24	81	48	0.7	0.4	
Granite breccia (Main) ore zone	$\bar{x}$	228	1223	1098	62	26	73	166	3.2	5.6	16
	SD	143	1132	516	51	20	67	221	3.1	0.9	
Levack breccia ore zone	$\bar{x}$	53	1350	1334	17	10	22	97	5.3	5.6	5**
	SD	58	729	401	25	12	36	94	2.5	.6	
Average all samples (Table 1)	$\bar{x}$	186	1253	1154	47	22	60	50	3.7	5.6	21**
	SD	148	1034	493	50	19	64	198	3.0	0.8	
Atypical Cu-rich stringers in Levack breccia	$\bar{x}$	11	5948	3370	0.3	2	3	167*	27.8	2.6	4
	SD	1	3801	3196	0.2	0	0	119	4.3	1.9	

* Sample F418565 was excluded because of an anomalously high value.

**Samples F418549, F418564, F418565, F418566, F418568 were excluded because they were atypical.

centrations in massive and disseminated ore types are similar, although Pd, Au and Cu values are significantly higher in the disseminated ore.

The characteristic values for these ore types converted to massive sulfide have been normalized to chondritic values and are shown logarithmically in Figure 2. The chondritic values used for the PGE are those given by McBryde (1972) and for Au that given by Crocket (1974). McBryde's compilation of PGE values was the only set available which included Rh. The absolute values given for the 'average' chondritic abundance are not important; they only provide a means of comparing the noble-metal data graphically in the fashion used for rare-earth-element data. This tends to smooth out the data, which range from a few ppb to thousands of ppb. Further details on the conversion to massive sulfide and chondritic normalization are given by Naldrett *et al.* (1979).

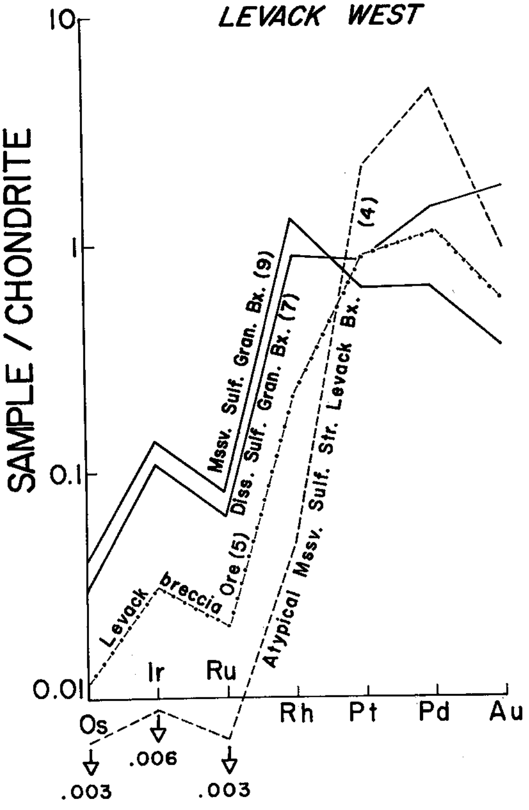

FIG. 2. Ore types recalculated to massive sulfide at the Levack West mine normalized to chondritic values. The number in parentheses refers to the number of samples.

DISTRIBUTION OF NOBLE METALS AT LEVACK WEST

Three hypotheses can be used to explain the distribution of the noble metals in the Levack West mine: (1) Late-stage hydrothermal remobilization of Pd, Pt, Au and Cu from the Main ore zone into the Levack-breccia copper-stringer zone. The plagioclase and potassium feldspar in the footwall-breccia fragments are fresh; they show no argillaceous, sericitic or saussuritic alteration. Naldrett & Kullerud (1967) reported similar observations for the Strathcona mine footwall breccia. They believed the temperature or the K^+/H^+ ratio (or both) were too high for the classical hydrothermal alteration conditions. The lack of hydrothermal alteration or extensive metasomatism tends to rule out the above hypothesis. (2) Segregation of a copper-rich residual magmatic sulfide liquid during crystallization of MSS. Hawley (1962) referred to this Cu-rich liquid formed from crystallizing pyrrhotite which would later crystallize to form chalcopyrite-rich ores. Hawley (1965) used the hypothesis of fractionation of a Cu-rich residual liquid to explain the increasing Cu/Ni ratio with depth at the Frood–Stobie mine. Although his observations were made prior to phase-relation studies in the system Cu–Fe–Ni–S, these indicate that this possibility certainly exists. The separation of a Cu-rich liquid is possible at temperatures as low as 850°C, in coexistence with MSS (Craig & Kullerud 1969).

Studies on the phase relations in the system Pt–Pd–Fe–As–S indicate that although Pt and Pd could enter pyrrhotite (MSS) in solid solution, the residual liquid would become enriched in these elements (Skinner *et al.* 1976). This would indicate that these metals could also be enriched in a Cu-rich residual liquid. Keays & Crocket (1970) showed that Pd and Au were enriched in chalcopyrite; this was caused, they suggest, by concentration of these metals in a Cu-rich melt of residual character. Data given by Chyi & Crocket (1976) showed that Pt and Ir were enriched in chalcopyrite, whereas Pd and Au were enriched in pentlandite in the deep ore-zone of the Strathcona mine. The latter authors believed that partition of Pt into a Cu-rich magmatic liquid may have been important; however, they attribute the distribution of Pd, Au and possibly Pt to subsolidus diffusion.

The estimate for the sulfide liquid for the Main ore zone at Levack West (including disseminated and massive ores) is 3.2 wt. % Cu, 5.6% Ni, 53.7% Fe and 37.5% S. Most probably a major proportion of the Cu would be held in solid solution in MSS as Yund & Kullerud (1966) have found that Fe-rich MSS can hold 4 to 5% Cu in solid solution at 700°C. Craig & Kullerud (1969) indicated that 5 wt. % Ni in MSS does not reduce the solubility of Cu significantly. Taking into account the amount of Ni present and the presence of pyrite, phase relations indicate that we would expect about 4 wt. % Cu to be soluble in MSS (Yund & Kullerud 1966). This would more than account for all the Cu in the Main ore zone. The estimate for the normal Levack breccia footwall-ore composition is 5.3% Cu, 5.6% Ni, 51.6% Fe and 37.5% S. If an attempt is made to estimate the overall mean composition of the orebody by using equal weighting of all samples (excluding the atypical Cu-rich Levack breccia ore), the Cu content of the resultant ore would be 3.7 wt. %. The exact amount is uncertain because the relative proportions of the two ore zones are unknown. If the atypical ore were included with equal weighting, the resultant composition would be significantly enriched in Cu. It is possible therefore that the mechanism suggested by Hawley did operate and did concentrate Pd and Au as shown by Keays & Crocket (1970). Chyi & Crocket (1976) prefer diffusion at subsolidus temperatures to explain Pd and Au and possibly Pt distribution. In their opinion, a mechanism of Cu-rich-liquid segregation is not the preferred one. (3) The third hypothesis involves the diffusion of metals down a thermal gradient in the presence of an aqueous fluid phase.

Naldrett & Kullerud (1967) and Cowan (1968) have remarked on the strong increase in Cu, Ni and Cu/Ni ratio at the Strathcona mine on passing across the orebody from hanging wall to footwall. The former authors considered the possibility of fractional crystallization coupled with filter pressing of the Cu-rich fractionated liquid into the footwall as suggested by Hawley. However, their studies indicated that the zoning occurs in ore that is emplaced in a breccia zone which is younger than the initial introduction of the mineralization. Field relations indicate that considerable disruption of the ore and host rocks would have occurred during brecciation; they concluded that zoning must have been superimposed upon the ore subsequent to brecciation. For this reason they suggested that it is due to diffusion of Cu and Ni along a thermal gradient induced by the overlying hot Irruptive. A similar thermal diffusion model is proposed on the basis of the evidence observed at the Levack West mine. Although there it has not been studied in the same detail as at Strathcona, a crude zoning of increasing Cu/Ni ratio away from the Irruptive into the footwall has also been observed. In addition, the geologic environments of the Strathcona and Levack West mines are similar: both are North-Range mines about 4.8 km apart. For these reasons the thermal diffusion model is preferred over that involving fractional crystallization.

The sequence of events is envisaged as

follows. The initial emplacement of sulfide ore at Levack West is interpreted to be due to gravitational segregation of dense sulfide liquid from the igneous sublayer magma. The bulk composition of the sulfide ores as expressed in terms of Ni, Fe and S lies within the phase boundary of monosulfide solid solution (MSS) of the system Fe–Ni–S at temperatures above 500°C. Much of the copper was also probably in solid solution in the MSS at high temperatures. This would suggest that immediately after emplacement and consolidation, the ore was essentially composed of homogeneous Ni- and Cu-rich MSS, possibly with minor chalcopyrite. Pentlandite and further chalcopyrite would have exsolved from the MSS on cooling.

Work by MacDougall *et al.* (1961) on the diffusion and volatilization of sulfides has shown that copper sulfide was 'conspicuously mobile' with 'vigorous surface diffusion an outstanding feature'. Copper sulfide was found to diffuse rapidly down a thermal gradient at temperatures above 450°C in the presence of small amounts of sulfur vapor. They attributed migration of copper sulfide into cracks in test specimens (gabbros) to solid diffusion processes. Nickel has been shown to diffuse in pyrrhotite in the presence of a fluid medium by Ewers (1971) and others. These experiments, although not directly applicable to this case, showed that Cu and Ni could be mobilized by various types of diffusion processes under certain conditions; however, we prefer the diffusion process as envisioned by Ewers (1971).

The emplacement of the Irruptive, and following this the igneous sublayer, into relatively cold (≈ 100°C) country rocks would have set up a thermal gradient decreasing from the hanging wall to the footwall. Using heat-flow calculations, Naldrett & Kullerud (1967) argued that a thermal gradient of 100°C existed over the first 150 m of the footwall rocks for a considerable time period (> 72,000 years) at the Strathcona mine. This would probably have permitted diffusion of the metals through an intergranular water-rich phase. They have given 250 bars as their minimum estimate of the water pressure at the time of brecciation of the Strathcona footwall rocks. They provided evidence that most of the pyroxenes in the footwall breccia have been converted to tremolite–actinolite, anthophyllite or talc, whereas the pyroxenes in the hanging-wall breccias and norites are relatively fresh. They suggested that more water was available at the pressure, $f(O_2)$ and temperature (amphibole stability-field) in the porous footwall breccias than in the overlying igneous rocks. If the processes mentioned above were occurring, the original distribution of the major elements and noble metals would have been altered at the Levack West mine. Fractures in the previously brecciated Levack complex would have provided channelways for the diffusing elements to form massive sulfide veins and stringers.

A corollary of the above thermal-diffusion hypothesis is that Cu, Pd, Pt and Au are more mobile than Fe, Ni, Os, Ru, Ir and Rh. Unfortunately, there is insufficient experimental evidence available on the diffusion characteristics of Cu and Ni and no evidence on the diffusion characteristics of the noble metals under the above conditions to help confirm the above model.

Geology of the Little Stobie Mine

The Little Stobie mine occurs at the base

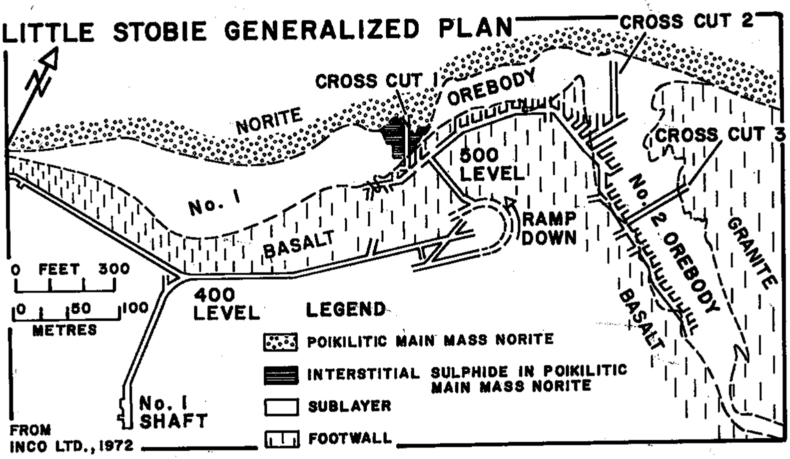

FIG. 3. Generalized plan of the Little Stobie mine.

of the main mass norite of the east-central portion of the South Range of the Sudbury Irruptive. The only published description of this mine is a brief summary by the staff of INCO Ltd. (1972). The geology is similar, however, to that of the Murray and parts of the Creighton mines, as given by Souch *et al.* (1969). Figure 3, a generalized plan of the Little Stobie mine, shows the two distinct orebodies that have been recognized.

The #1 orebody lies between the footwall rocks, which include metavolcanic and metasedimentary units, granites and Sudbury breccia, and the hanging-wall rocks of poikilitic norite, regarded as part of the main Irruptive. The orebody strikes N60°E, dips NW55° and extends for approximately 610 m, with an average width of 30 m. The mineralization extends from surface to a depth of at least 792 m.

The #2 orebody strikes S45°E for approximately 273 m into the footwall rocks and is emplaced between metabasalts and a boss of footwall granite. This orebody lies between 91 and 366 m and reaches an average width of 52 m. The environment of this orebody is somewhat similar to that of other offset deposits, *e.g.*, those along the Copper Cliff offset.

The principal ore minerals making up the sublayer ores are pyrrhotite, pentlandite and chalcopyrite, with lesser amounts of pyrite, magnetite and ilmenite.

Six ore types have been observed at Little Stobie. They include, in order of abundance: (1) gabbro-peridotite inclusion sulfide: mafic and ultramafic inclusions in an abundant matrix of sulfide and minor noritic material; (2) ragged disseminated sulfide: small closely packed gabbroic inclusions in a scanty matrix of sulfide and subordinate noritic material; (3) disseminated sulfide: blebs of sulfide dispersed in an inclusion-bearing matrix sublayer norite; (4) interstitial sulfide: norite with sulfides interstitial to euhedral silicates; (5) inclusion massive sulfide: sulfide with varying proportions of pyrrhotite, pentlandite and chalcopyrite containing occasional rock inclusions; (6) contorted schist-inclusion sulfide, characterized by twisted fragments of schist and inclusions of quartz in a sulfide matrix. A typical sequence from hanging-wall to footwall would be interstitial sulfide → ragged disseminated sulfide → gabbro-peridotite inclusion sulfide → inclusion massive sulfide.

No positive evidence exists on the age relationship between the main-mass norite and the ore-bearing sublayer. The contact relationships between individual ore types are generally gradational (the ore types are more descriptive terms than genetic ones) but may be sharp locally.

A composite, longitudinal section giving sample locations is shown in Figure 4. PGE, Au, major and trace elements in the ores and

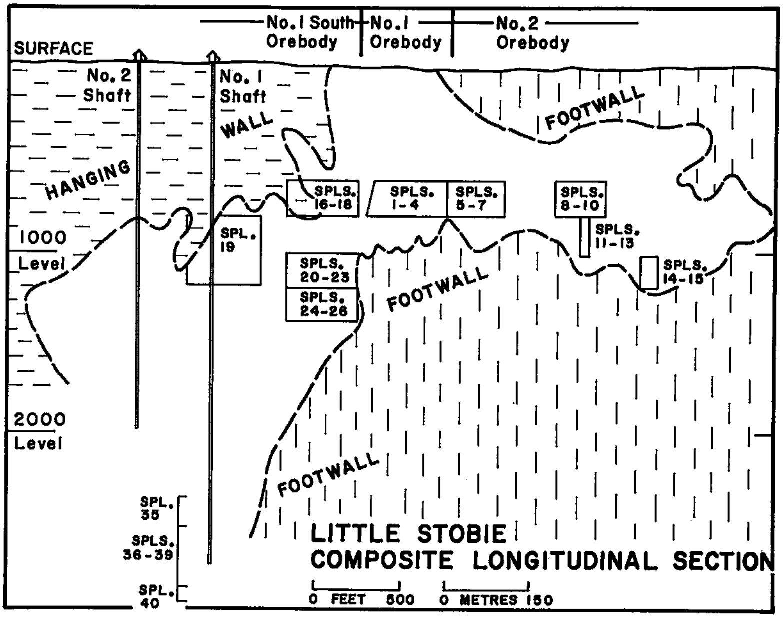

FIG. 4. Composite longitudinal section of the Little Stobie mine, showing sample locations.

TABLE 3. PGE, Au, Cu, Ni, Co, Fe, S, Zn and Pb ANALYSES OF LITTLE STOBIE MINE SAMPLES

SAMPLE	Rh ppb	Pd ppb	Pt ppb	Ir ppb	Os ppb	Ru ppb	Au ppb	Cu wt.%	Ni wt.%	Fe wt.%	Co wt.%	S wt.%	Zn ppm	Pb ppm	α Factor	Description
1	$25\pm_{(4)}1$*	$140\pm_{(4)}10$	$120\pm_{(4)}20$	$10\pm_{(4)}1$	$3\pm_{(3)}1$	$27\pm_{(3)}5$	$28\pm_{(3)}2$**	0.38	0.56	14.9	0.028	5.3	61	15	7.19	D.S.
2	$26\pm_{(4)}3$	$270\pm_{(3)}40$	$120\pm_{(3)}10$	$14\pm_{(3)}1$	$4\pm_{(3)}0$	$30\pm_{(3)}4$	$40\pm_{(4)}10$	0.36	0.57	15.1	0.028	5.6	48	14	6.80	R.D.S.
3	$78\pm_{(3)}1$	$380\pm_{(3)}40$	$330\pm_{(3)}30$	$42\pm_{(3)}3$	$18\pm_{(3)}3$	$80\pm_{(3)}7$	$80\pm_{(3)}20$	1.07	1.76	28.8	0.073	15.3	132	17	2.49	G.P.I.S.
4	$135\pm_{(16)}7$	$320\pm_{(16)}40$	$280\pm_{(17)}30$	$75\pm_{(15)}5$	$30\pm_{(15)}3$	$150\pm_{(16)}20$	$42\pm_{(17)}6$	0.33	2.95	41.7	0.125	24.4	51	11	1.57	I.M.S.
5	$52\pm_{(3)}3$	$530\pm_{(3)}30$	$480\pm_{(3)}10$	$20\pm_{(3)}2$	$8\pm_{(3)}2$	$47\pm_{(3)}4$	$130\pm_{(3)}10$	1.13	0.62	17.3	0.030	6.8	95	7	6.45	I.B.S.
6	$95\pm_{(4)}7$	$600\pm_{(3)}20$	$720\pm_{(4)}90$	$37\pm_{(4)}3$	$13\pm_{(4)}2$	$66\pm_{(4)}9$	$420\pm_{(4)}30$	1.11	1.04	21.7	0.046	9.9	86	21	3.85	G.P.I.S.
7	$120\pm_{(4)}10$	$1180\pm_{(3)}50$	$1170\pm_{(4)}80$	$43\pm_{(4)}3$	$18\pm_{(4)}1$	$90\pm_{(3)}10$	$170\pm_{(4)}20$	1.36	2.25	36.6	0.090	24.9	119	10	1.54	I.M.S.
8	$87\pm_{(3)}6$	$650\pm_{(3)}50$	$300\pm_{(3)}70$	$35\pm_{(4)}2$	$13\pm_{(4)}4$	$80\pm_{(4)}20$	$700\pm_{(4)}70$	0.83	0.82	18.8	0.036	7.8	60	11	4.88	I.B.S.
9	$180\pm_{(4)}20$	$1400\pm_{(3)}100$	$940\pm_{(3)}130$	$72\pm_{(4)}7$	$39\pm_{(3)}5$	$170\pm_{(4)}30$	$256\pm_{(3)}9$	0.90	1.97	30.3	0.077	15.8	51	14	2.42	G.P.I.S.
10	$120\pm_{(3)}10$	$1100\pm_{(3)}100$	$1460\pm_{(3)}30$	$43\pm_{(3)}2$	$14\pm_{(3)}1$	$60\pm_{(3)}2$	$200\pm_{(3)}10$	1.12	2.48	37.2	0.098	20.3	107	6	1.88	I.M.S.
11	$75\pm_{(3)}3$	$1000\pm_{(2)}100$	$600\pm_{(3)}100$	$31\pm_{(3)}3$	$12\pm_{(3)}3$	$92\pm_{(3)}1$	$100\pm_{(3)}4$	0.93	0.78	17.8	0.034	7.5	64	13	5.03	I.B.S.
12	$125\pm_{(4)}3$	$1300\pm_{(3)}100$	$1030\pm_{(2)}60$	$47\pm_{(4)}4$	$22\pm_{(2)}3$	$110\pm_{(3)}10$	$200\pm_{(4)}40$	1.72	1.67	28.8	0.066	14.7	112	17	2.51	G.P.I.S.
13	$150\pm_{(11)}10$	$1700\pm_{(11)}100$	$480\pm_{(11)}40$	$50\pm_{(11)}4$	$20\pm_{(11)}4$	$100\pm_{(11)}10$	$120\pm_{(11)}10$	0.41	2.57	40.2	0.097	20.8	67	17	1.84	I.M.S.
14	$58\pm_{(5)}3$	$880\pm_{(3)}20$	$340_{(1)}$	$21\pm_{(5)}3$	$5\pm_{(4)}1$	$41\pm_{(3)}3$	$6000\pm_{(5)}2000$	1.49	0.75	20.0	0.042	9.2	156	17	4.12	I.B.S.
15	$127\pm_{(2)}0$	$2300\pm_{(2)}200$	$520\pm_{(2)}70$	$23\pm_{(2)}0$	$14\pm_{(2)}1$	$36\pm_{(2)}1$	$256\pm_{(2)}4$	2.16	2.59	47.3	0.132	30.7	137	23	1.21	I.M.S.
16	$17\pm_{(4)}1$	$470\pm_{(2)}10$	$480\pm_{(4)}20$	$8\pm_{(4)}1$	$9\pm_{(4)}2$	$16\pm_{(4)}1$	$140\pm_{(4)}10$	0.94	0.60	16.6	0.030	6.4	83	21	5.92	D.S. norite
17	$14\pm_{(4)}2$	$340\pm_{(2)}9$	$220\pm_{(4)}20$	$9\pm_{(4)}1$	$4\pm_{(4)}1$	$15\pm_{(4)}1$	$73\pm_{(4)}9$	0.63	0.64	17.0	0.035	6.7	71	12	5.65	R.D.S.
18	$46\pm_{(3)}8$	$340\pm_{(2)}30$	$220\pm_{(3)}30$	$22\pm_{(3)}3$	$10\pm_{(3)}2$	$45\pm_{(3)}5$	$50\pm_{(3)}20$	0.67	1.51	28.0	0.076	14.9	39	16	2.58	G.P.I.S.
19	$9\pm_{(4)}1$	$360\pm_{(2)}10$	$190\pm_{(4)}30$	$3\pm_{(4)}1$	$2\pm_{(4)}1$	$<3_{(3)}$	$65\pm_{(4)}7$	0.52	0.56	18.1	0.340	6.7	51	23	5.75	D.S. norite
20	$10\pm_{(4)}1$	$200\pm_{(2)}9$	$230\pm_{(4)}10$	$4\pm_{(3)}1$	$2\pm_{(3)}0$	$7\pm_{(3)}0$	$77\pm_{(3)}5$	0.59	0.39	12.9	0.021	4.1	96	11	9.43	D.S. norite
21	$19\pm_{(4)}1$	$340\pm_{(2)}50$	$330\pm_{(4)}60$	$10\pm_{(4)}2$	$7\pm_{(3)}1$	$21\pm_{(4)}3$	$130\pm_{(4)}20$	0.61	0.51	14.5	0.027	5.1	53	10	7.35	R.D.S.
22	$23\pm_{(3)}2$	$390\pm_{(4)}30$	$200\pm_{(4)}100$	$13\pm_{(4)}1$	$5\pm_{(4)}1$	$22\pm_{(4)}4$	$180\pm_{(3)}10$	1.14	1.03	21.8	0.051	10.5	105	15	3.46	G.P.I.S.
23	$33\pm_{(4)}2$	$810\pm_{(3)}80$	$400\pm_{(3)}100$	$13\pm_{(3)}2$	$5\pm_{(2)}0$	$19\pm_{(2)}2$	$450\pm_{(3)}50$	0.99	1.91	31.7	0.086	17.6	110	13	2.17	I.M.S.
24	$8\pm_{(4)}1$	$740\pm_{(2)}40$	$900\pm_{(4)}200$	$4\pm_{(4)}1$	$7\pm_{(2)}1$	$11\pm_{(2)}3$	$280\pm_{(4)}50$	0.83	0.36	11.9	0.018	3.5	95	29	11.90	D.S. Norite
25	$12\pm_{(3)}3$	$360\pm_{(3)}40$	$660\pm_{(3)}30$	$7\pm_{(3)}1$	$<3_{(3)}$	$11\pm_{(2)}1$	$500\pm_{(3)}60$	2.12	0.47	15.0	0.023	5.3	143	18	6.94	R.D.S.
26	$26\pm_{(3)}3$	$390\pm_{(2)}20$	$890\pm_{(3)}90$	$11\pm_{(3)}0$	$4\pm_{(3)}1$	$17\pm_{(3)}2$	$160\pm_{(3)}10$	1.58	1.12	23.5	0.051	11.2	133	27	3.38	G.P.I.S.
27+28	$4\pm_{(5)}1$	$2600\pm_{(5)}200$	$1900\pm_{(5)}300$	$2\pm_{(5)}1$	$3\pm_{(3)}1$	$<5_{(3)}$	$1600\pm_{(5)}100$	4.35	0.34	15.9	0.019	6.7	400	25	5.41	F.W.S.Str.
29	$25\pm_{(3)}1$	$660\pm_{(3)}10$	$970\pm_{(3)}30$	$10\pm_{(3)}1$	$3\pm_{(3)}0$	$14\pm_{(3)}7$	$700\pm_{(3)}200$	3.30	0.85	18.5	0.036	8.5	395	12	4.33	F.W.S.Str.
30	$15\pm_{(3)}2$	$80\pm_{(3)}10$	$50\pm_{(3)}20$	$9\pm_{(3)}1$	$4\pm_{(3)}0$	$18\pm_{(3)}0$	$31\pm_{(3)}8$	0.22	0.28	10.6	0.018	2.9	360	12	13.20	H.W.Str.
31	$21\pm_{(4)}5$	$300\pm_{(3)}50$	$82\pm_{(2)}0$**	$10\pm_{(4)}2$	$3\pm_{(3)}1$	$14\pm_{(4)}3$	$55\pm_{(4)}9$	0.99	0.85	23.5	0.051	10.7	62	13	3.57	Po/Ni +30.0
32	$21\pm_{(3)}2$	$280\pm_{(3)}40$	$240\pm_{(3)}40$	$10\pm_{(3)}1$	$6\pm_{(3)}1$	$23\pm_{(3)}3$	$150\pm_{(3)}10$	0.81	0.74	19.1	0.041	8.2	64	16	4.67	Po/Ni 25-30
33	$19\pm_{(4)}2$	$390\pm_{(2)}20$	$210\pm_{(4)}20$	$11\pm_{(4)}1$	$3\pm_{(3)}1$	$24\pm_{(4)}1$	$70\pm_{(4)}10$	0.76	0.61	15.7	0.030	6.1	57	13	6.21	Po/Ni 20-25
34	$10\pm_{(3)}4$	$600\pm_{(3)}100$	$510\pm_{(3)}60$	$6\pm_{(3)}1$	$3\pm_{(3)}2$	$12\pm_{(3)}1$	$160\pm_{(3)}10$	1.02	0.50	14.0	0.022	4.6	70	13	8.13	Po/Ni 15-20
35	$<1_{(3)}$	$<5_{(3)}$	$<5_{(3)}$	$0.2\pm_{(3)}1$	$<1_{(3)}$	$<3_{(3)}$	$6\pm_{(3)}2$	0.03	0.03	6.3	0.005	0.3	48	9		H.W.Str.
36	$25\pm_{(3)}3$	$300\pm_{(3)}30$	$230\pm_{(3)}30$	$13\pm_{(3)}2$	$4\pm_{(3)}1$	$20\pm_{(3)}2$	$34\pm_{(3)}2$	0.57	0.80	17.7	0.041	8.0	47	16	4.78	R.D.S.
37	$12\pm_{(3)}1$	$305\pm_{(2)}5$	$220\pm_{(3)}20$	$7\pm_{(4)}1$	$3\pm_{(3)}1$	$13\pm_{(3)}3$	$75\pm_{(3)}2$	0.75	0.52	14.5	0.030	5.6	58	12	6.21	D.S.
38	$38\pm_{(5)}3$	$400\pm_{(4)}20$	$330\pm_{(3)}30$	$22\pm_{(5)}4$	$11\pm_{(4)}1$	$42\pm_{(5)}9$	$43\pm_{(5)}7$	0.75	1.21	24.3	0.058	12.6	41	14	3.04	G.P.I.S.
39	$155\pm_{(4)}8$	$1050\pm_{(3)}50$	$700\pm_{(3)}100$	$84\pm_{(3)}2$	$25\pm_{(3)}5$	$204\pm_{(3)}2$	$210\pm_{(3)}70$	1.06	2.19	36.8	0.095	21.3	67	16	1.80	I.M.S.
40	$10\pm_{(2)}0$	$50\pm_{(3)}10$	$60\pm_{(2)}30$**	$0.3\pm_{(3)}1$	$3\pm_{(3)}1$	$3\pm_{(3)}1$	$379\pm_{(3)}2$	1.11	0.10	3.6	0.033	1.5	118	22		F.W.S.Str.

* 1σ standard deviation. Number of analyses is in parentheses below each analysis. The α factor is used to convert samples to 100% sulfide in Table 5.

**Indicates sample which contained erratic analysis for either gold or platinum. The erratic value was omitted on calculating means and S.D. (A value was considered erratic if it varied from the other analyses for that element by more than 200 percent.)

Cu, Ni, Co, Fe were analysed by Inco Metals Company, by atomic absorption using $HCl-HNO_3-HF-HClO_4$ digestion. S was analysed by Inco Metals Company using Leco combustion methods. Zn, Pb were analyzed by S. Gentleman of University of Toronto, using atomic absorption techniques.

Hanging-wall mineralization = H.W.Str.
Ragged disseminated sulfide = R.D.S.
Diss. sulf. in sublayer norite = D.S. norite
Gabbro-perid. incl. sulf. = G.P.I.S.
Inclusion massive sulfide = I.M.S.
Footwall sulfide stringers = F.W.S.Str.
Inclusion blebby sulfide = I.B.S.
Pyrrhotite/Ni ratio = Po/Ni

host rocks are given in Table 3. The most distinctive variation of the noble metals in the Little Stobie mine is their higher concentration in the #2 orebody with respect to the #1 orebody (Fig. 5, Table 4). There is a significant (95% confidence level) enrichment of Rh (2.5X), Pd (1.5X), Ir (2.0X), Os (1.5X) and Ru (1.9X) in the #2 with respect to the #1 orebody. There is no significant difference in the Cu and and Ni values, nor significant and systematic variation for all the noble metals between the different ore types. On the other hand, for a given ore type common to both orebodies (*e.g.*, gabbro-peridotite inclusion

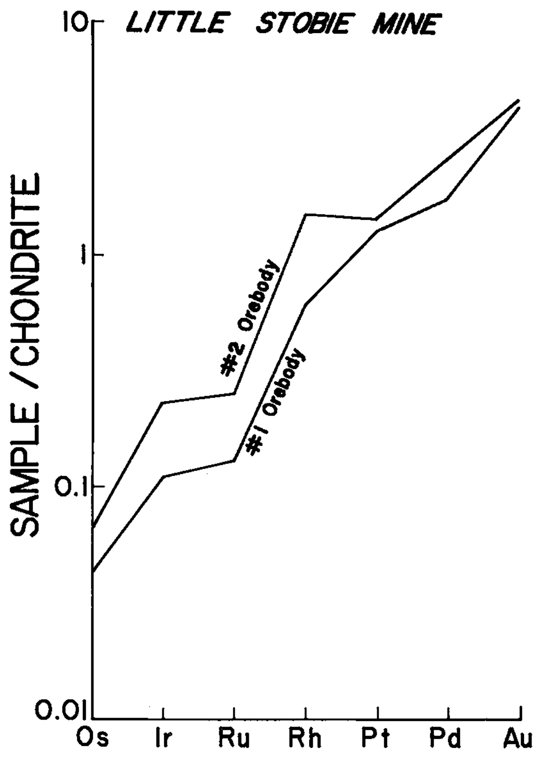

FIG. 5. Comparison of the noble-metal trends in massive sulfide for the #1 and #2 orebodies at the Little Stobie mine.

massive sulfide), the higher metal concentrations characteristic of the #2 deposit are maintained.

Copper-rich stringers in the footwall rocks are far less common in the Little Stobie mine than in the Levack West mine. There is, however, a similar enrichment trend of Pd, Pt, Au and Cu in these stringers at the #1 orebody with respect to the main mass of the ore.

DISTRIBUTION OF NOBLE METALS IN THE LITTLE STOBIE OREBODIES

The overall differences in noble-metal concentrations in the #1 and #2 orebodies do not seem to be due primarily to the same thermal diffusion process as invoked for the Levack West mine. The #2 orebody is enriched in all of the PGE except Pt by about a factor of 2 over the #1 orebody and yet shows no significant enrichment in Cu or Au. If the same process (diffusion) were responsible for the #2 orebody, one would expect to find the same enrichment in Cu and Pd (and possibly Pt and Au) and depletion in Rh, Ir, Os and Ru as seen in the Levack-footwall stringer ore.

The geological environments of the #1 and #2 orebodies are quite different. Evidence of gravitational settling of liquid sulfides from a silicate magma is present in the #1 deposit. The #2 deposit resembles other offset deposits: it seems to represent injection of a silicate magma or magmas carrying magmatic sulfides concentrated in certain zones at the time of intrusion. These seem to have been frozen *in situ* without significant gravitational settling. The PGE enrichment in the #2 orebody could be related to the differing processes that gave rise to this offset deposit as opposed to the sublayer deposits. The stage at which sulfides comprising an orebody separate during the fractional crystallization of their host magma can exert a major control on their PGE content. Significant variation in PGE levels can also result from variation in the ratio of the amount of sulfide reacting with a given mass of silicate magma (Naldrett *et al.* 1979).

Thermal diffusion seems to have been active only to the extent that it is responsible for the Cu-rich stringers at the #1 deposit, which show the same enrichment in Cu, Pd, Pt and Au as seen at Levack West. As stated above, these stringers are much less common than at Levack West. Souch *et al.* (1969) state that the South Range of the Sudbury basin has been uplifted at least 5 km with respect to the North Range. This implies that the Little Stobie deposit represents a section of the Irruptive at least 5 km deeper than the Levack West deposit. If, as much of the recent geological evidence (Guy-Bray 1972) seems to imply, the Irruptive is the result of meteoritic impact and if this event was responsible for the fracturing and brecciation of the country rocks, this fracturing would not have been as intense in the deeper section (represented by the Little Stobie deposit) as at Levack West. The estimate of burial depth at time of intrusion for Levack West is 3–8 km and for Little Stobie, 8–12 km. The higher lithostatic pressure at Little Stobie would also have tended to seal existing fractures at this deposit to a greater degree than at Levack West, implying the probability of a lower porosity at the former deposit. This difference in porosity may well be the reason for the less extensive development of the Cu-rich stringer ore at Little Stobie than at Levack West. An alternative explanation for the lower degree of fracturing of the footwall rocks at Little Stobie, as suggested by Keays (pers. comm.), might be the contrasting strain behavior of basaltic

TABLE 4. CONCENTRATION OF THE NOBLE METALS, Cu AND Ni IN MASSIVE SULFIDE FOR THE VARIOUS ORE TYPES AT THE LITTLE STOBIE MINE

ORE TYPE		Rh	Pd	Pt	Ir	Os	Ru	Au	Cu	Ni	n
					ppb				wt.%		
#2 Inclusion Blebby sulfide	x̄	344	3818	2288	136	49	326	1581*	5.5	3.8	4
	SD	79	810	986	37	19	124	1576	1.5	0.4	
#2 Incl. massive sulfide	x̄	211	2505	1520	67	27	117	278	1.9	4.0	4
	SD	56	614	964	28	8	56	36	0.8	0.8	
#2 Gab.-perid. incl. sulfide	x̄	370	3053	2553	145	66	315	913	3.6	4.3	3
	SD	58	635	237	28	24	84	624	1.2	0.4	
#2 Av.	x̄	303	3132	2081	113	46	247	859*	3.7	4.0	11
	SD	94	859	890	47	23	133	982	1.9	0.6	
#1 Diss. sulf.	x̄	100	3068	3092	44	35	97	989	5.2	3.1	6
	SD	43	2843	3607	18	28	60	1166	2.6	1.4	
#1 Ragged dis. sulfide	x̄	120	2034	2098	62	27	120	1108	6.0	3.6	5
	SD	41	462	1526	22	13	57	1326	5.0	0.3	
#1 Incl. massive sulfide	x̄	188	1380	883	99	34	213	475	1.5	4.2	3
	SD	106	764	425	64	20	164	464	0.9	0.4	
#1 Gab.-perid. incl. sulfide	x̄	119	1136	1244	62	27	125	324	3.2	3.9	5
	SD	45	222	1004	27	13	58	238	1.5	0.3	
#1 Footwall Cu-stringers	x̄	65	8430	7240	27	15	44	5850	19.1	2.8	2
	SD	61	7877	4327	23	2	24	3889	6.8	1.3	
#1 Av.	x̄	119	2108	1946	61	29	123	733	4.4	3.6	23**
	SD	55	1738	2161	31	17	77	892	3.1	0.8	

* excludes sample 14 because of an anomalously high value.

** excludes samples 27 + 28, 29 and 30 because they are stringer mineralizations in the footwall and hanging-wall rocks.

footwall rocks around Little Stobie #1 as opposed to the granitic gneiss around the Levack West deposit. This does not, however, explain the lack of development of stringer ore associated with the boss of Murray granite near the Little Stobie #2 orebody.

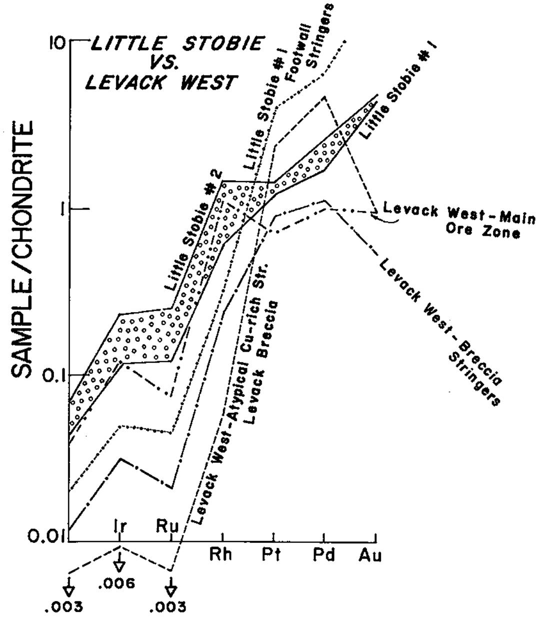

FIG. 6. Comparison of the noble-metal content in massive sulfide of the Levack West and Little Stobie mines.

COMPARISON OF PGE VALUES AT LITTLE STOBIE AND LEVACK WEST

It is apparent from Figure 6 that both the #1 and #2 orebodies at the Little Stobie mine are enriched in Pt, Pd and Au with respect to the Main ore zone at Levack West. These relationships are significant at the 95% confidence level. The Ir and Rh contents of the Main ore zone at Levack West lie between the #1 and #2 orebodies at Little Stobie; Os and Ru are somewhat lower than the #1 orebody values (not significant at the 95% confidence level). The general trend for Os, Ir, Ru and Rh for the Levack West Main ore zone is similar to that for the two orebodies at Little Stobie. There is also a similarity between the PGE trends of the Levack breccia Cu-rich

TABLE 5. CORRELATION COEFFICIENTS AND THE SORTED, ROTATED FACTOR MATRIX BASED ON NATURAL LOGARITHMS OF ANALYTICAL DATA FOR THE LITTLE STOBIE NO. 1 OREBODY

	Rh	Pd	Pt	Ir	Ru	Os	Au	Cu	Ni	Co	S	Fe	Zn	Pb
Rh	1.000													
Pd	0.183	1.000												
Pt	0.053	0.696	1.000											
Ir	0.981	0.208	0.076	1.000										
Ru	0.852	0.251	0.118	0.886	1.000									
Os	0.816	0.276	0.265	0.830	0.626	1.000								
Au	-0.184	0.665	0.723	-0.170	-0.089	-0.067	1.000							
Cu	-0.091	0.453	0.557	-0.052	0.049	-0.200	0.717	1.000						
Ni	0.911	0.306	0.107	0.874	0.667	0.747	-0.052	0.058	1.000					
Co	0.881	0.250	0.013	0.836	0.615	0.705	-0.101	0.026	0.987	1.000				
S	0.881	0.294	0.068	0.841	0.629	0.696	-0.046	0.103	0.988	0.994	1.000			
Fe	0.876	0.315	0.090	0.828	0.599	0.718	-0.021	0.092	0.984	0.988	0.994	1.000		
Zn	-0.145	0.248	0.529	-0.156	-0.124	-0.134	0.715	0.673	-0.040	-0.107	-0.054	-0.034	1.000	
Pb	-0.168	0.275	0.478	-0.232	-0.153	-0.086	0.303	0.310	-0.105	-0.124	-0.084	-0.066	0.356	1.000
$r_{.025}$	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414	0.414
n	23	23	23	23	23	23	23	23	23	23	23	23	23	23

SORTED ROTATED FACTOR LOADINGS (PATTERN)

	FACTOR 1	FACTOR 2
Ni	0.972	0
Rh	0.970	0
Ir	0.955	0
S	0.953	0
Co	0.951	0
Fe	0.949	0
Os	0.831	0
Ru	0.791	0
Au	0	0.913
Pt	0	0.856
Cu	0	0.816
Zn	0	0.772
Pd	0.313	0.717
Fe	0	0.542
Eigenvalue	6.983	3.661

The factor loading matrix has been re-arranged so that the columns appear in decreasing order of variance explained by factors. The rows have been re-arranged so that for each successive factor, loadings greater than 0.500 appear first. Loadings less than 0.250 have been replaced by 0.

stringer ore zone and the Cu-rich stringers in the footwall rocks at Little Stobie. However, the Cu-rich stringers in the Levack breccia occur in much greater volume at Levack West than those at Little Stobie and constitute a much greater proportion of the ore.

If the Levack Cu-rich stringer ore and atypical Cu-stringer ore are added to the Main ore zone, the shapes of the profile of the noble metals will resemble that of the Little Stobie deposits (albeit at a slightly lower overall concentration level) more closely than that of the Main ore zone alone. This is supportive evidence that the Pd, Pt and Au in the Levack breccia stringers may have been derived from the Main ore zone by the processes discussed.

CORRELATION OF THE NOBLE-METAL VALUES WITH THE CHEMICAL COMPOSITION OF THE ORE

An *R*-mode factor analysis has been applied to the natural logarithms of the concentrations of noble metals, Cu, Ni, Fe, Co, S, Zn and Pb in the deposits studied. This type of statistical analysis helps to clarify the mutual relationships among the noble metals, major and trace elements in the ores. Dixon's (1975) BMDP–4M computer program was used for the factor analysis. This program first computes the correlation matrix; then the factor loadings are estimated and finally the factors are rotated orthogonally to obtain a simple interpretation (either large or small factors).

Table 5 gives the correlation coefficients for all existing pairs of data for the Little Stobie #1 orebody. Values above $r_{0.025}$ are significant at the 95% confidence level for the number of samples indicated (n). Two factors given in Table 5 explain the variations in the response variables for the Little Stobie #1 orebody. Factor 1 shows high loadings for Ni, Rh, S, Co, Fe, Ir, Os and Ru. This seems to suggest that Rh, Ir, Os and Ru are spatially if not genetically related to nickel mineralization (pentlandite or pyrrhotite or both). Factor 2 shows somewhat lower but nevertheless high loadings for Au, Pt, Cu, Zn, Pd and Pb, which evidently suggests a relation of Au, Pt, Pd to processes that gave rise to Cu-rich ore.

Keays & Crocket (1970) have shown that Pd and Au were concentrated in chalcopyrite coexisting with pyrrhotite in the Strathcona mine. These findings are in agreement with the observed loadings on factor 2. It must be noted, however, that the previous study did not report on Pt distribution or any number of pentlandite concentrates. Chyi & Crocket (1976) found that Pd and Au were concentrated in pentlandite, whereas Pt and Ir were concentrated in chalcopyrite; this does not concur with our findings of the lowest Ir levels in the most Cu-rich atypical Levack breccia ore. Cabri & Laflamme (1976) have determined that michenerite "is thought to be the principal palladium mineral of the Sudbury deposits" and sperrylite was "the most common platinum mineral in the South Range and offset deposits." Those authors report that "michenerite is most frequently observed as inclusions in non-platinum group minerals, especially in chalcopyrite" and that the association of sperrylite "with chalcopyrite is distinct in some deposits but may occur as inclusions in pyrrhotite." In general, they have also found that "the majority of the platinum-group minerals occur as inclusions in chalcopyrite, in chalcopyrite–cubanite, in other platinum-group minerals (themselves mostly included in chalcopyrite), in hessite, or in hessite–chalcopyrite." The possibility of solid solution in the major sulfides and other phases has also been investigated: Cabri & Laflamme (1976) concluded that the PGE definitely occur in solid solution in arsenides and sulfarsenides and may occur as dilute solid solutions in silicates, sulfides or oxides but that these types of occurrence are of "minimal importance."

The above mineralogical findings are at odds with the data of Chyi & Crocket (1976) but concur with the findings of our factor analysis. The mineralogical implications of factor 1 cannot be determined as Rh, Ir, Os and Ru phases have not been identified in the Sudbury area (with the exception of trace amounts of Rh in some platinum-group-mineral phases).

Somewhat similar factor analysis results have also been obtained from the Little Stobie #2 orebody and the Levack West mine and are described by Hoffman (1978).

CONCLUSIONS

The following are the main conclusions from this study:

1. The ores of both the Little Stobie and Levack West deposits at Sudbury are marked by fairly high concentrations (relative to chondritic levels) of Au, Pd, Pt and Rh and very low concentrations of Ru, Ir and Os. Typically the Levack West deposit is somewhat similar in noble metals to the Little Stobie #1 orebody and is less rich than the #2 orebody.

2. Two distinctly different orebodies, one resembling the offset deposits and the other the Irruptive-contact deposits, are present at Little Stobie; the former contains almost twice as much of all noble metals except Pt and Au as the latter. These are regarded as the result of separate injections of ore magmas.

3. The Levack breccia ores are significantly depleted in Rh, Ir, Os and Ru and slightly enriched in Cu relative to the granite breccia ores. Atypical Cu-rich Levack breccia stringers are much richer in Pt and Pd but poorer in Rh, Ru, Ir and Os than the Main ore zone. We suggest that the Levack breccia stringer ore has been mobilized out of the main ore by thermal diffusion under the influence of a thermal gradient decreasing downward and outward from the overlying Nickel Irruptive. Minor Cu-rich stringers showing the same characteristics as the Levack stringers are also present at Little Stobie.

4. Factor analysis indicates that Rh, Ru, Ir and Os are spatially and perhaps genetically associated with Ni-rich ore, whereas Au, Pt and Pd are associated with Cu-rich ore.

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