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A HISTORY OF OUR UNDERSTANDING OF MAGMATIC Ni–Cu SULFIDE DEPOSITS

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ABSTRACT

Progress in the understanding of the origins of magmatic Ni–Cu sulfide deposits underwent a major acceleration with the advent of the 1960s. Prior to this decade, thinking had largely been influenced by observations on the Sudbury area, in Ontario, which was by far the dominant Ni producer. Discussion focused on the nature of the Sudbury Igneous Complex, and whether the ores were gravitational segregates from the complex, or whether they had been introduced by hot aqueous fluids. During the 1960s, the concept that Sudbury is an astrobleme was first proposed, the discovery of the Talnakh ore junction (Russia) elevated Noril'sk from minor to major status, and a new class of deposit related to komatiitic volcanism was recognized at Kambalda (Australia). The 1960s were also a turning point with respect to research funding, which led to an explosion both in the amount of research conducted, and in its global nature. Thereafter, progress was stimulated by the new thinking about Sudbury, and the very different environments of ore deposition observed at Noril'sk and Kambalda. It has turned out that a number of broad themes have evolved under which much of the progress over the past 40 years can be grouped. (i) Magmas rising directly from the mantle are unlikely to reach crustal depths saturated in sulfide, and contamination with crustal rocks is required for sulfide immiscibility to occur early in the crystallization process. (ii) With appropriate experimentally derived partition-coefficients, the relationship between the compositions of magma and sulfide can be modeled, and this modeling provides important constraints on geologically based hypotheses. (iii) The development of sulfide immiscibility commonly leaves a mark on the composition of the source magma and the rocks crystallizing from it that can act as a signpost for exploration. (iv) Sudbury is unique, probably because of the high degree of superheat that it experienced; sulfides have settled and accumulated over much of the base of the complex; in most other deposits, it has been the flow of magma carrying immiscible sulfides that has caused the sulfides to concentrate in economically exploitable proportions. The physical environment represented by a given part of an igneous body is therefore important when considering its potential. (v) Once concentrated, sulfide magmas cool and fractionate, and the fractionated residual liquid may migrate away from the initial site of crystallization to form rich concentrations of Cu, Pt, Pd and Au elsewhere. Observations at Voisey's Bay (Canada) over the past 10 years have confirmed the importance of these five themes.

Keywords: magmatic sulfides, history, nickel, copper, sulfide concentration, chalcophile-element depletion, sulfide fractionation, magma contamination.

SOMMAIRE

Du point de vue des connaissances à propos de l'origine des gisements magmatiques de sulfures de Ni–Cu, il y a eu des progrès importants au cours des années soixante. Avant cette époque, les interprétations ont été fortement influencées par les observations faites à Sudbury (Ontario), camp minier ayant alors la production la plus élevée en Ni. La discussion portait sur la nature du complexe igné de Sudbury, et sur deux hypothèses, que le minerai s'était séparé du magma silicaté par gravitation, ou bien qu'il avait une origine hydrothermale. Au cours de cette même décennie, le concept que Sudbury serait un astroblème a été présenté, la découverte de la culmination minéralisée de Talnakh a élevé le camp de Noril'sk (Russie) à un statut majeur, et une nouvelle classe de gisement impliquant un volcanisme komatiitique a été mise en évidence à Kambalda (Australie). Cette décennie a aussi été un point tournant du point de vue de la disponibilité des fonds destinés à la recherche, même à l'échelle du globe. Par la suite, le progrès dans ces thèmes de recherche a été stimulé par la nouvelle façon de percevoir Sudbury, et les milieux très différents de formation du minerai observés à Noril'sk et Kambalda. Quelques grands thèmes regroupent les progrès des quarante dernières années. (i) Les magmas en ascension directe du manteau sont peu probablement saturés en sulfures lors de leur entrée dans la croûte. Une contamination par les roches de la croûte serait donc nécessaire pour promouvoir l'immisciblité d'un liquide sulfuré tôt dans la cristallisation du magma. (ii) La relation entre le magma et le minerai dépend des coefficients de partage appropriés, déterminés expérimentalement. De tels modèles fournissent des contraintes importantes pour l'évaluation des hypothèses fondées sur les relations de terrain. (iii) Le développement de l'immiscibilité d'un liquide sulfuré laisse sa marque sur la composition du magma silicaté et les roches qui en sont dérivées, de sorte ces changements peuvent servir à des fins d'exploration. (iv) Sudbury serait un cas unique à cause de sa température très élevée, au delà du liquidus; les sulfures ont alors pu s'accumuler par gravitation à la base du complexe, tandis que pour la plupart des autres complexes minéralisés, c'est le flux

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d'un magma portant une fraction sulfurée immiscible qui a permis aux sulfures de s'enrichir jusqu'à des teneurs économiquement intéressantes. Les aspects physiques du milieu sont évidemment importants dans l'évaluation du potentiel d'un complexe igné quelconque. (v) Une fois concentrés, les magmas sulfurés refroidissent et deviennent fractionnés, et le liquide résiduel peut migrer loin du site de cristallisation initial pour former de riches concentrations de Cu, Pt, Pd et Au ailleurs. Les observations à Voisey's Bay (Canada) au cours de la dernière décennie viennent confirmer l'importance de ces cinq thèmes.

(Traduit par la Rédaction)

Mots-clés: sulfures magmatiques, historique, nickel, cuivre, concentration de sulfures, appauvrissement en éléments chalcophiles, fractionnement du liquide sulfuré, contamination du magma.

Introduction

On receiving the invitation to contribute to this 50th Anniversary number of *The Canadian Mineralogist*, I spent some time pondering on what I should write about. Progress is so rapid in research today, that it is the rare paper that is still referenced 15 years after its appearance. Having been involved with magmatic sulfide deposits rather longer than most of the current group of researchers, and having my scientific roots in the era preceding the 1960s when ideas started to change so quickly, I thought it worthwhile to attempt to document where the ideas came from, and how they have evolved up to the present. Hopefully, those working at today's cutting edge may find a quiet moment to reflect on the past.

Initially, I thought that I could cover magmatic sulfide deposits in general, that is both those prized for their Ni and Cu as well as those noted for their PGE, but as this paper has evolved, I have come to realize that the PGE-dominant deposits deserve their own account. Many of the principles are the same, but the setting and genesis of the two groups of deposits are very different. I have therefore chosen to focus on magmatic Ni–Cu–(PGE) deposits, and extend my apologies to the platinum-group elements.

The Early Days

An impure form of nickel was first isolated by the Swedish chemist Cronstedt as a result of his work on gersdorffite ore [(Co,Ni,Fe)AsS] from the Los cobalt mine in Sweden. He reported in 1751 that the residue, after removal of the iron and cobalt, and the burning off of the As and S, had the properties of a new semimetal, to which, in 1754, he gave the name "Nickel" (Howard-White 1963).

The earliest recorded magmatic sulfide deposits date from the days when Norway was the world's principal producer of nickel. The Norwegian deposits included those at Espedalen, 250 km north of Oslo, which operated from 1848 to 1855 (Barlow 1904, 1907), and Ringerike, 50 km north of Oslo, where both mining and smelting took place from 1850 to 1893 (Howard-White 1963). Mining also occurred at Flaad, 200 km southwest of Oslo, where a smelter was erected in 1886. Norwegian production reached its peak in 1876, when 360 tonnes was produced (Buck 1968). Commercial production of nickel started from the laterite deposits of New Caledonia in 1875 (Howard-White 1963), and thereafter, production from the Norwegian sulfide deposits went into decline.

Although Alexander Murray, who had served as William Logan's assistant, had drawn attention as early as 1856 to sulfide mineralization at Sudbury, Ontario, in an area that was later to be the site of the Creighton mine (Murray 1857), no systematic exploration was undertaken until massive sulfides were uncovered in the vicinity of the Murray mine in 1883, during construction of the Canadian Pacific Railway. A number of companies then started operations in the Sudbury area, the largest of which was the Canadian Copper Company. Production started in 1886 (Fig. 1). It is ironic to note that the Canadian Copper Company did not realize that they were mining nickel in addition to copper until a shipment of ore sent from the Creighton mine to the Orford Copper Co. in New Jersey proved difficult to smelt, and, on analysis, was shown to contain nickel (Holloway *et al.* 1917)! The nickel proved something of an embarrassment because world demand at the time was only about 1000 tonnes per year, but Samuel J. Ritchie, President of Canadian Copper, had contacts with General B.F. Tracy, Secretary of the US Navy, which resulted in the recognition of the importance of ferronickel alloys in armor plate. By 1905, Sudbury production was exceeding that of New Caledonia.

In 1886, the Geological Survey of Canada followed up on the early work of Murray by sending R. Bell and A.E. Barlow to begin a program of regional mapping. The results of this activity were published in 1891 (Bell 1891a), where the first reference is made to the basinal shape of the Sudbury structure. In a concurrent publication, Bell (1891b) described the ores and proposed that they are the result of the differentiation of the magma responsible for the Sudbury Igneous Complex (SIC), and separation and settling of a dense sulfide melt. Barlow (1904, 1907) recognized the subdivision of the SIC into two principal units, a lower noritic and overlying granophyric layer, and the occurrence of the orebodies in embayments along the lower contact of the norite, and also supported the idea of settling of sulfide liquid. A.P. Coleman commenced mapping for

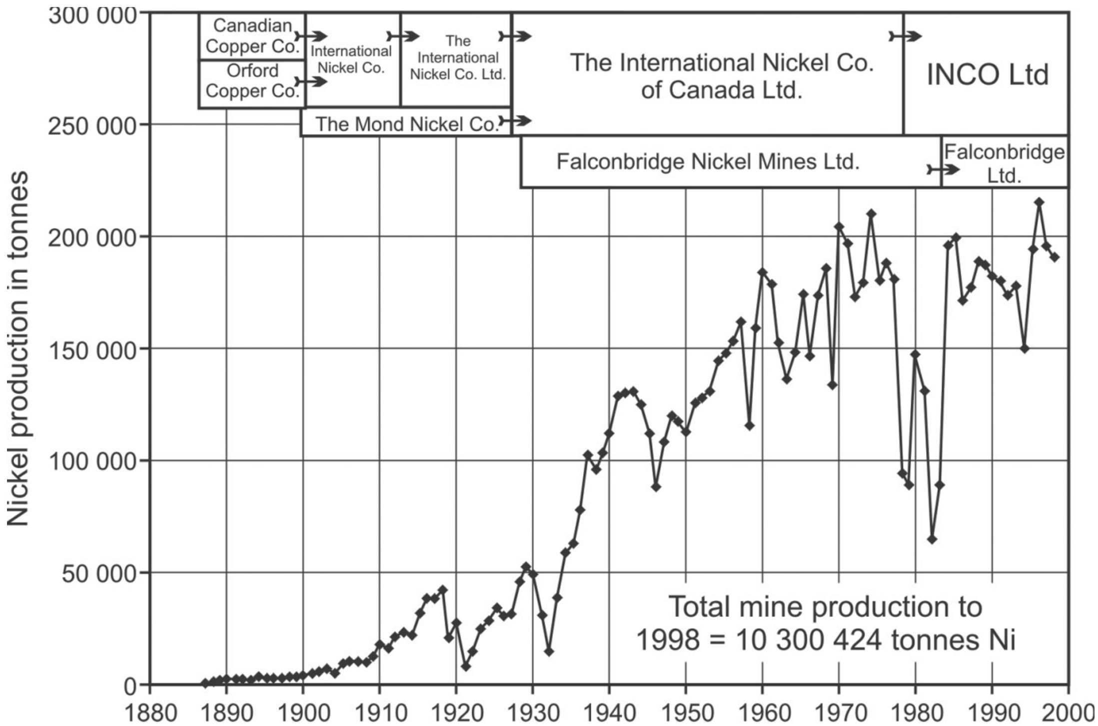
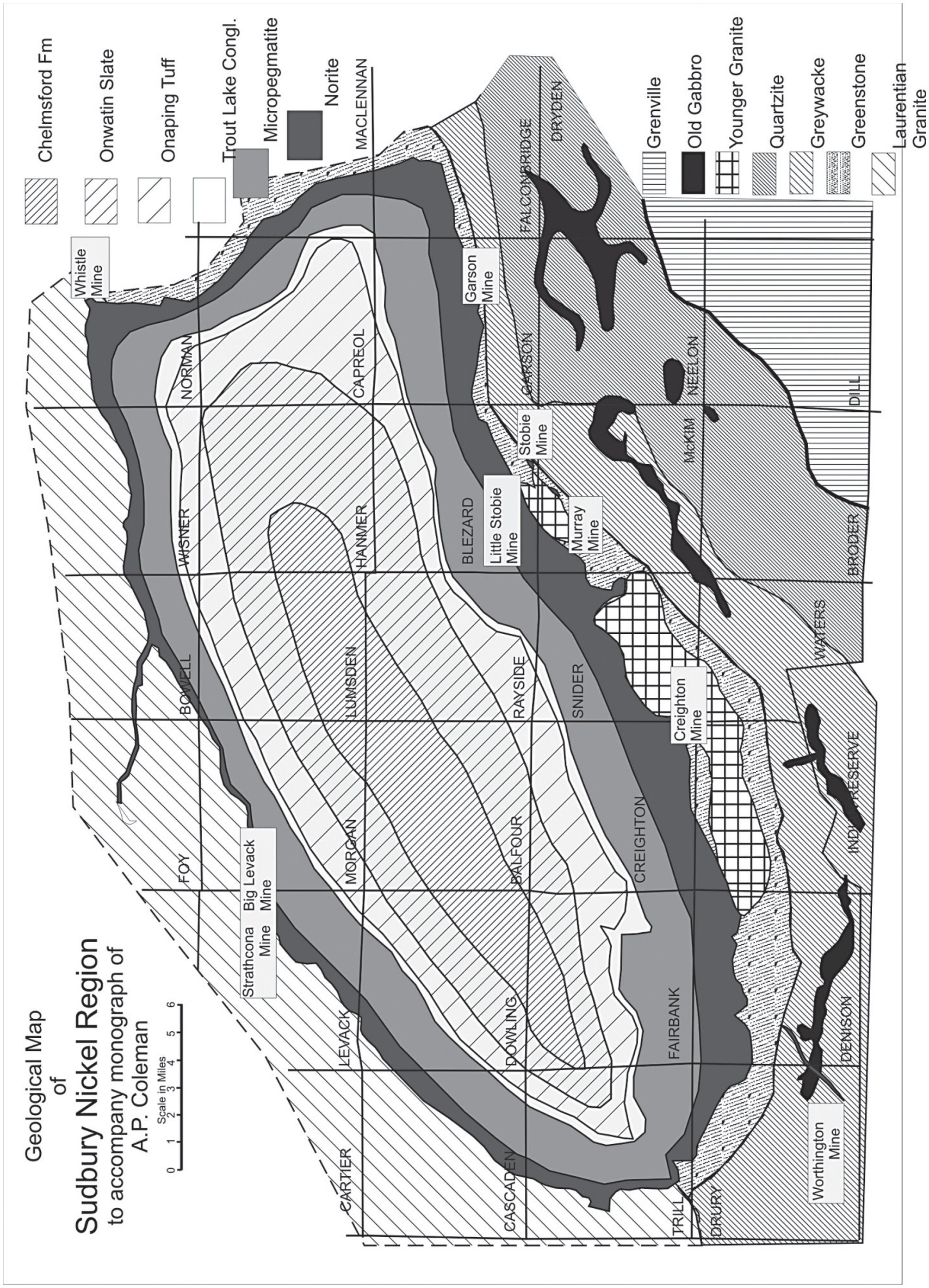


FIG. 1. Production of Ni metal from the Sudbury district, together with the companies responsible for the production. Arrows show the results of restructuring and mergers.

the Ontario Bureau of Mines in 1902. His initial map (Coleman 1905) was the first to show that the SIC outcrops around the whole of the Sudbury basin, and, in fact, defines the structure. He argued that the SIC had been intruded as a sill along the contact between the overlying breccias and metasedimentary units, which he correlated with the Animikie of the Lake Superior area, and older basement rocks. His revision of his 1905 map (Coleman 1913), of which a simplified copy is shown here as Figure 2, differs very little in the disposition of the rock types from the current map. Coleman was perhaps the most ardent advocate of gravitationally induced settling of sulfide liquid as a mechanism in part responsible for the origin of the ores. His arguments included the restriction of the sulfides to the outer (*i.e.*, lower) contact of the Sudbury Igneous Complex, the intimate mixture of sulfide and norite in all proportions, the lack of hydrothermal alteration, and the occurrence of the largest concentrations of sulfides in embayments of the lower contact into the footwall.

The magmatic viewpoint of the early field geologists at Sudbury did not go unchallenged. Dickson (1903) suggested that the mineralization had been deposited by hot aqueous fluids. C.W. Knight, in his contribution to the Report of the Royal Ontario Nickel Commission (Knight 1917), described the deposits, pointed to the almost universal occurrence of the ores in breccias in which partial replacement of the fragments could be observed, and concluded that they are hydrothermal in origin. In a footnote, he cited a review of Ni–Cu deposits by Tolman & Rogers (1916), who concluded that "ores of this class throughout the world have been introduced at a late magmatic stage by mineralizers, and that the ore minerals replace silicates" (Knight's words). Wandke & Hoffman (1924) made an extensive microscopic study of samples from Sudbury and also concluded that they are hydrothermal in origin.

Although many early investigators regarded the SIC as the product of differentiation of a single magma, starting with Knight (1917), the high proportion of granophyre to norite started to bother geologists, as did the absence of what they regarded as "Animikie"-type strata (the Onaping, Onwatin and Chelmsford formations) outside the structure. Knight (1917) proposed that the Sudbury basin is a caldera, that the center of the structure had collapsed, carrying the "Animikie" formations with it, and thus preserving them from the erosion that had removed them outside basin (Fig. 3b). He suggested that the norite and granophyre were not units of a sill, but rather two ring-dyke-like injections


Geological Map
of
Sudbury Nickel Region
to accompany monograph of
A.P. Coleman
Scale in Miles
0 1 2 3 4 5 6
Chelmsford Fm
Onwatin Slate
Onaping Tuff
Trout Lake Congl.
Micropegmatite
Norite
Grenville
Old Gabbro
Younger Granite
Quartzite
Greywacke
Greenstone
Laurentian Granite
Whistle Mine
Garson Mine
Stobie Mine
Little Stobie Mine
Murray Mine
Creighton Mine
Big Levack Mine
Strathcona Mine
Worthington Mine
MACLENNAN
FALCONBRIDGE
DRYDEN
NORMAN
CAPREOL
CARSON
NEELON
DILL
McKIM
WISNER
HANMER
BLEZARD
BRODER
BOWELL
LUMSDEN
RAYSIDE
SNIDER
WATERS
FOY
MORGAN
BALFOUR
CREIGHTON
RESERVE
LEVACK
DOWLING
FAIRBANK
DENISON
CARTIER
CASCADEN
TRILL
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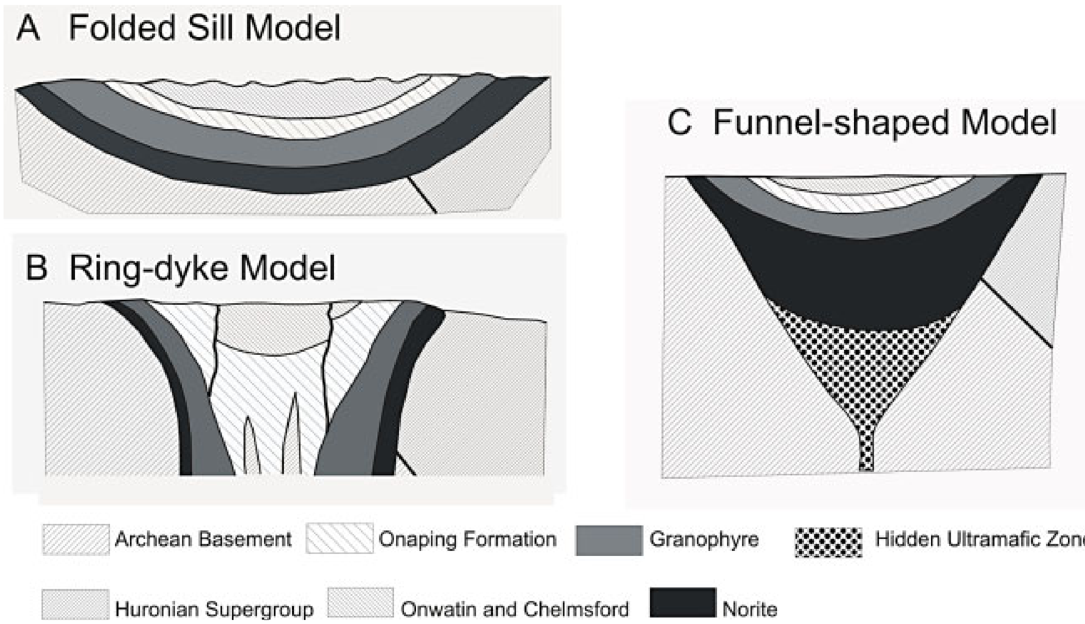


FIG. 3. The folded sill, ring-dyke and funnel-shaped intrusion models that dominated early thinking about the Sudbury Igneous Complex.

of magma up the circular fracture system encircling the collapse. The relative proportions of granophyre and norite continued to concern geologists well into the 1950s. Phemister (1926) endorsed Knight's viewpoint of two ring-dyke injections, re-affirming this view 10 years later (Phemister 1937). W.H. Collins of the Geological Survey of Canada undertook one of the most exhaustive studies of the SIC ever published (Collins 1934, 1935, 1936, 1937), and concluded that it is a differentiated sill from which dense sulfides had settled to form the ores. Wilson (1956) sought to address the question of the relative proportions of granophyre and norite by proposing that the SIC has the form of a lopolith, a funnel-shaped intrusion, and that the high proportion of granophyre exposed at surface is counterbalanced by a mass of ultramafic rock hidden at depth (Fig. 3C). This view was challenged by Thomson & Williams (1959) who, in their paper "The myth of the Sudbury Lopolith", reaffirmed the caldera model. They pointed to the enormous release of energy that was required to form the Onaping Formation, and suggested that it consists of a series of glowing avalanche deposits (*i.e.,* pyroclastic flows) into the caldera.

FIG. 2. A simplified copy of A.P. Coleman's (1913) revision of his 1905 map of the Sudbury area (Coleman 1913).

Throughout the 1930s, 1940s and 1950s, arguments about the magmatic *versus* hydrothermal origin of the Sudbury ores persisted, with those who mapped the SIC on the surface tending to favor a magmatic origin (Coleman *et al*. 1929, Collins 1934, 1935, 1936, 1937), and those who were most familiar with the mines [*e.g.,* Yates (Chief geologist of INCO) 1938, 1948; Davidson (Chief geologist of Falconbridge), 1948; and Lockhead (Chief Sudbury Mines geologist, Falconbridge), 1955] favoring a hydrothermal origin.

Whereas most early work was concentrated on the SIC and the ores, the 1950s saw increasing attention being paid to the breccias developed at Sudbury. These include the dykes of Sudbury breccia developed in country rocks external to the basin, and the Onaping Formation within the structure. Speers (1957) concluded that the former were the result of high-pressure fluids related to diatreme or volcanic activity. The early interpretation of Burrows & Rickerby (1930) that the Onaping Formation is volcanic was reinforced, as discussed above, by the work of Thomson (1957) and Williams (1957), who concluded that it was an accumulation of more than 1,200 cubic kilometers of pyroclastic flows, whose abrupt eruption from an underlying magma-chamber had given rise to the subsidence that is now preserved as the Sudbury basin. All geologists of this period recognized that the formation of the Sudbury structure had been accompanied by an enormous release of energy.

The appearance of J.E. Hawley's seminal study, "The Sudbury ores: their mineralogy and origin" (Hawley 1962) convinced the greater part of subsequent generations of mineral deposit geologists as to the magmatic origin of the Sudbury ores. This work comprises a review of previous work and outstanding problems at Sudbury (Part I), an extensive study of sulfide mineralogy conducted and co-authored with R.L. Stanton (Part II), and Hawley's personal conclusions as to the origin of the ores (Part III). This is not to say that all arguments regarding a hydrothermal origin of certain aspects of the mineralization at Sudbury became stifled, as is discussed below.

From the focus of the preceding discussion, it could be assumed that Sudbury was the only magmatic sulfide camp that was significant during the first half of the 20th century. This is not true. In 1921, Finnish geologists, working in conjunction with geologists of the International Nickel Co. Ltd., discovered economically interesting mineralization in the Petsamo area of the Kola Peninsula, which at the time was part of Finland. Following World War II, Petsamo reverted to the USSR, and the area (now called Pechenga) was extensively prospected by Soviet geologists, who discovered numerous deposits in mafic–ultramafic layered intrusions that together comprise the Pechenga ore field.

In 1920–1921, the Soviet geologist Urvantsev, following up on samples that had been brought to Tomsk University by one of the Sotnikov family (a family long established in Taimyr as fur traders), visited the Noril'sk area and recognized the similarity of the mineralization there to that at Sudbury (Kunilov 1994). Urvantsev's visit was followed by intense exploration in the 1920s and 1930s, and a railway was built from Noril'sk 110 km west to the port of Dudinka on the Yenesei River. The railway was completed in 1937, and the first ore was mined from the Noril'sk I intrusion in 1938. Despite some very PGE-rich zones of massive sulfide, the overall grade and tonnage at Noril'sk I were not very high, and it remained until the 1960s for the full potential of the region to be revealed.

Partly as a result of language differences and partly because the geologists concerned were more focused on exploration and mining than on academic studies, details of the geology and the implications of these details on genesis did not enter the mainstream of thinking on magmatic sulfide ores until the 1960s, as is discussed below.

Apart from developments within the Soviet Union, another area was attracting attention, that of the former Transvaal State in South Africa. Platinum was first recorded in chromitite layers of the Bushveld Complex in 1906 by William Bettel (as recorded by Bartholomew *et al.* 1989) and then by Hall & Humphrey (1908). Wagner (1924) reported the presence of sperrylite in the Ni–Cu sulfide ores of the Vlakfontein pipes of the Western Bushveld Complex. It was in 1924 that the Merensky Reef was discovered by A.F. Lombard on the farm Maandagshoek. As recounted by Cawthorn (1999), Lombard, who was an experienced prospector as well as a farmer, noticed a dense white metal in a dry river bed that he suspected was platinum. He sent this to Dr. Hans Merensky, who, after visiting the prospect, raised funds to support further work. The encouragement from this prospecting led quickly, in August 1924, to the discovery of the PGE-bearing ultramafic pipes of Mooihoek and Driekop, and then, in the following October, to that at Onverwacht farther south. It should be emphasized that these pipes, despite their high Pt grade, are not sulfide deposits, and the bulk of the Pt is present as ferro-alloys. For the first six months or so after their discovery, Merensky believed that the Mooihoek and Driekop bodies, along with other PGE-bearing zones in the vicinity, defined a continuous layer, and directed his assistants to prospect on this basis. Continuing prospecting with this erroneous model in mind, Lombard located the Merensky Reef in early September 1924. It remains a matter of active debate whether the mineralization of the Merensky Reef and underlying UG–2 chromitite are, or are not, the result of concentration by magmatic sulfides. Because of this, and because of their very different morphology to Ni- and Cu-rich deposits, PGE deposits are not discussed further in this paper. The development of ideas concerning their origin warrants a separate treatment.

The Beginning of a New Era

In retrospect, the year 1962 represents the end of an era and the beginning of a new one. Not only was it the year when J.E. Hawley's *magnum opus* appeared (as a special number of *The Canadian Mineralogist*), but it was also when the Talnakh deposit was discovered 30 km north of Noril'sk, and when Robert Dietz first came to Sudbury to look for evidence indicative that the Sudbury structure might be an astrobleme. The 1960s also marked the dawn of a new age with respect to the funding of research. October 1957 had seen the launch by the Soviet Union of the first world's satellite, Sputnik 1. The shock waves of this demonstration of technological superiority were felt throughout the West, and funding for all aspects of scientific research increased dramatically in the following 10 years. Organizations such as the NSF of the United States, Britain's NERC and Canada's NRC offered individual scientists the opportunity to obtain funding, subject to peer review, for well-conceived projects. Attendance at conferences became easier, specialized journals appeared and flourished, and organizations such as the IUGS and UNESCO facilitated international cooperation.

In the world of magmatic sulfides, it has turned out that many of the post-1962 advances in understanding have been accomplished through research on certain specific types of deposit, particularly as they are represented by a widespread, but still relatively limited group of major mining camps. These types comprise Sudbury (now recognized as being unique), flood-basalt-related deposits, as characterized by those at Noril'sk–Talnakh, komatiite-related deposits, as characterized by those at Kambalda, Australia, and anorthosite-complex-related deposits, as characterized by those at Voisey's Bay, in Labrador; the importance of these specific mining camps in terms of the estimated value of *in situ* metals (August 2004 prices) is shown in Figure 4. As is clear, the camps serving as type examples are not the only ones of economic importance, but because of their size, the undeformed nature of their geological setting, and the timing of their discovery, most of the new ideas have originated from work conducted on these examples. It has also turned out, perhaps because of the greater opportunities for international communication after 1960, that much of the research has been related to certain broad themes. Progress relating to individual types of deposit, and its relation to the broad themes, are the focus of the remainder of this paper.

Key progress related to each deposit type is summarized chronologically in Figure 5. A fifth column is included in the figure to show the major advances in thinking that have originated as a result of work that is not specific to the individual mining camps, but that has been stimulated by that on the camps. Specific cross-linking themes are distinguished by the use of different fonts and colors in the figure. The themes reflect: (i) how sulfide immiscibility came about in the host magma, specifically the importance of contamination (both sulfide and silicate), (ii) the relationship between magma composition and that of sulfides segregating from the magma, (iii) whether derivation of metals from a magma leaves a trace that can be used in exploration, specifically evidence of chalcophile metal depletion in the host rocks of deposits, (iv) how the sulfides came to be concentrated to mineable proportions, specifically the physical environment in which this has occurred, and (v) what has happened to the mineralization subsequent to its initial concentration, specifically the fractionation of sulfide magma with the development and migration of a Cu-, Pt-, Pd- and Au-enriched residual liquid, or, alternatively, the effect of hydrothermal fluids on an established concentration of sulfide. This last theme is important both in interpreting the representativeness of individual samples from ore bodies, and also in predicting the presence and location of Cu- and noble-metal-enriched zones within a deposit.

THE 1960S

Sudbury

Robert Dietz first came to Sudbury in May 1962. He was a US Navy oceanographer who, as a sideline, had developed an interest in astroblemes, the scars on the Earth's surface left by the impact of meteorites and comets. He had been working on the Vredefort dome in South Africa, and came to Sudbury to look for shatter cones, which he believed were the result of the enormous shock-induced pressures developed on impact. Regrettably, he had selected the wrong environment to investigate that year (as an aside, I should say that I know, because I was the young geologist in the Falconbridge office who was nominated to take him into the

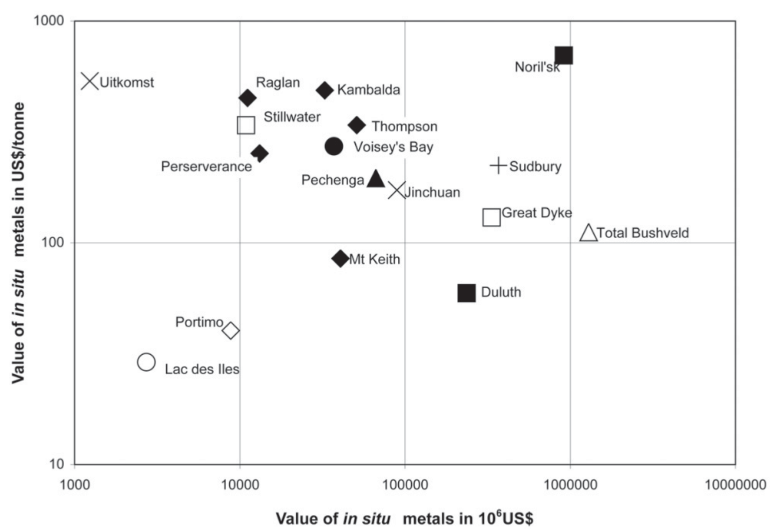


FIG. 4. Plot of the value of *in situ* metals per tonne against total value of a deposit (August 2004 prices). Open symbols: PGE deposits, filled squares: flood-basalt-related, filled diamonds: komatiite-related, filled triangle: ferropicrite-related, ×: magnesian-basalt-related, + impact-related deposits.

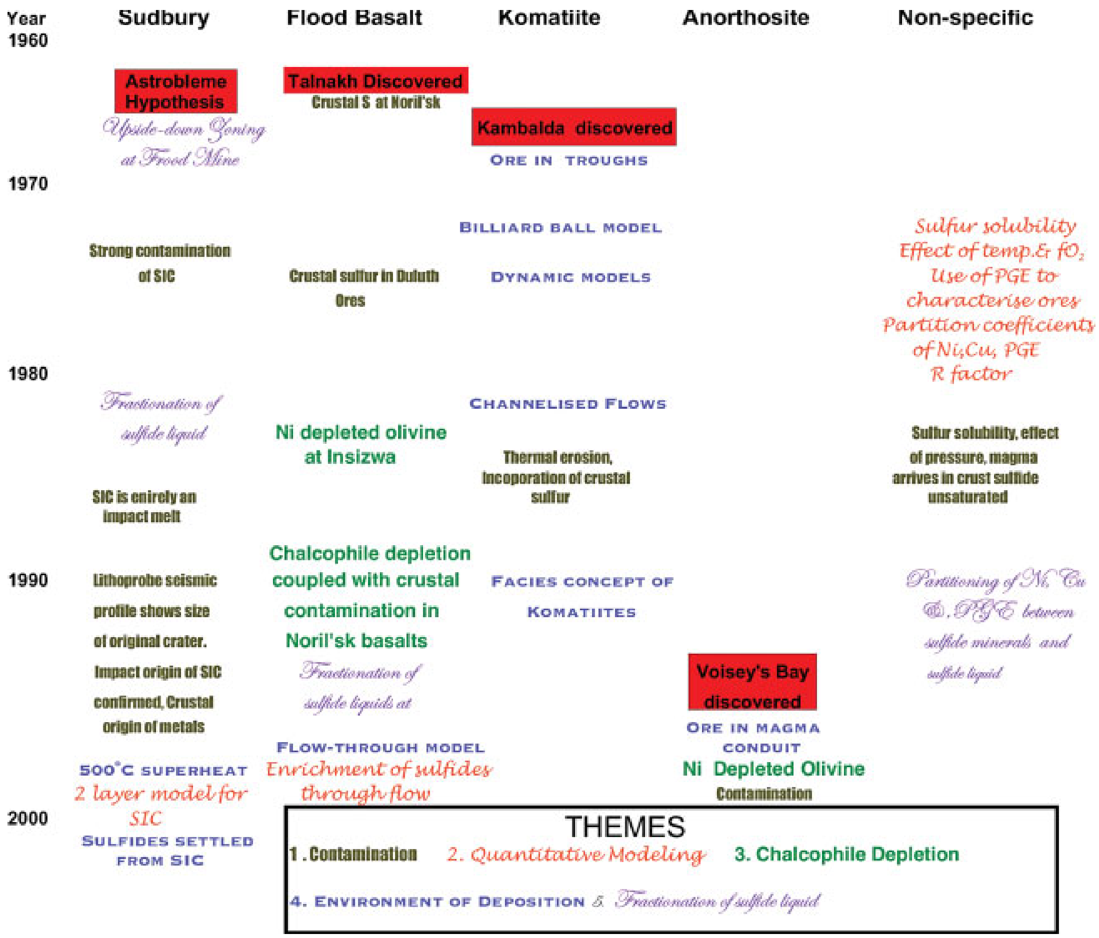


FIG. 5. Key advances in understanding certain major camps cross-referenced (by the use of different fonts) according to five major themes.

field and show him outcrops of the Onaping Formation), but the following year, after more thought, he returned to Sudbury, this time to the INCO field office, and was successful in identifying shatter cones in quartzite south of Kelly Lake. His 1964 paper (Dietz 1964) was the first proposing that the Sudbury structure is an astrobleme. The timing of this paper coincided with the awakening interest of NASA on the types of rock fabrics and structures that astronauts might find on the moon, and many scientists interested in extraterrestrial impact came to Sudbury to test out their hypotheses. The result was that over the next 10 years, visitors and local Sudbury geologists accumulated a tremendous amount of data supportive of the impact origin. These data included the wide distribution of shatter cones in the country rocks around Sudbury (Fig. 6B), the distribution of Sudbury breccia, which is equated to the Vredefort pseudotachylite (breccia dykes that are the consequence of shock melting; Fig. 6A), the presence and distribution of "shock-deformation" structures in quartz (Fig. 6C), and the analogies that can be drawn between the Onaping Formation and impact breccias as they were known from the Riess crater in Bavaria. Continued work on this theme has left very few in doubt that Dietz's hypothesis is fundamentally sound, although most believe that he was wrong in his suggestion that the bulk of the nickel came from the meteorite, since the abundance of copper, the terrestrial relative abundances of the PGE, and the large amount of sulfur in the ores all suggest a more local derivation for the mineralization.

Following his 1962 monograph, Hawley (1965) published a second seminal paper on the Sudbury ores in which he described "upside-down" zoning in the Frood–Stobie deposit. He was the first to suggest that this pattern might be due to fractional crystallization of

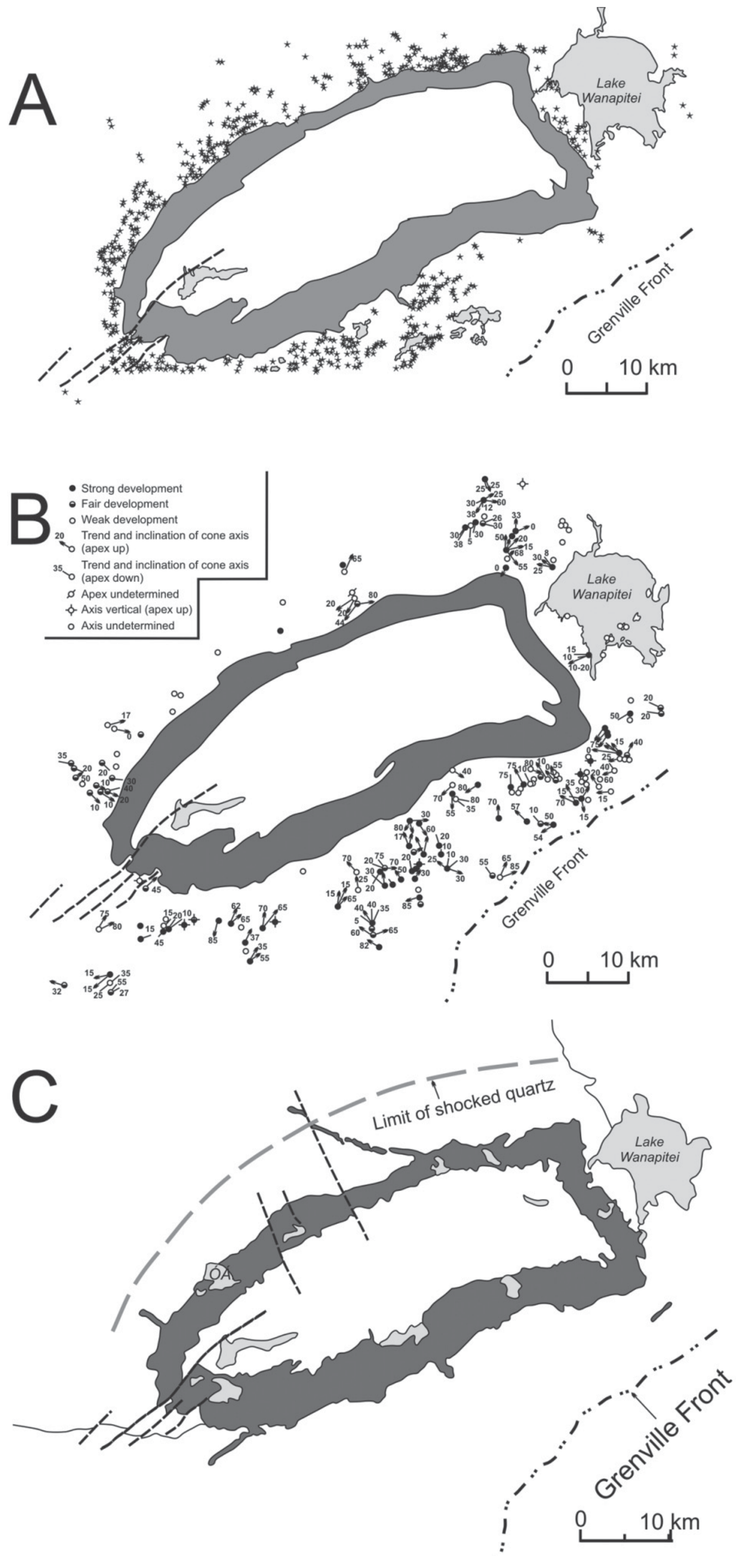


FIG. 6. Evidence supporting astrobleme origin of the Sudbury Igneous Complex. A. Distribution of zones of Sudbury breccia (shown by stars) around the margin of the SIC (after Dressler 1984). B. Distribution of shatter cones and their orientation in Sudbury area (after Dressler 1984). C. Limit of distribution of shocked quartz in the Sudbury area (after Grieve 1994).

a Fe–Ni–Cu sulfide liquid, with the fractionated liquid being expelled downward (theme 5).

Flood-basalt-related deposits

Also in 1962, geologists working for the Noril'sk Nickel Kombinat in Siberia discovered the mineralization at Talnakh, 40 km north of the Noril'sk deposits. It is no exaggeration to say that if this mineralization had not been found, Noril'sk would not feature as strongly as it does in Figure 4, but would be a minor, relatively obscure deposit. It is the enormous richness and variety of the ores of the Talnakh ore junction that have made the Noril'sk area the single most important Ni–Cu–PGE camp in the world.

The Noril'sk area is related to Permo–Triassic volcanism, which constitutes the largest known terrestrial flood-basalt province, amounting to 4×10^6 km^3 (Masaitis 1983). The volcanism followed the 250 Ma collision of the Euro-Americas plate with the Kazakh and Siberian plates, which gave rise to the Ural Mountains, and is thought to be due either to passive rifting due to the change in stress regimes after the collision, or to the development of a plume. The deposits occur in a series of elongate (7–20 km in length, 1–3 km wide), thin (100–300 m) igneous bodies that occur in sedimentary units beneath a 3.5-km-thick sequence of Permo-Triassic lavas. The intrusions, which some geologists regard as feeder conduits for the volcanism (*e.g.,* Godlevsky 1959, Naldrett *et al*. 1995), show a close relationship to a major, transcrustal fault, the Noril'sk–Kharaelakh fault, and have been brought to surface as a result of regional uplift that has affected the original volcanic basin (Fig. 7, regional map). The mineralization occurs as pools of massive sulfide, 10–49 m thick, overlain by 10–50 m of disseminated sulfide (Fig. 8, regional cross-section). Godlevsky & Grinenko (1963) conducted a sulfur isotope study on the ores at Noril'sk, and found high positive values of δ^{34}S, in the range of +6 to +12‰. On this basis, they suggested that much of the sulfur in the Noril'sk ores is of crustal origin (theme 1).

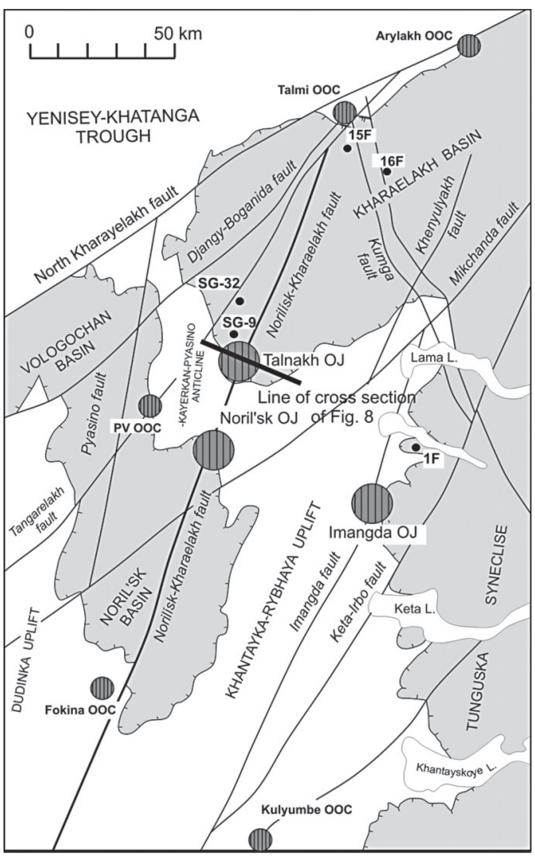
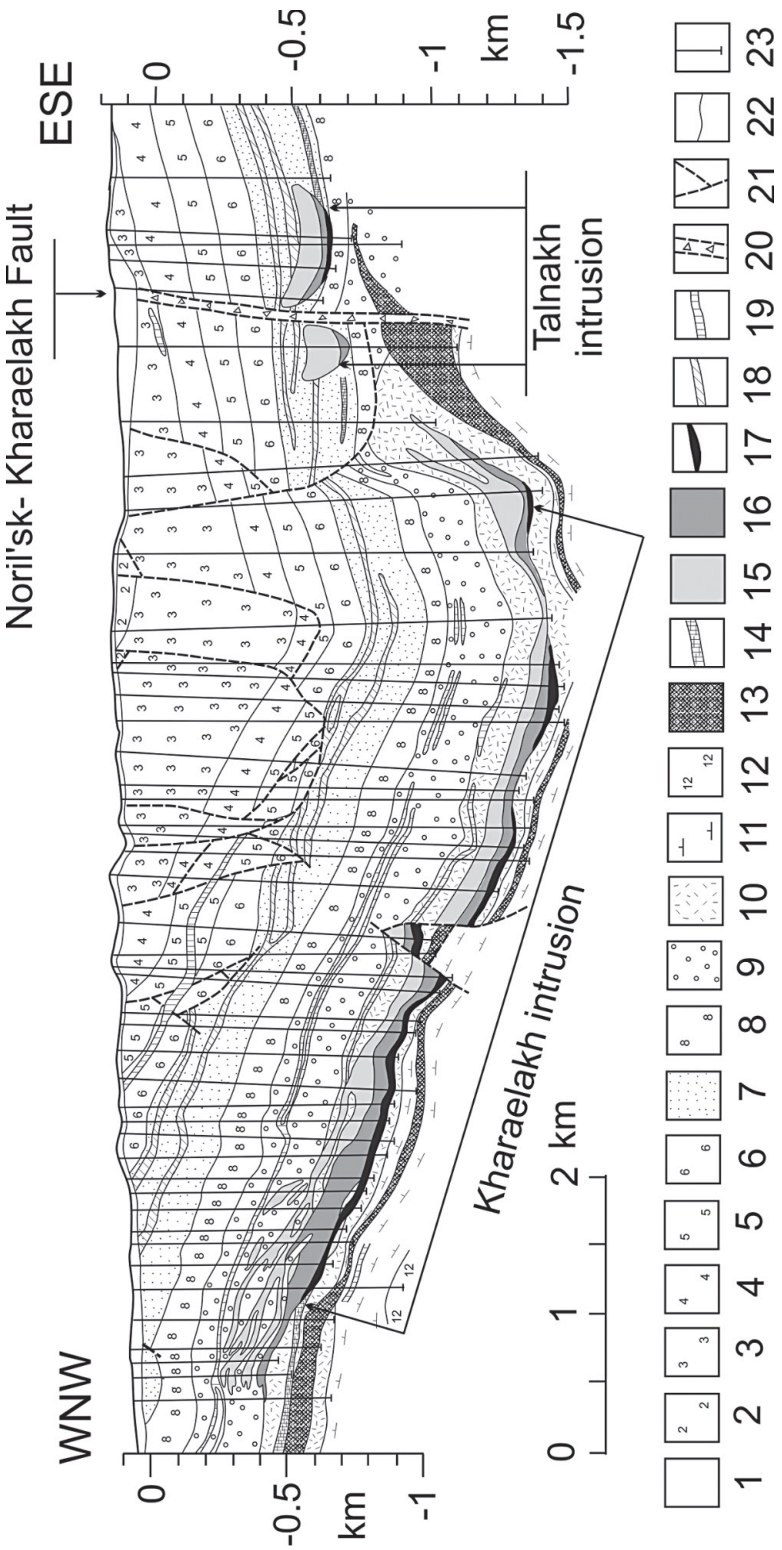


FIG. 7. Main structural elements of the Noril'sk region. The locations of Ore Junctions (OJ) and Ore-Occurrence Clusters (OOC) are shown. Modified after Naldrett *et al.* (1992). PV OOC: Pyasino–Vologochan Ore-Occurrence Cluster.

Komatiite-related deposits

During the 1960s, geologists had become intrigued by rocks in Archean greenstone belts that were characterized by a texture known as "chicken track" texture (Satterly & Armstrong 1949, Satterly 1949, 1951, 1952). It was recognized that the "chicken tracks" were the weathered expression of quenched olivine (Naldrett & Mason 1968). Studies in the Komati River area of the Barberton Mountainland showed that these textures

FIG. 8. East–west geological cross section showing the relationship between the Kharaelakh, Talnakh and Lower Talnakh intrusions. Section compiled by T.E. Zen'ko on the basis of data collected by NKGRE and TsNIGRI, and presented in Naldrett *et al*. (1992). Patterns: 1: Quaternary cover, 2–6: basalts (2: Mr, 3: Nd, 4: Gd, 5: Sv, 6: Iv), 7: Tungusskaya series (terrigenous coal-bearing sediments), 8: Kalargonsky, Nakokhzsky, Yuktinsky suites (Upper – Middle Devonian dolomites, limestones, marls, anhydrites), 9: Manturovsky Suite (Middle Devonian marls, anhydrites, argillites), 10: Kureysky and Razvedochninsky suites (Lower Devonian argillites, marls), 11: Yampakhtinsky, Khrebtovsky and Zubovsky suites (Lower Devonian marls, anhydrites and dolomites), 12: Silurian dolomites, 13: Lower Talnakh intrusion, 14: sills belonging to the Kharaelakh and Talnakh intrusions, 15–17: Kharayelakh and Talnakh intrusions (15: gabbrodolerites, 16: picritic and taxitic gabbrodolerites with disseminated sulfides, 17: massive sulfides), 18: trachydolerite sills, 19: dolerite, 20: Noril'sk–Kharayelakh fault, 21: other faults, 22: formation boundaries, 23: boreholes.



Noril'sk- Kharaelakh Fault
Talnakh intrusion
Kharaelakh intrusion
WNW
ESE
km
2 km

characterize the upper parts of ultramafic lava flows, now known as komatiites (Viljoen & Viljoen 1969), and Pyke *et al*. (1973) described an almost perfectly preserved sequence of spinifex-capped flows in Munro Township, Ontario (Fig. 9). In 1966, sequences of similar rocks, showing the same textures, which to the Australian eye resembled spinifex grass, were found to host Ni sulfide deposits (Woodall & Travis 1969) in the Kambalda dome of the Eastern Goldfields region of the Yilgarn Archean craton of Western Australia. The deposits occur mostly at the base of sequences of ultramafic lavas, within trough-like structures in the underlying basalts, although about 25% of the mineralization occurs at flow contacts above the lowermost contact. Many of the troughs are bounded by faults, and it was not clear whether these, and the troughs, were pre- or post-mineralization (theme 4).

Experimental studies

The 1960s were probably the period during which more focus was placed on experimental work related to ore deposits in general, than during any other equivalent period. Much of the work during that decade that was relevant to magmatic sulfides involved phase-equilibria studies of sulfide systems conducted in silica or gold tubes [Barton &Toulmin (1964), Craig (1966), Kullerud *et al*. (1969), and papers referenced therein]. These experiments allowed a better interpretation of the textural relations between the major ore-forming minerals in magmatic ores, and led to the realization that most minerals within the ores are the result of a complex series of subsolidus reactions (Naldrett & Kullerud 1967). The work also showed that on reaching their liquidus, most natural Fe–Ni–Cu sulfide liquids crystallize a monosulfide solid-solution with the residual liquid becoming enriched in Cu (theme 5).

MacLean (1969), in his study of the system Fe–S–O–SiO_2, found that the sulfur content of a silicate melt in equilibrium with sulfide liquid (*i.e.,* the sulfur content at sulfide saturation or SCSS) decreases with increasing oxygen content of the system. He attributed this to the fact that S dissolves by displacing oxygen bonded to Fe^{2+}, and that increasing oxygen increases Fe^{3+} at the expense of Fe^{2+}.

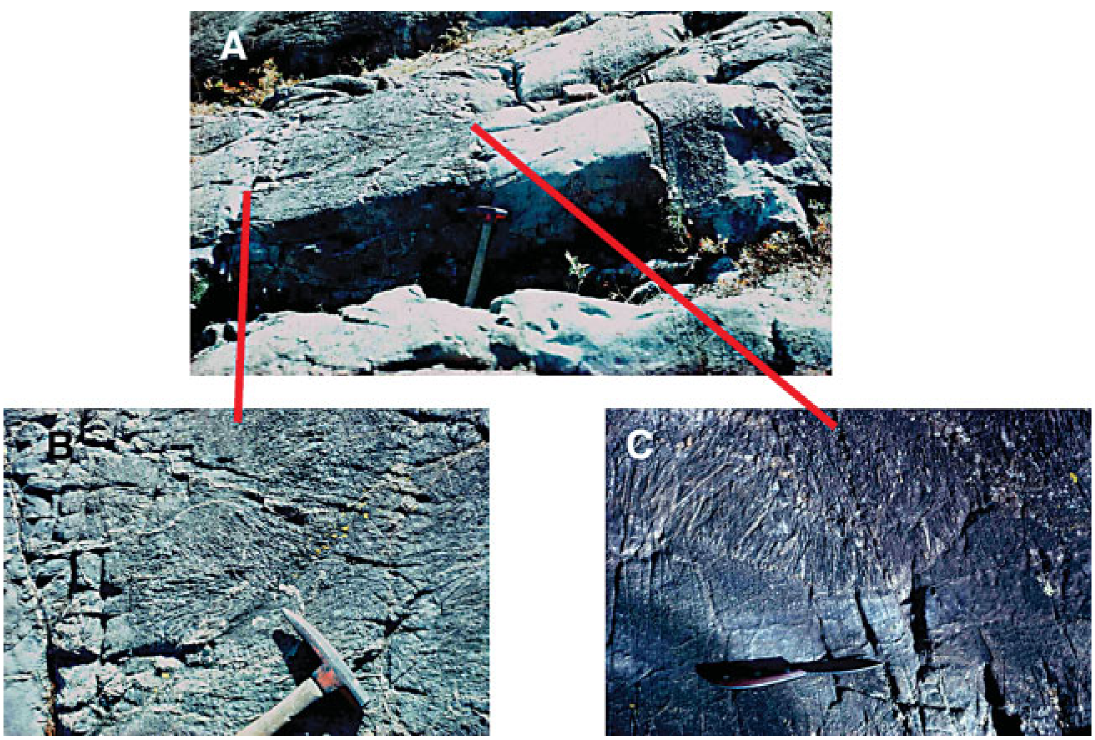


FIG. 9. A spinifex-capped flow from Munro Township, Ontario. A: complete flow, B: flow top and fine spinifex just below the top, C: contact between A and B zones, showing coearse bladed spinifex at the bottom of the A zone. (Photos: A.J. Naldrett).

Summary of the 1960s

The 1960s brought a major revolution in thinking about Ni–Cu deposits. Many geologists came to accept the concept that the Sudbury structure is an astrobleme, the importance of intrusions related to continental flood-basalt volcanism as hosts for major magmatic sulfides deposits was accepted, and an entirely new class of deposit, that related to komatiitic volcanism, was recognized. Experimental studies showed that the present mineralogy of the deposits is the result of a complex series of subsolidus re-equilibration reactions, and also that the early phase crystallizing from an Fe–Ni–Cu–S liquid was depleted in Cu and, to a lesser extent, Ni, so that the residual liquid becomes enriched in these elements (theme 5). A start was also made toward an understanding of the solubility of S in silicate melts; allied to this, the importance of the incorporation of crustal sulfur in mafic magma was recognized at Noril'sk (theme 1).

THE 1970S

Sudbury

At Sudbury, the 1970s was a period devoted in large part to "digesting" the implications of the impact hypothesis. As discussed above, two aspects of Sudbury geology had always puzzled investigators, the source of the energy that had given rise to so much brecciation, and the large proportion of granophyre to mafic rocks within the SIC. Impact explained the brecciation, and a large body of data was assembled documenting shock features in the surrounding rocks. The "norite" forming the lower part of the SIC was shown to exhibit cryptic variation indicative of *in situ* differentiation (Naldrett *et al.* 1970). Trace-element studies (Kuo & Crocket 1979) indicated that the initial magma had incorporated a high proportion of country rocks, which explained both its quartz-rich nature and the high proportion of granophyre, and which was attributed to heating of the country rocks as a result of impact. The impact hypothesis was by no means universally accepted during the 1970s, and considerable attention was placed on mapping and on interpreting features within the Onaping Formation, which, in the opinion of some, were inconsistent with a single, catastrophic impact, and were well explained by the pyroclastic flow hypothesis (see above).

Keays & Crocket (1970) were amongst the first to study the distribution of PGE in the Sudbury ores. They attributed variations in the distribution of PGE to their fractionation during the fractional crystallization of a sulfide liquid, and referenced Hawley's 1965 paper. Subsequently, this concept was enlarged upon by Chyi & Crocket (1976). Hoffman *et al.* (1979) documented the progressive enrichment in Cu, Pd, Pt and Au on proceeding from hanging wall to footwall at the McCreedy deposit (referred to as Levack West at the time), and Abel *et al.* (1979) described copper-rich veins in the footwall at the Strathcona deposit. The paper by Abel *et al.* was the first account of mineralization that is detached from and lies stratigraphically below the contact orebodies at Sudbury; subsequently it has transpired that this ore type, which has come to be known "footwall copper" ore, is an important feature of the northern and eastern "ranges" of the Sudbury structure (theme 5).

Flood-basalt-related deposits

Intrusions related to continental flood-basalt volcanism were receiving considerable attention from exploration companies, and, by the mid-1970s, 4×10^9 tonnes of sparsely disseminated mineralization containing 0.60 wt% Cu and 0.20 wt% Ni had been blocked out in intrusive bodies bordering the northwestern margin of the 1.08 Ga Duluth complex in Minnesota (Listerud & Meineke 1977). The mineralization lies close to the contact with underlying Proterozoic iron formation and slate, both of which are sulfide-bearing. Mainwaring & Naldrett (1977) showed that the sulfur of the mineralization in the Waterhen intrusion is heavy ($\delta^{34}S$ = +12 to +16‰), almost as heavy as that in the adjacent sedimentary units, and concluded that sulfur had entered the intrusions from the country rocks. The subsequent studies of Ripley (1981, 1986) have shown that this conclusion is applicable to all of the mineralization in the Duluth complex (theme 1).

Komatiite-related deposits

Komatiite-related deposits gave rise to considerable discussion about the environment in which the ore accumulated. As more mineralized shoots were opened up, it became clear that a typical ore-sequence consists of massive sulfide, overlain with a sharp contact by net-textured ore (ore in which sulfides occupy the spaces interstitial to cumulus crystals of olivine) overlain in turn, again with a sharp contact, by peridotite with sparsely disseminated sulfide. The sharp contacts between ore types corresponded to the horizontal at the time of emplacement. Naldrett (1973) proposed the billiard-ball model of sulfide accumulation, in which he compared deposits such as those at Kambalda to a large beaker of water and billiard balls, in which the balls were denser than the water so that they had sunk, and the pore spaces between them were occupied by the water. Mercury had been added to the beaker and had spread out over the base as a massive sheet; the lowermost balls were completely immersed in the mercury, and provided flotation for the overlying balls. He proposed that the balls represented olivine crystals, the mercury, sulfide liquid, and the water, silicate magma. This model was criticized by Ross & Hopkins (1975), who pointed out that in many cases the vertical height of the peridotite was too great to have been supported by the thickness of net-textured ore, and that, if the Archimedes principle was to be applied to the whole sequence of most mineralized flows, olivine crystals should have been forced down through the massive sulfide layer while it was still liquid, and that only net-textured ore should have been preserved. They suggested that each zone of the mineralization, massive sulfide, net-textured sulfide and sparsely mineralized peridotite, had been emplaced as a series of consecutive flows, with the lower one freezing before the other covered it (theme 4).

The increasing availability of data on the partition of metals such as Ni, Cu and Co among silicate melts, silicate minerals and sulfide melts (see below) made it possible to model the variations to be expected in the composition of a fractionating magma. Duke & Naldrett (1978) showed that their calculations based on olivine fractionation alone accurately predicted compositional variations in sequences of komatiites where no sulfide ores were known, such as those of the Barberton Mountainland. Comparison of the same models with compositions of komatiites from the Kambalda area showed that most of the Kambalda rocks are Ni-deficient in comparison with the modeled trend, but could be explained if sulfide liquid had also been segregating along with the olivine in a ratio of between 100 and 200 parts olivine to 1 part sulfide. Duke (1979, 1980) showed that olivine crytals from the komatiitic Dumont sill contain less Ni where they crystallized from Ni-depleted magma, which had also reacted with sulfide, than where they crystallized from undepleted magma (themes 2, 3).

Studies unrelated to specific mining camps

Probably the most important progress in understanding magmatic sulfides during the 1970s came from work that was unrelated to specific deposits. This included both experiments on the solubility of sulfur in mafic silicate melts and the partitioning of Ni, Cu and Co between sulfides and silicates.

Haughton *et al*. (1974) approached the container problem for conducting experiments at magmatic temperatures by ignoring pressure and by concentrating on the effect of composition and oxygen and sulfur fugacity. They used alumina crucibles to contain the silicate melts in a gas-mixing furnace, through which they passed precise mixtures of CO, CO_2 and SO_2. They found that the amount of sulfur that will dissolve in a basaltic magma decreases with increasing $f(O_2)$, and it increases with sulfur fugacity. Many of their experiments involved melts undersaturated in sulfide, but some achieved saturation and showed that the maximum amount of sulfur that any given melt will dissolve (*i.e*., the sulfur content at sulfide saturation or SCSS) is, amongst other factors, a function of the FeO content of the melt. Buchanan & Nolan (1979) confirmed the effect of FeO on the sulfur content of a melt at sulfide saturation and also demonstrated that the amount of sulfur dissolved at sulfide saturation decreases with increasing $f(O_2)$ (theme 2).

Questions concerning the history of the segregation of the Earth's core from the mantle meant that during the 1970s, experimental work was directed at the partition of siderophile metals, including Ni, among Fe alloys, olivine and silicate melts. Experimental work was also focused on the partition of the same elements between sulfides and silicates or silicate melts. Clark & Naldrett (1972) showed that experimentally derived partition-coefficients for Ni between monosulfide solid-solution (*mss*) and olivine are consistent with those observed in nature. Rajamani & Naldrett (1978) investigated exchange partition-coefficients for Ni, Cu and Co with Fe between sulfide and basaltic melts and found these to be 42, 35 and 15, respectively (theme 2).

The increasing availability of nuclear reactors suitable for analytical measurement during the 1970s meant that it became simpler to study the abundance of trace elements such as PGE in ores. Hoffman *et al*. (1978) developed a Ni-sulfide bead fusion coupled with instrumental neutron-activation analysis (INAA) that could be applied to relatively large samples (50 g). This development went a long way to overcoming errors due to the heterogeneous distribution of some PGE in ores.

Application of this technique to a wide range of deposits revealed that the relative abundances of the various platinum-group elements (PGE) are related (Fig. 10) to the type of magma from which the sulfide deposit was derived (Naldrett *et al*. 1979, Naldrett & Duke 1980). The PGE differ from Ni and Cu in being approximately 10,000 less abundant in mafic and ultramafic rocks, and in partitioning approximately 50–100 times more readily into a sulfide liquid from a mafic-ultramafic magma. Differences in the relative abundances of the PGE relative to Ni and Cu between sulfide ores and their source magmas have been used to interpret the proportion of magma with which any particular sulfide ore has equilibrated. This concept has proved important to the understanding of magmatic sulfides and has become known as the "R Factor" (Campbell & Naldrett 1979) (theme 2).

Distler *et al*. (1977) showed that differences exist in the extent of the partition of PGE between sulfide liquid and coexisting monosulfide solid-solution (*mss*), with Ru, Ir and Os favoring the *mss*, and Pt and Pd, the liquid. The residual liquid would not only become enriched in Cu (see above), but also in Pt and Pd. They pointed out that this behavior supported the concept that zoning of PGE within ore deposits is the consequence of the fractional crystallization of sulfide liquid, in reference to the zoning at Noril'sk and Talnakh, in particular (theme 5).

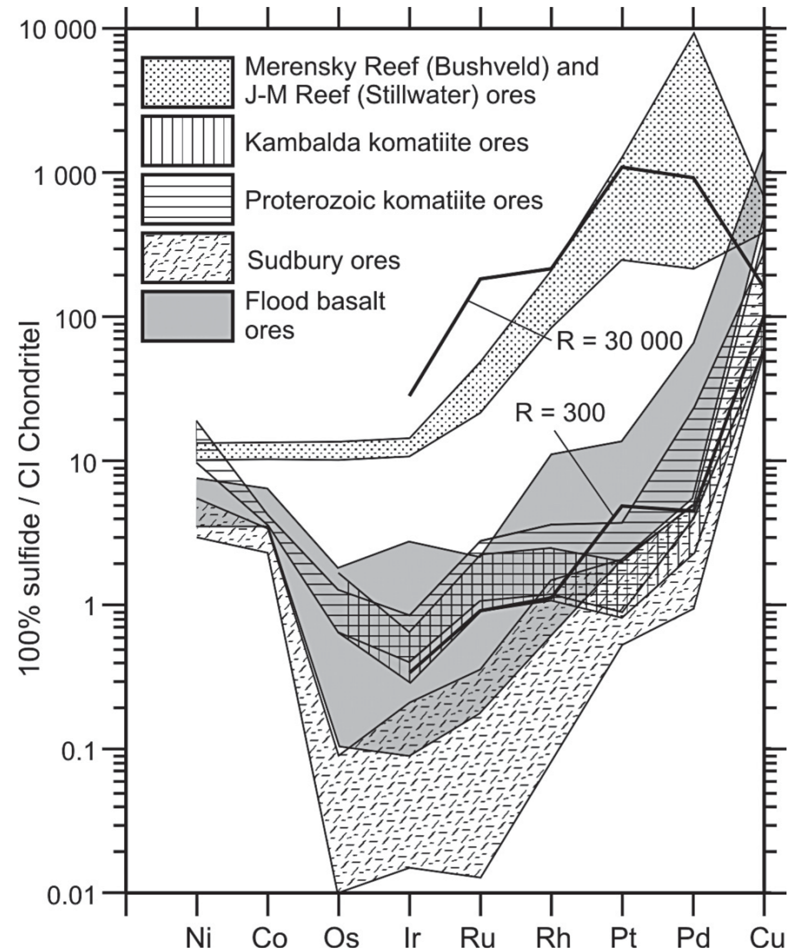


FIG. 10. Ranges of chondrite-normalized average PGE concentrations in 100% sulfides of a number of important types of magmatic ores (Naldrett 1989). The diagram illustrates that there is a large difference in PGE concentrations, but a relatively small difference in Ni, Cu and Co between sulfide-rich Ni–Cu ores and low-sulfide PGE-enriched ores. The effect of variation in magma : sulfide ratio (R) on the composition of sulfides segregating from a magma equivalent to the presumed magma responsible for the Lower Zone of the Bushveld Complex (Cawthorn & Davies 1983) at R = 300 (lower heavy line and at R = 30000 (upper heavy line) is shown. Differences in the value of R of this order can go a long way toward accounting for the difference in PGE concentrations between the two types of deposit.

Other factors influencing research progress on magmatic sulfide deposits

The 1970s also saw the start of two traditions that came to have a significant effect on international collaboration related to magmatic sulfide deposits. The first of these was the International Platinum Symposium, which was inaugurated at the University of Melbourne in 1971 and met for the second time in Denver in 1975. Meetings have been held every two to four years, and the tenth of these was held in Oulu, Finland in August 2005. The second tradition was the series of projects that have continued under the auspices of the UNESCO/IUGS International Geological Correlation Program or IGCP (now referred to as the International Geoscience Program). The first magmatic sulfide-related project, IGCP project No.161, “Magmatic Sulfide Deposits in Mafic and Ultramafic Rocks” met for the first time in Toronto in 1978, and continued with one to three meetings per year until the final meeting in Zimbabwe in 1987. The next project, No. 336, on "Intraplate Magmatism and Metallogeny", started with the Sudbury–Noril'sk symposium in Sudbury in 1992 and again held yearly or more frequent meetings. This was succeeded in 1998 by No. 427, on "Dynamic Processes in Ore-forming Magmatic Systems". The current project, IGCP No. 479 on "Sustainable Use of Platinum-group Elements" started in 2004 with a short course and workshop in Hong Kong, followed by field trips in China. These two traditions have resulted in most investigators in the field meeting at least once per year to exchange ideas, and the proceedings are an invaluable record for anyone interested in following progress in research through the years and the current state of understanding in the subject.

Summary of the 1970s

The 1970s were a decade marked by greatly improved international communication, and during which concepts originating in the 1960s, such as crustal contamination of mantle-derived magmas and the addition of crustal sulfur, became established (theme 1). The Kambalda deposits stimulated considerable debate about the physical environment in which sulfides were deposited (theme 4). New experimental approaches allowed investigators to reproduce some of the variables relating to the segregation of sulfide liquids from their source magmas. A start was made on an examination of the partition of Ni, Cu and Co between sulfide and silicate phases, and on the application of these data to a recognition of natural environments in which sulfide immiscibility had occurred. A new concept, the R Factor, emerged to assist in relating the composition of magmatic sulfides to that of their source magma. New analytical methods allowed variations in the PGE content of ores to be considered, in addition to Ni, Cu and Co; the results provided further insights into the process of ore genesis (theme 2). Zoning in the distribution of Cu and PGE was described at both Sudbury and Noril'sk; initial experimental work on the behavior of the PGE during the crystallization of sulfide melts supported the fractional crystallization of these melts as a likely cause of this zoning (theme 5).

The 1980s

Sudbury

As more information became available on the distribution of PGE within different styles of mineralization in different mining camps, the role of the fractional crystallization of sulfide ore-magmas became more recognized. In their paper on the distribution of PGE within the Sudbury ores, Naldrett *et al.* (1982) pointed out that Pt, Pd and Au behave incompatibly with respect to early crystallizing *mss*, and become concentrated in the residual sulfide liquid along with Cu, whereas Rh, Ru, Ir and Os are compatible and become concentrated in the *mss*. They showed that the zoning from top to base (hanging wall to footwall) across many Sudbury deposits could be interpreted as the result of the residual liquid migrating toward the footwall. The Falconbridge deposit stood out amongst all others in being deficient in the incompatible elements, and they suggested that as much as half of the deposit is missing, possibly as a result of faulting (theme 5).

Faggart *et al.* (1985) reported on Sm–Nd and Rb–Sr isotopic studies of the SIC and suggested that the whole of the complex crystallized from an impact melt. As discussed above, it had been recognized previously that considerable country-rock contamination had been involved at Sudbury, but the suggestion of Faggart *et al.* (1985) met considerable skepticism initially, since the trace element and isotopic data could be explained as a result of perhaps 50–60% contamination, and it was felt that the Ni and PGE content of the Sudbury ores required a component of the SIC magma to be of mantle origin, possibly triggered by the impact.

Publication of the volume, "The Geology and Ore Deposits of the Sudbury Structure" (Pye *et al.* 1984) provided a forum in which the impact *versus* terrestrial origin of the structure was debated 20 years after it was first formulated, and in which the then current understanding of the geology was summarized.

Flood-basalt-related deposits

The 1980s saw the publication of two important treatises on the deposits at Noril'sk, by Genkin *et al.* (1981) and Duzhikov *et al.* (1988). Genkin *et al.* (1981) described the geology of the deposits, with a focus on the mineralogy, and emphasizing the unique mineralogy of the Cu-, Pd- and Pt-enriched zone of the Oktyabr'sk deposit. Duzhikov *et al.* [translated and published by the Society of Economic Geologists in 1992] comprises a series of articles describing the regional setting of the deposits, their detailed geology, petrology and mineralogy, along with discussions of other types of deposits in the Noril'sk area. These two publications provided the first comprehensive accounts of what was becoming recognized as a mining camp equal to that at Sudbury. Ryabov (1982) described an unusual occurrence of PGE mineralization in chromite-bearing, variably-textured (taxitic) rocks at the upper contact of the Noril'sk intrusions. At the present time, when the Oktyabr'sk Cu zone is essentially exhausted, and with PGE prices relatively high, this mineralization has assumed a greater importance than previously, particularly at the Noril'sk I deposit where it is accessible from the surface.

Following her work with Godlevsky & Grinenko (1963) on the sulfur isotopic composition of sulfur at Noril'sk, Grinenko (1985) showed that the most heavily mineralized intrusions in the Noril'sk area have the heaviest sulfur, and that intrusions with very weak to no mineralization have sulfides with near-mantle isotopic values. She discussed the source of the heavy sulfur and suggested that it had been derived, not from the adjacent evaporites, but from sour gas, leaking from oil and gas reservoirs in the West Siberian Lowlands, 100 km and more west of Noril'sk. As mentioned above, Ripley (1981, 1986) showed that the likely source of the sulfur in the deposits of the Duluth complex was the adjacent, Animikie-aged Biwabic iron formation and Virginia shale (theme 1).

Continuing the theme of Ni depletion, Lightfoot *et al.* (1984) observed that the Insizwa and Tabankulu intrusions, which are part of the Karoo flood-basalt event in southern Africa, contain zones in which the olivine is significantly depleted in Ni when compared with olivine from most intrusions on the basis of forsterite content. They proposed that batches of magma involved in these intrusions had reacted with sulfide, and that a substantial amount of sulfide with an elevated Ni tenor remains to be discovered. Although not related to the theme of flood basalts, Thompson & Naldrett (1984) showed that assimilation of country-rock sulfur had resulted in markedly Ni-depleted olivine in the Moxie and Katahdin intrusions of northern Maine (theme 3).

Komatiite-related deposits

Gresham & Loftus-Hills (1981) noted that the environment of the ore deposits at Kambalda differs from that of unmineralized areas. One difference is the absence of sediments in the vicinity of mineralized troughs compared with its common presence between footwall basalts and the overlying komatiitic rocks away from the troughs. Another difference is the abundance of thin, spinifex-capped ultramafic flows away from the deposits, and the presence of thicker, more magnesian ultramafic units overlying the mineralization (theme 4).

Lesher & Groves (1982) and Lesher (1983) addressed the role that the troughs had played in concentrating mineralization. They showed that the troughs tend to form along the flanks of adjacent basaltic flows, and that quenched komatiite had developed on the sides of the troughs against the flanking basalt. Although these features had been obscured by later minor faults in many areas, their preservation in some areas served to show that the troughs are primary features that had played an important role in the ore-forming process. They likened the volcanic environment at Kambalda to the flanks of Hawaiian volcanos such as Mauna Loa, and suggested that the "ore-forming environment" as recognized by Gresham & Loftus-Hills (1981) was the focus of the principal flow of an eruption of komatiitic lava, a lava river or, in some cases, a lava tube, and that the off-ore environment, with its many thin, spinifex-capped flows, is the equivalent of a flood plain that was produced when the lava rivers overflowed their banks (theme 4).

Nisbet (1982) suggested that because of their high temperature, low viscosity and thus the turbulence of their flow regime, komatiites might have been capable of thermally eroding their substrates or wallrocks more readily than lower-temperature basaltic flows. Huppert *et al.* (1984) applied thermal modeling to a flowing lava river. They pointed out that the turbulent flow expected of komatiitic lavas, in contrast to the laminar flow experienced by typical flows of basaltic magma, implies that the temperature profile through a komatiitic flow would be essentially uniform, and would not show the downward decrease in temperature toward the base that is the consequence of laminar flow. Thus the footwall rocks would be subjected to the full temperature of the komatiitic lava, and would be highly susceptible to thermal erosion. Thermal erosion would be focused below the main flow-channels, and would lead to the lava eroding the trough that would then serve to constrain it, and also trap any liquid sulfides that were being dragged along at the base of the flow. They suggested that thermal erosion of sulfidic interflow sediments would provide a source of sulfur for the sulfide mineralization. Thermal erosion of sediment in zones where the lava flow was concentrated also accounts for the absence of such sediments in the mineralized environment and their presence elsewhere (theme 4).

Studies unrelated to specific mining camps

The most significant work unrelated to specific deposits in the 1980s was the continuation of the experimental studies on sulfur solubility in basaltic magmas. Buchanan *et al.* (1983) showed that the solubility of sulfur in basaltic melts at constant $f(O_2)$ increases with increasing temperature and would thus serve to cause the segregation of liquid sulfide from a cooling magma.

Huang & Williams (1980) investigated portions of the system Fe–Si–S–O at 32 kbar and found that the miscibility gap between sulfide and silicate liquids expands with increasing pressure. Wendlandt (1982) studied the variation in sulfur content at sulfide saturation (SCSS) in two basalts and an andesite at pressures between 12.5 and 30 kbar. He found that SCSS increases with FeO and temperature and decreases with increasing pressure. Comparison of his findings with other studies is difficult because he relied on the C–CO_2–CO buffer, which varies in $f(O_2)$ with changing pressure, and yet the magnitude of these variations was not calibrated in his experiments. However, his studies also indicated that under natural conditions, increasing pressure depresses the SCSS. Naldrett (1989) pointed out that most magmas cool at greater than adiabatic rates while ascending into the crust and that, given the uncertainties in Wendlandt's experimental approach, it was not clear that even decreasing pressure would have a net positive effect on the ability of a cooling magma to dissolve sulfide. [I am now going to jump ahead 17 years, because this is the appropriate place to mention the most recent contribution to this particular topic]. Mavrogenes & O'Neill (1999) studied SCSS in basaltic melts containing 6–14 wt% FeO using Fe and Fe–Ir capsules at pressures ranging from 5 to 90 kbar and temperatures of 1400 and 1800°C. Their data indicate that SCSS decreases exponentially with increase in pressure and increases only slightly with temperature. The data of both Wendlandt and Mavrogenes & O'Neill are summarized in Figure 11. Given the present data, it is highly likely that magma that is saturated when it leaves its source region in the mantle will be markedly undersaturated on emplacement into or onto the crust. The greater the depth that any magma last interacted with the mantle, the greater will be its degree of undersaturation (themes 1, 2).

Summary of the 1980s

The 1980s were a decade in which the physical environment within which sulfides are concentrated became better understood as a result of observations on the Kambalda nickel camp, where sulfides occur within channels that have been the locus of magma flow. The legacy of depletion on the chalcophile metal content of a magma due to interaction with sulfide came into increasing focus. A better understanding of the compositional changes that accompany fractional crystallization of a sulfide liquid led to the suggestion that deposits that are deficient in elements incompatible in *mss* should be accompanied by zones in which these incompatible elements are enriched. Experimentalists working on sulfur solubility posed the question of whether primary mantle-derived magmas, or their fractionated products, ever reach the crust saturated in sulfide.

1990–2004

Sudbury

In 1990, Sudbury became the target of Canada's Lithoprobe project, and a series of vibroseis traverses were conducted across the SIC. These revealed (Milkereit *et al.* 1992) that the base of the SIC, and the contact between the granophyre and underlying gabbronorite, are well defined by the seismic data, and that the base of the complex as seen on the North Range extends continuously as far south as the southern margin. The South Range has been thrust northward over the North Range along a zone of plastic deformation known as the South Range Shear Zone. This finding carried with it the implication that the original size of the Sudbury structure was far greater than the current dimensions (30 × 60 km), and of the order of 200 km. This led Grieve *et al.* (1991) to comment that the volume of impact melt likely to have formed during the generation of a crater of this magnitude was equal to or greater than the volume of the SIC, and to suggest that the whole of the SIC is an impact melt, with no primary mantle. Subsequently, Grieve (1994) showed, using least-squares mixing models, that the average composition of the SIC corresponds to a mix of an Archean granite–greenstone terrane, with possibly a small component of Huronian cover rocks.

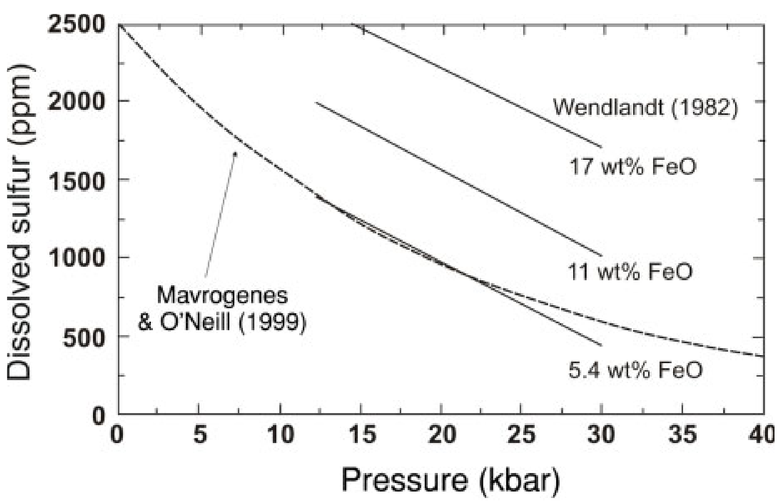


FIG. 11. Experimental determination of solubility of sulfur in basaltic melts of different FeO content estimated as a function of pressure at 1400°C. Based on the data of Wendlandt (1982) and Mavrogenes & O'Neill (1999).

Walker *et al*. (1991) showed that Re–Os isotope systematics required that the ancient crust had contributed 60–75% of the Os contained in the McCreedy West and Falconbridge ores, and probably nearly 100% of that contained in the Strathcona ores. Dickin *et al*. (1992) pointed out that, given the uncertainties involved in assumptions about the Os content and isotopic composition of continental crust, the Os isotopic data are consistent with 100% of the Os being of crustal origin. Morgan *et al*. (2002) concluded, on the basis of a very precise NITMS study of the $^{186}Os/^{188}Os$ and $^{187}Os/^{188}Os$ values in the Sudbury samples, that the Os is clearly crustal, and can be explained as a binary mixture of Archean Superior and Huronian metasedimentary rocks. However, they found that ores with low $^{190}Pt/^{188}Os$ values from two deposits, Falconbridge and McCreedy West, have $^{186}Os/^{188}Os$ values that are substantially superchondritic. They suggested that this could be due the admixture of a third component, most likely Archean or early Proterozoic mafic rock with $^{190}Pt/^{188}Os \gg 1$, that had also been sampled by the impact (theme 1).

Ariskin *et al*. (1999) modeled the crystallization of the SIC using the computer program COMAGMAT–3.5 that had been developed with respect to other differentiated mafic bodies. The marginal quartz-rich norite of Naldrett & Hewins (1984) that they used as a starting composition in their modeling gave a very close approximation to both the chemical variations and appearance and disappearance of phases in the lower, mafic portion of the SIC. However, whichever initial composition of magma they chose, they were unable to account for the proportion of granophyre exposed at surface. They concluded that the units of the SIC excluding the granophyre were the consequence of fractional crystallization of a magma similar to the quartz-rich norite in composition, and that the granophyre is largely the consequence of subsequent assimilation in the hot environment of an impact crater (theme 2).

Ivanov & Deutsch (1999) used a modified version of the SALE computer program for fluid flow (Amsden *et al*. 1980) (i) to construct a time-dependent model for the formation of the transient crater, and thus show the progression in the distortion of layers in the target area and the position of isotherms close to and beneath the crater following impact, (ii) to model the maximum shock pressures experienced in the target area, and (iii) to model the temperature evolution within and beneath the melt pool from 10^4 to 10^7 years after impact. Assuming acoustic fluidization of the target rocks, their modeling showed that a substantial amount of lower crust material could have been brought to surface as the result of fluid flow and not merely as inclusions or impact melt. This would account for the ring of granulitic gneiss 5–10 km wide that surrounds much of the northern rim of the SIC. Also, the transient crater would have had a diameter of 75–100 km, but would subsequently have collapsed to give rise to a crater with a 200 km diameter. Important points raised by their study are that the initial temperature of the impact melt would have been about 1727°C, and superliquidus temperatures (>1177°C) would have persisted for 100,000–250,000 years after impact (theme 4).

Lightfoot *et al*. (2001) found that the tenor of Ni and Cu in sulfides in a borehole from the eastern part of the SIC decreased upward asymptotically from values of 4–8 wt% of both metals within ore deposits and in immediately overlying norite to a value of around 1 wt% in norite 1200 m above the base. They interpreted these data to imply that the sulfides had segregated progressively from a body of magma that, as a result of the segregation, was itself becoming progressively depleted in Ni and Cu (theme 3).

Whereas the magmatic origin of the principal ore deposits at Sudbury is now firmly established, there is still debate about the origin of the Cu-, Pt-, Pd- and Au-rich veins in the footwall of the SIC. Li *et al*. (1993), Naldrett *et al*. (1994), and many other authors attributed the veins to the migration of a Cu-rich residual melt away from the site of crystallization of pyrrhotite-rich orebodies at the basal contact. Although the veins contain chloride-rich fluid inclusions, and have zones of alteration 5–20 cm across at their margins, authors favoring a magmatic origin have attributed these effects to fluids concentrated within the fractionated sulfide liquid. Farrow & Watkinson (1992, 1997) and Watkinson (1999) found that the fluid inclusions are extremely saline and have temperatures of trapping revealing multiple events between 100 and 400ºC. They cited stable isotope data that are consistent with fluids derived from mixed formational brines, and also with fluids that have equilibrated at high temperature with igneous and metamorphic rocks. They proposed that during the cooling of the SIC and its ores, a hydrothermal system became established that reworked magmatic sulfides and redeposited Cu, Ni and PGE in veins in the footwall (theme 5). Experimental evidence supporting derivation of chloride-rich brines from a fractionating sulfide melt has come from the studies of Mungall & Brenan (2003) and Wykes & Mavrogenes (2005) (see below).

Flood-basalt-related deposits

The more relaxed atmosphere between the Soviet Union and the West that started to develop in the late 1980s meant that collaborative projects could be initiated between Soviet geologists working on Noril'sk (at TsNIGRI, at institutes of the Russian Academy of Sciences, and with the Noril'sk Kombinat) and groups in the west (University of Toronto and U.S. Geological Survey). During the early 1990s, many samples of Noril'sk basalts, intrusive rocks and products of mineralization were the subject of isotopic and ICP–MS trace-element analyses. The resulting publications include Lightfoot *et al*. (1990, 1993), Naldrett *et al*.

(1992, 1996), Wooden *et al.* (1993), Brügmann *et al.* (1993), and Hawkesworth *et al.* (1995). It was shown that a 600 m-thick sequence of the 3.5 km of Siberian trap at Noril'sk had been contaminated by continental crust and was depleted to the extent of having lost 75% of its initial Ni and Cu and >90% of its PGE and Au. Naldrett *et al.* (1995) suggested that a portion of the metals lost from the basalts accounted for that in the ores, and that the ores comprised sulfides that had been trapped in conduits feeding the volcanism. Naldrett *et al.* (1996) noted that if the ore had formed from the most depleted intrusions, the Ni tenor (Ni content in 100% sulfide) of the sulfides would have been about 1.5 wt%, and it was likely that continued flow of magma through the conduits was responsible for upgrading the mineralization in Ni, Cu and PGE. They found that the overall tenor of mineralization in three different mineralized conduits, Noril'sk I, Kharaelakh and Main Talnakh, differed significantly and suggested that this reflects the different ratios of magma to sulfide in the different conduits (themes 2, 3).

Stekhin (1994) described the strong zoning within massive sulfides underlying the Kharaelakh ore system, in which Cu, Pt, Pd and Au reached their apogee in the massive Oktyabr'sk Cu orebody [Naldrett (2004) reported that an average of 20 samples gave 2.2 wt% Ni, 25 wt% Cu, 60 g/t Pd and 10 g/t Pt for this material]. Stekhin recorded field evidence that the massive sulfide lenses beneath this intrusion had not settled from above but had been injected as streams of sulfide liquid along the base. He used the variation in S/(Ni + Cu) values to interpret the flow directions of these streams. Torgashin (1994) described an unusual type of ore, rich in Cu and Pd, which occupies breccia zones and adjacent sediments along the roof of the Kharaelakh intrusion at Talnakh [Naldrett (2004) quoted grades of 1.5 wt% Ni, 5.8 wt% Cu, 13 g/t Pd, 1 g/t Pt over 42 m in this material] (theme 5).

Sluzhenikin *et al.* (1994) described a different style of low-sulfide mineralization in variably textured (taxitic) gabbros along the roof of the Noril'sk I intrusions (these have been referred to above). Whereas the S content does not exceed 1.5–2.0 wt%, and Cu+Ni contents are less than 1 wt%, they showed that PGE contents are of the order of tens of grams per tonne and may reach 60 g/t.

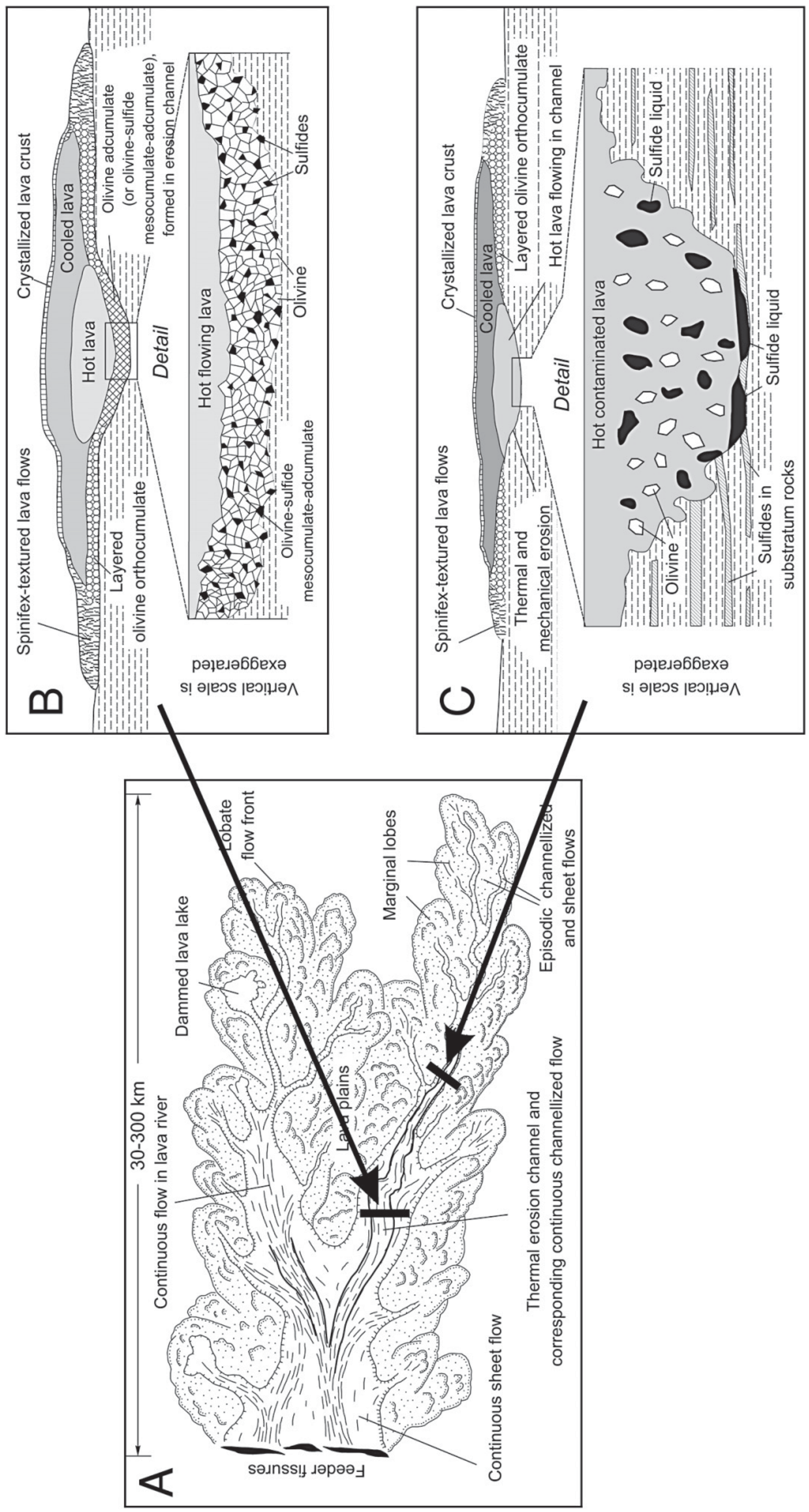
Komatiite-related deposits

Hill *et al.* (1990) presented a comprehensive synthesis of Archean komatiitic flow facies, showing the relationship between sheet flows, large, meandering lava rivers, and narrow channelized flows, and the likely settings of different styles of mineralization within the different facies. Their model (Fig. 12) went a long way to place observations made over the previous 20 years into an integrated concept. Williams *et al.* (1999) reviewed the thermal regime and fluid dynamics of komatiitic lavas and the conditions that would lead to sulfide mineralization. Their modeling supported the conclusion of Huppert *et al.* (1984) that thermal erosion depends on the temperature of the lava, turbulent flow within the lava, and the degree to which the flow is channelized. They also found that slower, prolonged flow will cause greater thermal erosion than faster, shorter-lived flow, and that the amount of erosion depends on the nature of the substrate; water in water-saturated, unconsolidated substrate will volatilize and disrupt the substrate, making it more susceptible to erosion than consolidated substrate. Given that the sulfur in komatiite-related deposits is thought to come from the substrate, the more this is eroded, the greater will be the likelihood of a deposit (theme 4).

In the most recent work describing the Thompson (Manitoba) deposits, Bleeker (1990) attributed them to subvolcanic reservoirs of komatiitic composition that had developed within a unit comprising chemical and pelitic sediments rich in sulfide and graphite. Citing Se/S values published by Eckstrand *et al.* (1989), he proposed that the magma had ingested sulfide from the surrounding sediments to give rise to magmatic ores. He also demonstrated that Ni and the PGE, particularly Pd, had migrated away from massive magmatic sulfide into adjacent massive to semimassive country-rock sulfide, and suggested that this had happened during the upper-amphibolite-grade metamorphism that had subsequently affected the Thompson belt.

During the 1990s, Falconbridge Ltd. placed their komatiite-related Ni deposits of the Paleoproterozoic Raglan belt in Ungava (Quebec) in production. The results of the geological studies undertaken prior to the start of production were summarized in Lesher (1999). The komatiites differ from those of Archean age in having formed from liquids containing a maximum of about 20 wt% MgO. Lesher *et al.* (1999) concluded that the ore zones, which consist of relatively small ones (100–200 m in diameter) of massive + disseminated sulfide at contacts of their host ultramafic bodies,

FIG. 12. A. Schematic illustration of construction and facies of a regional komatiite volcanic complex, formed by cataclysmic sustained eruption. Note that adcumulus (dunite) sheet-flow facies (ASF) develops close to the vent, and becomes channelized to adcumulus channel-flow facies (ACF) farther from the vent. Downstream, cooling lava gives rise to orthocumulus sheet-flow facies (OSF) within which a facies composed of mesocumulus channel-flows of dunite (MCF) may be present. The margins and farthest extremities of the volcanic complex consist of lava plains comprising flows of OSF intermixed with or capped by thin "Munro-type" flows (MunF). Cross-sections illustrate the formation of adcumulus (B) and mesocumulus (C) facies of lava channels. Modified after Hill *et al.* (1990).


B
Vertical scale is exaggerated
Spinifex-textured lava flows
Crystallized lava crust
Cooled lava
Hot lava
Layered olivine orthocumulate
Olivine adcumulate (or olivine-sulfide mesocumulate-adcumulate), formed in erosion channel
Detail
Hot flowing lava
Olivine-sulfide mesocumulate-adcumulate
Olivine
Sulfides
C
Vertical scale is exaggerated
Spinifex-textured lava flows
Crystallized lava crust
Cooled lava
Layered olivine orthocumulate
Hot lava flowing in channel
Thermal and mechanical erosion
Detail
Hot contaminated lava
Olivine
Sulfides in substratum rocks
Sulfide liquid
Sulfide liquid
A
30-300 km
Feeder fissures
Continuous sheet flow
Continuous flow in lava river
Thermal erosion channel and corresponding continuous channellized flow
Lava plains
Dammed lava lake
Lobate flow front
Marginal lobes
Episodic channellized and sheet flows

formed within a sequence of lava rivers. Sulfide immiscibility was the result of incorporation of sedimentary sulfur by the flowing magma farther upstream than the present location of the deposits. Subsequent underground exploration has raised some questions (Danielle Giovenazzo, pers. commun., 2004) as to whether all of the host ultramafic bodies were actually flowing at surface, or whether some were conduits feeding contemporaneous volcanism (theme 4).

Anorthosite-complex-related deposits

Prior to the discovery of the Voisey's Bay deposit in 1994 (Naldrett *et al*. 1996), anorthosite – troctolite – ferrodiorite – granite complexes had not been regarded as prospective for Ni–Cu sulfide deposits, despite evidence from their olivine compositions that the magmas responsible for the troctolites were reasonably rich in Ni. The widespread interest sparked by that discovery aided in raising funding for broadly based research on the deposit. The results of this research (reported in *Lithos*, volume **47**, No. 1, 1999 and in *Economic Geology*, volume **95**, No. 4) added support to many of the major themes that had been developing over the preceding 30 years and that are the subject of this paper. These are:

1. The importance of reaction between mafic magma and crustal rocks. At Voisey's Bay, this reaction is attested to by the altered inclusions in the mineralization and its host rocks (Li & Naldrett 2000), by trace-element geochemistry of the host rocks (Li *et al*. 2000) and by the Os isotope geochemistry of the ores and host rocks (Lambert *et al*. 2000) (theme 1).

2. The importance of the flow of sulfide-bearing magma in the concentration and localization of the sulfides. At Voisey's Bay, sulfide immiscibilty occurred during the crystallization of magma in a lower chamber located within sulfide- and graphite-bearing pelitic gneiss (Li & Naldrett 1999). A new pulse of magma entered the lower chamber and forced the sulfide-bearing magma up a feeder dyke (Evans-Lamswood *et al*. 2000) to create a sill at a higher level. Sulfides are concentrated in the dyke and at the entry line of the dyke to the upper chamber (theme 4).

3. The importance of fresh magma interacting with and upgrading an early generation of sulfide. At Voisey's Bay, the Ni/Fo ratio of olivine is much higher in products of the second wave of magma passing through the system. Sulfides in equilibrium with the first wave would have had a tenor of about 1.5 wt% Ni, and it is through equilibration with the second wave that their tenor was upgraded to 3.5–4.5 wt% (Li & Naldrett 1999) (theme 2).

4. Chalcophile element depletion as an indicator of reaction between magma and sulfide. The Ni content of olivine in rocks formed from the first wave of magma to pass through the Voisey's Bay system had Ni/Fo values that are very much lower than normal for mafic ultramafic rocks, and constitute a signal that the magma from which they have crystallized had interacted with sulfide (Li & Naldrett 1999) (theme 3).

Studies unrelated to specific mining camps

With a growing interest in modeling the relationship between magmatic sulfides and their source magmas quantitatively, the 1990s saw a major increase in experimental studies. Peach & Mathez (1993) demonstrated that $D^{\text{sulfide melt/silicate melt}}$ is a function of the prevailing ratio of $f(O_2)/f(S_2)$. In most silicate magmas, isopleths of $f(O_2)/f(S_2)$ are more or less parallel to isopleths of aFeO in sulfide–oxide liquids, so that the aFeO in a magma essentially controls the $f(O_2)/f(S_2)$ ratio, which accounts for the linear relationship observed between $\log D^{\text{sulfide}}_{\text{melt/silicate melt}}$ for Ni and FeO content of the silicate melt in experimental studies. Peach & Mathez concluded that for natural basaltic melts containing about 10 wt% MgO, values of D for Ni and Cu in the range of 250–800 and 1000–1400, respectively, are reasonable. Data on partition coefficients for PGE between sulfide and silicate melts are much more variable than for Ni and Cu (*e.g*., Stone *et al*. 1990, Fleet *et al*. 1991, Crocket *et al*. 1992, Bezmen *et al*. 1994, Peach *et al*. 1994), partly because of experimental problems. All studies indicate that the coefficients are very much higher than those for Ni and Cu, being of the order of 5×10^4 for Pd and 10^5 for Ir (theme 2).

Whereas work conducted during the 1960s had shown that Ni and Cu favor the residual liquid in an Fe–Ni–Cu–S melt crystallizing *mss*, the data were not suitable for quantitative modeling. Fleet & Pan (1994), Ebel & Naldrett (1996, 1997) and Li *et al*. (1996) studied the partitioning of Ni and Cu. Values of $D^{mss/}_{\text{sulfide liquid}}$ for Ni depend on the Cu content of the melt, varying from about 0.2 to >1, whereas those for Cu vary from <0.2 to 0.28 with the S content of the *mss*. Li *et al*. (1996) showed that partition coefficients for PGE also increase with the S content of the *mss*, with values for Ir and Rh generally greater than 1 and those for Pt and Pd less than 0.5, consistent with the distribution of these metals observed in natural ores (theme 5). These data support the hypothesis that the "footwall copper veins" at Sudbury and the Cu-rich zone of the Oktyabr'sk deposit at Noril'sk were deposited from a Cu-rich fractionate of the initial sulfide magma responsible for the deposits. Chlorine-rich hydrous alteration associated with the Sudbury Cu-rich deposits and fluid inclusions had been cited as evidence that the veins were deposited from hydrothermal fluids, as discussed above. However, Mungall & Brenan (2003) studied the partitioning of halogens between silicate magma and sulfide melt, and showed that whereas halogens prefer the silicate magma, sufficient Cl is partitioned into the sulfide melt that after 95% fractionation, the residual melt will contain enough Cl to account for the alteration. Experimental container problems mean that the H_2O content of Fe–S–O melts is difficult to determine, but Wykes & Mavrogenes (2005) showed that the presence of H_2O at 1.5 GPa lowers the eutectic in the system FeS–PbS–ZnS by 35ºC, which they interpreted to indicate that significant H_2O dissolves in the melt. They commented that application of their observations to Fe–Ni–Cu–S–O melts suggests that significant H_2O could be present in a fractionated Cu-rich Fe–Ni–Cu–S–O liquid, which, when combined with the observations of Mungall & Brenan (2003), provided an explanation for the alteration around the Sudbury footwall copper veins.

Arndt *et al*. (2004) addressed the problem of why alkaline intrusions are not favorable hosts for Ni–Cu sulfide deposits, despite their Ni, Cu and PGE contents comparable to those related to tholeiitic magma. They argued that alkaline magmas are the product of limited partial melting of the mantle, and therefore are volatile-rich. Their high volatile content means that they are less dense than tholeiitic melts, and thus tend to rise through the crust rapidly, with no tendency to pond and form sills on the way. Thus they do not have the opportunity enjoyed by tholeiitic magmas of interacting with, and gaining sulfur from, the crust and forming magmatic sulfides (theme 1).

Summary of 1990–2004

This period saw the benefits of the three previous decades. The end of the Cold War allowed a much freer flow of information, and deposits such as those at Jinchuan and Pechenga could be interpreted in terms of the lessons learned at Noril'sk, Kambalda, Sudbury and Voisey's Bay. The availability of experimentally derived partition-coefficient data, coupled with computer programs such as MELTS (Ghiorso & Sack 1995) and COMAGMAT (Ariskin 1997) allowed the modeling of the crystallization of layered intrusions under both sulfide-saturated and sulfide-unsaturated conditions, which provided constraints on models proposed purely on geological grounds. The SALE 2D hydrocode (Amsden *et al*. 1980) allowed Ivanov & Deutsch (1999) to investigate crater formation and, when coupled with thermal transfer models, the cooling history of the SIC.

Partition-coefficient data also showed that that Cu-, Pt-, Pd- and Au-enriched zones such as those at Noril'sk and in the footwall at Sudbury are consistent with an origin through fractional crystallization of a sulfide liquid. Arguments contrary to this origin, based particularly on hydrous, Cl-rich alteration around the veins at Sudbury, have been put forward, and this issue is still an open one. However, experimental studies have shown that fractionated Fe–Ni–Cu–S–O melts may contain sufficient Cl and H_2O to account for the alteration.

Work at Voisey's Bay showed that Ni depletion in olivine is both a diagnostic tool for recognition of rocks derived from magma that had undergone sulfide depletion, and also a powerful instrument for an interpretation of the history of an intrusive system. An improved understanding of the facies of komatiitic flows at Kambalda and its application to the Raglan camp, coupled with new studies at Noril'sk, and an understanding of the magma-plumbing system at Voisey's Bay, drove home the importance of the physical environment of flow in the concentration of sulfides. Experimental work on the effect of pressure on the SCSS of mafic magma showed that magmas are unlikely to reach the surface saturated in sulfide, and explained why so many deposits occur within or above sulfide-rich country rocks, and show evidence of containing a component of crustal sulfur.

SUMMARY AND A VIEW OF THE FUTURE

Early ideas about what is now regarded as magmatic sulfide deposits were dominated by observations at Sudbury and their interpretation. The SIC was viewed by many as a differentiated layered sill from which the sulfides had settled to collect in depressions along the footwall as it crystallized. The high proportion of granophyre and the nature of the Onaping Formation led some to prefer a model of caldera collapse, with the granophyre and norite being injected separately as ring dykes. This latter group favored a hydrothermal emplacement for the sulfides. The concept of gravitational accumulation of sulfides from a crystallizing layered intrusion dominated thinking about magmatic sulfides in general up until the 1960s, and Sudbury was used as the type model for exploration.

The revolution in ideas starting in the 1960s (Fig. 5) was sparked by the discovery of the deposits at Talnakh and Kambalda, and the consequent realization that Sudbury was not necessarily the type model for all deposits of this type. With the gradual acceptance of the astrobleme hypothesis, Sudbury, far from being the type model, came to be regarded as unique. Development of the deposits at Kambalda showed that they are related to flows of komatiitic lava, and intelligent exploration required that attention be paid to the particular flow-facies that is most prospective for ore. It came to be recognized that many of the deposits are located at the base of channels along which flow had been concentrated. The physical environment of ore deposition became an important theme in research, particularly where it was shown that the deposits at Noril'sk and Voisey's Bay also occur in conduits. A corollary to this theme is that the conduit flow must be of sulfide-bearing magma, which requires that sulfide saturation must have been achieved prior to the magma finally coming to rest.

Experimental work on controls on the sulfur content of mafic–ultramafic magmas at sulfide saturation showed that magmas rising directly from the mantle are unlikely to approach the surface saturated in sulfide. Sulfur isotope studies at Noril'sk and elsewhere highlighted the importance of crustal sulfur in the formation of the deposits. When coupled with evidence that many source magmas of magmatic sulfide deposits bear trace-element and isotopic evidence of having interacted with the crust, it is now appreciated that crustal contamination is a vital component in the development of a magmatic sulfide ore deposit.

Investigation of the Ni content of olivine in rocks related to deposits at Noril'sk, Voisey's Bay and many other areas has shown that the removal of sulfide leaves its mark in the form of Ni depletion in olivine, evaluated in terms of its Fo content. Studies at Noril'sk have shown that large volumes of basalt, which are penecontemporaneous with the mineralized intrusions, are strongly depleted in Ni, Cu and PGE. However, marked depletion in chalcophile elements is not necessarily the best indicator of the proximity of economic mineralization. Exposure of the sulfides to waves of fresh magma is commonly required to upgrade them to economic tenors of metal.

Many magmatic sulfide deposits exhibit zones enriched in Cu, Pt, Pd and Au. In some cases, these are small in extent, and serve no better purpose than to provide fodder for exciting press-releases in the course of an exploration program, but both at Noril'sk and Sudbury, these zones are highly significant. Experimental work has shown that they are the natural end-product of the crystallization of a sulfide liquid, although debate still continues as to their possible hydrothermal origin.

It can be seen from the foregoing that much of the understanding about magmatic sulfides that has been gained since the onset of the 1960s fits into the five themes, highlighted in Figure 5. But where will we go from here? I would like to close this paper with a few personal remarks about the future.

1. Much has been made of the importance of the addition of crustal sulfur to a magma to bring it to sulfide saturation. Nevertheless, how the transfer is achieved still is not understood. If the country-rock sulfur is in the form of pyrite, and the pyrite is affected by the metamorphic aureole of the intrusion, a high partial pressure of sulfur will be generated, and the resulting gradient in chemical potential can result in sulfur diffusing up the temperature gradient and into the intrusion. However, the country-rock sulfur is commonly pyrrhotite, and is, in the case of Noril'sk, anhydrite. Trace-element and isotopic evidence usually provides insufficient support for wholesale assimilation of the country rocks, and for the resultant winnowing out of sulfides distributed at the level of a few percent in these rocks. It is also difficult, although perhaps not impossible, to conceive of an intrusion carrying sufficient superheat to digest large volumes of country rock. With reference to the Kharaelakh intrusion at Talnakh, Naldrett (2004) has shown that if the sulfides are to be obtained by reducing the evaporite, and if the oxygen is to be taken up in the magma by the oxidation of Fe^{2+} to Fe^{3+}, and if the prevailing $f(O_2)$ before the reaction was close to 10^{-8} (QFM), the final $f(O_2)$ would be $10^{-3.3}$. This high oxidation state is totally inconsistent with the mineral assemblage of the Noril'sk intrusions, and, in any case, would require the sulfur to dissolve as SO_4^{2-}, which would preclude it forming an immiscible sulfide liquid. Li *et al*. (2003) have suggested that fluids that were circulating in the metamorphic aureole of the Noril'sk intrusions (bodies characterized by well-developed metasomatic assemblages within their metamorphic aureoles) contain dissolved sulfate, that the sulfate has become reduced as the fluids have circulated through carbonaceous strata, and then that the fluids have transported reduced sulfur into the intrusions. There is, however, no evidence that this process has operated. Further work on the problem of sulfur transfer is essential if for a full understanding of what progress over the last 40 years has shown to be a vital step in ore genesis.

2. The Noril'sk deposits occur in thermally eroded magma channels that feed part of a major system of sills. Apart from the areas known as the Ovoid and Eastern Deeps, the Voisey's Bay mineralization occurs largely in zones within the feeder dyke, where thermal erosion appears to have widened the structure from about 10 m to up to 100 m. A better understanding of the flow of two-phase silicate magma + sulfide liquid systems along conduits is essential. Why thermal erosion is prevalent in some places, whereas in other places, very little appears to have occurred, merits study.

3. Because of container problems, most experimental work to date has focused on dry sulfide-bearing systems. It is likely that solubility and partition-coefficient data are affected by the presence of volatiles, particularly H_2O. Fluids have clearly been active around the Noril'sk intrusions, and have been called upon to explain the footwall copper deposits at Sudbury. Experimental work on fluid-bearing silicate melt + sulfide systems is likely to increase the level of understanding of magmatic sulfide ore deposits substantially.

Acknowledgements

I am very honored to have been asked to contribute to the 50th Birthday celebrations of MAC, of which this number of *The Canadian Mineralogist* constitutes a part, and thank Frank Hawthorne for his efforts in realizing it. Clearly the contents of my article draw upon a lifetime in the field, and I take this opportunity to thank my colleagues, research associates, post-doctoral fellows and graduate students for their hard work through the years. It is only after one retires, and no longer has students working alongside, that one truly appreciates their contributions, not only in generating data and ideas, but in keeping one current as to what is going on! I thank Michael Lesher and Norman Halden for constructive reviews of this manuscript, and Bob Martin, our editor, for his efforts on this number, and for keeping our journal at the forefront of Mineralogy and Petrology for so long.

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