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THE SUDBURY SUBLAYER

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ABSTRACT

The copper–nickel sulfide ores of the Sudbury basin are associated with sublayer intrusions along the outer margin of, and as outward radiating offset dykes from, the main Sudbury Irruptive. Two major variants of sublayer are recognized: igneous-textured gabbro–norites and metamorphic-textured leucocratic breccias. Both are characterized by the presence of sulfide and abundant xenoliths. The gabbro–norites show enrichment in quartz and alkali feldspar towards the footwall, while their pyroxenes exhibit iron enrichment. These rocks are thus upside down with respect to normal crystal-settling paragenesis, suggesting that assimilation phenomena played a large part in their formation. Despite controversial interpretations, I submit that the gabbro–norites and the leucocratic breccias are contemporaneous, both pre-main Irruptive. The sulfide minerals in the sublayer are dominantly monoclinic and hexagonal pyrrhotite, pentlandite and chalcopyrite with minor but locally important cubanite, millerite and pyrite. Zoning trends within individual orebodies are attributed to subsolidus migration down a thermal gradient imposed by the main Irruptive. Comparison of Cu–Ni ratios in sulfides with average MgO content for various host rocks suggests that the hosts are not the liquid from which the sulfides precipitated. Two processes may explain the origin of the sublayer: (1) segregation of a sulfide-rich magmatic differentiate in the lower levels of an impact-triggered magma and its early intrusion along the contact between brecciated footwall rocks and overlying Onaping Formation; (2) direct emplacement of sulfide-enriched impact melt along the walls of the crater, the sulfides being derived from previous concentrations in basic magmatic country rocks. In either case, the leucocratic breccias were formed by mechanical attrition of brecciated footwall rocks as the igneous sublayer was intruded.

SOMMAIRE

On peut associer la minéralisation Cu–Ni du bassin de Sudbury à des intrusions sous-jacentes à la périphérie du complexe irruptif de Sudbury et des dykes en relais qui partent radialement de ce contact. Des deux variantes de cette sous-couche, l'une, gabbroïque à noritique, possède une texture ignée; l'autre consiste en brèches leucocrates à texture métamorphique. Toutes deux contiennent des sulfures et une abondance de xénolithes. Les gabbros–norites s'enrichissent en quartz et feldspath alcalin, et leurs pyroxènes deviennent plus riches en fer, vers l'éponte inférieure. Cette zonation, inverse de celle qui résulterait d'une séparation des cristaux par gravité, semble indiquer que des phénomènes d'assimilation ont présidé à la formation de ces roches. Compte tenu de la controverse, j'estime que les gabbros–norites et les brèches leucocrates sont contemporaines et antérieures au complexe irruptif. Les sulfures principaux de la sous-couche sont les suivants: pyrrhotine (monoclinique et hexagonale), pentlandite et chalcopyrite, avec cubanite, millérite et pyrite comme minéraux accessoires. La zonation au sein de gisements individuels serait le résultat d'une migration subsolidus, le long d'un gradient thermique imposé par le complexe irruptif. D'une comparaison entre le rapport Cu/Ni des sulfures et la teneur moyenne en MgO des diverses roches encaissantes, on conclut que ces roches ne peuvent représenter le liquide où les sulfures ont été précipités. Deux hypothèses expliquent la formation de la sous-couche à texture ignée: (1) différenciation et ségrégation à la base d'un magma sulfuré résultant de l'impact, et intrusion de ce magma le long du contact entre les brèches de l'éponte inférieure et la formation Onaping sus-jacente; (2) mise en place directe, le long des parois du cratère d'impact, de sulfures fondus sous l'impact, sulfures précédemment concentrés dans la portion magmatique basique des roches encaissantes. Dans chaque cas, les brèches leucocrates résulteraient de l'attrition mécanique des roches de l'éponte inférieure, sous l'effet de l'intrusion ignée sous-jacente.

(Traduit par la Rédaction)

INTRODUCTION

The geology of the main mass of the Sudbury Irruption and its subjacent and superjacent rocks is well known and is discussed in a voluminous literature. Excellent summaries of this literature are given by Souch *et al.* (1969) and Naldrett *et al.* (1972) among others. There exists a general consensus that the norite–gabbro–micropegmatite unit (hereafter termed simply the Irruptive) represents a differentiated intrusion consisting of one or more pulses of relatively siliceous magma (Souch *et al.* 1969, Naldrett *et al.* 1970, 1972). A major point of contention, whether or not the micropegmatite represents a separate intrusion, is discussed in some detail by Peredery & Naldrett (1975). Also, there is general, but by no means complete, agreement that the formation of the Sudbury structure and its associated intrusions could have been triggered by the impact of a large meterorite about 2.0 b.y. ago (Dietz 1964, French 1972, Dence 1972).

The origin and emplacement of the associated marginal copper–nickel sulfide deposits of the Sudbury sublayer have, however, engendered no such consensus. Fundamental concerns such as the timing of this emplacement relative to the overlying Irruptive, the method of emplacement, and the genesis of the sublayer and ores continue to generate controversy. Early workers proposed that the ores were an example of sulfide immiscibility in, and gravitative differentiation from, a magmatic source, in this case the norite–micropegmatite body (Coleman 1926, Collins 1937). In order to explain relatively minor details of mineral alteration and paragenesis, others (Knight 1917, Phemister 1925, 1937, Yates 1938, 1948) have suggested a hydrothermal origin for the ores. More recently, the concept of direct emplacement of the sublayer as a product of explosive meteorite impact has been invoked (Dietz 1972).

Field relationships coupled with petrological and petrochemical studies have indicated that direct magmatic derivation of the sulfide ores from the Irruptive *in situ* is not a viable concept. In two important papers, Naldrett & Kullerud (1967) and Souch *et al.* (1969) proposed that the sulfides and their associated silicate hosts were emplaced separately from the Irruptive (1) as a series of late sulfide- and inclusion-rich marginal intrusions or sublayer along the base of the Irruptive and (2) as a group of outward radiating and tangential offset dykes (Fig. 1). Because the silicate fraction of the exposed sublayer is obviously too small to hold the total known sulfide content in solution, the segregation and collection of immiscible sulfide were relegated by these authors to deeper, unexposed, portions of the Irruptive structure. Final emplacement of this sulfide-enriched magmatic fraction followed the intrusive contact between the barren Irruptive and the footwall.

Sulfurization has been suggested as a possible mechanism in the formation of the Sudbury ores and in other ore deposits of the so-called Sudbury type (Cheney & Lange 1967). For Sudbury at least, this proposal founders on the relationship of the sulfide ores to identifiable sublayer rock types, their absence from mineralogically similar main Irruptive norites and footwall rocks except where in contact with mineralized sublayer, and the spatial relationship of the ores to structural traps.

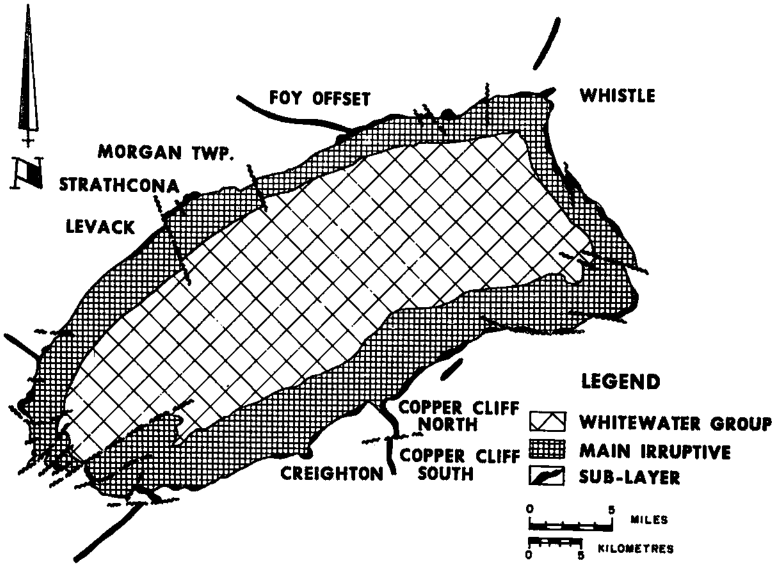


FIG. 1. Generalized geological map of the Sudbury basin showing the distribution of major occurrences of sublayer material (thickness somewhat exaggerated).

Conventional scenarios such as these demand an endogenic source for the several constituents of the sublayer (sulfide, silicate matrix, silicate inclusions) despite the probable role of meteorite impact as a trigger mechanism. Dietz (1972) postulated, however, that not only was the Sudbury structure the product of impact, but also that the sublayer and associated sulfides were the direct result of splash emplacement of impact-derived plasma, melt and complex breccias along the impact crater wall. Moreover, he proposed that the copper and nickel sulfides represented original components of the impacting bolide. These provocative hypotheses, although not inconsistent with many aspects of Sudbury geology, are opposed by the nearly unanimous opinion of the geological fraternity that such copper-rich meteorites are planetologically improbable.

It seems, then, that the major outstanding problems of Sudbury geology are the origin and nature of the sublayer, the nature of the relationship between the sublayer and its related sulfides, and the timing of the emplacement of the sublayer relative to the overlying Irruptive. This paper summarizes the results of detailed studies of sublayer bodies. Emphasis is placed on the general characteristics of the sublayer and on field relationships between the sublayer and the Irruptive.

GEOCHRONOLOGY

Very little work has been done on the radiometric dating of the sublayer. Numerous studies of the age of the Irruptive, summarized in Table 1, have shown that the sundry isotopic equilibria have been disturbed and that great care is necessary in their interpretation. Note the large spread of ages obtained by different workers, the large uncertainties in most of the ages and the fact that the micropegmatite gives consistently younger dates than the norite. Also, the relatively high initial $^{87}Sr/^{86}Sr$ ratios (0.706–0.708) seem to preclude a mantle derivation for the exposed portion of the main Irruptive, an observation in accord with its observed bulk composition and mineralogy.

Souch *et al.* (1969) were the first to attempt radiometric dating of the sublayer. They determined that three specimens of sublayer, all from the South Range, did not lie on or near previously defined Irruptive Rb–Sr isochrons and did not in themselves define an isochron. A zircon sample gave a minimum U–Pb age of 1900 m.y., close to the 1844 m.y. age for the Irruptive later determined by Krogh & Davis (1974). A five point Rb–Sr isochron age on samples from the Copper Cliff offset and Murray mine (Gibbins & McNutt 1975) of 1957 ± 156 m.y. is suspect because the samples from the Murray mine probably represent basal Irruptive. A two-point isochron on material from the Foy offset (Marchand 1976) gave an age of 1854 m.y., in excellent agreement with the work of Krogh & Davis (1974).

TABLE 1. SUMMARY OF GEOCHRONOLOGY

Reference	Material Dated	Method	Age	(Sr87/Sr86)
Fairbairn et al. (1968)	5 micropegmatite 1 norite (N.R.)	Rb-Sr rock	1700 m.y.	.7052
Souch et al. (1969)	3 norites (N.R.) Sub-layer (S.R.)	Rb-Sr rock U-Pb zircon	2000 m.y. 1915 m.y.	.706 -
Hurst & Wetherill (1974)	Norite (N.R.)	Rb-Sr rock	1785 ± 126 m.y.	.7073
Krogh & Davis (1974)	Norite (N.R., S.R.)	U-Pb zircon	1844 ± 3	-
Gibbons & McNutt (1975)	Norite (N.R.)	Rb-Sr rock	2054 ± 230 m.y.	.7063
	Norite (S.R.)	Rb-Sr rock	1977 ± 116 m.y.	.7057
	Micropegmatite (N.R., S.R.)	Rb-Sr rock	1680 ± 62 m.y.	.7083
	Sub-layer (S.R.)	Rb-Sr rock	1957 ± 156 m.y.	.7055
Marchand (1976)	Sub-layer (N.R.)	Rb-Sr rock	1854 ± ? m.y.	-

N.R. = North Range

S.R. = South Range

DISTRIBUTION AND MORPHOLOGY OF SUBLAYER

Sublayer was first defined as a sulfide- and inclusion-bearing silicate magma, and its areal distribution shown by Souch *et al.* (1969). This definition is still valid; however, some inclusion-bearing rocks, found near the interface of sublayer and basal Irruptive norite, have matrices that are petrographically similar to adjacent inclusion- and sulfide-free basal norite (quartz-rich norite on the South Range and mafic norite on the North Range). These rocks most likely represent contaminated basal Irruptive and are specifically excluded from the sublayer as here defined. A map showing the distribution of the sublayer, as modified by subsequent work, is given in Figure 1.

Bodies of sublayer occur as laterally extensive sheets and irregular flat lenses, as small bodies occupying embayments or troughs in the footwall, and as offset dykes that extend for many kilometres into the footwall. Most offsets extend radially outward from the Irruptive–footwall contact. An exception is the Frood–Stobie offset which is almost parallel to this contact.

MAJOR SUBLAYER FACIES

Following Naldrett *et al.* (1972), two fundamental facies of the sublayer can consistently be distinguished. These are: 1) igneous sublayer, a group of igneous-textured gabbroic, noritic and dioritic rocks; 2) leucocratic breccias, a group of metamorphic-textured felsic to mafic breccias. Both facies are characterized by the presence of Fe–Ni–Cu sulfide minerals and by the presence of xenoliths of recognizable footwall rocks and of cumulate-textured anorthositic–mafic–ultramafic rocks of uncertain exotic origin.

IGNEOUS SUBLAYER

Historically, two varieties of igneous sublayer have been distinguished: the two-pyroxene gabbro–norites of the marginal deposits (xenolithic, basic and sublayer norites of previous workers) and the hornblende–biotite quartz diorites traditionally associated with the offsets. Recent mapping has demonstrated that gabbro–norite sublayer is a common constituent of the North Range offsets and that much of the primary hornblende described by Souch *et al.* (1969) as typical of the South Range offset deposits is pseudomorphic after primary ortho- and clinopyroxenes (Fig. 2). The distinction between marginal gabbro–norites and offset quartz diorites is therefore nullified and the two can be considered as part of the same intrusive pulse, the quartz diorite representing deuterically (?) altered gabbro–norite.

Some doubt exists as to the exact nature of marginal igneous sublayer on the South Range. Hewins (1971a) has documented the differences between igneous sublayer and basal main irruptive norite in the Levack–Strathcona area. Similar, although not identical, sequences of rock types are found in South Range embayment structures. Weakly poikilitic, coarse-grained norite (Fig. 3) usually forms the basal main Irruptive units and is analogous to North Range mafic norite as described by Hewins (1971a). This basal main Irruptive norite, commonly inclusion- and sulfide-bearing, overlies sublayer gabbro–norites that are petrographically quite distinct from normal quartz-rich norite (Naldrett *et al.* 1970) and the poikilitic norite described here. A photomicrograph of typical North Range igneous sublayer is depicted in Figure 4 and two variants of South Range varieties in Figures 5 and 6.

The matrix of fresh igneous sublayer on both North and South Ranges consists of zoned plagioclase laths, prismatic to subophitic clino- and orthopyroxenes, minor amounts of primary biotite and hornblende, highly variable quantities of interstitial quartz, micrographic quartz-feldspar intergrowth and microcline, and Cu–Ni–Fe sulfides. Primary olivine is not a constituent of igneous sublayer except in the Whistle embayment and even there it is rare.

It is extremely difficult to define the whole-rock chemistry of these rocks because of their ubiquitous inclusions. Assimilation of material derived from mafic and ultramafic exotic inclusions and from basic to felsic footwall rocks has obscured the chemistry of any primary igneous matrix and created highly variable modal compositions. Table 2 gives data believed representative but which should nevertheless be treated with caution because of these uncontrolled variables. The data were obtained by averaging analyses of relatively inclusion-free material.

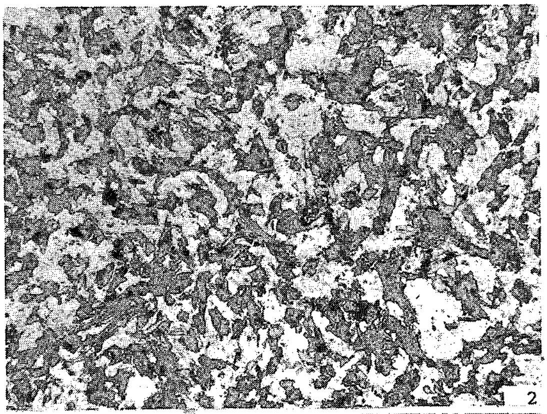
LEUCOCRATIC BRECCIAS

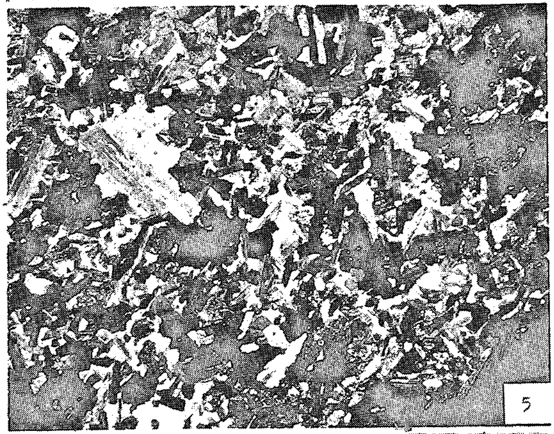
The various metamorphic-textured breccias of the North Range are perhaps the most puzzling of all Sudbury rocks. Many textural and compositional variants of these breccias can be defined locally. Contradictory cross-cutting and gradational contact relationships between these variants and between the breccias and spatially related igneous sublayer and basal Irruptive units are common, indicating a complex emplacement history for these rocks. Various factors contribute to the diversity of the leucocratic breccias. These include variations in bulk composition, fragment–matrix ratio, fragment size and lithology, and matrix texture, together with the presence or absence of an exotic frag-

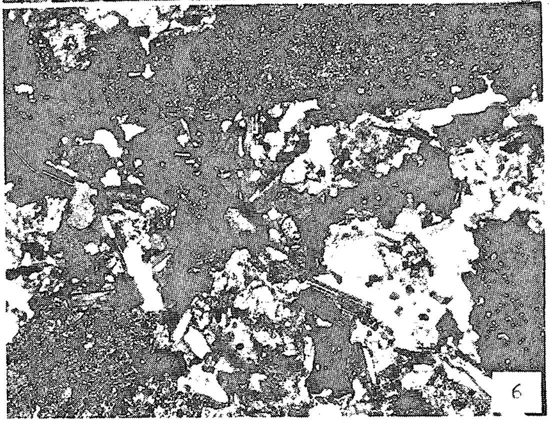
TABLE 2. PARTIAL XRF WHOLE-ROCK ANALYSES, SUDBURY SUBLAYER

	1	2	3	4	5
SiO_2	56.1	57.0	56.2	64.8	65.1
TiO_2	0.91	0.80	0.80	0.46	0.45
Al_2O_3	14.6	13.3	15.0	14.7	14.8
MgO	4.54	4.50	4.91	1.34	1.93
CaO	6.36	5.93	5.87	3.77	4.09
MnO	0.14	0.13	0.12	0.04	0.07
Total Fe	7.57	6.53	6.50	2.83	3.61
K_2O	1.90	1.73	1.64	1.40	1.59
Cr_2O_3	0.02	0.05	0.07	0.04	0.03

1. Average barren marginal quartz diorite, Copper Cliff North mine, $n = 22$; 2. Average barren igneous sublayer (basic norite), Foy offset, $n = 21$; 3. Average barren leucocratic breccia, Foy offset, $n = 11$; 4. Average barren leucocratic breccia, Strathcona mine, $n = 8$ (Greenman 1970); Average Levack breccia, Levack mine, $n = 9$.







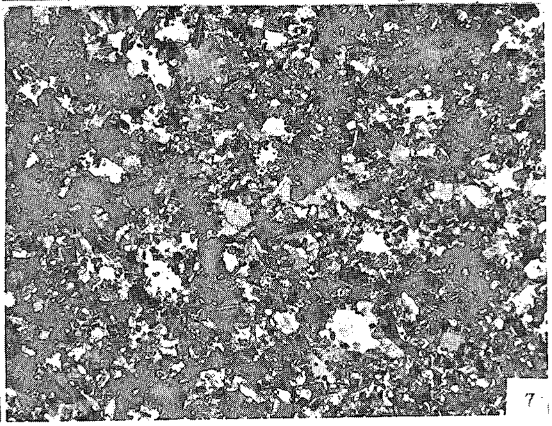


FIG. 2. Photomicrograph of altered igneous sublayer (quartz diorite) from the Copper Cliff offset showing actinolite pseudomorphs after ortho- and clinopyroxenes. X22, plane light.

FIG. 3. Photomicrograph of poikilitic basal main Irruptive norite from Murray mine. X22, crossed polars.

FIG. 4. Photomicrograph of fresh igneous sublayer (xenolithic norite) from Levack mine. The well-developed interstitial character of the sulfides is typical. X22, crossed polars.

FIG. 5. Photomicrograph of fine-grained, slightly porphyritic igneous sublayer from Murray mine. X22, crossed polars.

FIG. 6. Photomicrograph of highly porphyritic, orthopyroxene-rich igneous sublayer from Creighton mine. X22, crossed polars.

FIG. 7. Photomicrograph of sulfide-poor leucocratic breccia. X22, crossed polars.

ment population and of sulfide mineralization. Because the complex relationships between these factors have not been resolved in detail and as it is not certain that the differences have important genetic implications, all leucocratic breccias are here classified as one unit.

The major petrographic characteristics of the matrices of these breccias are mosaic-granoblastic metamorphic textures (Fig. 7) and heterogeneous modal compositions. The breccias consist of highly variable proportions of intermediate plagioclase (An_{20-45}), quartz, pyroxenes, amphibole and biotite. Sulfide may or may not be present. The presence of sulfide tends to be associated with a rather more igneous-looking texture in the matrix (Fig. 8).

The chemical data for the Foy offset presented in Table 2 show that the leucocratic breccias can have bulk compositions very similar to those of associated igneous sublayer (analyses 2 & 3). On the other hand, the data for the Levack-Strathcona area show that the composition of the leucocratic breccias can also be very similar to the bulk composition of associated footwall rocks as represented by the composition of Sudbury breccia (analyses 4 & 5). The significance of these observations is not entirely clear but it supports the suggestion by Greenman (1970) that more than one mode of origin for the breccias may have operated.

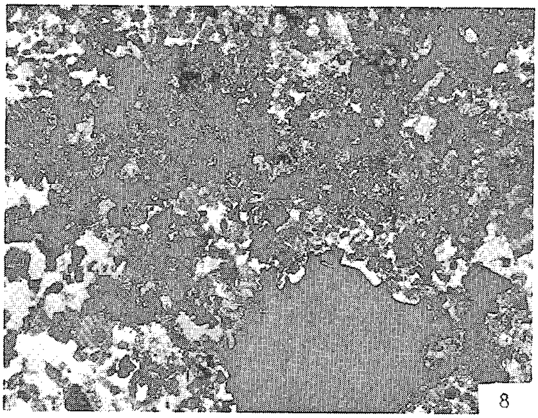


Fig. 8. Photomicrograph of sulfide-rich leucocratic breccia showing the typical blebby character of the sulfide aggregates. X22, crossed polars.

XENOLITH POPULATIONS

All facies of the sublayer characteristically contain xenoliths. Two major groups of inclusion types can readily be identified: i) the various footwall rock-types and their metamorphosed equivalents, and ii) a group of mafic to ultramafic rocks consisting of one or more of olivine, orthopyroxene, clinopyroxene and calcic plagioclase and usually some primary hornblende and biotite.

The footwall xenoliths are generally of local derivation. Rare xenoliths that might represent upper Huronian strata have been identified locally. These include blocks of well-sorted medium-grained feldspathic quartzite (Serpent or Mississagi Formations?) and calc-silicate assemblages (Espanola Formation?). If these identifications are correct, they imply either transport for a distance of several kilometres down the crater wall or derivation from the basal Onaping Formation where large blocks of Huronian sediments are common (Peredery 1972).

The second group, consisting of rounded mafic to ultramafic xenoliths, have generally been considered to have no counterpart in the exposed footwall. Rae (1975) suggests that they represent fragments of a layered intrusion, similar to the Muskox intrusion in chemistry and petrographic trends and genetically related to the Sudbury Irruptive. On the other hand, three pre-Irruptive rock suites known to exist in the exposed footwall could supply at least some of the exotic rocks. These are the Nipissing diabase (Sudbury gabbro) which is texturally, mineralogically and chemically similar to the dominant two-pyroxene gabbro inclusions of the South Range (Card & Pattison 1973), the anorthosite–gabbro–pyroxenite layered intrusions found at intervals along the Huronian–Archean unconformity (James & Harris 1977), and portions of the so-called mafic gneiss of the Levack complex. There is a possibility that these rock suites constituted a major proportion of the pre-Irruptive country rocks. Rae's mineral chemistry data (Figs. 9, 10) are compatible with his suggestion that the xenoliths represent part of a hidden layered portion of the Irruptive; however, until similar data are available for the above suites of rocks, Rae's data cannot be considered conclusive.

Regardless of their derivation, there is a strong spatial relationship between concentrations of the exotic inclusions and concentrations of Cu–Ni–Fe sulfide. A genetic link, although not proven, seems likely.

SULFIDE TEXTURES

Disseminated sulfide in leucocratic breccia has a distinctive blebby to fragmental texture

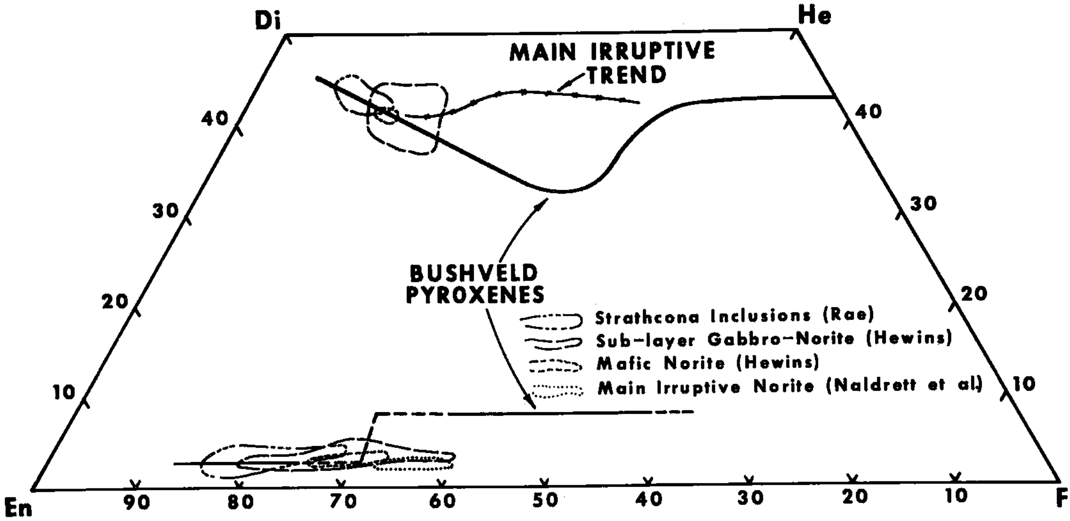


FIG. 9. The pyroxene quadrilateral with compositional fields for pyroxenes from the main Irruptive, the sublayer and the exotic inclusions. Bushveld pyroxene trends are shown for comparison. Data from Naldrett *et al.* (1970), Hewins (1971a, b), Rae (1975).

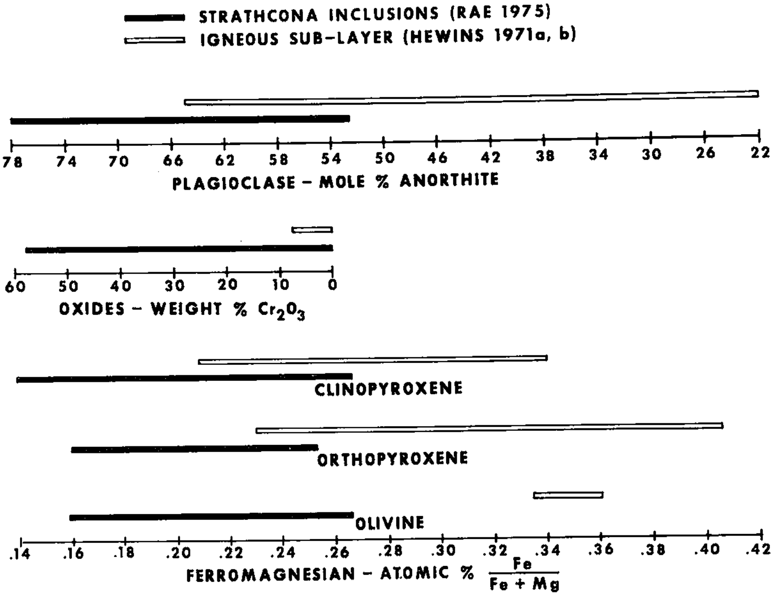


FIG. 10. Comparison of mineral compositional ranges for the sublayer and the exotic inclusions. Data from Rae (1975), Hewins (1971a, b).

(Fig. 11) in contrast to the interstitial sulfide characteristic of the adjacent igneous sublayer (Fig. 4). The fragmental nature of these sulfides, not previously reported in the literature, deserves comment.

Many specimens of leucocratic breccia from various localities around the Irruptive contain discrete bodies of rounded to angular sulfide that are clearly fragmental in character. These fragments vary from 1–10 cm in diameter, but occasionally exceed this range (Fig. 11). Every gradation in size and angularity can be found, as well as examples of large fragments stoped apart by the matrix component of the breccia. Sulfide concentrations smaller than 1 cm in diameter generally have the more usual blebby or globular shape normally associated with the ore minerals in the leucocratic breccia and South

FIG. 11. Fragmental sulfide in leucocratic breccia, Stobie mine.

Range offsets. The small sulfide blebs may possibly represent melted or abraded fragments of sulfide. As the matrices of these rocks are not brecciated, the sulfides may have been inherited from a pre-existing source.

SULFIDE MINERALOGY AND MINERAL ZONING

The ore mineralogy of the sublayer is generally quite simple although many minor phases may be present (Hawley 1962, Cabri & Laflamme 1976). The vast bulk of the Sudbury ore consists of varying proportions of pyrrhotite (both hexagonal and monoclinic), pentlandite and chalcopyrite. Minor but locally important phases include pyrite, cubanite and millerite.

Two superimposed zoning trends are present to some degree in many of the Sudbury orebodies. The most obvious is the increase in the Cu/(Cu+Ni) ratio towards the footwall. In addition, some deposits show marked increases in the (Cu+Ni)/Fe ratios towards the footwall, especially where sulfide bodies project into the footwall from the Irruptive contact for distances of the order of a hundred metres. Mineralogically these trends are manifested by increases in the amounts of chalcopyrite relative to pentlandite and in chalcopyrite plus pentlandite relative to pyrrhotite. In extreme cases, increasingly iron-deficient assemblages such as chalcopyrite–pentlandite and chalcopyrite–millerite are formed. Naldrett & Kullerud (1967) interpreted these zonations as indicative of subsolidus migration of mobile copper and nickel sulfides down a thermal gradient imposed by the overlying Irruptive. To date, no evidence contrary to this hypothesis has been found.

METAL RATIOS

Past production from the Sudbury Basin suggests that the overall Cu/(Cu+Ni) ratio is very nearly 0.5. Ratios for individual entire orebodies, however, can deviate widely from this mean, suggesting that some sort of preemplacement differentiation of the sulfides has taken place or, alternatively, that the sulfides were derived from an inhomogeneous source. These inhomogeneities can be demonstrated by plotting orebody Cu/(Cu+Ni) ratios against average MgO contents for the respective silicate hosts. It can be seen that all fall on the MgO-deficient side of the experimentally determined curve determined by Rajamani & Naldrett (1978) for liquid–liquid equilibrium conditions (Fig. 12). No genetic implications should be drawn from this plot as it is obvious that the silicate matrix of the leucocratic breccia does not represent a liquid composition and that the igneous sublayer is usually highly contaminated and thus does not represent a primary liquid composition.

RELATIONSHIP OF SUBLAYER TO FOOTWALL

The various sublayer facies intrude the Archean and Proterozoic footwall rocks. Evidence for this is clear along the offset dykes. Loci of intrusion for the offsets seem to be areas of above-average quantities of Sudbury breccia (Card 1968) although this may be partly a function of the density of mapping adjacent to the economically important offsets. In the Foy offset, igneous sublayer and leucocratic breccias are present in subequal proportions; the distribution of these rock types there suggests an essentially simultaneous emplacement rather than two intrusive events. The emplacement vector is outward from the Irruptive contact as shown by the distribution of gneissic footwall fragments in the leucocratic breccias. These gneissic fragments are derived from the Levack complex, and are now found in areas of the offset bounded by massive Cartier granite. This is also the case in the Copper Cliff offset where fragments of Lower Huronian pelitic sediments with distinctive large metastaurolite crystals have been transported approximately 3 km southward from their source in the Stobie Formation; they are now found in the underground workings of the Copper Cliff South mine.

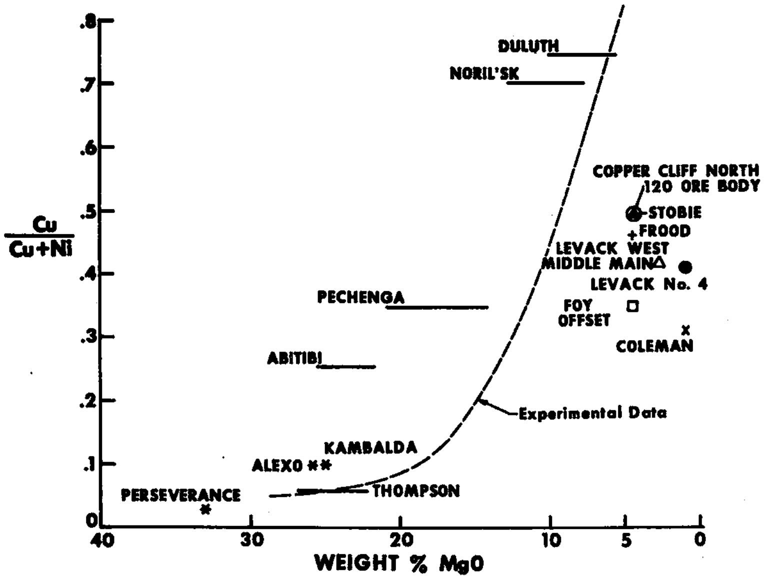


FIG. 12. Plot of Cu/(Cu+Ni) *versus* wt. % MgO for individual Sudbury orebodies. Also shown are data for other magmatic Cu–Ni sulfide deposits and the experimental relationship derived by Rajamani & Naldrett (1978).

In the embayment and sheet-like deposits of the North Range the contact relationships tend to be diffuse and gradational. A typical contact zone shows an increase in size of blocks of footwall rock towards the base, eventually becoming a megabreccia with interblock dykes of leucocratic breccia. Contacts between igneous sublayer and footwall on the South Range are sharp.

Relationships between sublayer and Sudbury (Levack) breccia indicate that the sublayer intrudes the Sudbury breccia. This is shown by clear-cut intrusive relationships along the offsets and by the common presence of small fragments of Sudbury breccia in leucocratic breccia.

RELATIONSHIP OF SUBLAYER TO IRRUPTIVE

Although it is generally agreed that the sublayer and the Irruptive represent separate intrusive pulses, the relative timing of these pulses is still in doubt. Naldrett *et al.* (1972) give a brief but cogent synopsis of the dispute. The main evidence in favor of a post-Irruptive age for the sublayer is the presence of xenoliths of Irruptive mafic norite in the leucocratic breccias of Strathcona mine, and several examples of this relationship are well exposed in a rock cut near the mine.

On the other hand a considerable body of evidence suggests that the sublayer is older than the Irruptive. The major points are: 1) Inclusions of sublayer, ranging from leucocratic breccia and igneous sublayer to massive sulfide, have been observed in the Irruptive, *e.g.*, the 10 m long slab of massive sulfide seen in a 500 Level cross-cut in Little Stobie mine (Fig. 13). 2) Basal Irruptive units contain copper-nickel sulfide mineralization only where in contact with mineralized sublayer. Characteristically, these hybrid norites contain isolated patches of inclusion- and sulfide-rich material although in places (*e.g.*, the railway cut east of Murray mine) intrusive relationships are evident; there, the hybrid unit consists of discrete blocks of sublayer veined and permeated by basal Irruptive rock. 3) The offset dykes consists of sublayer material. No Irruptive rock type has ever been observed in an offset environment. As the offsets are emplaced in pre-Irruptive breccia zones it seems probable that they would be filled with Irruptive material if that had been the first intrusive pulse. 4) Internal contacts within the sublayer are truncated by the basal Irruptive contact. 5) The offsets never cut the Irruptive.

The bulk of the evidence thus supports a pre-

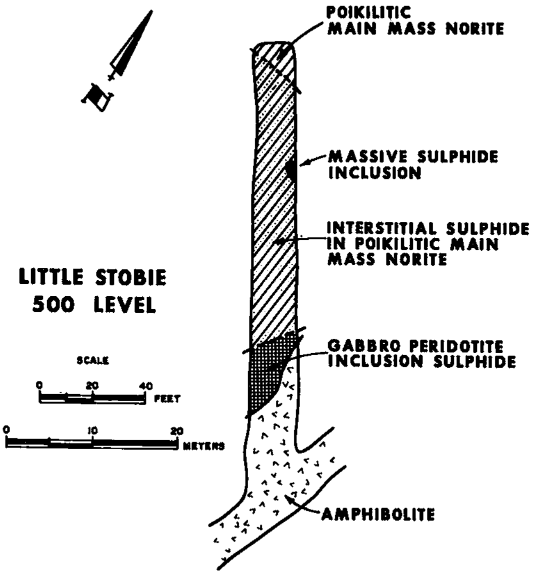


FIG. 13. Map showing position of slab of massive sulfide occurring as an inclusion in weakly mineralized basal Irruptive norite, Little Stobie mine.

Irruptive age for the sublayer. Inclusions of mafic norite in leucocratic breccia are rare and are probably attributable to late-stage intrusive re-adjustments subsequent to Irruptive intrusion and crystallization.

RELATIONSHIP OF IGNEOUS SUBLAYER TO LEUCOCRATIC BRECCIA

The interrelationships between the two major facies of sublayer are complex. The various units of the sublayer on the North Range normally have spatial relationships as shown in Figure 14. A complete section through an idealized sublayer occurrence would consist from top to bottom of: i) contaminated hybrid basal Irruptive, ii) igneous sublayer, iii) leucocratic breccia, iv) megabreccia, and v) Sudbury brecciated footwall. Relationships at the top and bottom of this sequence have been described above. Commonly the contact between igneous sublayer and leucocratic breccia is gradational over a few metres (Souch *et al.* 1969). Equally commonly, however, the contact is sharp but without clear evidence of age relationships. Greenman (1970) has suggested that one facies of the leucocratic breccia has intruded along the base of the igneous sublayer of the Strathcona mine incorporating much of the igneous sublayer, including sulfide and exotic inclusions. Relationships along the Foy offset suggest an essentially contemporaneous emplacement of the two facies and it seems likely that in most instances this simultaneous emplacement, followed by mutually intrusive readjustments, provides the best answer to the problem.

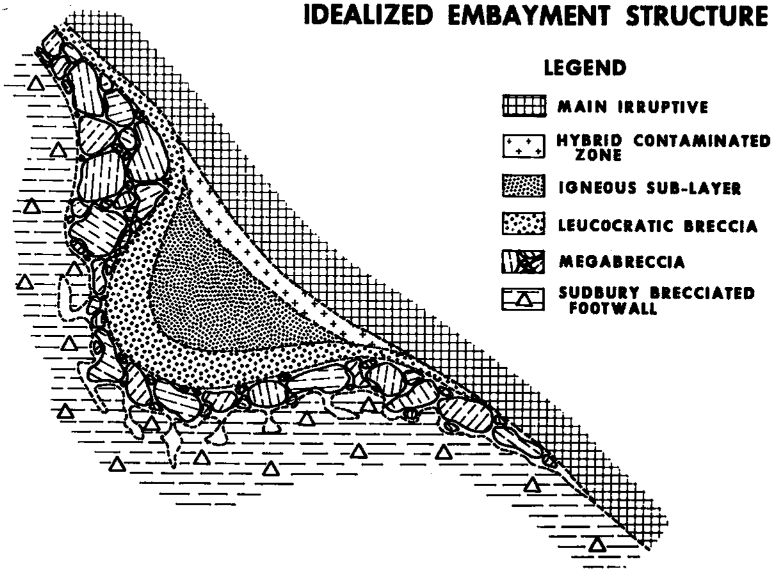


FIG. 14. Cross-section through an idealized sublayer occurrence on North Range of the Sudbury structure.

Description of Individual Sublayer Bodies

The deposits described here have been selected to show the range of morphologies and lithologies present in the sublayer environment. Most are on the North Range of the Irruptive, remote from the thermal and dynamic effects of the Penokean and Grenville orogenies which have variously affected the South Range.

Whistle offset

The Whistle deposit is at the extreme northeast corner of the Irruptive (Fig. 15). Sublayer rocks overlain by basal Irruptive mafic and felsic norites to the southweast occupy a funnel-shaped depression in the footwall which merges into a poorly defined offset dyke to the northeast.

The contact between the Irruptive and the sublayer is not exposed but borehole data show that there is an accumulation of mafic norite in small depressions in the sublayer contact, which suggests that the Irruptive is younger than the sublayer. This interpretation is supported by the presence of mineralized sublayer inclusions and disseminated sulfide in felsic norite and the apparent truncation by the Irruptive of internal contacts in the sublayer.

A well-defined zonation of sublayer rock types exists within the funnel; zones of orthopyroxene-rich and of olivine-bearing igneous sublayer occupying the core of the funnel are succeeded by progressively more siliceous varieties of igneous sublayer as the footwall contacts are approached. A few patches of leucocratic breccia found along these contacts have gradational relationships with the igneous-textured phase. A portion of the offset is occupied by a variety of leucocratic breccia phases and by areas of quench-textured igneous sublayer (Fig. 16). The breccias are very unusual in that they bear close resemblance to the

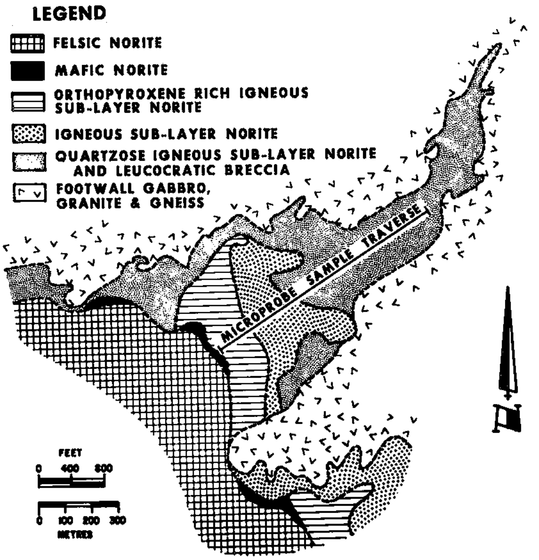
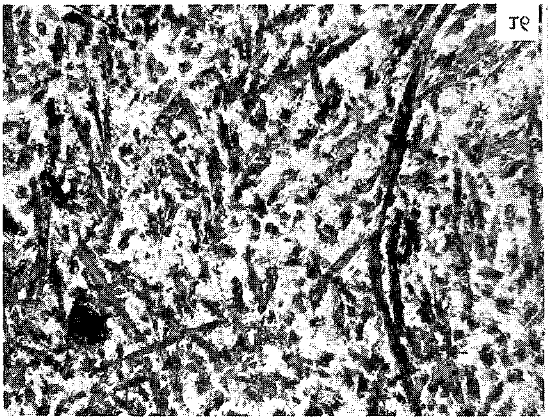


Fig. 15. Geological map of the Whistle embayment.



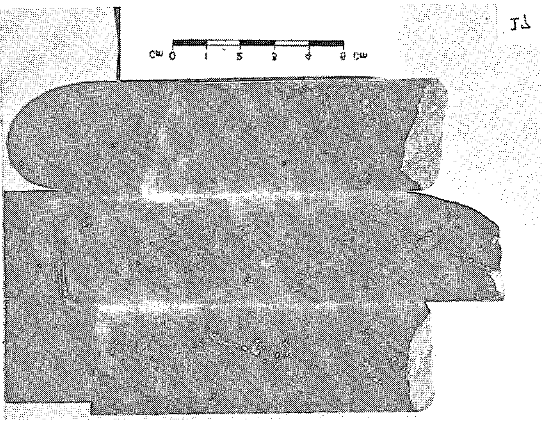


Fig. 16. Photomicrograph of quench-textured igneous sublayer, Whistle embayment. X50, plane light.

Fig. 17. Leucocratic breccias from the Whistle offset that resemble the basal breccia of the Onaping Formation. The core specimen at the bottom contains a dykelet of green glass that is very similar to glass found in the Onaping Formation.

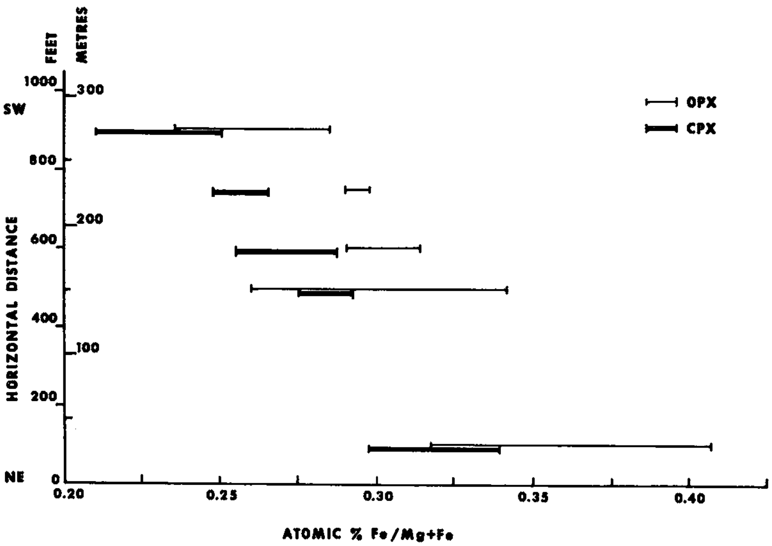


FIG. 18. Pyroxene compositions along a southwest–northeast traverse through the Whistle embayment (Hewins 1971b).

basal breccias of the Onaping Formation described by Peredery (1972). One example of rock indistinguishable from green Onaping Formation glassy breccia has been found within the offset. This evidence strongly suggests a genetic relationship between the leucocratic breccias and the Onaping Formation (Fig. 17).

Pyroxene microprobe analyses (Fig. 18) show that there is a definite iron enrichment in both ortho- and clinopyroxene as the footwall, or base of the funnel, is approached. This, together with the modal silica enrichment trend noted above, seems to be a typical feature of igneous sublayer.

Foy offset

The Foy offset (Fig. 19) is a typical offset dyke extending outward from the base of the Irruptive for some 20 km. It is about 400 m wide at the proximal end where it merges into a typical marginal sublayer deposit of the type described below. A well-exposed contact between leucocratic breccia and main Irruptive felsic norite at the southern contact of the offset is knife-sharp but provides no evidence regarding relative ages of Irruptive and sublayer.

For a distance of about 800 m from its contact with the Irruptive the offset consists of

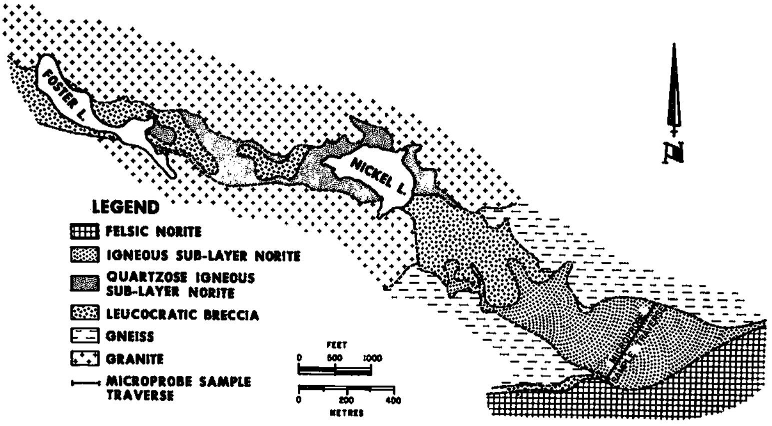


FIG. 19. Geological surface plan of the southern end of the Foy offset.

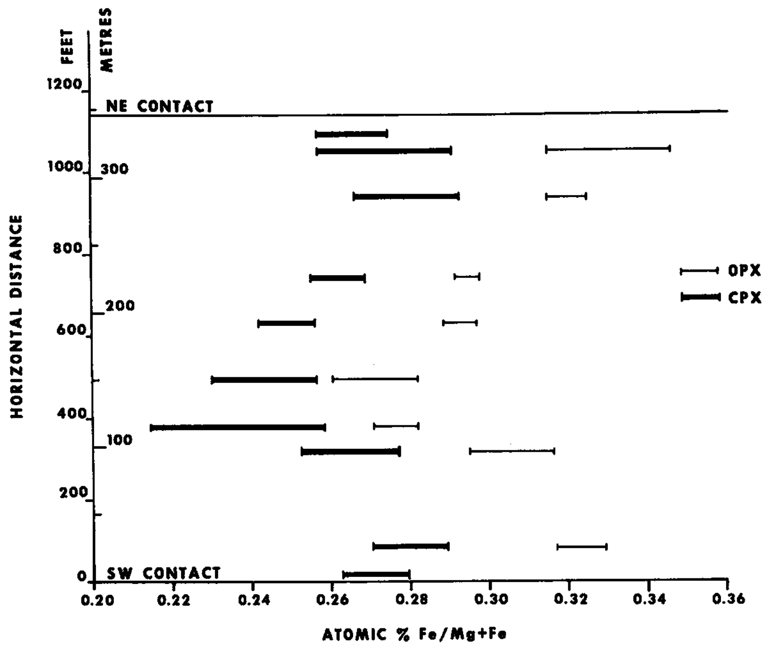


FIG. 20. Pyroxene compositions along a southwest–northeast traverse across the Foy offset (Hewins 1971b).

igneous sublayer made up of a core of quartz-poor material mantled by progressively more quartz-rich varieties adjacent to both contacts. This is analogous to Whistle although not to the same extremes, as orthopyroxene-rich and olivine-bearing varieties have not been recognized in the Foy offset. A rather peculiar alternation of leucocratic breccia and igneous sublayer bodies extends northwestward for a distance 2 km from the end of this body of igneous sublayer (Fig. 19), a pattern difficult to explain except by simultaneous emplacement of breccia and igneous material. The average chemical compositions of igneous sublayer and leucocratic breccias, moreover, are virtually identical (Table 2). The distal portions of the Foy offset show the more common pattern of relatively sulfide-deficient and inclusion-poor marginal zones enclosing a core of sulfide- and inclusion-rich material. These relationships are well illustrated at the now-defunct Nickel Offsets mine, 10 km northwestward along the offset from the Irruptive contact.

Microprobe analyses of pyroxenes from a

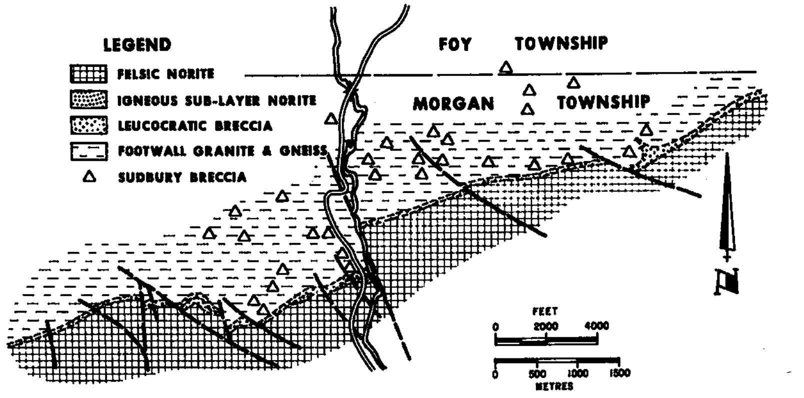


FIG. 21. Geological surface plan of Morgan Township sublayer.

section across the mouth of the offset (Fig. 20) show that the marginal quartz-rich rocks contain more iron-rich pyroxenes than the relatively quartz-poor varieties in the core. This is very similar to the result obtained from the Whistle offset.

Morgan Township sublayer

This 7 km stretch of the Irruptive contact is typical of areas of the North Range where no major embayments or offsets occur (Fig. 21). The sublayer is present as a continuous thin sheet 20–100 m in thickness with leucocratic breccia as the dominant sublayer component. Only a few small discontinuous patches of igneous sublayer are present along this stretch of the contact, lying as usual between basal Irruptive and leucocratic breccia.

Creighton embayment

The Creighton embayment is a trough-like depression in the South Range footwall that extends downward for at least 3 km and at the surface is approximately 1 km deep. Most of the embayment is filled with sulfide- and inclusion-bearing quartz-rich Irruptive norite. The sublayer rocks occupy the margins of the trough as an irregular branching sheet up to 150 m thick between the contaminated quartz-rich norite and the footwall (Fig. 22). Relationships are not clear here, but the contaminated, sulfide- and inclusion-rich nature of the quartz-rich norite suggests an emplacement later than the sublayer.

The Creighton sublayer, in common with many South Range embayment deposits, shows clear evidence of gravitative differentiation *in situ*. Massive sulfide, with few country-rock or exotic xenoliths, occupies the base of the embayment and fills fractures in the footwall. This grades upward, by increase in inclusion content and in igneous sublayer matrix, to increasingly silicate-rich facies of the sublayer known as gabbro–peridotite inclusion sulfide and ragged disseminated sulfide (Souch *et al.* 1969).

Figure 23 portrays the trends in pyroxene composition in one section through the basal Irruptive norite and the sublayer norites where trends similar to the North Range examples are seen. As in the North Range examples discussed above, evidence for iron enrichment towards the footwall is present. Data for a second section through the Creighton sublayer show a much more erratic distribution of pyroxene compositions. This is possibly similar to the Strathcona data discussed by Naldrett & Kullerud (1967) and Hewins (1971a).

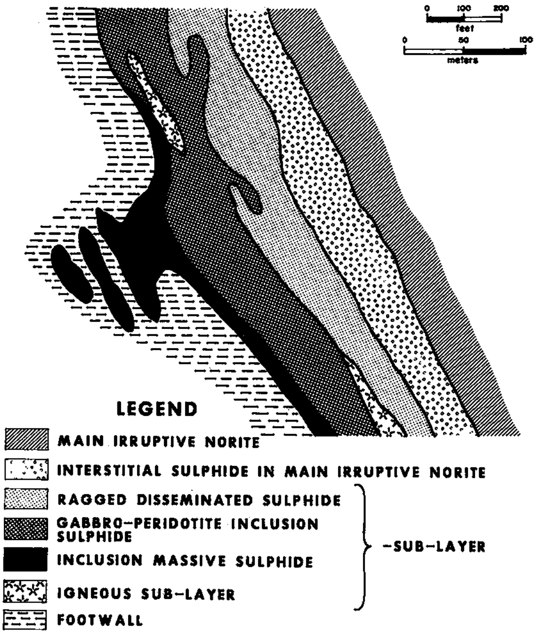


FIG. 22. Geological cross-section through the Creighton embayment (after Souch *et al.* 1969).

DISCUSSION

Any theory that purports to explain the origin and emplacement history of the sublayer should be compatible with the following points: (i) Formation of the Sudbury structure by hypervelocity asteroidal impact and impact-induced triggering of the various related intrusive events, *i.e.*, sublayer and Irruptive. (ii) The early age of the sublayer *vis-à-vis* the Irruptive. (iii) The consistent internal stratigraphy of the sublayer, *i.e.*, the general tendency, most clearly seen on the North Range, for an essentially continuous sheet of leucocratic breccia to lie on the footwall and to be overlain in turn by pods and lenses of mafic igneous sublayer. In addition it must explain: (iv) The fragmental nature of some of the disseminated and blebby sulfides in the leucocratic breccias. (v) The origin of the exotic inclusions. (vi) The contrast between the igneous texture of the mafic sublayer, which presumably has a relatively high liquidus temperature, and the metamorphic texture of the leucocratic breccia which should have a low temperature of formation.

In situ magmatic precipitation of sulfide from the Irruptive or sublayer, hydrothermal replacement, sulfurization or like processes seem unlikely to account for the Sudbury orebodies.

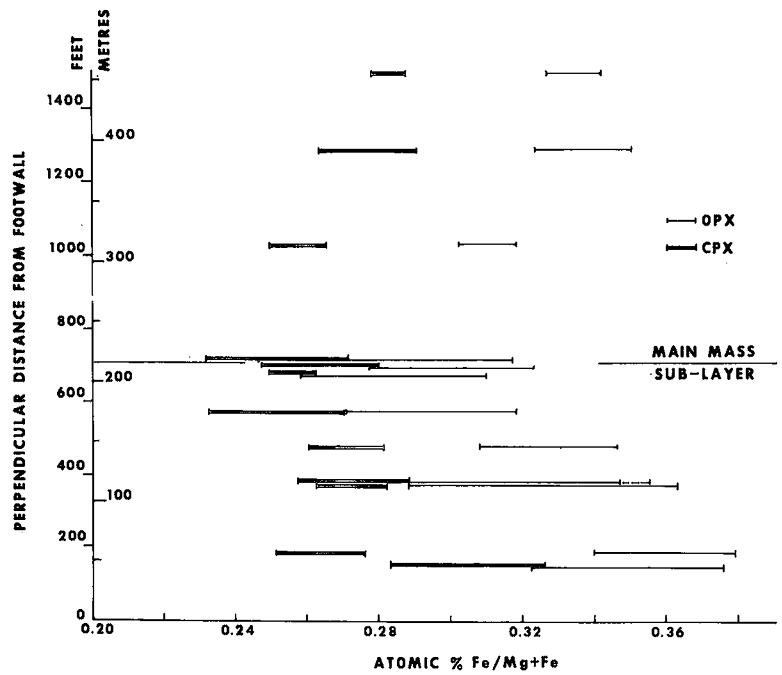


FIG. 23. Pyroxene compositions in the sublayer and basal main Irruptive of the Creighton embayment (Hewins 1971b).

Similarly there is no evidence for a cosmogenic origin for the ores although the Sudbury structure is evidently an impact site.

Sudbury is situated on a belt of the earth's crust that contains numerous copper-nickel sulfide-bearing mafic intrusions (Guy-Bray 1972, Card & Pattison 1973). This belt extends from Duluth in the southwest to Cobalt in the northeast. Furthermore, it has been shown above that there are three suites of such mafic intrusions (and source rocks in the upper mantle) which may have underlain a major portion of the Irruptive. These are the Nipissing diabase, the gabbro-anorthosite complexes and the layered mafic igneous (?) rocks of the Levack complex, all of which predate the Irruptive. The presence of the Sudbury orebodies themselves is sufficient evidence to show that the crust-mantle below the Irruptive was rich in Fe–Ni–Cu and sulfur, and required only the appropriate conditions for collection and emplacement of sulfides. Two hypotheses are compatible to a greater or lesser extent with the criteria (i) to (vi) listed above.

1) The sublayer could represent an early, sulfide-enriched segregation or differentiate formed in equilibrium with mafic and ultramafic layers in the Irruptive magma chamber. This fraction was then injected along the unconformity between footwall rocks and overlying Onaping Formation, stoping off fragments of hidden Irruptive and footwall to form the inclusion suite. The observed rock and mineral zoning patterns arose by progressive assimilation of brecciated crustal material along the lower contact of the sublayer intrusions. A second intrusive pulse of felsic residual magma followed the sublayer and crystallized to form the exposed Irruptive. The impact served only as a trigger mechanism for these relatively conventional magmatic processes. Heat from the energy of impact and lowering of the liquidus temperature due to crustal unloading fused large quantities of Fe–Ni–Cu sulfide-rich crust–mantle material, but impact played no direct part in emplacement of the sublayer. This hypothesis satisfactorily explains the timing of intrusive events between the sublayer and the Irruptive, the presence of apparently exotic blocks within the sublayer and the generation of a sulfide-enriched magma. It is also consistent with meteorite impact. It is not, however, compatible with points (iv) and (vi) listed above.

2) An alternative model satisfies the criteria

but requires a more intimate involvement of impact-related phenomena and, because of the time constraints imposed by the impact hypothesis, presents problems of sulfide concentration. Schematic representations of the suggested pre-impact geology, the maximum development of the impact crater and the final post-Irruptive geometry are given in Figure 24. The igneous sublayer is visualized as a mixture of sulfide-rich impact melt and brecciated basic and ultrabasic footwall rocks derived from the deeper levels of the crater structure to a maximum depth of 30 km (Dence 1972). This depth is in agreement with the nature of the ultramafic exotic inclusions; MacGregor (1968) has shown that xenoliths from greater depths than this should be spinel-bearing, which is not the case at Sudbury. The country rocks involved in the formation of these impact melts are known to have been sulfide-rich and capable of producing sizeable quantities of magmatic sulfides. However, as crater formation and melt emplacement would be virtually instantaneous, considerable restraints are imposed on the time available for sulfide accumulation. One possibility, and perhaps the most likely, involves derivation of the sulfides from pre-impact magmatic concentrations in basic to ultrabasic rocks lying in the zone of impact melting near the base of the crater. These concentrations need not have been of high grade as it seems possible that unique impact-related processes such as differential acceleration of phases of differing density (silicate ~ 3.0, sulfide ~ 5.50) could act as highly effective mechanisms for winnowing sulfide from associated silicate material (Dietz 1972). Again, this is an aspect of Sudbury geology that obviously requires much additional study.

The leucocratic breccia was formed by attrition of the shocked and brecciated rocks (the migmatitic and granitoid rocks of the Levack complex and Cartier granite) as the igneous sublayer (melt) moved rapidly up the wall of the crater (Dence 1972). Progressive contamination of the melt by entrained crustal material along its lower contact caused the observed upside-down chemistry evidenced by the trends of silica enrichment and iron enrichment in pyroxenes toward the footwall. Similarly, the leucocratic breccia incorporated material, including xenoliths and fragments of sulfide, from the melt. This zone of turbulent mixing between the two products also explains the confused contact relationships exhibited between the two main facies of sublayer. The usual relationships of leucocratic breccia overlain by igneous sublayer is an example of the overturned stratigraphy commonly seen along impact crater walls. The anomaly presented by the apparent difference in temperature attained by the two facies is explained by difference in provenance. The mafic igneous sublayer is derived from hot basic material deep in the structure and requires only a slight increment in temperature to melt. The leucocratic breccias, on the other hand, are derived from the relatively cool regions of the upper crust and thus do not, in general, reach their melting points. The already complex situation existing along the crater wall will be complicated further by postimpact structural adjustments and by the subsequent intrusion of the Irruptive.

This scenario is supported by evidence supplied by the sulfides themselves. When compared to the MgO content of the host silicate matrix, the metal ratios for individual orebodies suggest that the various host rocks as presently constituted are not the parent rocks for the sulfides. All the host rocks, including the most obviously magmatic ones, are deficient in MgO (Fig. 12), although this is explainable, at least in part, by rocks. The textures of the disseminated sulfides, primarily in the leucocratic breccias but also in some of the varieties of igneous sublayer, suggest that at least a portion of the sulfide was emplaced as part of the inclusion population, *i.e.*, as fragments. This is supported by the close spatial relationship of the sulfide with the exotic xenoliths. Because of the erratic temperature distribution within impact-melt bodies, some of the sulfide fragments will melt and sink to form the gravitationally differentiated massive and inclusion-massive ore types typical of the marginal deposits.

The offset deposits are envisioned as being formed by the forceful outward injection of slugs of sulfide-enriched impact melt along zones of impact-induced structural weakness. Flow differentation concentrated the heavy sulfide-bearing material in the central cores of the dykes and gravity settling then produced the vertically oriented pipe-like to lensoid orebodies typical of the offset environment.

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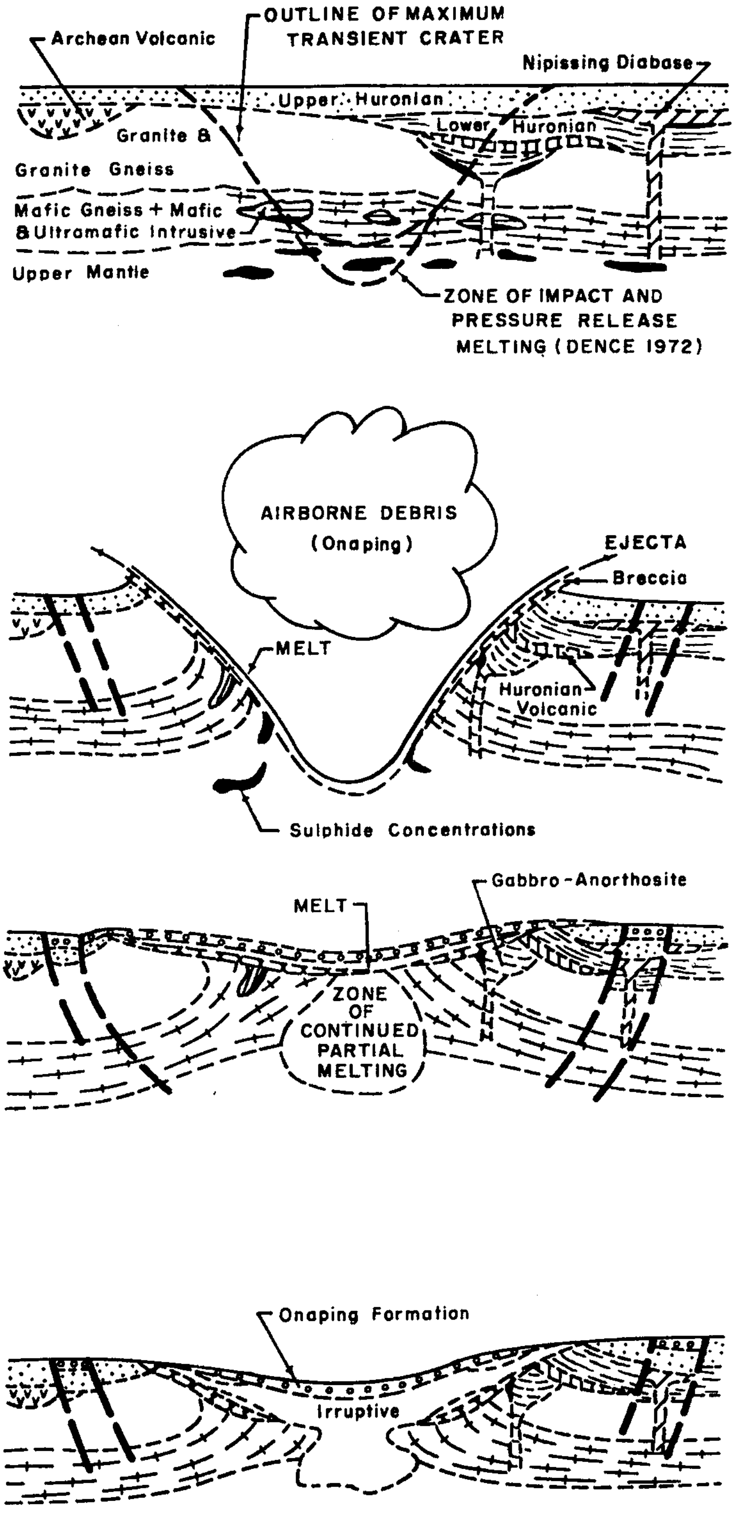

FIG. 24. Schematic representation of the development of the Sudbury structure as the result of a hypervelocity impact.

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