Atlantic Geology

Geological Association of Canada 2004 Annual Technical Meeting Newfoundland Section

Abstracts: Moncton, New Brunswick

Volume 40, Number 2-3, 2004

URI: https://id.erudit.org/iderudit/ageo40_2_3abs01

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Publisher(s)

Atlantic Geoscience Society

ISSN

0843-5561 (print)
1718-7885 (digital)

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Cite this document

(2004). Geological Association of Canada 2004 Annual Technical Meeting Newfoundland Section: Abstracts: Moncton, New Brunswick. *Atlantic Geology*, *40*(2-3), 245–256.

Geological Association of Canada 2004 Annual Technical Meeting Newfoundland Section

GAC AGC

ABSTRACTS

february 23–24, 2004

johnson geo centre

signal hill, st. john's, newfoundland

Abstracts published with financial assistance from the Newfoundland Section of GAC

Atlantic Geology 40, 245–256 (2004)
0843-5561|04|020245–12$2.80|0

Living with our legacy: mapping patterns of high soil-lead in St. John's, Newfoundland

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A pilot study to investigate the metal content of urban soils in St. John's, Newfoundland, was carried out in the summer and fall of 2003. The study was prompted by results of a geochemical analysis of sediments in urban lakes in St. John's that indicated historically high levels of lead and other toxic metals. Although lead levels in the sediments had declined over the last several decades, primarily due to the removal of lead from gasoline, the possibility that urban soils had accumulated a reservoir of toxic metals remained untested. Our project is ongoing, and further sampling and analysis are planned to adequately delineate patterns and sources; however, interim results provide some preliminary indication of the controls on soil lead in St. John's. The results from 383 samples range between 17 and 7048 ppm, with a median value of 264 ppm. Background levels were measured between 18 and 48 ppm, with a mean of 29 ppm. The Canadian Council of Ministers of the Environment (CCME) guideline for soil lead in residential areas is 140 ppm.

Examination of the spatial distribution of soil lead clearly indicates a concentration around the urban core of St. John's. For instance, suburban residential properties had a median soil-lead value of 165 ppm compared to 1076 ppm for urban residential properties. These high values for downtown St. John's are 8 times the CCME guideline. It is also important to note that high values exceeding the CCME guideline also occur on suburban properties close to older roads and houses. Although lead-based paint and coal-ash residue likely were major sources in residential settings, leaded gasoline contributed to high values next to major roads.

St. John's is an old city, with a long history of coal burning and vehicular traffic and a tradition of painted clapboard houses. The legacy of these activities appears to be high soil-lead levels. Considering the implications of lead for human health, especially young children, it is important that we understand the distribution of soil lead in our living environment and take precautions against inadvertent exposure.

Orphan Basin: hottest play on the east coast

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Orphan Basin is one of the Mesozoic rift basins around the North Atlantic. Located north of the Newfoundland Grand Banks, water depths in the basin range from 400 to 4000 m. The basin seems to have derived its name from the Orphan Knoll "a small continental remnant that now lies abandoned, isolated and generally neglected".

The Canada-Newfoundland Offshore Petroleum Board's 2003 land sale included ten land parcels in the Orphan Basin. Work commitment bids totalling $672 680 000 were received on eight of the ten parcels, with a record bid of $251 600 000 on one. Both the total sale and the high single bid represent the highest ever on the East Coast.

A number of wells have been drilled around the western and southern peripheries of the basin in the late 1970s and early 1980s. These include the Texaco et al. Blue H-28 well that was drilled in 1486 m of water in 1979 and held the world deep water drilling record at that time. Several seismic programs have been recorded in recent years and provide a glimpse into the hydrocarbon potential of the basin.

South Whale Basin: renewed hopes for a hybrid basin

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The South Whale Basin, an Atlantic rifted area situated mostly in shallow water in the southern part of Grand Banks and close to the Newfoundland Transfer Zone, is one of the recently revived exploration areas situated offshore Newfoundland and Labrador. On trend and close to petroliferous proven Sable Sub-basin and Jeanne d'Arc Basin, the South Whale Basin was drilled without success during the sixty, seventies and eighties. The 5 to 8 km deep basin is incised on the Grand Bank's Avalon and probably Meguma terranes and contains synrift sediments of Scotian Shelf affiliation. The basin was drastically affected by erosion during the Late Cretaceous and Early Tertiary and has a shallow Tertiary sedimentary cover. Its structure is dominated by spectacular salt diapirs and ridges and intervening sink-synclines.

The South Whale Basin is a hybrid basin that evolved initially as an early rifted area on the North American Margin and underwent significant tectonic subsidence within the Thethys rift system, including the accumulation of considerable amount of salt. At the end of the Thethys phase the basin failed as a rift and was later modified along a major transform zone. During the Late Triassic-Early Jurassic and Late Jurassic–Early Cretaceous the basin was interconnected to the other rift basins of the system including the adjacent Scotian Shelf and Slope areas. The favorite oil play off the early exploration efforts in the basin was the salt anticline, drilled generally crestal and at shallow depths but with no success. Repeated dry wells brought an early condemnation of the basin for lack of oil source rock and breaching of the traps at the Avalon (Base Aptian) Unconformity level. Basin re-mapping projects using newly acquired seismic data and re-evaluation of potential plays with focus in the inter-salt domains or on the slope has brought back several operators into the area.

The petroleum system of the South Whale Basin should include: a) ponded Kimmeridgian (Veryll Canyon and/or Egret shales) source rock in the sink-synclines and probably Albian source rocks on the slope; b) Late Jurassic (Mic Mac sandstones and Abenaki carbonates) and Early Cretaceous (Logan Canyon) reservoirs; c) large fault bounded roll-over anticlines and rotated fault blocks within deeper synclines and possibly sand-rich fans on the slope and d) source maturation, generation and short distance migration of oil and gas from a few existing ponds with mapped Kimmeridgian rocks into existing antiforms or sand-rich fans. The future of the exploration in the basin is to be decided this year (2004) by an exploration well scheduled to be drilled by Husky Energy over the Lewis Hill prospect.

A synthesis of geometric relationships and structural elements within the Voisey's Bay Ni-Cu-Co deposits

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The Voisey's Bay Ni-Cu-Co sulphide deposit occurs within troctolites and olivine gabbros of the 1.34 Ga. Voisey's Bay Intrusion. The Voisey's Bay Intrusion is a member of the Nain Plutonic Suite and straddles the ca. 1.85 Ga. suture between Archean orthogneisses of the Nain Province to the east and Paleoproterozoic paragneisses of the Churchill Province to the west.

The Reid Brook, Discovery Hill, Mini-Ovoid and Ovoid zones occur within a sub-vertical conduit dike system. The conduit appears to span two large troctolite intrusions, the Eastern Deeps chamber and the lower Western Deeps chamber. East of the Ovoid, mineralization is not found within subvertical domains, but occur in sub-horizontal sill-like intrusions branching from the sub-vertical dike intersecting the Eastern Deeps chamber. At Voisey's Bay, the distribution of sulphides and the morphology of the conduits appear to be controlled by the geometrical relationships produced between specific geological structures. The plunge of the conduit is coincident with an intersection lineation produced between the local gneissosity and prominent east-west lineaments. Within the sub-vertical domain of the conduit, the plunge of the mineralization is defined by intersecting lineations created between the adjacent orthogneiss and paragneiss fabrics. Furthermore, the Eastern Deeps deposit, located at the base of the Eastern Deeps chamber, occurs along an east-southeast trending structural trough constrained by two regional east-west lineaments.

Although magmatic processes generated the sulphides observed at Voisey's Bay, the morphology of the conduits and the amount of mineralization contained within them are controlled by geometric relationships formed between prominent structural elements.

An overview of basins and petroleum exploration activities, offshore Newfoundland

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Recoverable resources of 2.1 billion barrels of oil, 5.6 trillion cubic feet of natural gas and 324 million barrels of natural gas liquids have been discovered in the Jeanne d'Arc Basin on the Grand Banks of Newfoundland, with and additional 4.2 trillion cubic feet of natural gas and 123 million barrels of natural gas liquids located offshore Labrador. Production, currently at about 350 000 bopd is expected to reach 450 000 bopd in late 2005. These resources have been discovered by the drilling of only 133 exploration wells, that are predominantly concentrated within the Mesozoic sediments of Jeanne d'Arc Basin, although some 20 other basins and sub- basins ranging in age from Early Paleozoic to Cenozoic are located in and around Newfoundland and Labrador. Recent landsales and seismic surveys indicate increased interest in other basins that have not seen much activity in the past twenty years. This paper provides an overview of the geology and drilling history, and discusses future exploration opportunities.

An equatorial Laurentia at 550 Ma confirmed by Grenvillian inherited zircons dated by LAM ICP-MS in the Skinner Cove volcanics of western Newfoundland

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Volcanic rocks of the Skinner Cove Formation of western Newfoundland carry a primary remanence acquired at 550 Ma at a paleolatitude of 19°S. There has been doubt that this represents the latitude of the Laurentian margin at 550 Ma, because the Skinner Cove Formation is allochthonous. We present new evidence from inherited zircons in the volcanic rocks that should remove this doubt. Zircon crystals extracted from an ankaramite flow and a trachyte flow were dated individually by measuring U-Th-Pb isotopes for ~30 × 30 μm areas using a laser ablation microprobe (LAM) linked to an inductively-coupled-plasma mass spectrometer (ICP-MS). Most of the zircons from the ankaramite are concordant and yield a 550±5 Ma date indistinguishable from the 550+3/-2 Ma date previously reported using multi-grain thermal ionization mass spectrometry. About half of the zircons from the trachyte are

also concordant yielding an overlapping date of 556±5 Ma. The other half cluster at ~ 1000 Ma and at 1500–1600 Ma, which are characteristic ages of the Grenvillian basement exposed nearby in the Long Range Inlier. These zircon xenocrysts were very likely picked up as the Skinner Cove magma ascended through Grenvillian basement of the Laurentian margin. There can now be little doubt that the ~19°S Skinner Cove paleolatitude represents Laurentia's southern margin at 550 Ma. This makes it unlikely that Laurentia changed from south polar at ~ 523 Ma to equatorial at ~ 508 Ma due to a rapid ~90° change in the Earth's rotation axis. (This ~90° polar change, causing methane release, has recently been proposed as a trigger for the Cambrian faunal explosion.)

Mafic intrusions and Ni-Cu-Co mineralization in the Pants Lake area and their relevance to Voisey's Bay

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The Pants Lake Intrusions are located adjacent to the Nain-Churchill tectonic boundary, and intruded sulphide-bearing paragneiss bodies. The largest bodies, termed the North and South Intrusions, were dated by other workers at 1322 and 1337 Ma respectively. These ages, and their primitive initial Nd isotopic ratios, resemble those of mafic intrusions around Voisey's Bay area. The North Intrusion is the most varied, and its main compositional units have ambiguous contact relationships implying that they partially coexisted as liquids. Disseminated sulphide mineralization is widely present near the basal contacts of the North Intrusion, but massive sulphides are rare. Sulphides are hosted by a complex mineralized sequence, interpreted to record two or more magma influxes that carried sulphide liquids and reacted, resorbed paragneiss fragments. In the South Intrusion, sulphides are hosted by ultramafic cumulate rocks, also rich in paragneiss fragments, and probably formed via gravitational accumulation. The mineralized rocks are strikingly similar to those observed at Voisey's Bay, and sulphide mineralization is similarly associated with paragneiss fragments and unusual breccia-like rocks.

The two intrusions at Pants Lake formed from geochemically discrete magmas. The South Intrusion most closely resembles the Voisey's Bay Intrusion, whereas the North Intrusion resembles the less-mineralized Mushuau Intrusion near Voisey's Bay. However, both Pants Lake intrusions have interacted with the paragneisses, and both are widely mineralized. It is thus unlikely that such geochemical contrasts record differing contamination histories alone. Both intrusions display low whole-rock and olivine Ni contents, and low Cu/Zr ratios, indicating the removal of Ni and Cu by sulphide liquids. This pervasive depletion, coupled with consistent Ni:Cu:Co ratios and sulphide metal contents, suggests that sulphide liquids were developed in each on a large scale, probably at depth, rather than by more localized processes. The pervasive Ni depletion at Pants Lake contrasts with the more localized Ni depletion pattern observed at Voisey's Bay, and there is only limited evidence for undepleted mafic magmas. Sulphide Ni contents are ~ 2%, compared to ~ 4% at Voisey's Bay, although sulphide Cu contents are similar at ~ 2%. Nd and S isotope data from Pants Lake imply that country rock paragneisses played an important role as sulphur sources and/or triggers for immiscibility.

The striking similarities between the Pants Lake intrusions and their more famous sibling support some key aspects of genetic models for Voisey's Bay. The strong association between sulphides and resorbed paragneiss fragments supports an important role for these country rocks. Lower sulphide metal contents suggest that sulphide liquids at Pants Lake were not as efficiently "upgraded" by open-system processes, which may be an essential requirement for ore generation in mafic systems. The dominance of disseminated mineralization reflects the absence of suitable accumulation "traps" related to conduit geometry, although such may exist at depth. The Pants Lake area contains at least as much Ni and Cu as Voisey's Bay, and even larger amounts of metal are missing from these extensive mafic intrusions.

Ben Nevis and Avalon formations — A review

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From 1972 to present, more than 165 wells have been drilled in the Jeanne d'Arc Basin. Most of the wells have encountered an Early Cretaceous sandstone/shale section. The Ben Nevis and the Avalon formations have been formally described by McAlpine, 1990 who used as his type section the well, Mobil et al Ben Nevis I-45. Unfortunately, no cores were cut in the well. Sinclair, 1993 described the Gambo Member of the Ben Nevis Formation using as the type section the well, Mobil et al South Mara C-13.

At least 9 stratigraphic charts have been compiled for the Whiterose to Nautilus interval which includes the Ben Nevis and the Avalon formations. Lithostratigraphic picks show a distinct variability for the top of the Avalon Formation. Cross sections through a number of areas in the basin highlight the problem of the complexities of the two formations. The Ben Nevis Formation has been defined as a fining upward sandstone / siltstone sequence with the top of the Ben Nevis Formation being regularly picked at the emergence of the shales of the Nautilus Formation. In contrast, the Avalon has been represented as a coarsening upward cycle of shale, siltstone and sandstone. The Gambo member is composed of a highly variable lithology.

Biostratigraphy will not give absolute age dates for the two formations. Ranges for age dating is also presented in various charts. The Ben Nevis has been dated from Late Aptian to Late

Albian while the Avalon has been dated as Late Barremian to Late Aptian.

Isopach maps of the units show the variability within the basin. Isopachs for the Ben Nevis Formation differ from 5m to over 300 m while the Gambo Member varies from 6 m to 124 m. Similarly the Avalon Formation fluctuates from 40 m to over 250 m.

Lithostratigraphic picks for the Jeanne d'Arc basin are best established by using all available data such as sedimentology, biostratigraphy and seismic. Above all, a consistent approach is required. Development areas have a higher volume of applicable data leading to a more detailed treatment.

The Voisey's Bay deposits – discovery to pre-feasibility: an exploration perspective

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The discovery of the Voisey's Bay deposits on the north coast of Labrador is one of the most significant mineral discoveries made in Canada in the last 35 years. The surface discovery by Archean Resouces in 1993 was followed by a five-hole diamond drill program in October of 1994. By July 1995, a major near-surface deposit, designated as the Ovoid, had been outlined and immediately to the west, the Discovery Hill zone, site of the original discovery, was also delineated.

A step-out drilling program east of the Ovoid commenced in August 1995 and resulted in the discovery of the Eastern Deeps zone. The Reid Brook zone was discovered in January of 1997 while testing geophysical conductors in the deeper portions of the host troctolitic dyke west of the Discovery Hill zone. Further exploration to the east along the strike of the deposit trend resulted in the discovery of a zone of mineralization referred to as the North Eastern Deeps zone in 1998, the Ryan's Pond zone in 1999 and the Red Dog zone in 2000.

VBN is currently engaged in an Advanced Surface Exploration program. This is a multi-faceted, two-staged program. Stage 1 is a surface drilling and geophysical program designed to provide the information required to complete pre-feasibility studies on the underground resources. Positive results from Stage 1 will lead to an underground exploration program in Stage 2. The Stage 1 program includes detailed drilling, geophysics, mineralogical and geochemical investigations and geotechnical assessments required to assess the economic potential of the underground resources.

Memorable mathematical models of suicidal sulphide segregation

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Economic sulphide deposits rely on segregation of metals from a silicate magma into an immiscible sulphide liquid phase. In equilibrium, the ratio of the metal concentrations in the sulphide liquid and silicate magma is given by the distribution coefficient D, which is about 500 for Nickel and 1000 to 100 000 for PGE. However, that does not mean that sulphide Ni content is upgraded 500 times relative to the initial magma, because as the sulphide becomes upgraded the silicate magma becomes more metal-depleted: the sulphide metal contents depend on the relative quantities of silicate and sulphide (the "R" factor) as well as D. For a single batch of magma, this can be expressed as a very simple mathematical equation. When several batches of sulphur-saturated magma equilibrate with one batch of sulphide, e.g. in a magma conduit, a different equation results. This "multistage" upgrading actually requires less total silicate magma but, as in the single batch system, upgrading is limited to a maximum value of D. However, when the batches of magma are sulphur-undersaturated, as would normally be the case, the equations allow for radically different results. As the sulphide phase dissolves, upgrading of base metals in the remaining sulphide becomes greater than D, and PGE can experience "upgrading runaway". A valuable deposit may result if solidification occurs before the sulphide is entirely consumed.

The head and tail of the Voisey's Bay feeder dyke

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Since the discovery of the very unique Voisey's Bay Ni-Cu sulphide deposit 10 years ago, much about ore genesis associated with troctolitic magmatism in Labrador has been learned owing to close collaboration between research and exploration personnel. There are, however, many questions that still remain to be answered. These include magma flow direction in the feeder dike and magma replenishment in the Eastern Deeps chamber. In the previous model it was thought that the magma flowed eastward from the Reid Brock zone through the Discovery Hill zone to the Eastern Deeps chamber. It now appears that such an interpretation is not consistent with the spatial variations of metal contents of the sulphide ores in the different parts of the deposit. In the feeder dike the concentrations of Ni, Cu, Pt and Pd in the sulphide ores (recalculated to 100% sulphides) decrease westward from the

Ovoid ore body through the Discovery Hill zone to the Reid Brock zone, which is consistent with magma flowage westward instead of eastward. Nickel, Cu and PGE all have high partition coefficients between sulphide liquid and coexisting magma. Consequently, the sulphide liquid that reacts with the magma earlier will become more enriched in these elements than the sulphide liquid that reacts with the magma later because the magma becomes depleted in these elements with time. In the Eastern Deeps chamber the contents of Ni, Cu, Pt and Pd increase upward in the mineralized units, suggesting continuous replenishment of chalcophile element undepleted magma to the chamber. Olivine from the feeder dike is much more evolved than olivine from the Eastern Deeps chamber (Fo_{40}–Fo_{55} versus Fo_{55}–Fo_{75}), suggesting that the parental magma of the Eastern Deeps is more primitive than that of the feeder dike. Thus, it is unlikely that the feeder dike is the feeder of the Eastern Deeps chamber.

Mechanism and timing of sulphide saturation in mafic magmatic systems: evidence from Sudbury, Noril'sk, and Voisey's Bay

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The understanding of the process by which large Ni sulphide deposits are formed in mafic systems has advanced significantly since the early 1990's. Access to historic drill samples from Noril'sk-Talnakh has resulted in a much clearer understanding of the geological relationships in an essentially fresh and undeformed system with extensive deposits of massive and disseminated Ni-Cu-PGE mineralization. In the mid 1990s, the Voisey's Bay discovery offered an enormous opportunity for an academic understanding of the deposit and host rocks, developed in parallel with Inco's exploration efforts. After 100 years of mining at Sudbury, the geological relationships in the individual deposits and the Sudbury Igneous Complex (SIC) are becoming far clearer. A central theme in understanding the evolution of each of these very different systems has been an understanding of the importance of dynamic processes in ore deposit formation.

At Sudbury, Noril'sk, and Voisey's Bay, there is a clear association of mineralization with a chaotic assemblage of host rocks. In each case there is a physical concentration of the sulphides, and the location of these concentrations appear to be linked to the geometry of the host rock body. At Sudbury, there is a record of the sulphide saturation history in the Main Mass norites that are depleted in Ni, Cu, and PGE. The thickest portion of metal-depleted norites are located proximal to the largest known deposits at Sudbury. It is believed that the formation of the Sudbury ores took place by early sulphide saturation and segregation from the crustal melt sheet. The geological data provide important constraints on the sequence of events that formed the different ore bodies in contact, footwall and offset environments.

The Ni-Cu-PGE deposits of the Noril'sk region appear to have been generated by sulphide saturation and accumulation from large volumes of basaltic magma that erupted to form the Siberian Trap. The formation of the economically mineralised intrusions is believed to have occurred at depth during the formation of the contaminated and Ni-Cu-PGE-depleted Nadezhdinsky magma. The Noril'sk deposits are localized in areas where the Nadezhdinsky Formation is thickest. The mineralised intrusions carry several hundred times more sulphide than could be dissolved in the observed silicate melt, and so it appears increasingly likely that the sulphides were emplaced as magmas, or they were introduced in a dynamic open system process. As with Sudbury, there is record of ore deposit formation in spatially associated rocks that contain no sulphide mineralization.

The Voisey's Bay deposits occur in a dyke and at the entry point of the dyke into a larger intrusions. There is clear evidence for geometric localization of sulphides at the entry points of the dyke into the chamber, and in widened domains in the dyke. Although there is some evidence of metal depletion in the system, a key feature of the deposit is the development of a halo of sulphide-enriched variable-textured troctolite in the chamber overlying the Eastern Deeps mineralization. In the case of Voisey's Bay the sulphides appear to have been emplaced late in the evolution of the intrusion.

The geological relationships can be used to understand the sequence of events, constrain process-driven geological models, and expand the range of tools that can be used in exploration and delineation of ore bodies.

Characterization and modeling of $\delta^{18}O$ variations accompanying mineral reactions in pelitic xenoliths at the Voisey's Bay Ni-Cu-Co deposit, Labrador, Canada.

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Massive sulphide mineralization at Voisey's Bay Ni-Cu-Co deposit is closely associated with country rock xenoliths, which are extremely abundant in a horizon referred to as the Basal Breccia Sequence. Therefore, Ni-Cu-Co sulphide mineralization at Voisey's Bay is in part attributed to the reaction between country rocks and host magma. Potential country rock contaminants include the Proterozoic Tasiuyak paragneiss, which occurs in the western part of the intrusion (Reid Brook Zone). The endebitic orthogneiss and a variety of mafic to quartzofeldsparthic gneisses of Archean age constitute the immediate country rocks to the eastern part of the deposit (Discovery Hill, Ovoid, and Eastern Deeps). Variation in country rock types across the deposit poses a dilemma in trying to determine the main contaminant to the Voisey's Bay magma, which is also compounded by the fact that all xenoliths at Voisey's Bay, regardless of their protolith, have reacted to produce a typical assemblage that is dominated by pseudomorphous hercynite, anorthitic plagioclase and corundum. Extensive interaction of magma and xenoliths induced mineralogical and geochemical changes within the suite of xenoliths, as well as distinct concentric mineral zonation which is defined by hercynite, plagioclase, and to a lesser extent by corundum.

Four types of xenoliths referred to as zoned, banded, massive and variegated were identified across the deposit, and each type of xenolith is characterized by a distinct sequence of mineral zonation. A comparison of xenoliths from the Reid Brook and Eastern Deeps sections shows variation in shapes, sequence of mineral zonation, and $\delta^{18}O$ signatures. Xenoliths from the Reid Brook zone exhibit less mineral zonation (massive and banded) and are more lenticular in shape, with width vs. length ratios between 0.14 and 0.77, compared to 0.08–0.92 obtained from the Eastern Deeps. Seventy percent of xenoliths from the Reid Brook have an aspect ratio below 0.5, compared to 54% in the Eastern Deeps. The $\delta^{18}O$ signatures of xenoliths in the Reid Brook zone are ~1‰ higher than those in the Eastern Deeps. The $\delta^{18}O$ values of protolith mineral assemblages indicate equilibration temperatures in excess of 800°C. We have modeled both closed and open system destruction of garnet via a reaction that produces cordierite, orthopyroxene and K-feldspar. Computed closed system $\delta^{18}O$ values (‰) for an 11.3‰ protolith are: cordierite-11.5, orthopyroxene-10.3, and K-feldspar-12.7. Progressive dehydration of cordierite under closed system results in expulsion of ^{18}O-enriched water and the production of hercynite and quartz with final values of 8.7 and 16.3‰, respectively. Open system dehydration of cordierite produced hercynite and quartz with final values of 1.3 and 8.9‰, respectively. The final $\delta^{18}O$ system value of 5.87 indicates 5.63‰ deviation from the starting value of 11.5‰. Such values are consistent with low $\delta^{18}O$ values obtained from xenolith mineral separates, indicating loss of ^{18}O-enriched partial melts from the xenoliths.

PGE, Au and base metal distribution in soil over the Voisey's Bay Ni-Cu-Co deposits

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In the summer of 1995, following the announcement by Diamond Fields Resources Ltd. of the discovery of massive sulphides in the Voisey's Bay area of Labrador, the Department of Mines and Energy conducted a soil survey across some of the area before it was disrupted by exploration and development activities. Samples of primarily B-horizon soil were collected from 45 sites and the <180 μm fraction was analyzed for 46 elements by a variety of methods. Analyses included platinum, palladium, gold and base metals. Six north-south sampling lines were made from one to two kilometres apart with sample spacings averaging 250 metres. One line was deployed across Discovery Hill, one to the west of Reid Brook and the others to the east in a glacially "down-ice" direction. The Reid Brook and Ovoid zones were not included. Of the four major mineralized zones, only the Discovery Hill zone outcrops. The others are "blind" or, in the case of the Ovoid, subcrop beneath a considerable thickness of Pleistocene sediments. Results of the survey reveal that the Discovery Hill zone is clearly reflected in the soil data. Although the mineralized zone is less than 100 metres wide on the Discovery Hill transect, the anomalous soil zone is at least 850 m wide for the elements Ni, Cu, Au, Pt and Pd. This is likely due in part to dispersion of the anomaly by soil creep and possibly by groundwater transport down the steep hillside to the south of the mineralized zone. That the soils are clearly anomalous in the ore metals Ni and Cu is not surprising. More so are the high levels of PGE and Au in a few samples. Maximum values include 824 ppb Pd, 12.3 ppb Pt, 434 ppb Au, 468 ppm Ni and 1100 ppm Cu.

3-D seismic data in the Newfoundland and Labrador offshore area

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Effective exploration for hydrocarbons in remote offshore areas has been made possible by improvements in seismic technology, computing and positioning. The first 'moving seismic collection' in the U.S. occurred in 1961. By 1964, 2-D seismic data was being collected by Amoco Petroleum in the Newfoundland and Labrador Offshore Area.

The concept of 3-D seismic data collection was tested by Gulf in 1974 and the benefits were quickly recognized. Following the discovery of the Hibernia field in 1979 Newfoundland and Labrador's first 3-D survey was recorded. Since then several large surveys have been recorded in the offshore area. Under the Atlantic Accord legislation non-exclusive data collected under an Authorization granted by the Canada-Newfoundland Offshore Petroleum Board (C-NOPB) becomes 'non-privileged' five years after completion of the work. Several large 3-D data sets, acquired in the late 1990s are now released and have been used by the C-NOPB for regional geoscientific studies, a part of the C-NOPB's mandate.

Over 3000 sq. km. of industry 3-D seismic data, have been interpreted and merged to show the superimposition of the tectonic expressions of the last two rift stages that affected the Grand Banks of Newfoundland. Evidence of changing palaeodrainage patterns is also seen. A late Jurassic/early Cretaceous northerly trending system deposited the fluvial reservoir unit for the Terra Nova oil field, while in the Tertiary an easterly trending system deposited submarine fans, which now contain hydrocarbons in such fields as Mara and Springdale.

The northwards opening of the northern Atlantic Ocean separated the Grand Banks of Newfoundland from the Iberian

Peninsula in late Jurassic-early Cretaceous. This was the second rift phase to affect the Banks and resulted in a strong north-south overprint on the original northeast-southwest fabric of the initial basins. The third and final rifting phase to affect the Banks, also related to the opening of the Atlantic, started in mid-Cretaceous when the British Isles separated from the Grand Banks and the Labrador rift opened.

The trials, tribulations, and rewards of making art in stone

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There is a subjective gradation from stone crafts to stone art, with traditional stone sculpture being at the upper end. Jamie and the artisans at Meyer's Minerals create work in all of these areas, constantly sharing equipment, technical expertise, and ideas. The supply and variety of stone in Newfoundland and Labrador is so incredible that often the approach is simply to display geological history in an artistic and high quality presentation.

Small business is challenging enough, but putting bread on the table while creating art and/or crafts of any kind requires an incredibly supportive spouse. Meyer's Minerals had to evolve into a geotourism business to try and stay alive financially. In the process it became apparent that there is a tremendous interest the beauty of stone blended with geological history.

An unexpected and extremely rewarding spin-off has been a longtime collaboration with Labrador sculptor Gilbert Hay. Jamie now carries out finishing work on Gilbert's anorthosite sculptures. This has led to work in Nunavut, involving prospecting and teaching modern stoneworking techniques.

Controls of sedimentary fabrics on permeability heterogeneity and anisotropy

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An important part of reservoir characterization is the definition of permeability anisotropy, that is, the relative magnitudes of horizontal and vertical permeabilities. In addition, essential for the consideration of enhanced recovery schemes is the permeability structure or, more simply, the relative heterogeneity of horizontal and vertical permeability distributions. Reservoir engineering parameters such as sweep efficiency or volume of bypassed oil are clearly dependent on the degree of homogeneity of the permeability structure. In this presentation I review the results of outcrop- and subsurface core-based studies of permeability distributions at different scales.

In the first study I categorize types of plug permeability distribution for different lithofacies corresponding to metre-scale (1–5 m) slightly consolidated sandstone units within the Virgelle Member at Writing-on-Stone Provincial Park (WOSPP), southern Alberta. Among the details of the data, I can single out two aspects in particular: (i) most of the permeability distributions can be approximated by the square-root function, rather than normal or lognormal distributions; and, (ii) vertical permeability (kV) distributions often appear more homogeneous than the corresponding horizontal permeabilities (kH). Inferred homogeneity of kV distribution appears to decrease from lithofacies with strongly current laminated structure, to bioturbated/burrowed, poorly laminated intervals.

Small-scale probe permeability measurements on differently oriented core faces of quartz-cemented Viking Formation sandstones also yield permeability distributions that appear to be diagnostic of the grain- and lamina-scale fabric. Permeability anisotropy of a single 'structureless'-appearing sample is low, reflected by a kV/kH-ratio = 0.7; corresponding k-distributions are homogeneous. Permeability anisotropy of a strongly laminated sample is variable, with kV/kH-ratios = 0.1 and = 2.8, thought to be a function of the variability of the pore network connectivity for any given lamina. Significantly, the pore network anisotropy established during deposition appears to have been maintained even after several kilometres of burial, and cementation and dissolution processes. As in the earlier study, lamina-perpendicular permeability distributions are relatively homogeneous, which is taken to imply that fluid-fluid displacement processes are potentially more efficient in that orientation.

How do supercontinents form?

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Repeated amalgamation and dispersal of supercontinents have profoundly affected Earth's evolution since the Archean. The formation of Pangea in the Late Paleozoic and Gondwana in the late Neoproterozoic are cornerstones in our understanding of tectonics. Although their configurations are controversial, there is general acceptance of the existence of older supercontinents, Rodinia from about 1.0 to 0.75 Ga, and Columbia from 2.0–1.75 Ga. Each period of supercontinent assembly is succeeded by fragmentation and creation of oceanic lithosphere between the dispersing continental fragments, followed by subduction and re-assembly of the next supercontinent. However, we do not understand the geodynamic forces that drive these global-scale events.

When supercontinents rift, fragment and disperse, there are two contrasting types of ocean lithosphere, (i) an exterior ocean which surrounded the supercontinent with oceanic lithosphere that is older than the rifting event, and (ii) interior oceans formed between the dispersing blocks, with oceanic lithosphere that is younger than the rifting event. Although subduction of oceanic lithosphere during continental convergence generally destroys much of the primary evidence that would identify the vestiges of these contrasting oceans, remnants are preserved in ophiolite complexes and terranes accreted to the continental margins prior to terminal collision. As some of these terranes are generated by the subduction process itself, their crust-formation ages, rather than crystallization ages, are the key to distinguishing between remnants of interior and exterior oceans. This information can be derived from Sm-Nd isotope systematics.

Using Pangea and Gondwana as examples, we propose that Sm-Nd isotopic systematics can distinguish between two end-member models of supercontinent amalgamation. The first model is the classical Wilson cycle, in which terminal collision is produced by the destruction of the oceanic lithosphere that was generated since the separation of the previous supercontinent. These supercontinents turns "inside in" or "introvert". An example is the Appalachian-Caledonian-Variscan orogen of eastern North America and Europe in which the rifting events that opened the Iapetus and Rheic oceans gave way to subduction, terrane accretion and continent collision associated with the amalgamation of Pangea. Such an origin is indicated by Sm-Nd crustal formation ages of accreted mafic complexes that are younger than the onset of Iapetan rifting.

The second model, in which the supercontinent is driven towards areas of mantle downwelling, the supercontinent is turned "outside in" or "extroverts", that is, the exterior continental margins of the supercontinent at the dispersal stage become the interior orogenic belts of the next supercontinent. Since the oceanic lithosphere consumed is from the exterior ocean, its lithosphere pre-dates the breakup of the previous supercontinent so that Sm-Nd crustal formation ages of mafic complexes generated in that ocean are older than the age of rifting. These complexes are preserved as terranes in collisional belts. For example, crustal formation ages of mafic complexes accreted during the amalgamation of Gondwana are older than 750 Ma, i.e. their proto-crust pre-dates the breakup of Rodinia and therefore must have been part of the exterior ocean.

The data indicate that Pangea and Gondwana formed in different geodynamic regimes, suggesting that traditional views of a "supercontinent cycle" may well be flawed.

Avalon-Meguma relationships during the Paleozoic: implications for the development of the Appalachian orogen

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The Paleozoic evolution of the Avalon and Meguma terranes is crucial to the understanding of the Appalachian orogen. In the Avalon terrane of Nova Scotia, Ordovician–Early Devonian rocks consist of bimodal volcanics at the base (Dunn Point Formation) disconformably overlain by ca. 1900 m of fossiliferous siliciclastics (Arisaig Group) which contain Llandoverian to Lochkovian fossils. U-Pb zircon data from a rhyolite yields 460.0 ± 3.4 Ma for the Dunn Point Formation, and together with paleomagnetic data suggest development on a microcontinent at 30°S, outboard from both Laurentia (20°S) and Gondwana (60°S), possibly in a rifted arc setting. Geochemical, Sm-Nd isotopic tracer, and detrital zircon age data for Arisaig Group clastic rocks contrast with underlying Avalonian units, indicating a provenance source other than Avalonian basement. These rocks are characterized by negative ε_{Nd} (-4.8 to -9.3), TDM > 1.5 Ga, abundant 620–520 Ma zircons, with lesser concentrations at ca. 0.9–1.2 Ga and 1.5–2.2 Ga. Archean zircons are minor. The Arisaig Group is inferred to be primarily derived from Baltica-Laurentia, with increasing input from more ancient basement in the early Devonian.

Detrital zircon populations from coeval strata (White Rock and Torbrook formations) of the Meguma terrane also contain abundant ca. 620–520 Ma zircons and an important Mesoproterozoic population (1.0 to 1.4 Ga), that strongly suggests contiguity with Avalonia by the Late Ordovician–Early Silurian. These coeval clastic rocks are interpreted to have been deposited adjacent to the trailing edge of Avalonia-Meguma during Appalachian accretionary events. As Avalonia had accreted to Laurentia-Baltica by the Late Ordovician, these data suggest that the Meguma terrane also resided along the same (northern) margin of the Rheic ocean at that time. This interpretation is supported by the absence of a Cambro-Ordovician accretionary event, the lack of intervening suture zone ophiolitic units, and the similarity of Avalonian and Meguma basement Nd isotopic signatures in Paleozoic igneous suites. This conclusion implies that the Siluro-Devonian Acadian orogeny was not related to collision of the Meguma terrane with the Laurentian margin. Instead, we suggest that the Acadian orogeny occurred in an Andean-type setting.

Geology of a transect across the Nain Plutonic Suite in the vicinity of Voisey's Bay

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A five year research project at Memorial University, supported by VBN/INCO and NSERC, is studying the geology of a transect across the Nain Plutonic Suite to better understand the geological setting of the Voisey's Bay Ni-Cu-Co deposit. This study is based on new geological mapping at a scale of 1:20 000, completed between 1999–2003. The gneisses that host the mineral deposit were mapped at 1:10 000 by Alana Rawlings as the foundation of her MSc thesis completed in 2001. Other theses are at writing stages: PhD theses by Ron Voordouw and Donald Wright, MSc theses by Owen Gaskill and Tanya Tettelaar, and BSc (Hons) theses by Cory Furlong and Clare Goddard. The talk outlines the regional geology determined by this collective study in a transect ~80 km long and ~40 km wide.

The Nain Plutonic Suite forms a batholith comprising numerous plutons, dykes and sheets of anorthosite, leuconorite, leucotroctolite, troctolite, ferrodiorite, monzonite and granite. The batholith is ~70 km wide and over 200 km long and was emplaced from ~1360 to 1290 Ma along a ~1860 Ma suture between two Archean continents. The host rocks in the studied transect include Archean and Paleoproterozoic tonalitic and metasedimentary gneisses, and ultramafic, gabbroic and anorthositic gneisses of (?)Paleoproterozoic age. All these rocks were intruded by basaltic dykes and then, except for Archean gneisses to the east of the Nain Plutonic Suite, were strongly deformed and recrystallized to granulite grade at ~1860 Ma during the Torngat orogeny.

Within the Nain Plutonic Suite, pluton and dyke emplacement was associated with intermittent extension and transcurrent movements on east-west and NNW–SSE faults. During successive emplacement, older structures tended to be reactivated by younger intrusions. The same kinds of magmas were intruded intermittently throughout the development of the batholith. In many cases, intrusion was accompanied by fragmentation of the adjacent wall and roof rocks, and probably involved cauldron subsidence. Anorthosite and granite form large tabular plutons whereas composite ferrodiorite/monzonite intrusions mostly form arcuate dykes, small circular plutons, or narrow remnants in the margins of large anorthosite plutons. Relatively small amounts of troctolite mainly form sheet-like bodies. There is an overall longitudinal asymmetry to the batholith with rapakivi granite predominant in the west and anorthosite in the east. The anorthosite is further spatially divided into older, partly deformed and recrystallized anorthosite and leuconorite in the west and north, and younger, undeformed and unrecrystallized anorthosite and leucotroctolite in the east and south.

Geophysical characterization of a Late Proterozoic mafic sill – Cape St. Francis, Newfoundland

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The aim of this study is to characterize a mafic sill and its environs in the vicinity of Cape St. Francis, Newfoundland, so as to investigate its implications for late Proterozoic bimodal magmatism in the Avalon Zone of the Appalachians. Northwesterly dipping arkosic sandstones and a thick overlying sequence of pillow basalts bound the mafic sill and, in the northern section of the study area, cogenetic rhyolite domes are present.

As part of the study, detailed magnetic and elevation surveys have been carried out, and larger scale regional geophysical surveys are being analysed, to build a three-dimensional model of the sill morphology and to define the subsurface vertical of the sill. This geophysical data and their interpretation will be the focus of this presentation. Future work will include petrological and geochemical investigation of the sill coupled with U-Pb geochronology from the sill and surrounding units.

Stable isotopic constraints on magma-country rock interaction and ore genesis: future directions

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Stable isotopic data can provide useful evidence of contamination and mixing associated with magma-country rock interaction. Careful consideration of the systematics of S solubility relationships in mafic magmas strongly points to the need for S assimilation to generate world-class sulphide mineral deposits. Because of the potentially large difference between the sulphur isotopic compositions of sedimentary sulphur-bearing minerals and sulphur of mantle origin (~0‰), sulphur isotopic measurements provide perhaps the most direct indication of the assimilation of external sulphur by mafic magma. Many deposits have now been evaluated that show strongly anomalous sulphur isotopic signatures. However, the distribution of isotopic values in potential contaminants must be carefully considered; $\delta^{34}S$ values of igneous rocks that are near 0‰ may not necessarily rule out the derivation of the bulk of the contained S from external sources. We have shown that the range in $\delta^{34}S$ values of S in the Tasiuyak Gneiss (country rock for at least a portion of the Voisey's Bay deposit) is large (-20 to +20‰), and efficient mixing could lead to a bulk contaminant $\delta^{34}S$ value not far removed from 0‰. The difference in $\delta^{34}S$ values between sulphide minerals from the Reid Brook zone at Voisey's Bay, and the Ovoid/Eastern Deeps assemblages has been interpreted in terms of variable mixing ratios and localized sources of S contaminants. Although these potential causes of isotopic variations are viable, spatial variations of Ni, Cu, and PGE contents of the sulphide ores from different parts of the deposit suggest that the difference may be more indicative of distinct, unrelated magmatic systems. The presence of sulphur in high-grade metamorphic rocks in the Voisey's Bay area highlights what should certainly be a major research focus for coming years. The mechanisms of sulphur incorporation into mafic magma are poorly understood, yet may be critical with respect to the temporal development of high-grade deposits.

The discovery of mass-independent S isotopic fractionation during the formation of sedimentary sulphides in the Archean potentially provides a new tool for the evaluation of contamination in systems that have been difficult to probe using conventional S isotopic methods. If the anomalous $\Delta^{33}S$ found in sedimentary rocks are preserved in the magmatic environment (and our preliminary data suggest that they are), then isotopic measurements in Archean systems should prove to be particularly informative.

At Voisey's Bay our oxygen isotopic data clearly indicate that the igneous matrix in the breccia units was not in contact with the xenoliths for a protracted time period; isotopically normal troctolite matrix indicates that contaminated magma has been removed from the conduit system. In the absence of overlying volcanics the fate of this magma remains an intriguing question, and has ramifications with respect to magma replenishment and metal upgrading. Both experimental and field studies of isotope exchange mechanisms and rates are needed to enhance our understanding of assimilation processes.

The technical developments in the field of multi-collector ICP-MS have provided the potential for accurate and precise isotope measurements of a host of elements that are of significance for ore genesis, including Fe, Cu, Zn, Cr, and Se. Isotopic measurements of these elements are becoming more routine, and will provide a foundation for the evaluation of metal sources in magmatic systems.

My changing perceptions of the landscape

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I have observed that over the 30 years that I have been painting this landscape, that it has changed very little geographically. However, the longer I have observed and allowed the landscape to enter into me, the more my perceptions of it have changed. I would like to show in a series of slides how these changing perceptions have influenced my interpretation of the landscape over the years.

Future directions: overview of mineral resource research planned for the Inco Innovation Centre at Memorial University

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An Inco Innovation Centre is in development on Memorial University's campus in the (former) Thompson Student Centre. The Centre is funded by contributions from Inco, Ltd., and grants from the Atlantic Innovation Fund and other programs. Research to be undertaken in the Centre will focus both on mineral resource development, particularly at Voisey's Bay, as well as on a host of other more general innovative activities. For mineral science research, there will be geophysics and geochemical components that will aid in advanced exploration, sulphide ore delineation and mine planning; and process engineering components that will support development of hydrometallurgical technologies. More than sixteen Memorial faculty members from Earth Sciences and Engineering will be involved, as well as several researchers from Voisey's Bay Nickel Company and Inco Ltd.

As an example of the planned mineral resource research, state-of-the-art analytical instrumentation will be developed for geochemistry and mineralogy. The equipment will include a multicollector magnetic sector ICPMS coupled to a deep-UV excimer laser, and a scanning electron microscope (SEM) equipped with an electron backscattered diffraction (EBSD) system for mineral identification. Isotopic work on a variety of metals that are relevant to ore systems – iron, copper, osmium, lead – will be possible with the multicollector ICPMS. Using the laser, spatial variations in isotopic compositions within minerals will be documented with the expectation of resolving temporal changes in the physical and chemical environment of sulphide ore genesis. The SEM-EBSD system will provide a platform by which to quantify mineralogical variations within the deposit, which will be critical to understanding the metallurgical response of ores to processing. Results from both instruments will be integrated with three dimensional models of the orebodies to facilitate better understanding of their spatial distribution.

Although the immediate applications for geochemical research will be focussed on ore systems, the vision of the Centre as a facility for general innovative research will lead to new applications in related fields such as crustal evolution, global change, groundwater quality and geoarchaeology.

Petrogenesis of an anorthosite-mangerite-charnockite suite in the western margin of the Nain Plutonic Suite: petrological and geochronological evidence

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The study area is located at the western boundary of the Nain Plutonic Suite and focuses on the Pearly Gates anorthosite pluton (PGA) and the adjacent composite body of mangerite and jotunite called the Tessiarsuyungoakh intrusion (TI). The contact between these intrusions is deformed and original relationships are obscured. The PGA consists of an inner zone of massive anorthosite and an outer zone of foliated, partially recrystallized layers of anorthosite and norite. Undeformed norite bodies intruded the inner and outer zone of the PGA. The contact-parallel fabric in the TI is pervasive through most of the unit, except along the western contact with the older Tasiuyak paragneiss. Where the fabric is weakest, jotunite can be seen to have intruded into the mangerite and the contact is irregular and cuspate. Field evidence, petrography and new U-Pb zircon TIMS geochronology ages have been combined to propose a mechanism for mid-crustal emplacement of these intrusions.

Based on zircon crystallization ages obtained from six major rock units with well-constrained field relationships, there appear to be 4 temporally distinct events. 1) The growth of prismatic zircons at 1370 ± 5 Ma in a sample from the PGA. In thin section these zircons were observed as inclusions in plagioclase and are thought to pre-date the intrusion of the PGA and be related to the development of a plagioclase crystal mush at depth. 2) The intrusion and crystallization of the TI composite body at ca. 1360 Ma. 3) The intrusion of anorthosite at 1355 ± 1 Ma into the TI. However, it is unknown whether this anorthosite is part of the PGA. 4) Norite intruded the PGA at ca. 1340 Ma and post-dates the deformation of the PGA and TI. Interstitial, fragmental zircon from a sample of the PGA provides a crystallization age of 1335 +7/-3 Ma, which places it within error of the crystallization age of the norite.

The model suggested here for the emplacement of this suite of rocks is as follows. Reactivation of Paleoproterozoic structures in the Tasiuyak paragneiss provided conduits for the ascent of mangeritic and jotunitic magmas of the TI. An older plagioclase crystal mush that had formed at depth later followed the same conduit system in intermittent pulses. The margins of the PGA and TI were deformed and recrystallized and then intruded by norite.

Mineral resource estimation methods used at Voisey's Bay: Eastern Deeps Ni-Cu-Co deposit

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The Eastern Deeps chamber is part of the 1.34 Ga. Voisey's Bay intrusion, a member of the Nain Plutonic Suite. The nickel-copper-cobalt deposit is located near the base of the chamber where a feeder dyke merges with the chamber.

The deposit consists of two mineralized domains, a large "cloud" of disseminated sulphides and a central core of massive sulphide. Metal grades within the disseminated domain are quite variable and range from 0.3 % Ni up to 1.5 % Ni with local barren layers. The massive sulphide domain is relatively homogenous in grade and averages about 3.0 % Ni.

A two-stage geostatistical approach was used to estimate the mineral resource contained within the Eastern Deeps. Due to the wide range in metal grades the disseminated domain was estimated using multiple indicator Kriging with a cut-off of 0.3% Ni. The massive sulphide estimation was completed using simple Kriging and the two models were then combined into a single block model.