THE
SUDBURY-NORIL'SK SYMPOSIUM

PROGRAM AND ABSTRACTS

October 3 to 5, 1992
Auditorium
Minerals Research Centre
Ontario Geological Survey
Sudbury, Ontario

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PROGRAM

Friday evening, October 2

	IGCP Project 336, inaugural meeting (time and place to be announced)

Saturday morning, October 3

0800-0815	WELCOME
0815-0900	**G.G. Rempel** Regional geophysical characteristics of the Noril'sk region
0900-0945	**O.N. Simonov** Geological structure of the Noril'sk region
0945-1015	COFFEE
1015-1100	**V.A. Fedorenko** Evolution of Permian–Triassic mafic–ultramafic magmatism in the Noril'sk region
1100-1145	**A.P. Likhachev** Ore-bearing intrusions of the Noril'sk region
1145-1200	DISCUSSION
1200-1330	LUNCH

Saturday afternoon, October 3

1330-1415	**V.E. Kunilov** Geology of the Noril'sk region: prospecting, exploration and mining of the deposits
1415-1500	**A.I. Stekhin** Mineralogical and geological characteristics of the Talnakh ore junction
1500-1530	COFFEE
1530-1615	**A.S. Torgashin** Geological characteristics of massive and Cu-bearing ores in the western part of the Oktyabr'sky deposit
1615-1700	**V.V. Distler** Platinum mineralization of the Noril'sk deposits
1700-1730	DISCUSSION
1930	BANQUET, Science North (optional)

Sunday morning, October 4

0800-0845	**B. Milkereit** Third dimension of the Sudbury Structure: results from reflection seismic profiling
0845-0915	**P.H. McGrath* & H.J. Broome** Gravity modelling of the Sudbury Structure
0915-0945	**R.B. Hearst*, W.A. Morris & M.D. Thomas** Potential field interpretation and modelling along the Sudbury Structure Lithoprobe transect
0945-1015	COFFEE
1015-1100	**G.G. Morrison*, B.C. Jago & T.L. Little** Sudbury footwall mineralization, with particular reference to the McCreedy East and Victor deposits
1100-1145	**J.P. Golightly** Fitting a crater to the Sudbury Structure
1145-1200	DISCUSSION
1200-1330	LUNCH

Sunday afternoon, October 4

1330-1415	**W.P. Binney*, R.A. Foy, S.H. Halladay, R.Y. Poulin & J.M. Sweeny** The Lindsley Ni–Cu–PGE deposit and its geological setting
1415-1500	**C.M. Moore* & S. Nikolic** The Craig nickel deposit, Sudbury, Ontario
1500-1530	COFFEE
1530-1615	**E.J. Cowan, W.S. Shanks & W.M. Schwerdtner*** Geometrical significance of the geological map pattern of the Sudbury Structure
1615-1700	**R.S. James* & B.O. Dressler** Nature and significance of the Levack gneiss complex – footwall rocks of the North and East ranges of the Sudbury Igneous Complex
1700-1730	DISCUSSION
2000	EVENING DISCUSSION SESSION, Science North (organized by the Sudbury Geological Discussion Group)

Monday morning, October 5

0800-0845	**J.L. Wooden*, G.K. Czamanske, R.M. Bouse, M.L. Zientek, R.J. Knight, J.R. Budahn, A.P. Likhachev & V.A. Fedorenko** Pb and Sr isotopic evidence for the genesis of ores and magmas in the Noril'sk – Talnakh district, Siberia
0845-0930	**R.J. Walker*, J.W. Morgan, M.F. Horan, G.K. Czamanske, A.P. Likhachev & V.E. Kunilov** Rhenium–osmium isotopic systematics of ores rich in platinum-group elements, Noril'sk – Talnakh district, Siberia
0930-1000	COFFEE
1000-1045	**G.K. Czamanske*, J.L. Wooden, T. Zen'ko, V. Fedorenko, A.P. Likhachev, M.L. Zientek, R.J. Knight, J.R. Budahn, D.F. Siems & J. Kent** The ore-bearing intrusions of Noril'sk – Talnakh: composite but "comagmatic"
1045-1130	**M.L. Zientek* & A.P. Likhachev** Compositional constraints on the genesis of ore deposits of the Noril'sk – Talnakh district, Siberia
1130-1300	LUNCH

Monday afternoon, October 5

1300-1345	**P.C. Lightfoot*, A.J. Naldrett, C.J. Hawkesworth, N. Gorbachev, V. Fedorenko, J. Hergt & W. Doherty** Source and evolution of Siberian trap lavas, Noril'sk district, Russia: implications for the origin of sulfides
1345-1430	**A.J. Naldrett*, M. Asif, N.S. Gorbachev, V.E. Kunilov, V.A. Fedorenko & P.C. Lightfoot** The composition of the Ni–Cu ores of the Noril'sk region
1430-1500	DISCUSSION
1500-1530	COFFEE
1530-1615	**A.J. Naldrett*, A. Pessaren & Chusi Li** Variation in the Ni, Cu and PGE content of ore on the North Range at Sudbury, between the Hardy and Longvack mines
1615-1700	**R.A.F. Grieve** An impact model for Sudbury
1700-1715	DISCUSSION
1715-1730	CLOSING REMARKS

Monday evening, October 5

	IGCP Project 336, second meeting

ABSTRACTS

Saturday morning, October 3

GENERAL GEOPHYSICAL CHARACTERISTICS OF THE NORIL'SK REGION

G.G. REMPEL

Ministry of Geology of the USSR, NPO "SIBGEO"

1. The general geophysical characteristics of the Noril'sk region are determined by two major geological factors: a) the location of the Noril'sk region in the northern portion of a relatively mobile zone, which defines the western border of the Siberian platform; b) the wide development of trap magmatism.

2. The mobile zone stretches along the Yenisei river from the Upper Proterozoic folded structures of the Yeniseisky mountain ridge to the Mesozoic–Cenozoic Yeniseisko–Khatangsky regional trough in the North. The most distinct geophysical characteristic of the mobile zone is its reduced magnetic field. This indicates that the body of the mobile zone differs considerably from that of the Siberian platform, not only in the extension and age of the fold structures, but also in the composition of the constituent rocks.

3. The gravity field of the central part of the Noril'sk region is characterized by a positive anomaly, which has a north–northwesterly direction. In the east, it joins with a very intense negative anomaly. Present thinking is that the positive anomaly is accounted for by relief at the Moho discontinuity and by the main characteristics of the distribution of the intrusions within the platform cover. The negative anomaly is attributed largely to the isostatic adjustment.

4. Deep seismic probing data have led to the interpretation of a sequence of subhorizontal discontinuities, including the Moho discontinuity, in the Noril'sk region within the basement. These data have indicated a general picture of deep fault systems. It is too early to evaluate the reliability of these data. However, it is very interesting that the Noril'sk–Kharayelakhsky fault (which has been interpreted as an ore-controlling structure) appears to be a trans-crustal fault.

5. The study of the deep structure of the Noril'sk region by gravity and magnetic methods is hampered by the fact that gravity and magnetic anomalies from deep-seated objects can be extremely obscured by or lost amongst a background of intense anomalies (interferences), which are caused by the trap formations.

6. The study of the deep structure was started in the 1940s. At that time, an attempt was made to interpret the differentiation of the relatively thin (no more than 350 m) ore-bearing intrusions as being the result of preliminary separation of magma in intermediate chambers, which were located at a considerable depth.

7. The aeromagnetic data, from a survey at a height of 2400 m, and the results of mathematical modelling, were applied to the problem of the intermediate magma chambers. Mathematical modelling was used to calculate and then eliminate the most intense interferences from the observed magnetic field. These interferences are a product of the tuff lava sequence, which is up to 3500 m thick in the Noril'sk region.

8. Mathematical modelling of the Noril'sk region showed magnetic anomalies of up to 160 nTl, which are associated with all of the Cu–Ni deposits and mineralization. These magnetic anomalies are most likely attributed to large (probably serpentinized) intrusive bodies at depths of 12 to 17 km. There is a tentative correlation between the vertical dimension of the intermediate chambers and their productivity. An abnormally high ratio of the amount of metal to mass of silicate rock is observed in the Noril'sk deposits.

9. The thick intrusions (including the deep-seated ones) are believed to be one of the *necessary* conditions for the formation of the Noril'sk type of Cu–Ni deposits (and some other deposits as well).

10. The application of these necessary criteria allows one to considerably reduce the areas of interest at an early stage in geological exploration.

GEOLOGICAL STRUCTURE OF THE NORIL'SK REGION

O.N. SIMONOV

Noril'sk Expedition, Noril'sk, Russia

The Noril'sk Ni-bearing region is localized within the mobile zone, which forms the northwestern margin of the ancient Siberian platform; this is marked by a series of linear depressions (troughs and basins). These depressions are filled with a very thick succession of Riphean to Early Mesozoic sedimentary and volcanogenic strata, separated by anticlines, and referred to as the North Siberian Ni-bearing region.

The geological structure of the Noril'sk region is determined by its position in the northwestern portion of the ancient Siberian platform, which adjoins young Caledonian to Hercynian and Kimmerian structures of the West Siberian plate (the Yeniseisky geosynclinal area) to the west and abuts the Taimyr fold belt to the north. The Taimyr fold belt is separated from the platform by the Mesozoic to Cenozoic Yeniseisko–Khatangsky rift-related trough. The Noril'sk Ni-bearing area occupies the territory of one of the constituent depressions of the North Siberian region, namely the Noril'sk–Kharayelakhsky depression; this is superimposed on the Pre-Yeniseisky (Noril'sk) major basement block along the similarly named fault zone.

Geophysical data show that the Noril'sk Ni-bearing region is characterized by an excessively thick, double-layer continental crust, which is comprised of a volcanogenic–sedimentary cover 6 to 18 km thick and a crystalline basement 36 to 42 km thick. The Moho discontinuity is localized at a depth of 42–48 km.

The cover has a two-membered structure, being divided into a lower structural portion (the Orogenic and Pre-Orogenic complexes) and a plate portion. The lower parts consist of (i) the Gubinsky and Staromostovsky molassoid sequences, which were deformed during the Riphean, (ii) the Ludlovsky volcanogenic schist and Medvezhinsky carbonate flischoid sequences, and (iii) the weakly deformed Vendian Cu-bearing molasse, comprising the Izluchinsky, Rybninsky and Graviisky suites.

The Noril'sk–Kharayelakhsky fault has played a very important role in the development of the structure of this section, since it controls the distribution of the sedimentary facies and magmatic formations.

The region of the plate is divided into three subsections, which were developed during three tectonic cycles. The first subsection is composed of the Vendian to Early Carboniferous marine and lagoonal–marine terrigenous carbonate rocks 3–5 km thick. These form the Noril'sk–Kharayelakhsky consedimentation depression, which to the west is outlined by the Dudinsky anticline and to the east verges on the Khantaisko–Rybninsky paleo-uplift.

The second subsection has in general a similar structure to the first subsection and consists of the Tungussky terrigenous coal-bearing rocks (C_2–P_2), 40 to 600 m thick, and of the tuff-lava sequence, which is up to 3500 m thick. The third subsection comprises the Mesozoic–Cenozoic weakly lithified terrigenous sediments, which are 0 to 5000 m thick.

The present structure of the Noril'sk Ni-bearing region was formed prior to the Jurassic as a result of tectonic activity. At this time, the Noril'sk–Kharayelakhsky depression broke down into a series of brachysynclines (the Turumakitsky, Noril'sk, Vologochansky, Kharayelakhsky, Talovsky and Ikonsky), which are separated by cross-cutting anticlines and flexure-related faults. The metallogenic picture of the region is determined by the sulfide copper–nickel ore formation, which is closely associated with the magmatic formation known as the Siberian trap.

With regard to structure and composition, the extrusive basalt complex (trap formation) is divided into two portions: the lower (Ivakinsky–Nadezhdinsky) differentiated lavas, which are developed only within the Noril'sk Ni-bearing region, and the overlying (Morongovsky–Samoyedsky) "trap" sequence, which has a different structure.

The intrusive formations occur in Ordovician to Lower Triassic strata, and comprise nine intrusive complexes: the Yergalakhsky, Pyasinsky, Oganersky, Fokinsky (Gudchikhinsky), Noril'sk, Morongovsky, Daldykansky, Avamsky trap sequence and Bolgokhtokhsky gabbro–granite formations. The Cu–Ni deposits are associated with layered intrusions that comprise the Noril'sk intrusive complex. This complex consists of a triad of intrusive phases, which form the ore junctions. Spatially, the ore junctions are related to structures that developed in the upper part of the plate; the role of the long-lived Noril'sk–Kharayelakhsky fault was predominant. The degree of mineralization of the Noril'sk intrusions is determined by both their composition and the structural–tectonic conditions of their generation.

EVOLUTION OF PERMIAN-TRIASSIC MAFIC-ULTRAMAFIC MAGMATISM IN THE NORIL'SK REGION

V.A. FEDORENKO

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During a short period coinciding with the boundary between the Permian and Triassic (247–248 Ma), 152,000 km^3 of igneous rocks covering 45,300 km^2 were formed in the Noril'sk region. These are volcanic (94%) and intrusive (6%) formations. Much of the magmatic activity falls into three mafic–ultramafic formations: high-Ti (HT), low-Ti and low-Fe (LTLF), and low-Ti and normal Fe (LTNF).

The volcanic sequence is 3500 m thick. The ratio of effusive to pyroclastic rocks is 90 to 10. The sequence is divided into 11 suites, which are, from the base upward: the Ivakinsky, Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, Nadezhdinsky, Morongovsky, Mokulayevsky, Kharayelakhsky, Kumginsky and Samoyedsky. The Ivakinsky and Gudchikhinsky suites consist of alkaline and subalkaline basaltic and picritic lavas of the HT group, characterized by Yb/Gd ratios of 0.33 to 0.47. The Khakanchansky suite is composed essentially of tuff. The Tuklonsky to Early Morongovsky effusive rocks are represented by LTLF basalts and picrites with Yb/Gd ratios from 0.52 to 0.63. The Tuklonsky lavas are noncontaminated (Ce/Yb = 6 to 9). The Nadezhdinsky and Early Morongovsky lavas reveal different degrees of crustal contamination (Ce/Yb up to 15 to 19). All of the rocks are considerably depleted in Ni, contain contaminated formations and have low Cu contents. The Late Morongovsky – Samoyedsky lavas consist of noncontaminated basalts of the LTNF group (Yb/Gd 0.56 to 0.67, Ce/Yb 6 to 8), which are characterized by normal Cu and Ni contents. HT basalts and ankaramites (the Kaltaminsky association) may be found in the upper part of the Morongovsky suite; these have Yb/Gd in the range 0.22 to 0.23.

The intrusive rocks are mainly represented by unmineralized dolerites (or with only sporadic sulfides); there is evidence of trachydolerite and picrite. They can be divided into 12 types, and include both those comagmatic with the effusive rocks and those independent of the effusive suites.

The mineralized intrusions (layered bodies with individual layers containing between 3 and 28 wt% MgO) consist of the Lower Talnakh type, which have poor, primarily pyrrhotite-rich, disseminated sulfide, and the Noril'sk type. The latter is subdivided into several subtypes, including the Talnakhsky, which hosts the economic Cu–Ni–PGE mineralization. The Lower Talnakh intrusions (Yb/Gd 0.52–0.62, Ce/Yb 10 – 15) reveal distinct crustal contamination and are depleted in Ni and Cu. Their development is associated with activity in an intermediate magmatic chamber, the upper part of which is believed to be the source of the Nadezhdinsky – Early Morongovsky lavas. The Noril'sk intrusions (Yb/Gd 0.62–0.69, Ce/Yb 6–8) are not contaminated. Despite the abundant sulfides, the silicate material of these bodies is not depleted in Cu and Ni. It is suggested that the silicate magma responsible for them was associated with sulfide within the body of the intrusions. Whereas this magma is geochemically similar to the Late Morongovsky lavas, the sulfides themselves segregated during the formation of the Nadezhdinsky – Early Morongovsky effusive rocks; the intrusions were emplaced during the Middle Morongovsky period.

The intense and diverse magmatic activity of the Noril'sk region is attributed to the existence of a long-lived system of deep faults (the Noril'sk system of disruptions). The evolution of magmatism with time was controlled by changes in the tectonic regime. The HT formations resulted from rifting within the Yenisei–Khatangsky trough and its south–southwestern branches (the Noril'sk–Kharayelakh volcano-tectonic depression), which lie along the Noril'sk system of disruptions. The LTLF formations developed only within the Noril'sk–Kharayelakhsky paleo-depression as a result of a tectonic regime transitional between rifting and incipient spreading. The LTNF formations were formed during a regime of incipient spreading; they cover large areas of the Siberian platform. Each group of volcanic formations is probably associated with an independent mantle source.

The development of the sulfide-bearing magma coincided with the transition between the LTLF and LTNF formations. This process has apparently taken place in a vast intermediate chamber, in which a LTLF mantle melt was undergoing crustal contamination. This was followed by immiscibility of a sulfide liquid, differentiation and intermixing between differentiates and fresh LTNF magma. Evidence for this (considered a regional prospecting indication) is the development of the voluminous formations of Cu- and Ni-depleted magma as represented by the Nadezhdinsky – Early Morongovsky lavas and the Lower Talnakh intrusions.

ORE-BEARING INTRUSIONS OF THE NORIL'SK REGION

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There are five ore-bearing intrusions in the Noril'sk region, which are associated with the similarly named Cu–Ni deposits. These are: the Noril'sk I, Talnakhsky, Kharayelakhsky, Noril'sk II and Chernogorsky intrusions. The intrusions are elongated sill-like bodies from 50 to 300 m thick, from 500 to 2000 m wide and more than 15 km long; they are 2.47 Ga old. They have intruded: into the base of the Lower Triassic basaltic sequences, at the contact of the Triassic basalts with the Tungussky Upper Permian continental sediments, within the Tungussky suite and in the underlying Devonian carbonate deposits. The intrusions are distinctly stratified in vertical section. The base consists of a 1- to 10-m-thick zone of medium- to fine-grained contact gabbro dolerite (Gc). This is succeeded upward by horizons of: coarse- to medium-grained taxitic (Gt), picritic (Gp), olivine–biotite (Gob), olivine (Go), olivine-bearing (Gob) and olivine-free (Gno) gabbro dolerite and then by gabbro diorite (Gd). The combined thickness of these units is 50 to 300 m. Bodies of breccia combined with taxitic and picritic gabbro dolerite and coarse-grained leucocratic gabbro (G) occur within the intrusions at their upper contacts. These bodies vary from several cm to 20 m in thickness and several cm to several hundred m in length. The lower parts of the intrusions split into sills of leucocratic gabbro and taxito-poikilo-ophitic (taxitic) gabbro dolerite, which extend from hundreds of m to several km away from the main intrusions.

The Cu–Ni sulfides are associated with the lower intrusive differentiates (Gob, Gp, Gt, Gc) and with the underlying rocks. Disseminated sulfides are present in the branching sills and in the breccia bodies of the upper contact. The average Ni, Cu and PGE content in the disseminated ores are 0.4–0.6 wt%, 0.6–0.8 wt%, and 3–5 g/t, respectively.

The massive ores (these are vein bodies and deposits up to 45 m thick) are emplaced mainly in the lower endo- and exocontacts of the intrusions; in some cases, they occur in the middle and upper parts of the picritic horizon. The Ni, Cu and PGE contents of these sulfides are 2–4 wt%, 3–25 wt% and 2–200 g/t, respectively. The massive ores comprise 10 to 40 wt% of the total amount of the sulfide material, and correspond to about 3% of the mass of the intrusions.

All of the ore types reveal chemical and mineralogical zoning, which gives rise to complex associations of minerals. In contrast to other deposits, these ores are characterized by specific compositional features, similar to those of chondritic and primitive mantle material.

A quantitative estimation of the volume and thickness of the different phases of the intrusions (massive sulfides, Gc, Gt, Gp, Go, *etc.*) reveals that there is no correlation between them. The sulfide material is concentrated in the frontal parts of the intrusions, and shows a regular step-like distribution of maximum concentrations. Relatively thin intrusions (100–150 m) are accompanied by excessively thick (150–250 m) and abundant high temperature (>500°C) zones of hornfels at the upper endocontact.

The formation of the observed amount of hornfels and sulfides should require twenty-five times more magmatic material than is present. This is possible if the magma was extremely slow cooling as a result of continuous magmatic flow lasting more than 1500 years. Most probably, this came about as a result of the longitudinal circulation of magma from the rear (initial and intermediate chambers) to the frontal parts of the magmatic column and *vice versa*. This was accompanied by chemical and physical mass-transfer reactions and by the transfer of kinetic energy.

Saturday afternoon, October 3

GEOLOGY OF THE NORIL'SK REGION: PROSPECTING, EXPLORATION AND MINING OF THE DEPOSITS

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The history of the geological discoveries in the Noril'sk region dates back to the 19th century. In 1865, the merchants Sotnikov claimed the present mining area. However, geological studies of this region have been conducted since 1919, when the first Siberian Geological Expedition started its work under its chief, Urvantsev. The 1920s and 1930s were marked by intensive regional geological studies and resulted in an outline of the main complex of mineral deposits, which provided a source of raw materials for a developing group of enterprises. The location of the Noril'sk region at the margin of the northwestern portion of the Siberian plate, where it adjoins the West Siberian and Karsky plates, accounts not only for the strong development of the Cu–Ni mineralization, but for a variety of other mineral deposits as well. The deep faults, along which troughs accompanied by transverse uplifts developed, contributed significantly to the present-day structure of the Noril'sk region. The maximum concentrations of ore-bearing differentiated intrusions are associated with faults intersecting the upfolded margins of the troughs containing Devonian, Tungussky and Triassic sequences.

Coal, sandstone, carbonate, gypsum, anhydrite, siltstone, tuff, argillite, clay and deposits of other building materials, together with gas and underground water, *etc.*, were discovered in the area of the main ore-bearing sulfide Cu–Ni deposits of Noril'sk I and Noril'sk II.

The discovery during the second half of the 20th century of the Talnakh ore junction is the most important milestone in the history of the Noril'sk region. Different stages of exploration, the organization and methods of prospecting, and experience provided important foundations for further geological studies of the region.

The ore-bearing horizon of the Noril'sk I deposit (its northern part has been essentially mined out) consists mainly of disseminated picritic, taxitic and contact gabbro doleritic ores. These are mined in the "Zapolyarny" underground mine and in the "Medvezhy Ruchei" (Bear's Brook) open pit. In the Talnakh ore junction, all of the economic ore types (disseminated, rich and "copper-rich") form an almost unique zone in the lower parts of the intrusions and in the underlying rocks. The rich (massive) ores comprise deposits and lenses in the exocontact of the intrusion. The "copper-rich" ores are associated with the frontal zones of the deposits and form the most complex horizons (with regard to their shape and structure). The orebodies are up to several tens of meters thick. Mining is underway at the underground "Mayak", "Komsomolsky", "Oktyabrsky" and "Taimyr" mines. The "Skalisty" mine is under development. The "copper-rich" ores are the most mineralogically and technologically complicated of all the ores.

Geological factors contribute to difficult mining conditions These include: low dips, "multilevel" structure and remarkable thickness of the ore zone, the presence of several tectonic zones which have resulted in discontinuities, and pressure, which increases with depth of mining.

Other aspects that will be discussed include the geometry of the deposits, water influx and the presence of gas, the mineral processing systems applied to various ore types from different mines, with their specific characteristics, the losses and contamination of ores during their exploitation, the methods used for additional prospecting and exploitation, the sampling methods, geological and technological mapping, the geological resources for the mining industry, the structure of the Geological Survey and its place within the State Geological Survey. Finally, the organization of geological studies, using the Noril'sk region as an example, and including mapping, prospecting and exploration of the deposits will be discussed.

MINERALOGICAL AND GEOLOGICAL CHARACTERISTICS OF THE TALNAKH ORE JUNCTION

A.I. STEKHIN

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The Talnakh deposits are characterized by different shoots of Cu–Ni sulfide ore, which show mineralogical variations in directions both parallel and perpendicular to the Noril'sk–Kharayelakhsky fault. The Noril'sk–Kharayelakhsky fault is the ore-feeding channel. With regard to temperature, Cu, Fe, Ni, Co mobility and sulfur regime, the shoots contain three types of pyrrhotite-rich massive ore (A): fine-grained pyrrhotite-dominant (A_1), chalcopyrite - pyrrhotite (A_2), and chalcopyrite-rich chalcopyrite - pyrrhotite (A_3); three types of cubanite-rich massive ore (B): chalcopyrite - pyrrhotite (troilite) - cubanite (B_1), troilite - chalcopyrite (talnakhite, mooihoekite) - cubanite (B_2), and chalcopyrite (talnakhite, mooihoekite) - cubanite (B_3); three types of chalcopyrite-rich massive ore (C): pyrrhotite - chalcopyrite (C_1), cubanite - chalcopyrite (talnakhite, mooihoekite) (C_2), and chalcopyrite (talnakhite, mooihoekite) (C_3). The pyrrhotite ores form the near-root zones of the shoots; the cubanite and chalcopyrite ores have been deposited in the distal, frontal parts of the shoots.

The disseminated and "copper-rich" ores display similar variations. The pyrrhotite variant of the "copper-rich" ore has been altered intensely by secondary processes, which have given rise to valleriite, tochilinite, pyrite, magnetite and millerite.

The ores contain all of the known structural modifications of pyrrhotite: monoclinic, hexagonal (intermediate) and troilite. There is evidence of a distinct increase in the content of Ni and Co held in solid solution on proceeding from troilite to hexagonal to monoclinic pyrrhotite; Co and Ni solid solutions also show other variations within this progression.

The chalcopyrite group is represented by tetragonal chalcopyrite (including its iron-bearing variety), mooihoekite, talnakhite and Ni-bearing putoranite. Ni in solid solution attains 2%. Pentlandite is observed as two morphological varieties: 1) coarse grained, and 2) fine grained (flame-like intergrowths in pyrrhotite). Ni-rich pentlandite is associated with high-Ni pyrrhotite, whereas the Fe-rich pentlandite is associated with low- Ni pyrrhotite. Cubanite is characterized by a constant chemical composition. Magnetite occurs as grain-like and lamella-like variants.

Different variants have been singled out on the basis of crystal chemistry. Pyrrhotite compositions are divided into high-Ni and low-Ni varieties of hexagonal and monoclinic type. Pentlandite is represented by Ni-rich and Fe-rich varieties; tetragonal chalcopyrite is divided into Cu-bearing and Fe-bearing varieties.

The different types of massive ore are characterized by certain sulfide modifications: A_1, by a high content of Ni-bearing monoclinic pyrrhotite, magnetite and Ni-bearing pentlandite; A_2, by a high content of Ni-bearing hexagonal pyrrhotite and flame-like pentlandite; A_3, by predominant low-Ni hexagonal pyrrhotite.

The Cu content of the copper minerals and the Fe content of pyrrhotite and pentlandite increase from the pyrrhotite toward the chalcopyrite ores. With regard to sulfur, sulfides ranging from pyrrhotite to chalcopyrite have the stoichiometric values of metal-to-sulfur ratio characteristic for each mineral in areas that are characterized by the absence of ores with an intermediate composition. The transitional zones (which are areas that mark the change in the crystalline structure of minerals) can be traced out on the basis of variation in elements such as Cu and Ni. These zones form a symmetrical net. The chemical composition of the different varieties of ore that are defined in terms of the chemical composition and structural nature of the minerals defines population maxima that correspond to the stable ore mineral variants.

GEOLOGICAL CHARACTERISTICS OF MASSIVE AND Cu-BEARING ORES IN THE WESTERN PART OF THE OKTYABR'SKY DEPOSIT

A.S. TORGASHIN

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The main characteristics of the Oktyabr'sky deposit are the presence of thick layers of massive ore, which reveal a distinct zonal structure, and veinlet-disseminated brecciated (copper) ore in the endo- and exocontacts of the intrusion. The copper ores are located on the northwestern flank of the deposit, within the upper endo- and exocontacts of the intrusion, and can be described as a relatively continuous zone of disseminated, veinlet-disseminated and breccia sulfide ores. The morphology and structure of the mineralized zone are controlled mainly by a combination of the configuration and spatial location of the borders of "foundered" structural blocks of the intrusion, coupled with the presence of an extremely fractured, highly permeable sequence of anhydrite and marl within the roof of the intrusion. A considerable variation in the composition and structure of country rocks accounts for the remarkably diverse ore textures, which are determined by the proportions of sulfide and ore metals.

Pyrrhotite, chalcopyrite and pentlandite are the main ore minerals in the Cu-bearing ores. Pentlandite is present in relatively constant amounts (about 10% of the total sulfides), whereas chalcopyrite and pyrrhotite reveal considerable variation. This accounts for the classification of mineral varieties, which is based on their pyrrhotite and chalcopyrite contents. The chalcopyrite-rich varieties usually are associated with the upper part of the ore zone.

The massive ores are associated mainly with the lower exocontact (and to a lesser extent with the endocontact) of the intrusion. The endocontact massive ores fill a complicated system of fractures, that is subparallel to the base of the intrusion. These ores form relatively consistent lens-like bodies and veins up to several meters thick and from several tenths to several hundreds of meters long. The greatest accumulation of massive ore is located in the lower exocontact of the ore-bearing intrusion. This is a large deposit, which is characterized by a flattened lens-like shape (almost plate-like), ranging from a few to several tens of meters in thickness. The deposit concordantly overlies Lower to Middle Devonian hornfelsic sedimentary rocks, which accounts for its shallow easterly dip. The morphology of the massive ores depends on the composition of the host rock.

The eastern part of the deposit is localized in sedimentary–metamorphic rocks, several meters below the lower contact of the intrusion. The rocks at the contact either contain disseminated sulfides or are absolutely barren.

Elsewhere, massive ores are in contact both with the intrusion and with sedimentary–metamorphic rocks. The latter are usually barren, whereas the differentiates commonly contain disseminated sulfides. In both situations, the massive ores show sharp contacts with the country rocks.

Areas where the massive ores are localized in fractures within the contact rocks of the intrusion are characterized by sharp (bench-like) decreases in the thickness of the deposit. The structural position of the massive ore is taken by the intrusive rocks, so that the total thickness of "ore + intrusion" remains the same as in adjacent parts of the deposit.

The deposit wedges out as a series of apophyses of ore that have invaded the sedimentary–metamorphic rocks along the sedimentary layering or cut these rocks as a well-developed series of veins. These veins extend from the main part of the deposit and fill fractures in the intrusion. They are observed in the northern part of the intrusion, where they transect the thickness of the intrusion, connecting up massive and disseminated ores.

The presence of two types of mineral zoning within the deposit is regarded as its most distinctive feature. The first type consists of the relative enrichment of the chalcopyrite – pyrrhotite ores that occur in silicates in the upper part of the mineralized section; this is accompanied by a decrease in chalcopyrite and a strong development of monoclinic pyrrhotite. The second type of zoning is observed within the massive ores, where they occur in intrusive rocks. It is marked by sulfide assemblages that contain low sulfur-minerals: mooihoekite, talnakhite, putoranite and Ni-bearing putoranite. These assemblages form the core of a zonal distribution of minerals in the deposit and are surrounded by cubanite-bearing assemblages that form an irregular concentric zone. These assemblages are replaced by chalcopyrite–pyrrhotite-bearing assemblages in other parts of the deposit.

PLATINUM MINERALIZATION OF THE NORIL'SK DEPOSITS

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The study of PGE distribution in the Noril'sk deposits provides a unique opportunity for analyzing the behavior of these metals during the formation of magmatic ores associated with the mafic and ultramafic magmas. Metal concentration is usually accompanied by various phenomena of sulfide mineralization; however, the PGE reveal a remarkable independence of the total volume of the sulfide present, whereas in general they follow the evolution of the ore-forming magmatic system. This is shown by data on the distribution of PGE concentrations within each genetic ore type and even more so by the variation of the total PGE concentrations between ore types. Thus the disseminated ores in the picritic and taxitic gabbro dolerite horizons of the totally differentiated intrusions contain: (in g/tonne) Pt, 0.6–1.0, Pd, 3.0–4.0, Rh, 0.03–0.06, Ru, 0.14–0.20, Ir, 0.01–0.03, Os, 0.02–0.04. The taxitic gabbro dolerites are slightly richer in PGE than the picrites. The concentration of the sulfides is 8–10% of the igneous rock. A strong contrast exists between the concentrations of the different platinum-group elements in different types of massive Cu–Ni ores; these are almost completely composed of sulfide (90–95 vol.%). PGE variations occur between ores of varying mineral composition; these are, in g/tonne, in ores identified in terms of their predominant ore-forming sulfide: pyrrhotite ores: Pt 1.5–2.0, Pd 7.0–9.0, Rh 0.6–1.2, Ru 0.2–0.3, Ir 0.06–0.10, Os 0.03–0.05; cubanite ores: Pt 3.5–5.0, Pd 20.0–25.0, Rh 0.2–0.5, Ru 0.05–0.10, Ir 0.01–0.03, Os 0.02–0.03; chalcopyrite (mooihoekite, talnakhite) ores: Pt 15.0–25.0 (up to 250), Pd 40.0–100.0 (up to 1000), Rh 0.01–0.02, Ru 0.04–0.09, Ir 0.01–0.02, 0s 0.01–0.03. Veinlet-disseminated ores normally contain 30–40 vol.% of sulfide material; their formation is associated genetically with deposition of the massive sulfide ores. They are characterized by the following PGE concentrations (g/tonne): Pt 1.6–2.6, Pd 6.0–9.0, Rh 0.05–0.10, Ru 0.20–0.30, Ir 0.02–0.03, Os 0.03–0.08.

Finally, the primitive Pt mineralization in the olivine–chromite-bearing taxitic gabbro that occurs close to the upper contact of totally differentiated intrusions is characterized by the most variable PGE distribution, in comparison with the three ore types considered above. This Pt mineralization forms an horizon, which genetically matches the Merensky reef of the Bushveld complex and the JM reef of the Stillwater complex; it has similar to identical chondrite-normalized PGE profiles. The concentration of sulfides in this horizon is no more than 1-3 vol.%. The distribution of PGE is characterized by the following values (g/tonne): Pt 1–4 (up to 10), Pd 6–10 (up to 60), Rh 0.07–0.12, Ru 0.14–0.20, Ir 0.01–0.03, Os 0.02–0.04. With regard to the relative values of the total concentration of the PGE in 100% sulfides, these are one hundred times richer in these ores than are the average PGE concentrations in the massive sulfide ores. These massive ores, in turn, are three to five times poorer than the disseminated mineralization in the totally differentiated intrusions and are 1.5–2 times poorer than the veinlet-disseminated mineralization.

Moreover, the nature of the PGE concentration within each particular ore type clearly indicates the correlation between the fractionation of certain PGE and the evolution of a magmatic sulfide liquid. It has been proved for the disseminated massive sulfide ores that no less than 50 to 70% of the total Pd and practically all of the Ir, Rh, Ru and Os are precipitated together with the major ore-forming sulfides, which gives rise to solid solutions of Pd, Rh and Ir in pentlandite and Ru and Os in pyrrhotite. The absolute concentrations of certain metals in the ore sulfides depend on the characteristics of ore deposition (temperature, sulfur and oxygen fugacities, activities of metals) and can vary within a wide concentration range. For example, Pd in pentlandite ranges from 30 to 1400 g/tonne, and Rh in pyrrhotite, from a fraction of a gram to 30 g/tonne. The formation of discrete Pt and Pd mineral phases is caused by the fact that these PGE attain their maximum solubility in sulfides under specific conditions of ore formation, whereas the selection of the ligands and stoichiometry of the ratios of the components in these phases are controlled by the general characteristics of ore deposition.

Analytical study of the ore parageneses shows that these characteristics differ greatly during formation of different ore types, particularly between those controlling Pt deposition during the formation of the veinlet-disseminated ores and the horizon of the olivine–chromite-bearing gabbro. There is no evidence of any substantial PGE solubility in the ore-forming sulfides, and the paragenesis of Pt-bearing phases in the complex consists of low- temperature sulfides and barren minerals, which contain volatile components. The precipitation of the PGE mineral phases may not be attributable to sulfides. The parts characterized by the richest Pt mineralization reveal a sharp increase in the bulk concentration of fluid components.

Thus PGE precipitation in the Noril'sk deposits is interpreted as a sequence of consecutive events. The most important of these are: partitioning of PGE between the sulfide fluid and the coexisting silicate magma, the dissolution of PGE in the sulfide liquid and their coprecipitation in the form of solid solutions in the crystallizing major ore sulfides, the crystallization of the Pt-bearing phases, which is caused by the accumulation of components in the subeutectic residual fluid of the sulfide melt, redistribution of the PGE in a fluid, and their concentration under the conditions comparable to hydrothermal ore deposition.

Sunday morning, October 4

THIRD DIMENSION OF THE SUDBURY STRUCTURE: RESULTS FROM REFLECTION SEISMIC PROFILING

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The Sudbury Structure is situated at the contact between Early Proterozoic Huronian supracrustal rocks of the Southern Province and Archean basement rocks of the Superior Province. It is located within a band of broad, east-west-trending positive gravity anomalies and is outlined by an elliptical positive magnetic anomaly. As part of the Canadian LITHOPROBE project, more than 100 km of conventional (10–55 Hz sweep, 60-fold) and 40 km of high-frequency (30–140 Hz, 120-fold) Vibroseis reflection data were acquired along three profiles across the Structure.

The main objectives of the study were to determine the shape of the Sudbury Structure at depth and to evaluate the performance of seismic exploration techniques in a complex, mainly intrusive setting. Special attention was paid to refraction static corrections in order to preserve the high-frequency content of the seismic data; DMO-processing was applied to improve estimates of stacking velocity and to image steeply dipping reflections. Many prominent dipping reflections on the stacked sections can be traced directly to the surface; frequency analysis confirms that most shallow reflections are well imaged by high-frequency events (≥ 70 Hz). Interpretation of the seismic data is constrained by information from several deep boreholes along the transect, geophysical logging and vertical seismic profiling of selected boreholes, studies of physical properties of representative rock samples, and electromagnetic profiling.

The new seismic images show that the Sudbury Structure is markedly asymmetrical at depth. Beneath the northern half of the Structure, reflection seismic profiling outlines lithological contacts. High-quality seismic images are obtained from the Chelmsford–Onwatin, Onwatin–Onaping, Granophyre–Norite and Norite–Footwall contacts. The seismic data confirm that the North Range of the Sudbury Structure comprises moderately (25–30°) south-dipping layers of footwall gneisses and overlying rocks of the Sudbury igneous complex (SIC), and sedimentary strata with only minor superimposed structural relief. An important result of the high-frequency reflection profiling is the spectacular change in structural style beneath the center of the basin. The sedimentary layers and upper layers of the SIC are interrupted or truncated by faults near the central axis of the SIC (*i.e.*, the center line through the Chelmsford Formation), whereas the footwall gneisses and mafic units of the SIC continue dipping southward to reach a depth of 4.5 km beneath the basin and 10 km beneath the South Range. The mafic unit of the SIC appears to be tightly folded or truncated near the Creighton fault. The seismic image of the South Range is dominated by steeply ($\geq 45°$) and south-dipping reflections. Some of the south-dipping reflections project up into the South Range Shear Zone, a broad zone of pervasive ductile shear; other reflections are interpreted as major discrete shear or fault zones. On these shear or fault zones, imbrication of lithological units and considerable northwest–southeast shortening of the Sudbury Structure took place. Near the southern rim of the Sudbury Structure, prominent north-dipping reflections probably originate from the Norite–Granophyre contact.

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GRAVITY MODELLING OF THE SUDBURY STRUCTURE

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High-resolution seismic reflection data along the LITHOPROBE profile across the Sudbury Structure (SS) provide new geometrical constraints that are evaluated by modelling coextensive gravity data. Previous gravity models of the SS by Popelar (1972) and Gupta *et al.* (1984) were constrained primarily by surface geology and by density measurements of surface rocks, but also by some borehole samples. Gravity data over the SS were obtained from the National Geophysical Data Centre, Geological Survey of Canada, and include gravity data provided by the Ontario Geological Survey. This data-set, which has an average station spacing of 2 km, was augmented in 1991 by supplementary gravity observations at a nominal station-spacing of one km along most of the LITHOPROBE survey line.

To model the gravity data, a straight gravity-profile line was selected; it crosses the SS close to the location of the segmented LITHOPROBE seismic line. Sixty-three evenly spaced gravity values at a one-km interval were interpolated along the selected line using the Bouguer gravity values calculated at the randomly spaced gravity stations, and within a corridor adjacent to the gravity-profile line. The two-dimensional interpolations were achieved using a minimum curvature algorithm. The modelling of the resultant data was constrained by (1) surface geology, (2) subsurface geometry provided by the seismic reflection data, and (3) surface and near-surface data on rock density (Gupta *et al.* 1984, Fig. 18.4). A concern was the selection of a background density value with which all other rock densities are contrasted. The modelling process is generally simplified by choosing the density of the most commonly occurring rock-type as background, but it must be emphasized that the choice is entirely arbitrary. The density value of 2.73 g/cm^3 for Archean gneisses was selected for the present study. An obvious consequence of this decision is that the gravity field tends to a zero value over rock units of background density. Based on this criterion, the Bouguer gravity value of -42.2 mGal derived for the present study provides a compatible zero (base) level for use with the chosen background value of density. Given these conditions, the removal of a regional gradient from the gravity profile was not required.

Conclusions derived from the present study are: (1) the seismic model yields calculated values of gravity that closely match the observed data, (2) the positive gravity anomaly south of the Sudbury Structure, and extending much farther to the west, can be explained in terms of the composite effect of Huronian mafic and ultramafic rocks, and Nipissing diabase, (3) the large gradient in gravity that parallels the northwest margin of the SS is probably a reflection of a moderately northwesterly to northerly dipping contact between the Levack gneiss and Cartier granite, and (4) the presence of a hidden mafic layer beneath the Sudbury Structure with a density over 3.0 g/cm^3 (Gupta *et al.* 1984), although not disproved, is not required to model the gravity data. Unexplained is a small observed positive gravity anomaly over the Chelmsford–Onwatin sediments.

POTENTIAL FIELD INTERPRETATION AND MODELLING ALONG THE SUDBURY STRUCTURE LITHOPROBE TRANSECT

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High-resolution seismic reflection data along the LITHOPROBE transect across the Sudbury Structure have provided new constraints for potential field modelling. Previous interpretations by Popelar (1972) and Gupta *et al.* (1984) were constrained primarily by surface geology and limited rock-property data obtained from surface and subsurface samples (Morris 1984, Tanczyk 1991). Initial attempts at reconciling a composite seismic model interpreted along a north–south idealized line crossing the Sudbury Structure (Milkereit *et al.* 1992) with available magnetic and gravity data have yielded mixed results (Hearst *et al.* 1992). The seismic model is conditionally consistent with the gravity data, but inconsistent with the data on magnetic field and rock magnetic properties.

The Sudbury Structure is characterized by a number of rock units in which remanent magnetizations dominate over induced magnetizations (Morris 1984), and thus the use of both measured magnetic susceptibilities and natural remanent magnetizations in the modelling process is obligatory. Accordingly, such data as were available were incorporated into the seismic model. However, even though the broader, regional features of the observed magnetic profile were reproduced, the resultant calculated magnetic profile exhibited major departures from the observed magnetic profile along the idealized LITHOPROBE seismic section. These are particularly evident over the South Range, North Range and the central sedimentary basin. To resolve this problem and to maximize the utility of the magnetic data, new rock-property measurements have been made on samples collected directly along the LITHOPROBE transect.

The potential field signatures have also been defined in some detail along the LITHOPROBE transect. Ground magnetic and gravity observations have been completed at 25-m intervals along the main transect section from Highway 17 north to Larchwood, which crosses the Huronian Supergroup, South Range and the central sedimentary basin. Ground magnetic observations at the same spacing have been completed along the Nelson Lake Road and Windy Lake sections of the transect, which traverse the North Range and Levack Gneiss, respectively.

In concert with forward modelling of the potential field data, Euler deconvolution filtering has been applied to gravity and magnetic data-sets provided by the Ontario Geological Survey and Geological Survey of Canada, to high-resolution airborne magnetic data made available by Falconbridge Limited, and to the ground data. The solutions from these approaches will be collated and presented in section–profile format to provide a unique perspective of the magnetic and gravity characteristics of the Sudbury Structure. A cross section of the structure based on the seismic model and refined by potential field modelling also will be presented.

SUDBURY FOOTWALL MINERALIZATION, WITH PARTICULAR REFERENCE TO THE McCREEDY EAST AND VICTOR DEPOSITS

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There are three main types of orebody environments associated with the Sudbury Basin. The base of the Sudbury Igneous Complex, especially where it is associated with large depressions in the underlying wallrocks, is commonly host to ore deposits. These "contact"-type deposits generally have a Cu \ Ni ratio slightly less than 1 and have low PGE values, except for locally high rhodium. Long, multikilometer dykes of predominantly igneous rocks that are genetically related to the Sudbury Igneous Complex, and extend out from it into the wallrocks, also are host to ore deposits. The "offset dyke" deposits have a Cu/Ni ratio generally greater than 1 and are usually enriched in PGE relative to contact deposits. Copper- and PGE-enriched orebodies, commonly associated with major contact-type ore deposits, occur within the footwall rocks of the Sudbury Igneous Complex. These are the "footwall orebodies", and they appear to be migrated segregations or differentiates of the contact ore. The contact mineralization that occurs in the vicinity of footwall deposits is generally copper-depleted; however, where a footwall deposit has a direct lead to a contact ore deposit, that particular contact ore will tend to be copper-enriched relative to other nearby contact deposits. The footwall deposits penetrate into the country rocks for hundreds and possibly thousands of meters. They are generally small deposits relative to the contact and offset dyke deposits, but their high-grade nature increases their total metal content to significant levels.

The material that makes up the footwall deposits accesses the footwall rocks along Sudbury Breccia zones, and the fracture systems developed in association with these breccia zones. The deposits themselves are invariably associated with thermally metamorphosed Sudbury Breccia.

The sulfide assemblages that make up the ore of the footwall orebodies are characteristically low in pyrrhotite and dominated by chalcopyrite, with local concentrations of bornite, cubanite and minor chalcocite. Pentlandite and millerite are commonly major constituents of the ore; nickel arsenide assemblages are occasionally associated with those footwall orebodies in the South Range of the Sudbury Basin. High PGE contents also are characteristic of the footwall deposits; the South Range footwall deposits generally have an arsenide-dominated PGE mineralogy, whereas those of the North Range have a bismuth–tellurium- dominant PGE mineralogy.

Both the McCreedy East and Victor footwall deposits have a chalcopyrite–pentlandite assemblage, with minor pyrrhotite and local concentrations of millerite and bornite. The deposits have platinum-group minerals that are typically less than 5 μm across, although composite grains are abundant and may reach 30–40 μm in diameter. The precious-metal assemblage in these deposits is dominated by significant amounts of tellurides, bismuthides, bismuth tellurides, stannides, native elements and alloys. Arsenic-rich phases occur in trace amounts only.

FITTING A CRATER TO THE SUDBURY STRUCTURE

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In the more than 25 years since meteorite impact was proposed for the origin of the Sudbury structure, the theory has gained wide acceptance. There remains considerable disagreement as to the size and geometry of the original crater, the amount of the Sudbury Igneous Complex (**SIC**) that comprises impact melt, and its relationship to the origin of the Ni + Cu sulfide orebodies. It is attempted here to present a consistent history of the impact event.

The extent of the relatively undeformed northern half of the SIC, the distance to the partial ring of half grabens of Huronian sediment northwest of the structure (taken to represent the collapsed rim of the crater), the most distal occurrence of breccias and the apparent depth of formation of mafic–ultramafic inclusions in the ore-bearing Sublayer of the SIC all suggest an excavated crater having a radius of 50 km. The combined volume of granophyre and mafic SIC are consistent with the amount of melt expected for a crater of this radius (= R) fitting the theoretical $R^{3.55}$ equation proposed by O'Keefe & Ahrens to melt-rock data for five Canadian craters.

Unfolding the crater floor reveals valleys in the footwall, defined by orebody outlines, which, in original plan view, form acute angled "V" or chevron configurations, with the inwardly directed apices of the Vs taken to point toward the crater centre. The Vs are tentatively interpreted as dynamic excavational features, analogous to "bow-waves" that formed by debris, flowing around major, high-density, high-inertia footwall lithological units. On this basis, the crater center originally lay about 10–12 km northwest of the Murray mine on the South Range and 35 km southeast of the Levack district on the North Range. The pattern is consistent with a normal, high-angle impact and not a grazing impact.

A plausible reconstruction of a pre-impact geological section of the structure, assuming 8–10 km of erosion, suggests that the proportion of mafic and acid melt-rocks is approximately consistent with the proportions of mafic and acid target-rocks. The impact probably did not strongly mix large (km scale) lithological units, and inertial forces may have produced some density stratification during excavation. The melt sheet thus immediately separated into a two-layered pluton. The overlying acid pluton increased in volume by melting upward into the overlying low-density breccia, Onaping Formation, and by collecting "bubbles" of partially melted acid footwall units, which continued to melt at the footwall of the mafic melt.

A pattern of radial and conical fractures are injected during excavation with impact breccia and melt rock. Maxwell's Z-model of crater-excavation dynamics was used to calculate the strain field of the excavation. The inwardly pointing breccia rings and shatter cones are overturned in the excavation flow-field to finally dip inward in the crater floor, steeply in the proximal zone (South Range) and shallowly (about 15°) in distal areas such as the North Range.

The crater collapsed quite promptly under compressional stresses (late Penokean orogeny) from the south east. The limbs had rotated inward as much as 40° relative to each other by the time the SIC received its initial magnetization.

The role of cracks and valleys in the crater floor in collecting the sulfide orebodies is obvious. An association of the ores with mafic and "exotic" ultramafic clasts and large mafic footwall units suggests that the ores may be reconcentrated from proto-ores or precipitated from impact-melted mafic rock that has assimilated admixtures of more siliceous target-rocks, in effect, a bizarre variant of the usual silica-contamination theory for sulfide precipitation. The unusual degree of superheat may have been instrumental in allowing an exceptional amount of mixing and in facilitating the precipitation process by providing an exceptionally low viscosity. Ore fragments in the Sublayer raise the possibility that the target rocks may already have hosted some ores that could have been coconcentrated with mafic and ultramafic clasts during crater formation.

Sunday afternoon, October 4

THE LINDSLEY Ni–Cu–PGE DEPOSIT AND ITS GEOLOGICAL SETTING

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The Lindsley deposit is one of many nickel–copper orebodies hosted by the Sudbury Structure (1.85 Ga), on the northern margin of the Penokean Fold Belt in central Ontario. Surface diamond drilling during the period 1941–1989 delineated a mineral inventory of 6.4 million tonnes containing 1.6% Ni, 1.5% Cu and 0.06% Co. Four zones lie at depths of 660 to 1500 m below surface. A 1637-m shaft was completed by March 1991, and underground exploration on the 1310 m and 1585 m levels is in progress to delineate the deeper portions of the deposit not adequately tested by drilling from the surface.

The Lindsley deposit shares many characteristics with other Ni–Cu–PGE deposits of the South Range of the Sudbury Igneous Complex (SIC). Most of the mineralization occurs in the sublayer, a breccia located at the base of the SIC. The sheet-like sublayer appears continuous along the contact where investigated by underground drilling. Surface mapping demonstrates the discontinuous distribution of the sublayer over the property as a whole. The sublayer, or basal contact of the SIC, strikes 055° and dips 45°NW from surface to a depth of 1200 m. Below this depth, the contact reverses and dips to the southeast at 45°. Sublayer-hosted mineralization comprises a mixture of pyrrhotite, chalcopyrite and pentlandite, with minor pyrite and magnetite in the matrix of a breccia that includes fragments of norite, basalt, granite, and ultramafic rock. The mineralization is not continuous and, in many areas, dilution of sulfides by large lithic blocks precludes economic development. Total sulfides in the sublayer vary from 5 to 65%.

The footwall rocks to the SIC at the Lindsley deposit comprise Huronian (2.45 Ga) volcanic and intrusive rocks of the Elsie Mountain Formation, and the Murray Granite (2.38 Ga). The 4B zone of mineralization occurs in the granite adjacent to the reversal in dip of the SIC contact. This zone is an irregular, vein-like body of massive pyrrhotite–chalcopyrite–pentlandite, lithic xenoliths and minor magnetite. The metal content of the ore averages 2.5% Ni and 4.5% Cu. Sperrylite, michenerite, merenskyite and native gold contribute approximately 15 g/tonne of precious metals to the value of the ore. Lithic fragments from 1 mm to 3 m in length comprise less than 20% of the ore and include granite, Sudbury Breccia, basalt, norite, quartz diorite and amphibolite. The 4B zone is enclosed by an irregular network of Sudbury Breccia veins within the granite and is bounded, in part, by quartz veining. Diamond drilling indicates the zone is located from 2 to 80 m from the basal sublayer contact of the SIC.

Emplacement of the mineralization at the Lindsley deposit appears compatible with the theory of crystallization from a sulfide melt, with partial fractionation and migration of Cu–PGE-rich sulfides into pre-existing zones of structural weakness within the adjacent granite.

THE CRAIG NICKEL DEPOSIT, SUDBURY, ONTARIO

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The Craig deposit is located in the Onaping–Levack area on the North Range of the Sudbury Igneous Complex. Mineral inventory of the Craig deposit consists of a total of 13.5 million tonnes containing 2.00% Ni and 0.74% Cu, which is present within nine discrete zones stretching over a strike length of 1000 m and lying between 650 and 1700 m below surface. The ore zones are extremely variable in dimension and attitude, but for the most part strike northeast and dip 40–45° southeast. A distinct southwesterly plunge to the mineralization is evident in most of the zones.

Host rocks to the nickel–copper mineralization include the Sublayer Unit at the base of the Igneous Complex, Footwall Breccias beneath the contact, and gneissic footwall rocks adjacent to the Footwall Breccia. The greater proportion of Craig ore is within zones hosted by Footwall Breccia, where disseminations, irregular stringers and massive sulfide pods occur within or entirely replace the matrix of the host breccias.

Sulfides are comprised of the typical Sudbury assemblage of pyrrhotite, pentlandite and chalcopyrite. The mineralization at Craig exhibits the metal zonation common to many North Range deposits. In the sulfides, nickel and copper values increase, and cobalt values decrease progressively away from the contact into the footwall rocks.

GEOMETRICAL SIGNIFICANCE OF THE GEOLOGICAL MAP PATTERN OF THE SUDBURY STRUCTURE

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The areal distribution of Sudbury breccia and shatter cones attests to a huge cryptoexplosion structure in central Ontario (Lakomy 1990, *Meteoritics* **25**, 195-207; Grieve 1987, *Ann. Rev. Earth Planet. Sci.* **15**, 245-270; Dressler 1984, *Ont. Geol. Surv. Spec. Vol.* **1**, 97-136). By contrast, the suboval map pattern of the Sudbury Structure (defined here as Whitewater Group rocks and Igneous Complex) conjures up the image of a modest-sized crater, its lithified sedimentary fill and a differentiated igneous body. We believe that this image is misleading and that the curvature of the Sudbury lithological units is due mainly to large-scale folding of the huge crater and its overburden. Indeed, the overall form of the Sudbury Structure adheres to the general style of the Penokean fold-interference system.

Created at a late stage of the Penokean Orogeny, the Sudbury Structure is intermediate in size between the McGregor Bay anticline and the oval Bass Lake syncline (Card & Lumbers 1977, *Ont. Geol. Surv., Map* **2361**), and only slightly larger than the Quirke Lake syncline (Robertson & Card 1972, *Ont. Div. Mines, Geological Guide Book* **4**). The map pattern suggests that the footwall contact of the Sudbury Structure is gently folded, particularly at the North Range and the "lobes" of the East Range. Such parasitic folding characterizes dome-and-basin structures in rebuckled anisotropic rocks (Lisle *et al.* 1990, *Tectonophys.* **172**, 197-200), and supports the idea that the Sudbury Structure is a fold basin.

The unstrained igneous rocks of the NE lobe are characterized by oriented feldspar crystals with well-preserved corners, an earmark of magmatic foliation (Paterson *et al.* 1989, *J. Struct. Geol.* **11**, 349-363). In thin section, typical granophyre, gabbro or norite lacks evidence of solid-state deformation. By contrast, the foliation in the Onaping Formation developed by flattening of lithified breccia. Collectively, the foliations in the Onaping Formation and Igneous Complex, which are being confirmed by magnetic anisotropy measurement, adhere to a fan pattern about the axial plane of the NE lobe (see also Kligfield *et al.* 1977, *Tectonophys.* **40**, 287-308). Individual trajectories of axial-plane foliation can be traced from the Onaping Formation into the Igneous Complex without being refracted. All trajectories, in rocks of the Sudbury Igneous Complex, would be parallel to the trace of the footwall contact, had the foliation been generated by upward flow of magma along a folded synformal lithologic boundary (Schwerdtner *et al.* 1983, *J. Struct. Geol.* **5**, 419-430). This evidence implies that the Sudbury Igneous Complex was folded *in situ*, together with its wall rocks, before the magma had been totally consolidated. After lithification, the Igneous Complex deformed ductilely, notably in the South Range Shear Zone (Shanks & Schwerdtner 1991, *Can. J. Earth Sci.* **28**, 411-430, 1677-1686). Its thrust shear reduced the NW-SE dimension of the Sudbury Structure, and probably removed the fold-induced curvature of the southern footwall contact at the present erosion level.

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NATURE AND SIGNIFICANCE OF THE LEVACK GNEISS COMPLEX - FOOTWALL ROCKS OF THE NORTH AND EAST RANGES OF THE SUDBURY IGNEOUS COMPLEX

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Granulite- and amphibolite-facies gneisses and migmatites of the Levack Gneisses form a 5- to 8-km-wide zone around the East and North Ranges of the Sudbury Igneous Complex (SIC). To the north, this zone is intruded by the granitic Cartier Batholith. The gneisses are predominantly granodioritic to tonalitic in composition, but also contain zones of mafic to ultramafic and semipelitic gneisses. Granulite-facies gneisses near the SIC grade northward into amphibolite-facies gneisses, the latter showing a close spatial relationship to the granitic rocks of the Cartier Batholith. Rock units and gneissosity trend ENE at a very low angle to the northern, lower contact of the SIC.

There, Archean gneisses are as old as 2.711 Ga. At 1.850, they were subjected to shock metamorphism related to the catastrophic Sudbury event and contact metamorphism related to the intrusion of the SIC. Shock-metamorphic features such as planar features in quartz and feldspar, and kink bands in biotite, occur up to 10 km north of the SIC. The contact-metamorphic zone is approximately 1 km wide.

Thermobarometric investigations of the garnet-bearing Levack Gneisses indicate that the 2.711 Ga granulite-facies assemblages formed at crustal depths of 21 to 28 km (6–8 kbar) assuming temperatures in the range of 750–800°C. A second, younger metamorphic event occurred at 5 to 11 km and temperatures as low as 500–550–C, and probably is related to the emplacement of the Cartier Batholith. The 1.850 Ga contact-metamorphic overprint occurred at similar crustal levels (1.5–3.0 kbar) and temperatures from 800–1015°C.

These results allow two interpretations of the timing of the crustal uplift of the Levack gneisses: a) the gneisses were tectonically uplifted prior to the Sudbury Event (possibly during the intrusion of the Cartier Batholith), or b) the gneisses were raised to epizonal levels as a result of meteorite impact at 1.850 Ga.

Monday morning, October 5

Pb AND Sr ISOTOPIC EVIDENCE FOR THE GENESIS OF ORES AND MAGMAS IN THE NORIL'SK - TALNAKH DISTRICT, SIBERIA

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The Noril'sk - Talnakh district contains the thickest and most complete section (>3400 m, 11 suites) of the approximately 250 Ma Siberian flood-basalt province. Extensive intrusive activity, represented by both undifferentiated and differentiated mafic sills, overlapped the period of basaltic eruption. The world-famed, Cu–Ni–PGE ore bodies of the district are associated with a special class of fully differentiated mafic sills that intrude the lower flood-basalt suites. Chemical, isotopic, and geochronological data indicate that the ores, intrusions, and flood basalts probably represent a single, complex magmatic system of mantle origin that was active over a few million years. The Pb isotopic system is one of the few geochemical parameters that can be applied to both the ores and magmas of the district. The $^{206}Pb/^{204}Pb$ ratios of the ores divide them into two groups that correspond with geographic location: ores of the Noril'sk I intrusion have $^{206}Pb/^{204}Pb$ = 17.98–18.09, whereas those at Talnakh have $^{206}Pb/^{204}Pb$ = 18.12–18.37. Two-thirds of the samples from Talnakh form a tight cluster with $^{206}Pb/^{204}Pb$ = 18.12–18.18; of the remaining samples, one orebody in the Kharaelakhsky intrusion forms a distinctive group with more radiogenic ratios. Variations in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ in the ores could be interpreted as the result of crustal contamination; however, an extremely tight, linear correlation between $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios, and the fact that the majority of the Pb isotopic data lie in the upper part of the MORB field, suggest an Archean lithospheric mantle source.

Pb isotopic analyses of the intrusions have concentrated on detailed profiles through the Noril'sk I (borehole NP–29) and the Kharaelakhsky (borehole KZ–1879) intrusions. The data show that these differentiated intrusions have a range of initial Pb isotopic compositions that suggest mixing of two or more isotopically distinct magmas within each intrusion. The ranges of data for each intrusion overlap but are different, with the samples from borehole NP–29 having an average Pb isotopic composition similar to the ores of the Noril'sk district, and the samples from borehole KZ–1879 having an average similar to the ores of the Talnakh district. These data suggest that the ores and associated intrusions have a close genetic link and that the magmatic pumping systems at Talnakh and Noril'sk are separate, and received different proportions of isotopically distinct magmas. Ores accumulated in separate magmatic staging chambers for each area and effectively averaged much of the Pb isotopic variability in the magmas.

Pb isotopic data for 22 samples of flood basalt that span, but do not well represent, the approximately 3500-m-thick section, are more varied than those for the ore-intrusion system. Only a few flood-basalt samples lie close to the field of data defined by the intrusions. The possibility that the intrusions represent mixtures of isotopically heterogeneous magmas makes it more difficult to eliminate individual suites of lava on the basis of Pb isotopic data alone. The combination of major- and trace-element data and the Sr and Pb isotopic data suggests that there is no obvious lava suite that can be related to the intrusions. Basalts of the upper two-thirds of the section, the Morongovsky through Samoesky suites, have the closest geochemical affinities with the intrusions, but initial Sr isotopic ratios of 0.7050 or lower for these lavas, *versus* 0.7055 or higher for the Noril'sk I intrusion, suggest that even this correlation is unlikely. There is an obvious need to derive the large mass of ore in the Noril'sk–Talnakh district from volumes of magma many times greater than those represented by the intrusions. The flood-basalt suites, seemingly the most obvious representatives of large volumes of magma, cannot be related by geochemical and isotopic criteria to the intrusions. The intrusions, therefore, appear to represent large volumes of magma that are under-represented in present exposures, a situation further emphasizing the complexity of this magmatic system.

RHENIUM–OSMIUM ISOTOPIC SYSTEMATICS OF ORES RICH IN PLATINUM-GROUP ELEMENTS, NORIL'SK – TALNAKH DISTRICT, SIBERIA

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The decay of ^{187}Re to ^{187}Os has a half-life of approximately 42 Ga. Large fractionations of Re from Os in magmatic and other ore-forming processes and the enrichment of these elements in sulfide minerals make this isotope system valuable for determining the age of certain types of ore deposits. In addition, Os is one of the six platinum-group elements (PGE); thus, the Re–Os system serves as a superior petrogenetic tracer for PGE-bearing ores. In addition, the slow, chondritic-like evolution of the Os isotopic system in the mantle contrasts with the much more rapid growth of radiogenic Os in most crustal rocks, so that Os isotopes are ideally suited for distinguishing ancient crustal components from mantle-derived melts.

High-precision Re–Os measurement techniques are currently being applied to a broad suite of ores from the ore-bearing intrusions of the Noril'sk–Talnakh district, Siberia. We have examined the Re–Os isotopic systematics of ores rich in PGE from Medvezhy Creek mine of the Noril'sk Intrusion, the Oktyabr'sky mine and several boreholes of the Kharaelakhsky intrusion, and the Komsomolsky mine and one borehole of the Talnakh intrusion.

The orebodies are isotopically dissimilar. Ores from the Oktyabr'sky mine give an isochron age of 246 ± 3 Ma (using α for ^{187}Re = 1.64 × 10^{-11}yr^{1}) and an initial ^{187}Os/^{186}Os = 1.186 ± 0.020. In contrast, Medvezhy Creek ores give an isochron age of 244 ± 2 Ma and an initial ^{187}Os/^{186}Os = 1.134 ± 0.016. The samples from the Talnakh intrusion, including the Komsomolsky ores, do not have a sufficient spread in ^{187}Re/^{186}Os to determine an isochron age. These samples have calculated initial ratios (for 250 Ma) that range from 1.114 to 1.129.

Several conclusions can be drawn from these data: (1) The isochron ages are as much as 2% younger than preliminary ^{40}Ar/^{39}Ar and zircon ages for the intrusions; however, these small differences may be the result of uncertainty in the decay constant for ^{187}Re. Hence, the Re–Os systematics evidently show closed-system behavior since the time of crystallization. Our two isochrons support previous findings which suggest that the intrusions were produced within a short period of time. (2) Ores from the different orebodies have different initial ^{187}Os/^{186}Os isotopic compositions, implying that they formed from melts derived from mantle sources with different Os isotopic compositions, or that they were variably contaminated with crustal materials. (3) All of there ores have higher initial ^{187}Os/^{186}Os ratios than chondrite-like mantle (^{187}Os/^{186}Os = 1.05). Plume-derived rocks are the only known modern rocks that are derived from the mantle with Os isotopic compositions similarly higher than chondritic mantle. (4) If crustal contamination played a part in the production of these ores, it was either quite minor (only a few percent), or the crust that contaminated the melts was young and not very radiogenic.

THE ORE-BEARING INTRUSIONS OF NORIL'SK–TALNAKH: COMPOSITE BUT "COMAGMATIC"

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Extensive geochemical data have been obtained for Siberian flood basalts (78 samples), the Noril'sk I intrusion (borehole NP–29; 22 samples), the Kharaelakhsky intrusion (borehole KZ–1879; 28 samples), the Talnakh intrusion (boreholes KZ–1713 and –1799; 18 samples), and the weakly mineralized Lower Talnakh intrusion (borehole SG–28; 17 samples). Data for the three intrusions that host commercial ore overlap extensively in tight groups on such plots as Ta/Yb *versus* Th/Yb (0.11 ± 0.04, 0.40 ± 0.15) and La/Sm *versus* Tb/Yb (2.2 ± 0.5, 0.26 ± 0.04), whereas flood-basalt samples show the ranges Ta/Yb = 0.076–0.52, Th/Yb = 0.27–1.56, La/Sm = 1.81–5.49, and Tb/Yb = 0.21–0.41. In notable contrast, data for the Lower Talnakh intrusion are scattered on these plots, and the 12 samples that do cluster form a group distinct from the groupings shown by the ore-bearing intrusions or any flood-basalt suite (Ta/Yb, Th/Yb = 0.16 ± 0.25, 0.9 ± 0.15; La/Sm, Tb/Yb = 3.2 ± 0.5, 0.27 ± 0.2). These incompatible-element signatures for the ore-bearing intrusions are comparable to those of the Tuklonsky suite and basalts above the middle of the Morongovsky suite. However, Pb- and Sr-isotopic compositions and Th/U ratios for these basalt suites are not permissive of a tight correlation with the intrusions and show that trace-element chemistry may be a misleading part of the petrogenetic puzzle.

Indeed, despite the limited ranges in many trace-element ratios evidenced individually and collectively by the ore-bearing intrusions, each intrusion must be considered the product of multiple intrusive events, as indicated by various criteria, only several of which will be noted here. Borehole NP-29, which penetrated the full 160 m of the Noril'sk I intrusion, abruptly passed through an ~5-m-thick biotite-bearing, magnetite–olivine cumulate (27.6 wt.% Fe) about 65 m beneath the roof of the intrusion. Most samples from above this cumulate contain minor quartz and are enriched by a factor of 2–3 in a broad suite of incompatible elements with respect to the lower part of the intrusion, which shows downward gradation into progressively more olivine-rich cumulates. Sharp variations in the concentrations of these trace elements and TiO_2 just above the magnetite–olivine cumulate probably indicate interfingering of two magma types.

An equally sharp but geochemically dissimilar break occurs over 10 m, about midway in the 100-m-thick section of the Kharaelakhsky intrusion represented by core from borehole KZ–1879. Samples immediately above this break contain 2–3 times as much Al_2O_3, CaO, Na_2O, and K_2O as those below it, whereas S content jumps from 0.03–0.06 wt.% above the break to 0.95–2.9 wt.% below it. Whereas apparent olivine-control lines on plots of MgO *versus* CaO content suggest that olivine fractionation played a role in each of the intrusions, two parallel olivine-control lines, offset by ~2 wt.% CaO over the range of 12–18 wt.% MgO, characterize data for the Kharaelakhsky intrusion; data for the upper part of the intrusion fall on the olivine-control line for CaO-rich compositions. Moreover, the average-weighted Cr content of a 17.7-m thickness of picritic gabbrodolerite in the lower part of this core is roughly one-half that of a 40-m thickness of less magnesian olivine gabbrodolerite in the upper part of the intrusion. A sample from borehole KZ–1713, taken from about 80 m below the roof of the Talnakh intrusion, represents a sulfide-bearing olivine cumulate of markedly different chemistry from the rocks immediately above and below it; the sample is more chemically extreme than samples of comparable sulfide-bearing olivine cumulates that occur some 20 m lower, near the base of the intrusion. Four samples from borehole SG–28, representing a 30-m-thick interval about midway in the ~160-m thickness of the Lower Talnakh intrusion, have Th/U ratios of 3.8–5.2, well outside the range of 1.7–3.1 that characterizes the 13 samples above and below this interval.

Elucidation of the magmatic evolution of the ore-bearing intrusions and their mineralization will require far more detailed study than our "first pass" sampling at irregular intervals will allow. However, our geochemical data firmly support field interpretations of multiple intrusive events and raise serious problems for any models that involve fixed stratigraphies for individual intrusions based on single magma-pulses and, perhaps, extensive *in situ* differentiation. The petrogenetic complexity of the problem is underscored by observations that (1) the most compelling evidences of multiple intrusive activity vary from intrusion to intrusion, (2) many incompatible-trace-element ratios show little variation within and among the ore-bearing intrusions, and (3) the ore-bearing intrusions cannot be well related to any of the 11 basalt suites. Moreover, some abrupt discontinuities in borehole sections may be caused by intrachamber movement of magma during the solidification process.

None of our current geochemical and isotopic data require that crustal contamination played a role in the genesis of the ores, ore-bearing intrusions, or flood basalts of the Noril'sk–Talnakh district. Instead, these data suggest that a family of magmas distinct from those parental to the flood basalts, with significant variations in major-element and absolute trace-element concentrations but tightly limited ranges in incompatible-trace-element ratios, were derived from a heterogeneous mantle source-region and were parental to the ore-bearing intrusions. A mantle plume is an attractive source for these families of mafic magma.

COMPOSITIONAL CONSTRAINTS ON THE GENESIS OF ORE DEPOSITS OF THE NORIL'SK–TALNAKH DISTRICT, SIBERIA

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The Cu–Ni–PGE deposits of the Noril'sk–Talnakh district occur in relatively small, hypabyssal, differentiated mafic sills that are temporally and spatially related to the Siberian continental-flood-basalt province. Previous investigations provided support for models involving S assimilation, sulfide liquid immiscibility, metal concentration, and sulfide accumulation at the site of sill emplacement. These simplistic models now seem untenable; new data and observations suggest a complex and dynamic mode of origin. There is a material imbalance between the amount of metals and S in the ores compared to amounts that could have been derived from the volume of magma represented by the spatially associated sills. From what is known about the concentrations of PGE in mafic melts and their partitioning behavior into sulfide liquids, the PGE content of the ores must have been derived from at least 200 times more mafic magma than is represented in the intrusions. Much of the spectacular compositional and mineralogical zonation that is typical of the sulfide accumulations, ranging from hand-specimen scale to mineable orebodies, can be attributed to fractionation of monosulfide solid solution (*Mss*). However, decreases in concentrations of elements (Pt, Pd, Au, Sb. As, Bi, Te, and Ag) that behave incompatibly in the most Cu-rich ore samples, non-correlation of elements (Co or Fe *versus* Ir, Ru, or Rh) that should behave compatibly during fractionation, differences in composition between spatially associated disseminated and massive sulfide ores (higher Co, Rh, and Ag contents and lower Ni/Pd and Cu/Ir ratios in disseminated ores), and differences in compositions between orebodies in various intrusions (higher Cu/Ni, and lower Fe/Cu, Co/S, Pt/S, Pd/S, and Te/S in Oktyabr'sk than in Noril'sk I) indicate that *Mss* fractionation is not the sole mechanism that gives rise to compositional variability of the ores. Field observations show sharp and locally transgressive contacts of massive sulfide with the spatially associated mafic intrusions; this temporal relation also is supported by the lack of matrix ore in most intrusions and the virtual absence of entrained igneous silicate minerals in massive ores. These relations, coupled with the occurrence of rounded droplets of zoned sulfide in the picritic parts of the intrusions, suggest that the intrusions and the associated sulfide deposits formed by injection of mafic silicate magma laden with large amounts of immiscible sulfide liquid that separated at some location other than the current site of sill emplacement. The compositional diversity of the ores, field relations, the Pb isotopic distinctions among orebodies, and mineralogical and compositional discontinuities with the intrusions, indicate that these sills were fed by multiple pulses of magma with different histories of sulfide extraction and equilibration, derived from different isotopic reservoirs. The timing and location of sulfide extraction and equilibration remain problematic.

Monday afternoon, October 5

SOURCE AND EVOLUTION OF SIBERIAN TRAP LAVAS, NORIL'SK DISTRICT, RUSSIA: IMPLICATIONS FOR THE ORIGIN OF SULFIDES

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Whether crustal contamination of mafic flood-basalt magmas occurs within the continental crust or the crustal contribution is inherited from subducted sediments incorporated into the continental mantle lithosphere is an important question that bears on models for the origin of magmatic sulfide mineralization associated with the intrusive portions of continental flood basalts. Contemporary models call upon assimilation of crustal materials to trigger the segregation of magmatic sulfide minerals; these models have been proposed for the formation of sulfides associated with the Noril'sk intrusions. We investigate the timing of contamination and sulfide segregation using new data for the sequence of eruptive basalts at Noril'sk.

The stratigraphy of the sequence of flood basalts at Noril'sk consists of a lower subalkaline series (the Ivakinsky Formation) and tholeiitic series (Syverminsky Formation), overlain by tholeiitic and picritic basalts (Gudchichinsky Formation containing the Gudchichinsky picritic basalt unit [GPBU]). These are separated from the overlying Tuklonsky Formation tholeiitic and picritic basalts by the Khakanchansky Formation tuff. The Ivakinsky through Syverminsky flows constitute the Lower Series and are characterized by relatively high TiO_2 (GPBU: 1.2–2.2 wt.%) and Nb/La (GPBU: 0.98–1.04), and radiogenic ϵNd_{CHUR} (GPBU: +3.8 to +7.3). The Tuklonsky Formation and the Tuklonsky picritic basalt unit (TPBU) are part of the Upper Series and are characterized by low TiO_2 (TPBU: 0.5–0.8 wt.%), low Nb/La (0.43–0.50) and ϵNd_{CHUR} (TPBU: -2.6); the tholeiitic members have a high Mg-number (0.64–0.68). The overlying sequence of tholeiites, belonging to the Nadezhdinsky, Morongovsky, Mokulaevsky amd Kharaelakhsky formations, then are relatively low-TiO_2 rocks (1.2–1.4 wt.%), with low Nb/La (0.43–0.71). These rocks show a progressive upward decline in SiO_2 (55–48 wt.%), La/Sm (4.5–1.6), Ti/Zr (88-38), ϵSr_{UR} (+63 to 0), with little change in Mg-number (0.54–0.60).

Both picritic and tholeiitic basalts are subdivided into a low-Ti and a high-Ti series in the context of Gondwanan flood basalts. The low-Ti series carries the geochemical signature (high Ti and Nb/La) of enriched melts from the asthenospheric mantle, and these lavas may carry a significant chemical contribution from a deep plume source, perhaps spatially correlated with the Permian location of the Jan Mayen hotspot. The Upper series carry the geochemical signature of melts of rather depleted mantle, which have variable contributions from the continental lithosphere (low Ti and Nb/La). Recent models have suggested that the gradual change in composition (in terms of major and trace elements) of the Nadezhdinsky through Morongovsky formations is due to a progressive decline in the amount of contamination by tonalitic upper crust, accompanied by minor fractional crystallization. This model requires extremely large amounts of assimilation (approaching 40% for the most contaminated flows). Alternatively, it has been suggested on the basis of these data and new Sr–Nd–Pb isotope data that these geochemical features are inherited from ancient depleted lithospheric mantle. Assuming a contaminant represented by average post-Archean shale, as little as 5% contamination of the source of these magmas, followed by melting and fractional crystallization, would produce the same features as contamination within the continental crust as the magmas ascend. Ni/Yb, Sc/Yb, and Th/Yb correlate equally well with La/Yb, which suggests that whatever the mechanism of contamination, the segregation of Ni-rich sulfides does not postdate assimilation. The fact that there is no significant change in Mg-number as the Sr-isotope ratio changes further suggests that assimilation and silicate fractionation remained decoupled. Variations in Ni/Yb and Cu/Yb indicate that the most contaminated lavas also are the most depleted in the chalcophile elements. The degree of depletion is strongly correlated with the magnitude of the crustal signature, and this in turn suggests that the segregation of chalcophile elements predated or accompanied the contamination of the magma.

THE COMPOSITION OF THE Ni–Cu ORES OF THE NORIL'SK REGION

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Samples of massive, disseminated and Cu ore have been analyzed for Ni, Cu, Co, S, Pt, Pd, Rh, Ru, Ir, Os and Au from the Oktyabr'sky #1 and #2, Taimyrsky and Komsomolsky mines of the Oktyabr'sky deposit of the Talnakh region. In addition, disseminated ore has been analyzed from the Komsomolsky and Mayak mines of the Talnakh deposit, Talnakh region, and from the Bear's Brook open pit of the Noril'sk I deposit, Noril'sk region.

The Cu content of the ore is one of the major compositional variables. In the case of the massive, disseminated and Cu-ore samples of the Oktyabr'sky deposit, Ni initially increases and then decreases, Rh, Ir, Ru and Os decrease exponentially, and Au, Pt and Pd increase, all with increasing Cu. The Rh/Ni ratio also decreases sharply with increasing Cu. Attempts to model the covariation of Au and Cu in terms of fractionation of monosulfide solid solution (*Mss*) from an Fe–Ni–Cu–S melt are successful if the initial concentrations of Cu and Au (X_{Cu} and X_{Au}) are respectively 5 wt% and 0.200 ppm, and the partition coefficients D_{Cu} and D_{Au} into (*Mss*) from sulfide liquid are 0.4 and 0.001, respectively; D_{Cu} cannot be less and D_{Au} greater than these values to account for this covariation. Assuming D_{Cu} to be equal to 0.4, Ni variation is well modelled if X_{Ni} = 4.5 wt% and D_{Ni} = 0.8 for $1>F>0.7$, D_{Ni} = 1.0 for $0.7>F>0.6$, and D_{Ni} = 1.2 for $F<0.6$ (where F is the fraction of initial liquid remaining uncrystallized); Pt, Pd, Rh anf Ir variations are well modelled if X_{Pt} = 2.4, X_{Pd} = 9, X_{Rh} = 1.333 and X_{Ir} = 0.12 ppm, and D_{Pt} = 0.1, D_{Pd} = 0.3, and D_{Rh} and D_{Ir} = 3.0. These partition coefficients also account well for variation of Rh/Ni with Cu. The modelling indicates that massives ores are cumulate-enriched, containing an average of about 80% cumulus *Mss*, whereas the disseminated and Cu ores are closer to the composition of a fractionating PGE-bearing Fe–Cu–Ni–S liquid.

Other ore types for which data are available include: (i) breccia ore composed of fragments of intrusion and sedimentary country rock at the top of the massive sulfide: the sulfide composition of this ore is close to that of typical massive ore; (ii) ore in the contact gabbrodolerite of the intrusion, which consists of cm-thick veins of sulfide filling fractures: here the sulfide compositions correspond to a mixture of moderately fractionated sulfide liquid and *Mss* in equilibrium with it; (iii) magmatic breccia ore within mineralized picritic and taxitic gabbrodolerite and consisting of sulfides filling the matrix of a breccia composed of fragments of the surrounding igneous rock: in this case the sulfides have the same composition as the disseminated sulfides in the adjacent unbrecciated igneous rock; (iv) exocontact breccia ore in which sulfides form part of the matrix of brecciated and metasomatically altered rocks overlying the intrusion: this ore, which has a lower Ni and Cu concentration in sulfides and higher Pt/Cu and Pd/Cu ratios, cannot be related to fractionation of the sulfide liquid that is apparently responsible for all other ore types; it may be the result of deposition or compositional modification by a fluid phase.

Disseminated ores from the Oktyabr'sky, Talnakh and Noril'sk I deposits have the following approximate ratios,all multiplied by 10^4; Pt/Cu = 0.5, 2 and 3; Pd/Cu = 2, 5 and 7; Au/Cu = 0.14, 0.33 and 0.53, respectively. These wide variations in ore from different intrusions are interpreted in terms of the model of Naldrett *et al.* (1992) and Brügmann *et al.* (1992), in which sulfides are regarded as segregating in relatively large amount from a limited volume of magma at the top of a magma chamber, severely depleting it in chalcophile elements. As they settle deeper in the chamber, they interact with underlying, undepleted magma, gaining chalcophile elements in a manner similar to the accumulation of impurities in the transient liquid phase as it passes through a bar of metal undergoing zone refining. The degree to which the sulfides have become chalcophile-element-enriched depends on the amount of magma through which they have settled.

VARIATION IN THE Ni, Cu AND PGE CONTENT OF ORE ON THE NORTH RANGE AT SUDBURY, BETWEEN THE HARDY AND LONGVACK MINES

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The rim of the Sudbury structure between the Hardy and Longvack mines is the most intensely mineralized stretch of the North Range, containing numerous ore shoots. These consist of some or all of the following ore types: sulfides disseminated within Sublayer norite, disseminated and stringer sulfides within Footwall breccia, massive veins within Tonalite gneiss and Sudbury breccia cutting this gneiss, and veins of massive chalcopyrite 200 to 500 m beneath the basal contact of the Sudbury Igneous Complex (SIC).

Sampling has been undertaken at all accessible locations from the McCreedy West and Onaping deposits in the west, to Strathcona in the east. The ore shoots show a strong compositional zoning, both within themselves and from one shoot to another, on progressing from the SIC into the footwall. Thus sample sites were selected to take this into account. In order to evaluate the statistical validity of the data for each site, approximately six samples were collected from each. A total of 238 samples have been collected from 40 sites. These have been analyzed in duplicate, and where the duplicates differed by more than 20%, reanalyzed. The analytical method was fire assay using a Ni-sulfide bead collector, followed by leaching with HCl, and analysis of the residue by instrumental neutron activation (Hofmann *et al.* 1978).

The Onaping deposit in the east is characterized by ore in the Sublayer norite with very low Cu/(Cu + Ni) and Pt + Pd/(Ru + Ir + Os) ratios (0.05 and 1.5, respectively) and very high Rh content (>1000 ppb). In each case, the sample site closer to the contact had slightly higher values of the ratios and distinctly lower Rh content than that farther into the Sublayer norite. Mineralization in Sublayer norite at the Fraser and Strathcona mines in the east has higher values of the same ratios: [Cu/(Cu + Ni) = 0.104 and 0.107, respectively; Pt + Pd/(Ru + Ir + Os) = 6.4 and 2.2, respectively], and low Rh (263 and 60 ppb, respectively). Ore in footwall breccia located immediately adjacent to the basal contact of the Sublayer between Hardy and Longvack has higher values of the Cu/(Cu + Ni) and (Pt + Pd)/(Ru + Ir + Os) ratios (0.080 to 0.26 and 6.0 to 9.0, respectively) and lower Rh (145 to 75 ppb); it shows very marked zoning, with the ratios rising and Rh content decreasing sharply away from the contact. Ore shoots 50–150 m from the contact have Cu/(Cu + Ni) between 0.10 to 0.35, (Pt + Pd)/(Ru + Ir + Os) between 12 to 100), and Rh between 50 to 10 ppb, but relatively little zoning across the 10–20 m widths of the shoots.

The changes in Cu/(Cu + Ni) and (Pt + Pd)/(Ru + Ir + Os) ratio and Rh content of the ore are attributed to fractionation of *Mss* from a sulfide liquid, with the crystallizing *Mss* remaining at the site of crystallizing sulfide liquid, and the fractionated residual liquid penetrating progressively farther into the footwall. At Strathcona, this process reaches its apogee with in the chalcopyrite-rich veins of the Copper Zone and Deep Copper Zone. If these ores are included in the deposit, the bulk Cu/(Cu+Ni) and (Pt + Pd)/(Ru + Ir + Os) ratios are 0.51 and 34. The high values of these ratios are due solely to incorporation of the Chalcopyrite-rich ore in the reserves and close to values reported by Hofmann *et al.* (1978) for Little Stobie No. 1 and 2 deposits, and are thought to represent the norm for Sudbury ore. They are much higher than the analogous ratios in all of the individual ore shoots between McCreedy West and Strathcona, which indicates that similar Cu-rich ore shoots likely exist at depth in the footwall along this intervening stretch as they do at Strathcona.

With the exception of the chalcopyrite-rich veins, Ni is very constant in each of the ore types from the deposits studied between McCreedy West and Fraser. Hardy, Strathcona and Longvack contain substantially less Ni in sulfides (from 2.5 wt% at Longvack to 3.6 wt% at Strathcona). The Strathcona ore also contains 50% less Cu and 66–75% less of each of the PGE than the high nickel deposits. Reasons for the variation in the metals contents of ore are not understood at present.

AN IMPACT MODEL FOR SUDBURY

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The Sudbury Structure, defined as the Sudbury Basin, the Sudbury Igneous Complex and the surrounding brecciated basement of the Superior and Southern provinces, covers an area of >15,000 km^2. The origin of the Structure has been controversial. Most models call for a major impact event, based on the occurrence of shock metamorphic effects in the basement and in the Onaping Formation overlying the Igneous Complex, followed by impact-induced igneous activity. Although the evidence for impact in unequivocal, totally igneous models are still being proposed; Sudbury is unique amongst terrestrial impact structures in having this proposed link to impact-induced igneous activity. Since the original proposed impact hypothesis for the Sudbury Structure, however, much has been learnt about the impact processes in general and the nature of terrestrial impact craters in particular. Much of the controversy at Sudbury is due to the earlier misunderstanding of the size of the original Sudbury Structure. By analogy with other terrestrial impact structures, the spatial distribution of shock features in the basement and the Huronian cover rocks at the Sudbury Structure suggests that the transient cavity produced by the cratering flow- field was 100 km in diameter, which places the original final structural rim diameter in the range of 150–200 km. Model calculations and empirical relationships indicate that, under terrestrial conditions, an impact of this size will result in 10^4 km^3 of impact melt, more than sufficient to produce a melt body the size of the Igneous Complex (present volume 4–8 10^3 km^3). For the Igneous Complex to be an impact melt sheet, it must have a composition similar to that of the target rocks. Evidence for this has been presented for Sr and Nd isotopic data, which suggest a crustal origin. Least-squares mixing models also indicate that the average composition of the Igneous Complex corresponds to a mix of Archean granite–greenstone terrane, with possibly a small component of Huronian cover rocks. This is a geologically reasonable mix, based on the interpreted target-rock geology and the geometry of melt formation in an impact event of this size. The impact-melt origin for the Sudbury Igneous Complex implies that the Sudbury Cu–Ni ores also are crustal in origin, a hypothesis that is largely supported by resent Re–Os isotopic data. The igneous complex is differentiated, which is not a characteristic of previously studied terrestrial impact-melt sheets. This can be ascribed, however, to its great thickness and slower cooling. With both the Sudbury Structure and Igneous Complex due to impact, previous hybrid impact – igneous hypotheses can be discarded, and the Sudbury Structure studied specially for the constraints it provides for the formation of basin-sized (multi-ring?) impact structures. Conversely, current knowledge of impact-cratering processes and crater structure can provide important constraints for future mineral exploration strategies at Sudbury.