ISSN 1916-6117 [online]
ISBN 978-1-4435-3972-2 [PDF]

ISSN 0826-9580 [print]
ISBN 978-1-4435-3971-5 [print]

THESE TERMS GOVERN YOUR USE OF THIS DOCUMENT

Your use of this Ontario Geological Survey document (the "Content") is governed by the terms set out on this page ("Terms of Use"). By downloading this Content, you (the "User") have accepted, and have agreed to be bound by, the Terms of Use.

Content: This Content is offered by the Province of Ontario's *Ministry of Northern Development, Mines and Forestry* (MNDMF) as a public service, on an "as-is" basis. Recommendations and statements of opinion expressed in the Content are those of the author or authors and are not to be construed as statement of government policy. You are solely responsible for your use of the Content. You should not rely on the Content for legal advice nor as authoritative in your particular circumstances. Users should verify the accuracy and applicability of any Content before acting on it. MNDMF does not guarantee, or make any warranty express or implied, that the Content is current, accurate, complete or reliable. MNDMF is not responsible for any damage however caused, which results, directly or indirectly, from your use of the Content. MNDMF assumes no legal liability or responsibility for the Content whatsoever.

Links to Other Web Sites: This Content may contain links, to Web sites that are not operated by MNDMF. Linked Web sites may not be available in French. MNDMF neither endorses nor assumes any responsibility for the safety, accuracy or availability of linked Web sites or the information contained on them. The linked Web sites, their operation and content are the responsibility of the person or entity for which they were created or maintained (the "Owner"). Both your use of a linked Web site, and your right to use or reproduce information or materials from a linked Web site, are subject to the terms of use governing that particular Web site. Any comments or inquiries regarding a linked Web site must be directed to its Owner.

Copyright: Canadian and international intellectual property laws protect the Content. Unless otherwise indicated, copyright is held by the Queen's Printer for Ontario.

It is recommended that reference to the Content be made in the following form:

Golightly, J.P., Pattison, E.F. and Lightfoot, P.C. 2010. Ni-Cu-PGE mineralization in the South Range of the Sudbury Igneous Complex: A field trip for the 11th International Platinum Symposium; Ontario Geological Survey, Open File Report 6252, 41p.

Use and Reproduction of Content: The Content may be used and reproduced only in accordance with applicable intellectual property laws. *Non-commercial* use of unsubstantial excerpts of the Content is permitted provided that appropriate credit is given and Crown copyright is acknowledged. Any substantial reproduction of the Content or any *commercial* use of all or part of the Content is prohibited without the prior written permission of MNDMF. Substantial reproduction includes the reproduction of any illustration or figure, such as, but not limited to, graphs, charts and maps. Commercial use includes commercial distribution of the Content, the reproduction of multiple copies of the Content for any purpose whether or not commercial, use of the Content in commercial publications, and the creation of value-added products using the Content.

Contact:

FOR FURTHER INFORMATION ON	PLEASE CONTACT:	BY TELEPHONE:	BY E-MAIL:
The Reproduction of the EIP or Content	MNDMF Publication Services	Local: (705) 670-5691 Toll Free: 1-888-415-9845, ext. 5691 (inside Canada, United States)	Pubsales.ndm@ontario.ca
The Purchase of MNDMF Publications	MNDMF Publication Sales	Local: (705) 670-5691 Toll Free: 1-888-415-9845, ext. 5691 (inside Canada, United States)	Pubsales.ndm@ontario.ca
Crown Copyright	Queen's Printer	Local: (416) 326-2678 Toll Free: 1-800-668-9938 (inside Canada, United States)	Copyright@gov.on.ca

Ontario

Ontario Geological Survey
Open File Report 6252

Ni-Cu-PGE Mineralization in the South Range of the Sudbury Igneous Complex: A Field Trip for the 11th International Platinum Symposium

2010

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6252

Ni-Cu-PGE Mineralization in the South Range of the Sudbury Igneous Complex: A Field Trip for the 11th International Platinum Symposium

by

J.P. Golightly, E.F. Pattison and P.C. Lightfoot

2010

Parts of this publication may be quoted if credit is given. It is recommended that reference to this publication be made in the following form:

Golightly, J.P., Pattison, E.F. and Lightfoot, P.C. 2010. Ni-Cu-PGE mineralization in the South Range of the Sudbury Igneous Complex: A field trip for the 11th International Platinum Symposium; Ontario Geological Survey, Open File Report 6252, 41p.

Users of OGS products are encouraged to contact those Aboriginal communities whose traditional territories may be located in the mineral exploration area to discuss their project.

Open File Reports of the Ontario Geological Survey are available for viewing at the John B. Gammon Geoscience Library in Sudbury and at the regional Mines and Minerals office whose district includes the area covered by the report (see below).

Copies can be purchased at Publication Sales and the office whose district includes the area covered by the report. Although a particular report may not be in stock at locations other than the Publication Sales office in Sudbury, they can generally be obtained within 3 working days. All telephone, fax, mail and e-mail orders should be directed to the Publication Sales office in Sudbury. Purchases may be made using cash, debit card, VISA, MasterCard, American Express, cheque or money order. Cheques or money orders should be made payable to the *Minister of Finance.*

John B. Gammon Geoscience Library
933 Ramsey Lake Road, Level A3
Sudbury, Ontario P3E 6B5
Tel: (705) 670-5614

Publication Sales
933 Ramsey Lake Rd., Level A3
Sudbury, Ontario P3E 6B5
Tel: (705) 670-5691 (local)
1-888-415-9845 (toll-free)
Fax: (705) 670-5770
E-mail: pubsales.ndm@ontario.ca

Regional Mines and Minerals Offices:

Kenora - Suite 104, 810 Robertson St., Kenora P9N 4J2

Kirkland Lake - 10 Government Rd. E., Kirkland Lake P2N 1A8

Red Lake - Box 324, Ontario Government Building, Red Lake P0V 2M0

Sault Ste. Marie - 875 Queen Street East, Suite 6, Sault Ste. Marie P6A 2B3

Southern Ontario - P.O. Bag Service 43, 126 Old Troy Rd., Tweed K0K 3J0

Sudbury - Level A3, 933 Ramsey Lake Rd., Sudbury P3E 6B5

Thunder Bay - Suite B002, 435 James St. S., Thunder Bay P7E 6S7

Timmins - Ontario Government Complex, P.O. Bag 3060, Hwy. 101 East, South Porcupine P0N 1H0

Cette publication est disponible en anglais seulement.

Parts of this report may be quoted if credit is given. It is recommended that reference be made in the following form:

Golightly, J.P., Pattison, E.F. and Lightfoot, P.C. 2010. Ni-Cu-PGE mineralization in the South Range of the Sudbury Igneous Complex: A field trip for the 11th International Platinum Symposium; Ontario Geological Survey, Open File Report 6252, 41p.

Contents

FIGURES

PHOTOS

PHOTOS cont'd

TABLES

Preface

This geological field trip guidebook was prepared initially for use with a two-day field trip (trip number A6) held in conjunction with the 11th International Platinum Symposium meeting in Sudbury, Ontario, June 20–24, 2010.

Sudbury is one of the world's premier nickel-copper mining districts, a significant platinum group element (PGE) producer, and one of the oldest, largest, and best-exposed meteorite impact sites on Earth. As the world's largest integrated mining technology cluster, Sudbury has a vibrant mineral exploration and mining community that includes several major producers, numerous junior exploration companies, dozens of mining supply and service companies, 3 post-secondary educational institutions and associated exploration and mining centres, and several Ontario government mining and mineral ministry offices, making Sudbury one of the best places in the world to host a multidisciplinary meeting of this type. The City of Greater Sudbury, the largest city by landmass in Ontario, lies amidst glacially-shaped ridges, green boreal forests, and contains 330 lakes over 10 hectares in size and 112 lakes over 100 hectares in size. The success of more than 30 continuous years of environmental reclamation efforts has led to numerous national and international awards, including a Government of Canada *Environmental Achievement Award*, a United States *Chevron Conservation Award*, and a United Nations *Local Government Honours Award*. All of these features made Sudbury an ideal place to hold the 11th International Platinum Symposium Meeting from June 20–24, 2010, on Laurentian University Campus.

The theme of the meeting was "PGE in the 21st Century: Innovations in Understanding their Origin and Applications to Mineral Exploration and Beneficiation". The mining industry is presently in a recovery, so this was a very appropriate time to examine ways to make exploration efforts more efficient, to identify problems that need to be addressed, and to ensure that we pass our expertise along to the new generation. In addition to the technical program of oral and poster presentations, 3 workshops and 9 field trips were run in conjunction with the meeting.

The meeting was hosted by the *Department of Earth Sciences* and *Mineral Exploration Research Centre* (MERC) at Laurentian University and the *Ontario Geological Survey.* It was sponsored by *MERC*, the *Society for Geology Applied to Mineral Deposits*, the *Mineralogical Association of Canada*, the *Mineral Deposits Division* of the *Geological Association of Canada*, and the *Society of Economic Geologists*.

11th INTERNATIONAL
PLATINUM SYMPOSIUM
SUDBURY
ONTARIO CANADA
JUNE 21-24 2010

11th IPS Local Organizing Committee

Chairman	Prof. Michael Lesher (Laurentian University)
Treasurer	Edward Debicki (Geoscience Laboratories)
Technical Program	Dr. Pedro Jugo (Laurentian University)
Poster Displays	Nicole Tardif (Laurentian University)
Core Displays	David King (QuadraFNX Mining Limited)
Registration	Merilla Clement (Geoscience Laboratories)
Website	Jennie Byron (Laurentian University)
Transportation	Dr. Phil Thurston (Laurentian University)
Catering	Ruth Debicki (Ontario Geological Survey)
Accommodation	Dr. Bruno Lafrance (Laurentian University)
Facilities	Dr. Douglas Tinkham (Laurentian University)
Guest Program	Olga Brinkman
Photographer	Beatrice Ulrich
Field Trip Program	Dr. Michael Easton (Ontario Geological Survey) David King (QuadraFNX Mining Limited)
Field Trip Leaders	
– Surface	Brian Atkinson (Ontario Geological Survey) John Corkery (North American Palladium Ltd.) Dr. Michael Easton (Ontario Geological Survey and Laurentian University) Curt Freeman (Avalon Development Corporation) Robert Galyen (Franconia Minerals Corporation) Dr. Paul Golightly (Consultant/Laurentian University) David Good (Marathon PGM Corporation) Dr. Jacob Hanley (St. Mary's University) Dr. Peter Hollings (Lakehead University) Dr. Michel Houlé (Geological Survey of Canada and Laurentian University) Prof. Richard James (Laurentian University) Tim Jefferson (Teck American Incorporated) Dr. Scott Jobin-Bevans (Caracle Creek International Consulting Inc.) Natalie MacLean (Wallbridge Mining Company Limited) Al MacTavish (Magma Metals Limited) Dr. James Miller (University of Minnesota – Duluth (UMD)) Richard Patelke (PolyMet Mining Corp.) Edward Pattison (Wallbridge Mining Company Ltd. and Laurentian University) Attila Péntek (Wallbridge Mining Company Ltd.) Dr. Walter Peredery (Consultant) Dean Peterson (Duluth Metals Limited) Sonia Préfontaine (Ontario Geological Survey and Laurentian University) Mark Severson (UMD and Natural Resources Research Institute) Mark Smyk (Ontario Geological Survey) Mike Sweeney (Xstrata Nickel Exploration) Andrew Ware (Rio Tinto) Chris White (Cardero Iron Ore Company)
– Underground	Steve Dunlop, Steven Gregory and Renée Parry (Levack Mine) Roger Lichty, Mynyr Hoxha and Thomas Maxwell (McCreedy West Mine) Judd Fee and Chelsey Protulipac (Podolsky Mine) (QuadraFNX Mining Ltd.)
Advisory Committee	Paul Davis (First Nickel) Sergei Diakov (BHP-Billiton) Dr. Catherine Farrow (QuadraFNX Mining Limited and Laurentian University) Nic Fenner (Xstrata Nickel Exploration) Dr. Andy Fyon (Ontario Geological Survey)

Abstract

The Sudbury Igneous Complex (SIC) is defined as comprising all igneous rocks formed during the creation of the Sudbury Structure at 1850 Ma. The Sudbury Igneous Complex is usually considered to consist of 3 major components:

- the differentiated igneous rocks of the Main Mass sequence – consisting, from base to top, of quartz-bearing norites; a gabbroic unit formerly called the transition zone; and an upper unit of granophyre,
- the Contact Sublayer – a group of relatively small, inclusion-filled gabbronoritic bodies localized along the basal contact of the Sudbury Igneous Complex between norites and the various country rock units that form what is termed the footwall to the Sudbury Igneous Complex, and
- the Offset Sublayer – a number of dikes that either radiate outward from the base of the Sudbury Igneous Complex (radial offsets) or are subparallel to the basal contact of the Sudbury Igneous Complex (concentric offsets).

The Contact and Offset Sublayer units are of major economic importance because they are the hosts for much of the copper-nickel-platinum group element (PGE) mineralization associated with the Sudbury Igneous Complex.

Because of the economic importance of these Contact and Offset Sublayer units, this field trip examines 5 field trip stops in the south range of the Sudbury Structure, 4 of which are located on properties belonging to 4 different mining companies. The combination of road-accessible as well as walk-in stops is designed to illustrate important aspects of the geology, structure and mineralization found in the Contact and Offset Sublayer units in the Sudbury area.

Surface exposures of massive and semi-massive sulfides are normally selectively weathered and/or eroded, or both, and because most known near-surface deposits of ore-grade mineralization in the Sudbury area have been mined out, most surface exposures are restricted to subeconomic disseminated and vein-type mineralization. Consequently, the 5 field stops visited during this trip represent some of the best available, most accessible exposures of Ni-Cu-PGE mineralization in the South Range of the Sudbury Structure.

Ni-Cu-PGE Mineralization in the South Range of the Sudbury Igneous Complex: A Field Trip for the 11th International Platinum Symposium

J.P. Golightly[1], E.F. Pattison[2] and P.C. Lightfoot[3]

Ontario Geological Survey
Open File Report 6252
2010

[1] Geoscience Consultant, Sudbury, Ontario, Canada

[2] Geoscience Consultant, Sudbury, Ontario, Canada

[3] Vale Inco, Technical Services, Highway 17 West, Copper Cliff, Ontario, Canada, P0M 1N0

Geology of the Sudbury Structure (E.F. Pattison)

INTRODUCTION

The magmatic copper-nickel-platinum group element (PGE) sulfide deposits at Sudbury are part of the Paleoproterozoic Sudbury Structure (1850 Ma; Krogh, Davis and Corfu 1984; Krogh, Kamo and Bohor 1996; Davis 2008), which comprises:

- the Sudbury Igneous Complex (SIC),
- heterolithic breccias, mudstones, siltstones and wackes of the Whitewater Group, which occupy the centre of the Sudbury Basin, and
- a ring of brecciated and shock metamorphosed Archean Superior Province and Paleoproterozoic Southern Province footwall rocks that surround the Sudbury Igneous Complex.

This Sudbury Structure, as defined by occurrences of brecciated footwall (Sudbury Breccia), may have a radius of at least 100 km and is commonly, but not universally, accepted to be the result of a major meteorite impact at 1850 Ma.

Major components of the Sudbury Igneous Complex include the differentiated norite-gabbro-granophyre “main mass” and a group of minor intrusions, collectively termed “sublayer”, with which the copper-nickel-PGE deposits are associated. The Sublayer occurs in structural or thermally eroded depressions or “embayments” along the contact between the main mass and footwall rocks of the Sudbury Igneous Complex (Contact Sublayer) and as radiating and concentric dikes or “offsets” which intrude footwall rocks (Offset Sublayer). The Contact Sublayer comprises igneous-textured rocks of noritic to gabbronoritic composition and is associated with “Footwall Breccia”, which consists of cataclastic, thermally metamorphosed and remobilized material. The Offset Sublayer is usually of quartz dioritic composition (QD) but may also contain noritic and gabbronoritic phases.

The Sudbury Igneous Complex is separated into North and South Ranges, which differ in some of the details of the igneous petrology of the Sudbury Igneous Complex, the character of their respective footwall rocks and their structural and metamorphic histories. These changes occur across a series of ductile shears that exit the Sudbury Igneous Complex at its southwestern and southeastern corners.

Rocks of the Sudbury Structure are variably affected by several phases of regional deformation and metamorphism, including

- Kenoran metamorphism, which affected only Archean rocks of the North Range;
- a poorly-defined pre-impact event of Paleoproterozoic age (Blezardian Orogeny);
- the Penokean Orogeny, with peak metamorphism occurring in the United States portion of the orogen at 1835 Ma (Holm et al. 2001), but poorly defined in the Sudbury area;
- the Yavapai Orogeny between 1800 and 1700 Ma, responsible for some felsic intrusions south of Sudbury and likely the earliest folding and faulting of the Sudbury Igneous Complex (Piercy et al. 2007); and
- the Grenville Orogeny, which occurred in 2 main pulses between 1180 and 1160 Ma and 1080 to 1040 Ma (Carr et al. 2000), but whose waning stages lasted until approximately 1000 Ma, especially in the Sudbury area.

The Penokean orogenic event thus overlapped the formation of the Sudbury Structure.

The Sudbury Structure is cut by a number of regional and local mafic dike swarms. Archean footwall rocks on the North Range are cut by members of the Matachewan swarm (2473 Ma; Heaman 1997). Northwest-trending olivine tholeiite dikes of the Sudbury swarm (1238 Ma; Krogh et al. 1987) cut all rocks within the Sudbury Structure. At least 2 sets of less well-defined and undated dikes, including a series of lamprophyres (so called trap dikes) and a set of quartz diabase dikes, cut the Sudbury Igneous Complex, but are older than the Sudbury swarm dikes.

FOOTWALL ROCKS

Footwall rocks of the Sudbury Structure are defined as units characterized by deformational and metamorphic features related to the Sudbury impact event. In practice, this includes those units that can be shown to exhibit one or more of Sudbury breccia, shatter cones and shock-induced microscopic deformation features.

Footwall rocks on the North Range consist dominantly of Archean migmatitic gneisses of the Levack Gneiss Complex, small relicts of Archean greenstone belts, a variety of granitoid intrusive rocks and unconformable to structurally emplaced patches of Southern Province sedimentary strata. Small to medium-sized layered mafic plutons of the East Bull Lake intrusive suite (EBLI, *circa* 2475 Ma; Krogh, Davis and Corfu 1984) are found close to the Archean–Paleoproterozoic boundary. All are cut by bodies of Paleoproterozoic Nipissing Gabbro (*circa* 2220 Ma; Corfu and Andrews 1986; Noble and Lightfoot 1992). Footwall rocks on the North range are generally unaffected by Penokean and later orogenic events.

Footwall rocks on the South Range are Paleoproterozoic in age and consist of a thick sequence of mafic to felsic metavolcanic rocks, coeval felsic to mafic subvolcanic intrusions, cyclic sequences of coarse to fine clastic metasedimentary rock, subsequently intruded by Nipissing Gabbro intrusions. The metavolcanic and metasedimentary rocks are part of the Huronian Supergroup (2450 to 2300 Ma; cf. Bennett, Dressler and Robertson 1991) and have been affected by Penokean orogenic events including folding about east-northeast-trending fold axes and by greenschist to amphibolite grade metamorphism.

All footwall rocks older than the Sudbury Event are cut by Sudbury Breccia variably occurring as small veinlets, irregularly-shaped patches and large, crudely tabular bodies that may be traced for many kilometres along strike. The breccia consists of locally derived footwall lithologies within a cataclastic to locally vitric or igneous-textured matrix. Sudbury Breccia is interpreted as a pseudotachylite formed by violent *in situ* milling processes during the decompression and crater collapse phases in the development of the Sudbury Structure. Occurrences of Sudbury Breccia have been noted as far as 80 to 100 km away from the centre of the Sudbury Structure, providing the best estimate for an original diameter of the structure of approximately 200 km (cf. Dressler, Gupta and Muir 1991).

WHITEWATER GROUP

Rocks of the Whitewater Group are found only within the central core of the Sudbury Structure and are totally enclosed by magmatic rocks of the Sudbury Igneous Complex. Four conformable formations are defined; these are, in order from oldest to youngest, the Onaping, Vermilion, Onwatin and Chelmsford formations.

The **Onaping Formation** consists of up to 1600 m of a complex of heterolithic breccias. The rocks are formed of varied quantities of footwall rock fragments, bodies of massive to flow-laminated devitrified glass, finely comminuted matrix material and minor sulfide mineralization. Small bodies of inclusion-bearing igneous-textured "melt" intrude the clastic members of the formation. Many of the rock fragments exhibit evidence of strong shock metamorphism. The Onaping Formation has been interpreted as a sequence of ash flow tuffs and lavas; as impact-generated fallback breccia and melt; and most recently, as impact-generated breccias modified by internally generated volcanic processes.

The chemical composition of the vitric and "melt" phases of the Onaping Formation, closely resembles that of the quartz diorite dikes visited in 3 of the field tour stops and has been interpreted as the bulk composition of the Sudbury Igneous Complex prior to crystallization (Ames et al. 2002).

The **Vermilion Formation** occurs discontinuously at the top of the Onaping Formation and consists of bedded carbonate, siltstone, argillite and chert. Significant occurrences of volcanogenic Cu-Pb-Zn-Ag massive sulfide are locally present. The unit is interpreted as an exhalite-rich sequence deposited during the waning stages of Onaping Formation deposition by a regional hydrothermal system.

The Onwatin Formation comprises carbonaceous and sulfidic, massive to laminated, argillite, siltstone and minor interbedded wacke deposited in a stagnant, anoxygenic environment.

The **Chelmsford Formation** is a unit of thick, massively bedded, proximal turbidites which exhibit well-developed Bouma sequences. This unit is the uppermost, preserved, unit of the Whitewater Group.

SUDBURY IGNEOUS COMPLEX

The Sudbury Igneous Complex (SIC) is defined as comprising all igneous rocks formed during the creation of the Sudbury Structure at 1850 Ma. The Sudbury Igneous Complex is usually considered to consist of 3 major components:

- ♦ the differentiated igneous rocks of the Main Mass sequence – consisting, from base to top, of quartz-bearing norites; a gabbroic unit formerly called the transition zone; and an upper unit of granophyre,
- ♦ the Contact Sublayer – a group of relatively small, inclusion-filled gabbronoritic bodies localized along the basal contact of the Sudbury Igneous Complex between norites and the various country rock units that form what is termed the footwall to the Sudbury Igneous Complex, and
- ♦ the Offset Sublayer – a number of dikes that either radiate outward from the base of the Sudbury Igneous Complex (radial offsets) or are subparallel to the basal contact of the Sudbury Igneous Complex (concentric offsets).

The Contact and Offset Sublayer units are of major economic importance because they are the hosts for much of the copper-nickel-PGE mineralization associated with the Sudbury Igneous Complex.

To these traditional subdivisions of the Sudbury Igneous Complex might also be added the various small intrusions and glass components of the Onaping Formation (cf. Ames, Stoness and Rousell (2009) for a full description) and, possibly, the glassy and pseudotachylitic matrices of some of the Sudbury Breccia bodies that surround the Sudbury Igneous Complex as part of the Sudbury Structure (cf. Fedorowich, Golightly and Rousell 2009). The rationale for including these as part of the Sudbury Igneous Complex lies in their coeval formation, at 1850 Ma, as part of the Sudbury Structure.

The Main Mass and Contact Sublayer portion of the Sudbury Igneous Complex that are now preserved after 1.85 Ga of deformation and erosion, outcrop as an east-northeast-trending elliptical or bean-shaped ring, with long and short axes of approximately 60 and 27 km, respectively. Maximum horizontal outcrop widths of the Sudbury Igneous Complex are approximately 4 km on the North Range and 7 km on the South Range, corresponding to true thicknesses of about 2 km and 5 km, respectively. The figures for the South Range are minima because of the tectonic shortening caused by the south-dipping, northerly directed thrusting mentioned above.

Over the years, the Sudbury Igneous Complex has been described as a sill, a laccolith, a ring dike, a lopolith, a funnel-shaped complex and an impact-generated melt pool. The present three-dimensional form of the Sudbury Igneous Complex is well constrained to a depth of 2 to 3 km by cumulative data from over 100 years of mining and subsurface exploration (cf. Pattison 2009). These data suggest that the basal contact of the Sudbury Igneous Complex generally dips inward, with the dips varying from about 35° to the south along much of the North Range contact to about 50 to 55° northward in unfaulted portions of the South Range. Despite these generalities, major portions of the South Range have been tectonically steepened to vertical or even locally overturned. Similarly, much of the East Range has been tectonically steepened so that its average dip is about 70° to the west. Collectively, these observations confirm the general basin-like configuration of the Sudbury Igneous Complex and are strongly supported by the results of seismic profiling carried out as part of a major Lithoprobe program in the 1990s.

Offset dikes extend for as much as 30 km into the footwall. These dikes are usually less than 100 m in width, although the proximal portion of the Foy Offset on the North Range is greater than 200 m wide near its junction with the Main Mass of the Sudbury Igneous Complex. The dikes always thin with increasing distance from the Main Mass and are often only a few metres to centimetres wide when last seen at their distal extremities.

The Sudbury Igneous Complex is often described as a layered complex but this is only so in a very simplistic sense. Although it is true that the Sudbury Igneous Complex consists of concentric rings of norite, gabbro and granophyre and, thus, is certainly a differentiated igneous body, it lacks most of the defining features that are usually present in true layered complexes. Fine- to meso-scale igneous bedding features such as graded beds, modal layering and other depositional features such as cross-bedding and scour-and-fill structures are totally lacking. Parts of the norite unit on the South Range do exhibit a reasonably well-defined igneous lamination due to a parallel alignment of lathy plagioclase crystals, but this is the only visual evidence for convective processes at work within the Sudbury Igneous Complex. Good examples of this can be seen in roadside rock cuts along the major highways that cross the South Range (cf. Rousell and Brown 2009).

On the South Range, **the Main Mass** of the Sudbury Igneous Complex is subdivided as follows:

- a basal unit or border facies of relatively fine-grained **quartz-rich norite** with as much as 15 modal percent quartz which often has an opalescent blue colour;
- the **south range norite** (the major noritic member), which is characteristically medium-grained and has a consistently low quartz content of around 5% except near its upper contact with the quartz gabbro, where it rapidly increases;
- a unit of **quartz gabbro**, often conspicuously enriched in magnetite, ilmenite and apatite, overlying the south range norite; and
- the **granophyre** unit (previously known as micropegmatite) gradationally overlying the quartz gabbro.

The Main Mass sequence on the North Range of the Sudbury Igneous Complex is as follows:

- a unique basal unit or border facies of **mafic norite,** characterized by a high modal percentage of cumulus orthopyroxene poikilitically enclosed in large plates of plagioclase. It is sporadically present along the North Range contact and typically overlies embayment structures where bodies of contact sublayer are present.
- a medium-grained **felsic norite,** which is the main norite unit on the North Range.
- a **quartz gabbro** unit, which is similar to that on the South Range, and
- the **granophyre** unit, which is similar to that on the South Range.

The **contact igneous sublayer** comprises a variety of typically noncumulate, igneous-textured gabbronoritic rocks occurring as discontinuous lenses and irregular sheet-like bodies at, as the name implies, the contact between the Main Mass of the Sudbury Igneous Complex and the surrounding footwall rocks on both the North and South Ranges of the Sudbury Igneous Complex. Its thickness is controlled by the topography of the footwall contact and locally exceeds 700 m. Major bodies of contact igneous sublayer are emplaced within kilometer-scale radial depressions or "troughs", along which are developed smaller secondary embayments or "terraces". Embayment structures are often interpreted as slump features similar to those visible in large Lunar, Martian and Venusian impact craters. They apparently formed during the very early stages of crater collapse. Other scenarios are possible, however, including the suggestion that they represent subradial erosional grooves in the crater ecavational flow (Golightly 1994) or thermal erosion channels formed by melting and assimilation of footwall rocks by superheated impact melt (Lesher et al. 2009).

The **offset sublayer** (commonly referred to as "quartz diorite" or "QD") comprises a variety of noncumulate, sometimes quench-textured, igneous rocks filling a number of relatively thin, dike-like intrusions on both the North and South Ranges of the Sudbury Igneous Complex. Three important groups of offset dikes are recognized:

- Offset dikes that radiate from the base of the main mass of the complex are termed radial offsets. These include the well-known Copper Cliff, Worthington, Ministic, Foy and Whistle-Parkin Offsets, as well as the recently discovered Trill and Pele Offsets.
- Offsets that are oriented subparallel to the base of the contact are called concentric offsets. These are the Hess and Manchester Offsets.
- Isolated lenses of varied size within zones of Sudbury Breccia are classified as discontinuous or breccia-hosted offsets and include the Frood-Stobie and MacLennan Offsets, although the Frood-Stobie offset was previously thought of as a concentric offset. Small metre- to decimetre-scale quartz diorite bodies of the third type are commonly referred to as "melt pods".

Most offset dikes typically appear to be composite intrusions consisting of 2 phases: a central core of inclusion- and sulfide-enriched quartz diorite encased in a marginal sheath of essentially inclusion- and sulfide-free quartz diorite. The nature of the contact relationships between the 2 phases are often obscure but xenoliths of the inclusion-free phase in inclusion- and sulfide-bearing quartz diorite have been described from Copper Cliff, Worthington and Trill. A possible alternative mechanism for producing the apparent composite nature of the offsets invokes flow differentiation, a process whereby relatively heavy components within a moving magma in a dike, such as sulfide droplets, tend to move towards the center of the dike.

In the North Range, the mouth of the Flett and Parkin Offsets is filled by a screen of sublayer norite and footwall granite breccia that separates it from the Main Mass of the Sudbury Igneous Complex. This is not true of the major South Range Offsets where the transition between the lowest member of the Main Mass norite and QD is more gradual.

GENESIS OF NI-CU-PGE MINERALIZATION IN THE SUDBURY STRUCTURE

Ni-Cu-PGE mineralization associated with the Sudbury Structure (1850 Ma) can be attributed to

- a large impactor, generating a large mass of superheated crustal melt,
- pre-existing sulfide mineralization in the impact site, permitting metal-poor impact melt to reach saturation in sulfide and react with sulfide melt prior to crystallization,
- thermomechanical erosion of footwall rocks, generating embayments and sulfide-inclusion-rich Sublayer, and locally remelting sulfides to generate large amounts of very fractionated sulfide melts and fluids, and
- slow cooling, permitting even unrefined sulfide melts to fractionate.

"Offset' ore systems occur in radial/concentric quartz diorite dikes and breccia belts, cross-cut impact breccias, have barren inclusion-free margins and mineralized inclusion-rich cores, and were emplaced after the impact melt cooled enough to achieve sulfide saturation and mechanically erode footwall rocks but early enough to preserve near-original compositions. Some are fractionated (Cu-PPGE-poor to Cu-PPGE-rich) concentrically, consistent with capillary infiltration of fractionated sulfide melts into surrounding rocks. Others are fractionated downward through to Ag-Au-PPGE-Pb-Zn-Sn-Bi-As-Te-rich mineralization. Compositional variations and masses can be modeled by partial fractional crystallization (PFC) of monosulfide solution (MSS) ± intermediate sulfide solution (ISS).

"Contact" ore systems occur in footwall embayments and are hosted by Sublayer and footwall breccias. Ores are typically less fractionated over mafic lithologies and more fractionated over felsic lithologies. Field relationships, textures, mineralogy, and geochemistry suggest that sulfide melts infiltrated and mechanically-eroded footwall rocks; variations in geochemistry and S-Pb isotopes confirm local derivation of many components in the Sublayer. High density, very low viscosity sulfide melts wetted and percolated into fractured footwall rocks, filling and widening fractures, and ultimately surrounding, isolating, and buoying-up individual fragments. Copper-rich melts penetrated farther because of greater densities and wetting abilities, and lower solidus temperatures. Fragments generated earlier were completely incorporated into the Sublayer; those generated later were only partially rotated and melted. Compositional variations and masses in slightly to moderately fractionated contact systems can be modeled by partial fractional crystallization (PFC) of monosulfide solution (MSS) ± intermediate sulfide solution (ISS).

"Footwall" ore systems occur up to hundreds of metres below contact systems and are hosted by cataclastic/pseudotachylitic breccias. The large masses of very Cu-PPGE-rich mineralization and partitioning constraints preclude models involving fractional crystallization or PFC (not enough Cu-PPGE-rich melt), equilibrium crystallization (not enough Cu-PPGE in the final melt), or sulfide-sulfide liquid immiscibility (distribution coefficients too small). Geological, thermal, and fluid dynamic constraints suggest derivation by dynamic remelting of contact systems. The rate of thermomechanical erosion along the basal contact initially exceeded the rate of heat conduction into footwall rocks, allowing even Cu-PPGE-rich melts to penetrate only short distances into footwall rocks but supercritical aqueous fluids derived by dehydration/melting of footwall rocks were able to dissolve Au-Pd-Pt-Bi-Te and infiltrate farther. With cooling, the rate of erosion declined and contact metamorphic isograds expanded, permitting deeper infiltration of Cu-PPGE-rich sulfide melts into brittle fractures, overprinting earlier-formed mineralization. Compositional variations and masses in strongly fractionated contact-footwall systems can be modeled numerically as a multi-stage remelting process or analytically as a zone-refining process.

Field Trip Stops

INTRODUCTION

Because surface exposures of massive and semi-massive sulfides are normally selectively weathered and/or eroded, or both, and because most known near-surface deposits of ore-grade mineralization in the Sudbury area have been mined out, most surface exposures are restricted to subeconomic disseminated and vein-type mineralization. The 5 field stops listed in Table 1 and shown on Figure 1 represent some of the best available, most accessible exposures of Ni-Cu-PGE mineralization in the South Range of the Sudbury Structure.

Table 1. Location and company contact information for the field trip stops visited on this trip. All UTM co-ordinates are in Zone 17, WGS 1984.

Stop	Description	Easting	Northing	Contact for Access
1	Copper Cliff Offset near South Mine	494715	5147701	Vale-Inco
2	Footwall Contact, Murray Mine Discovery Site	495935	5151976	not required
3	Footwall Contact, Sheared Sublayer at Victoria West Mine	469793	5141241	Quadra FNX Mining
4	Worthington Offset at Worthington Mine	465319	5136841	Vale Inco
5	Trill Offset Deposit	454915	5147264	Wallbridge Mining

ACCESS

With the exception of Stop 2, which is a public access roadside location, the field stops described herein are on private land held by mining and exploration companies that may be hazardous or active exploration sites, or both. Permission must be sought from the following companies to visit them. Please respect the property rights of others, so that future access for other geologists is not adversely affected.

Vale-Inco Ltd. Attention: Manager – Sudbury Basin Exploration, Highway 17 East, Copper Cliff, Ontario, P0M 1N0, Tel: +1 (705) 682-8451 *or* Attention: Superintendent Mines Exploration, General Office, Copper Cliff ON P0M 1N0, Tel: +1 (705) 682-5201.

Xstrata Nickel Ltd. Attention: Manager – Geology, Xstrata Nickel, Sudbury Operations, Onaping ON P0M 2R0, Tel: +1 (705) 966-3411.

Quadra FNX Mining Ltd. Attention: Manager – Exploration Technical Services, 1300 Kelly Lake Road, Sudbury ON P3E 5P4, Tel: +1 (705) 671-1779.

Wallbridge Mining Company Ltd. Attention: VP – Exploration, 129 Fielding Road, Lively ON P3Y 1L7, Tel: +1 (705) 682-9297, Fax: +1 (705) 682-2144, Email: info@wallbridgemining.com.

SAFETY

For users of this guidebook, please bear in mind that some of the stops listed in this guidebook involve hiking in the bush. Therefore, standard bush safety practices should be followed by users of this guidebook. Such practices include travelling in pairs; advising others of your starting time and location and your expected return time; carrying sufficient water for the trip; being prepared for sudden changes in the weather; and carrying the appropriate emergency and safety gear.

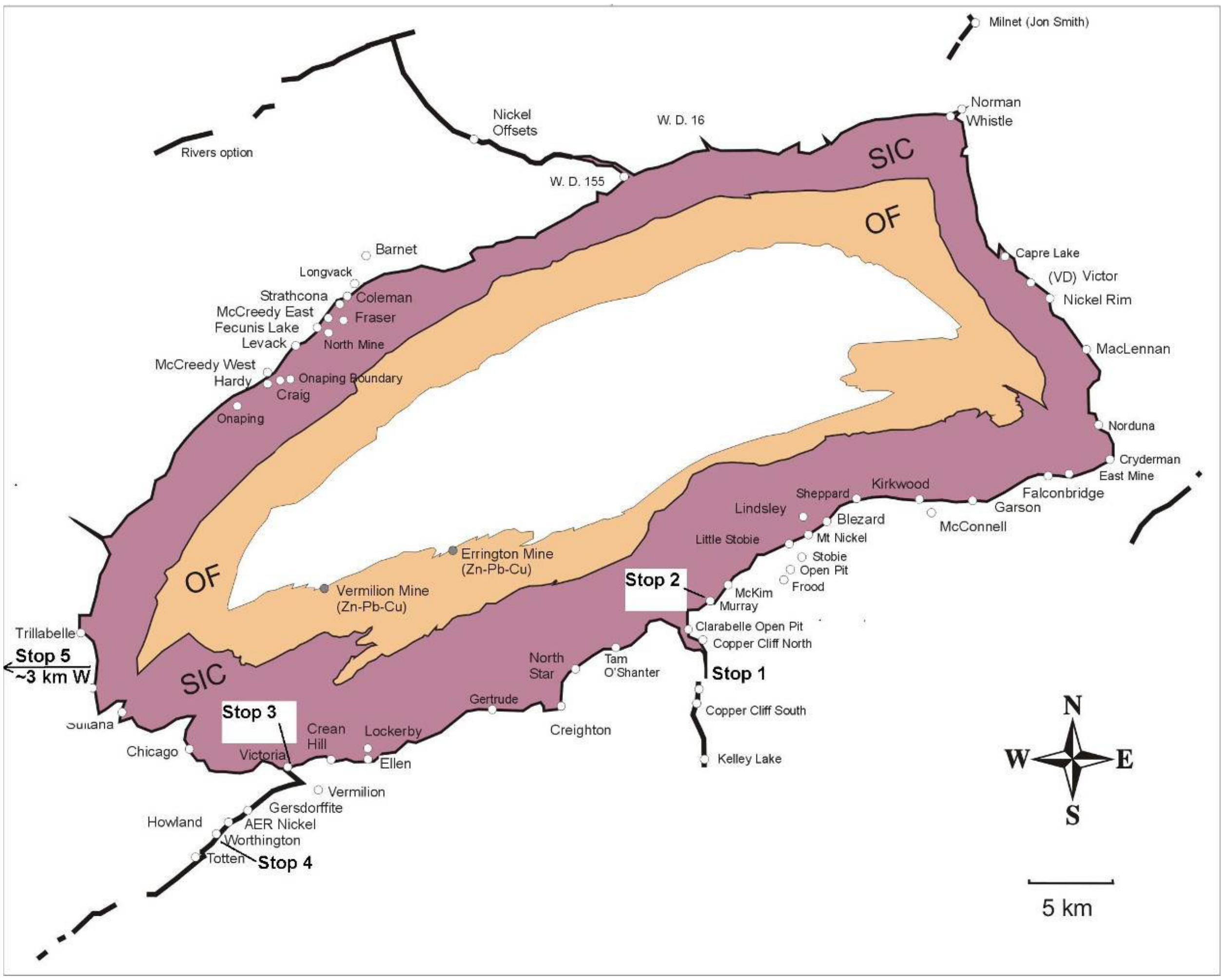

Figure 1. Location map of Ni-Cu-PGE and Zn-Pb-Cu deposits and occurrences, Sudbury, Ontario, Canada. Field trip stops are also indicated. Abbreviatons: OF = Onaping Formation, SIC = Sudbury Igneous Complex.

STOP 1. COPPER CLIFF OFFSET DIKE (E.F. PATTISON)

Location

This stop is located at UTM 494715E, 5147701N (Zone 17, WGS84) on the northwest side of Regional Road 55 at the southwest end of the town of Copper Cliff. From the intersection of Regional Road 55 and Power Street in Copper Cliff (Figure 2), drive northeast on Power Street, turn left onto Cobalt Street, and park in the small parking area at the base of the hill at UTM 494413E, 5146028N (Zone 17, WGS84). Walk west halfway up the hill to outcrops of quartz diorite cutting well-bedded McKim Formation turbidites and Sudbury Breccia (UTM 494191E 5146096N, Zone 17, WGS84). The head frame of the Vale Inco Copper Cliff South Mine and Vale Inco Nickel Refinery are visible to the south across Regional Road 55 and the railroad.

Figure 2. Location of Stop 1 in Copper Cliff.

Background

The Copper Cliff Offset is the most heavily mineralized quartz diorite offset dike in the Sudbury Structure, and contains approximately 20% of the total nickel sulfide production from the Sudbury Igneous Complex. Sulfide mineralization in the Copper Cliff Offset occurs as pipe-shaped bodies of disseminated and inclusion-bearing semi-massive sulfide in quartz diorite (QD), usually occurring in the central portion of the offset and flanked by inclusion and sulfide-poor quartz diorite.

The relatively barren marginal quartz diorite is interpreted to be an early pulse of quartz diorite magma followed by a later mineralized phase. Evidence for these relationships is shown by inclusions of barren quartz diorite in mineralized quartz diorite and by a fine-grained chilled contact of the mineralized phase against the marginal barren phase that is believed to represent an approximate estimate for the initial composition of the melt sheet.

The Stop 1 site covers the surface exposure of the 850 Orebody environment (Figure 3a). The mineralization associated with the 850 Orebody at surface is small, discontinuous and generally uneconomic. The 850 Orebody does improve in grade and size with depth. Mineralization in this area is spatially associated with a nontectonic break, similar to others that occur along the length of the dike. These breaks are zones where the dike may pinch out along strike or undergo abrupt changes in strike. The many offset discontinuities are associated with an abundance of Sudbury Breccia in the wallrocks of the dike. These discontinuities or irregularities are commonly associated with enhanced sulfide content in the dike. The mineralized parts of the dike are also characterized by the presence of increased

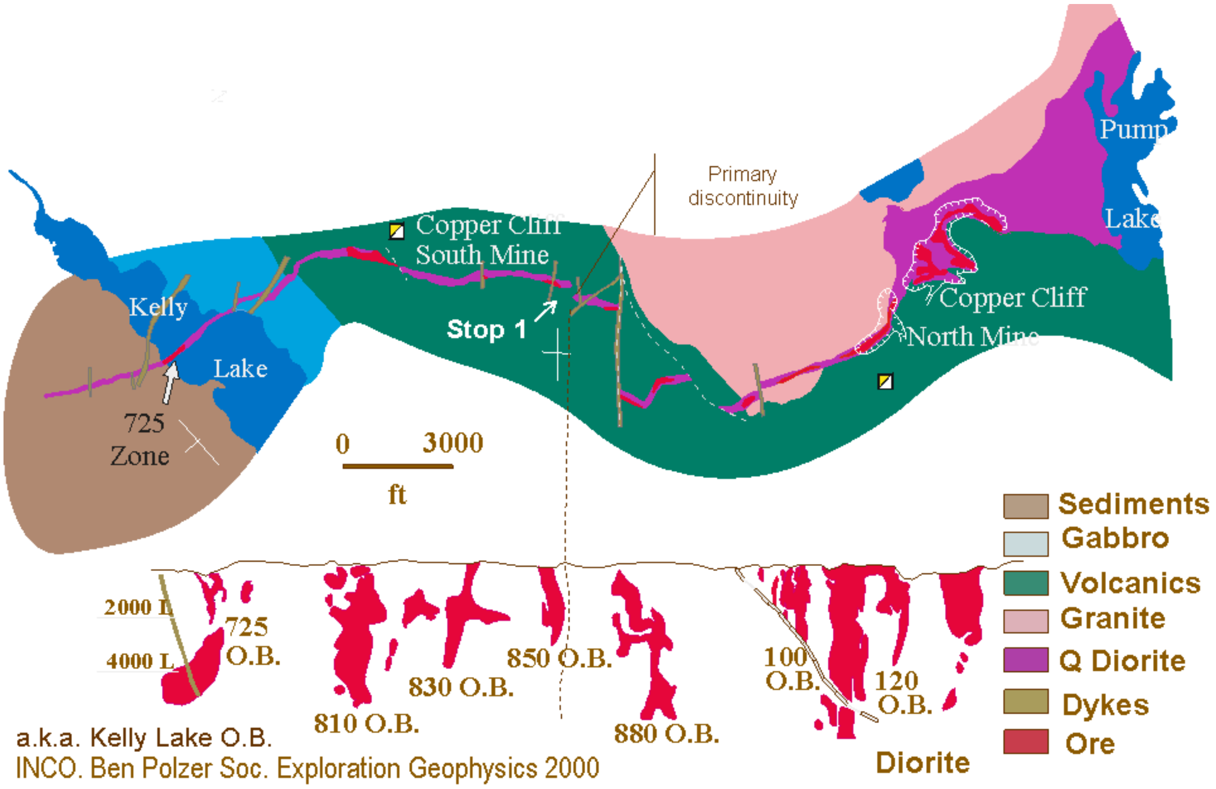

Figure 3a. The orebodies (O.B.) of the Copper Cliff Offset (*modified from* Cochrane 1984). L = level (in feet).

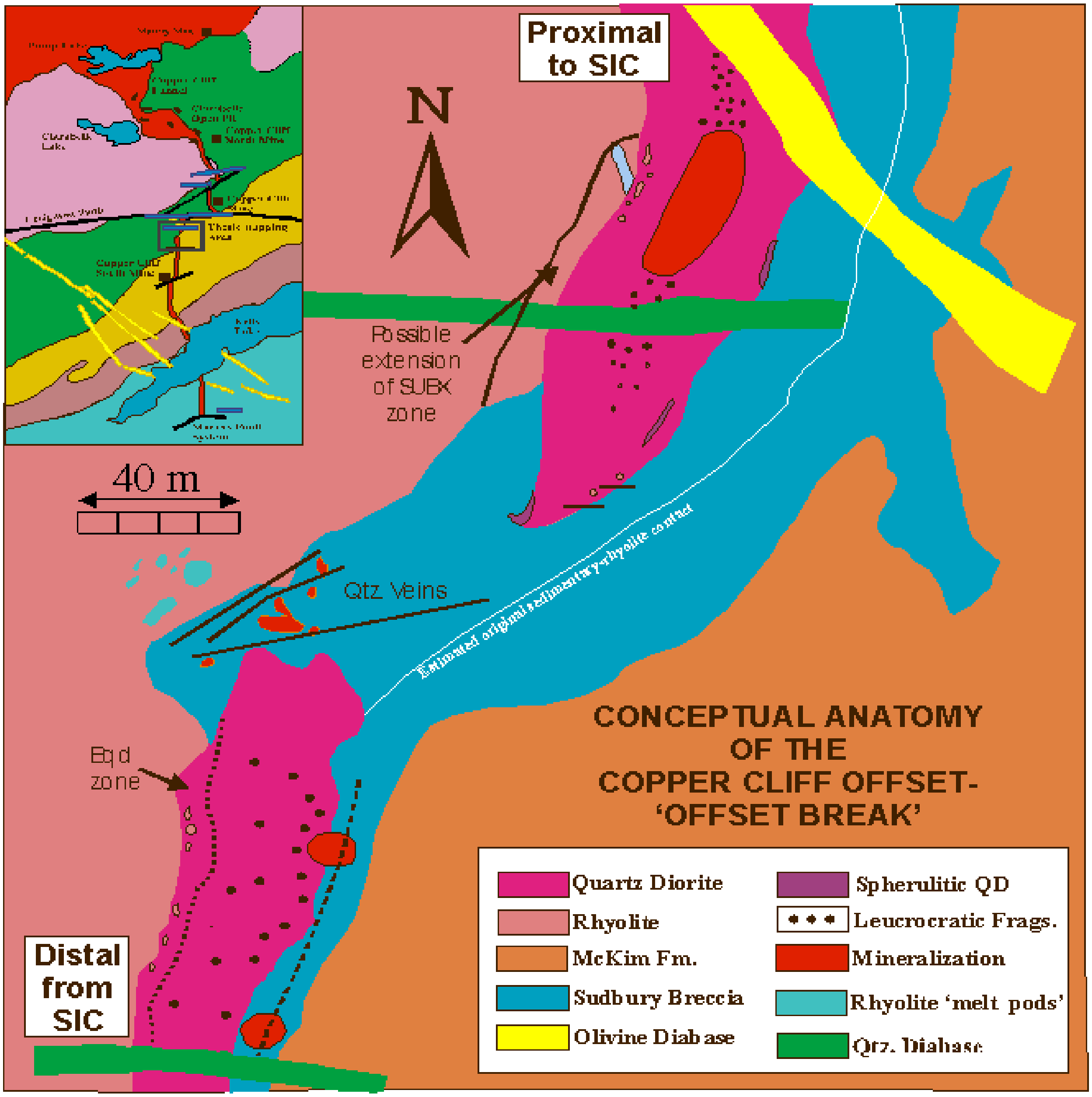

Figure 3b. Geological map of Stop 1. Parking lies just off the middle right edge of the map. Figure is *from* Mourre (2000).

proportions of inclusion material within the dike. The inclusion population consists of both exotic (allochthonous) mafic to ultramafic inclusions and local wallrock material. Typically, the greater the exotic inclusion content the greater the amount of sulfides.

The Offset Dike is made up varied phases of quartz diorite, the most common being medium-grained with amphibole and biotite as the dominant ferromagnesian minerals. It is common for the contact phases to have a much higher proportion of biotite, and when in contact with metasedimentary rocks, biotite may be the only mafic mineral present in the quartz diorite dike. In certain environments, where the dike becomes very narrow, a spherulitic, hypersthene-bearing variety is often present. The geology of the stop is shown in Figure 3b.

Site 1, Stop 1. McKim Formation rocks and Sudbury Breccia

This stop is representative of the rocks on the east side of the dike in this area where it is in contact with strongly Sudbury-brecciated McKim Formation metasedimentary rocks. The McKim Formation here, comprising greywacke and thin-bedded siltstones, exhibits well-developed bedding that is totally disrupted by the Sudbury Breccia, with large blocks of the metasedimentary rock being rotated in the rock flour of the breccia (Photo 1). Sudbury Breccia is not uniformly distributed along the length of the dike but occurs at intervals, commonly at the interface of rock types with different physical characteristics. Within the stop area, the Sudbury Breccia formed at the interface between rhyolite of the Copper Cliff Formation and the metasedimentary rocks of the McKim Formation.

Site 2, Stop 1. East contact of dike with metasedimentary rocks

Proceed up the hill to a flat area. Here the east contact of the dike is in contact with McKim Formation metasedimentary rocks cut by Sudbury Breccia. There are also numerous large blocks of rhyolite within the Sudbury Breccia near the dike contact. The offset here consists of both inclusion-bearing and inclusion-free quartz diorite and shows well-developed back injection phenomena with irregular dikelets of melted wallrock lithology being intruded into the quartz diorite. Blocks of rhyolite are being stoped off in the quartz diorite. The sequence of events was Sudbury brecciation along the McKim/rhyolite contact followed by the emplacement of the Offset Dike along the brecciated contact.

Photo 1. Large blocks of McKim Formation metaturbidite in Sudbury Breccia at Site 1, Stop 1.

Site 3, Stop 1. East contact of dike with metasedimentary rocks

This location is similar to Stop 2, showing the contact between quartz diorite and flow-banded Copper Cliff Formation rhyolite. The rhyolite is cut by Sudbury Breccia. Here, a sharp contact between 2 phases of quartz diorite can be seen as well as an approximately 30 cm diameter inclusion of one phase in the other (Photo 2).

Site 3a, Stop 1. Crosscutting quartz diabase dike

The Offset Dike is commonly crosscut by quartz diabase dikes that are roughly orthogonal to the strike of the Offset Dike. An example can be seen between Sites 3 and 4. The quartz diabase dikes are obviously younger than the Offset Dike but an exact age is not known. A second set of dikes, the olivine diabase dikes also crosscut the Offset Dike. These are part of the regional Sudbury dike swarm dated at *circa* 1240 Ma (Krogh et al. 1987). A good exposure of an olivine diabase dike occurs immediately north of the tour area.

Site 4, Stop 1. Weakly mineralized inclusion-bearing quartz diorite dike

Proceed northward along the dike to a small pit in the central portion of the Offset. Here the Offset Dike is weakly mineralized with small, scattered blebs of sulfide and rare small inclusions. In the pit, minor occurrences of more concentrated sulfide mineralization can be found. Barren inclusion and sulfide-free quartz diorite occurs to the west. The hill further to the west comprises massive Copper Cliff Formation rhyolite.

Site 5, Stop 1. West contact of dike with rhyolite

The barren quartz diorite contact with the rhyolite on the west margin shows partial melting of the rhyolite and incorporation into the dike magma (Photo 3). The quartz diorite becomes progressively finer grained towards the contact, presumably due to more rapid cooling, but it does not become aphanitic or markedly chilled.

The rhyolite is cut by Sudbury Breccia along the contact with the quartz diorite dike. Sudbury Breccia is essentially a milled rock with the composition of its host parent, in this case the rhyolite. The Sudbury Breccia is interpreted to be essentially coeval with the Offset Dike and would be poorly consolidated and likely permeable to magmatic fluids. The incorporation of the rhyolite inclusions in the quartz diorite was likely facilitated by the unconsolidated nature of the Sudbury Breccia. The matrix of the Sudbury Breccia exhibits much more extensive thermal recrystallization and partial melting than does the massive rhyolite. Given that the Sudbury Breccia and the rhyolite are compositionally very similar here, the difference in degree of thermal metamorphism could be attributed to the greater permeability of the breccia matrix to magmatic fluids. Alternatively it could result from accumulated frictional heat from the autogenous comminution event. Elsewhere in the South Range Breccia Belt, isolated, spherical melt bodies could be attributed to this process.

Photo 2. A 25 to 30 cm inclusion of one variety of quartz diorite (QD) in very weakly mineralized inclusion-rich quartz diorite, (IQD) from Site 3, Stop 1.

Photo 3. Re-melted rhyolite wisps in mineralized quartz diorite at Site 5, Stop 1.

Site 6, Stop 1. Spherulitic quartz diorite at offset break

Proceed southward to the first fresh-air raise. Here is a good example of a primary (not fault related) pinch out of the dike where it rapidly narrows and disappears. The quartz diorite that occurs at the break shows signs of rapid cooling such as the well-developed spherulitic texture visible within the dike at this stop (Photo 4). The dominant mafic mineral within the spherulitic quartz diorite is hypersthene, which exhibits a radiating or snowflake-like texture. The hypersthene can be fresh or variably altered to amphibole and biotite.

Site 7, Stop 1. Mineralized quartz diorite on east contact

Proceed about 20 m south of the second fresh-air raise. An excellent complete cross section of the Offset Dike is exposed here. The east margin of the dike comprises mineralized, inclusion-rich quartz diorite as opposed to its more normal position in the center of the offset. The quartz diorite in this area contains numerous inclusions and disseminated sulfides. The inclusion population is a mixture of allochthonous gabbros and gabbro hornfels and some local metasediment fragments. The sulfide occurs as disseminated blebs (Photo 5) and small massive pods and veins and exhibits lateral zoning with relatively weak mineralization along the east and west contacts of the mineralized zone and a more intensively mineralized zone in the core of the mineralization. The mineralization extends along the east contact here for about 25 m and averages 8 m in thickness. This surface mineralization is small and discontinuous, but becomes more continuous at depth into the 850 and 865 orebodies.

Toward the west end of the large trench, the mineralized quartz diorite is chilled against the barren marginal quartz diorite, providing further evidence of the relative timing of the 2 phases of quartz diorite.

Site 8, Stop 1. Melt bodies within massive rhyolite

On the west side of the south part of the break, there is a cluster of irregular, lozenge-shaped “melt bodies” within the massive rhyolite. These melt bodies are fine-grained, acicular-textured rocks similar in composition to the rhyolite host rock and in sharp contact with the rhyolite. The melt bodies have elevated PGE contents within them, up to 200 ppb, as compared to the host rhyolite, with 1ess than 10 ppb. The nature of these melt bodies is not well understood.

Photo 4. Spherulitic texture in quartz diorite at Site 6, Stop 1. Field of view is about 10 cm across.

Photo 5. Typical weakly mineralized inclusion-rich quartz diorite (IQD) from Site 7, Stop 1, with small rusty, weathered-out blebs of sulfide and scattered small xenoliths.

STOP 2. MURRAY MINE ENVIRONMENT AND DISCOVERY SITE (J.P. GOLIGHTLY)

Location

This stop is located at UTM 495935E, 5151976N (WGS84) on the northeast side of Regional Road 35 (formerly Ontario Highway 144), 2.9 km northwest of the Regional Road 71 (Lasalle Boulevard) turnoff. Park in the small parking lot on the northeast side of the road, opposite the now-flooded Murray Mine open pit (Figure 4). **Warning.** This is a very busy highway and the stop is on a bend, so be careful when exiting and turning back onto the road.

History

The Murray deposit was discovered in August 1883 when the Canadian Pacific Railway was put through this site. The original discovery cut was on the other side of the current road and the railroad was re-routed around the orebody to allow exploitation of the open pit. Although the Creighton deposit had been found by a prospector in 1858, the Murray discovery stimulated the rapid development of mining in the Sudbury district. The Murray deposit was worked for a number of periods until its final closure in 1971. It belonged to INCO since 1925.

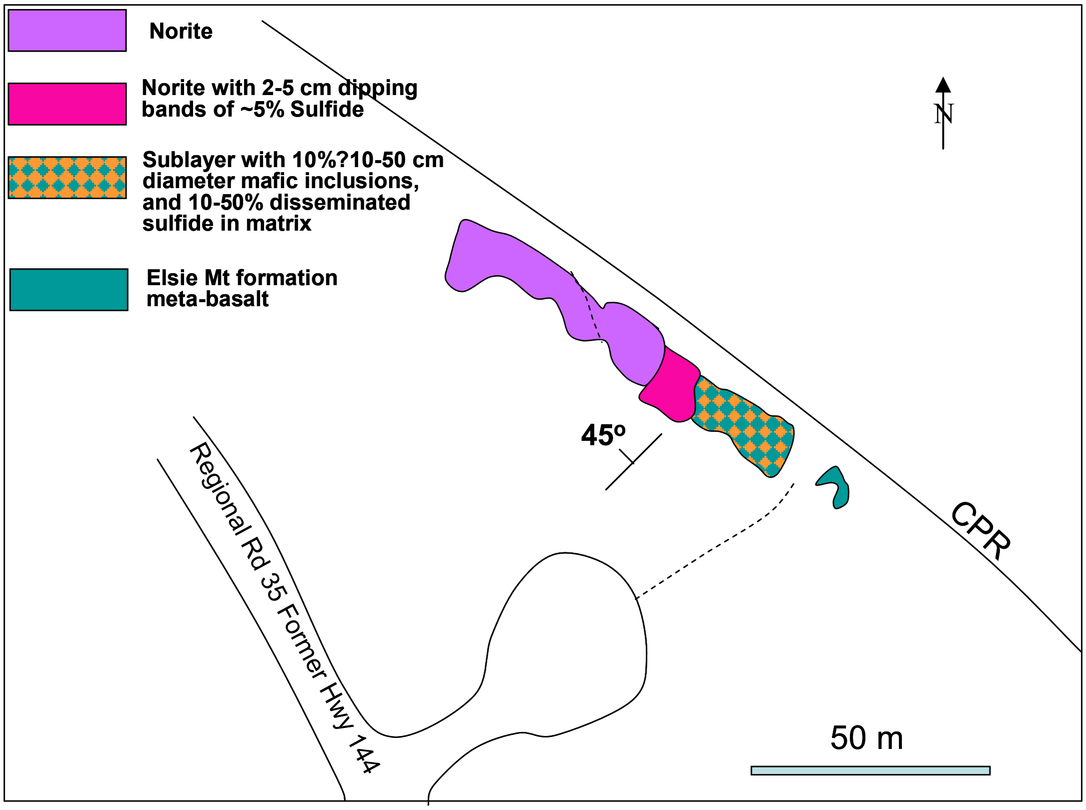

Figure 4. Sketch map of the southwest side of the railroad cut near the Murray Mine "Discovery Site".

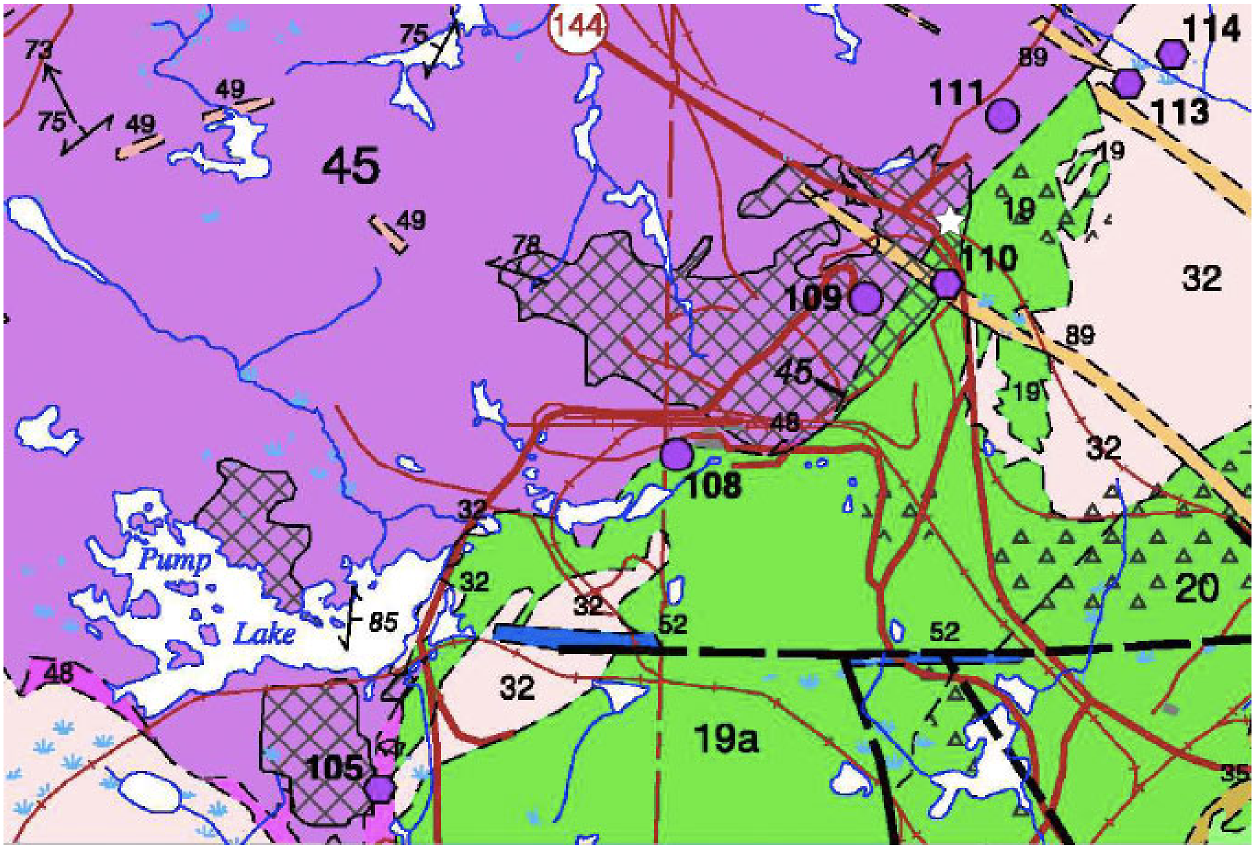

Figure 5. Surface geology of the Murray Mine area and Discovery Site (extracted from Ames et al., 2005). Field trip stop is marked by a white star in the middle of the upper right quadrant of the figure. Rock types: 19a (green), Stobie Formation (primarily basalt); 32 (pink), Murray Granite; 44 (magenta), (on sides of Copper Cliff embayment near showing 105) quartz diorite; 45 (purple), South Range norite and 48 (magenta), sublayer norite (triangles–Sudbury Breccia; light brown crosshatch–surface projection of mineralization); 89 (tan), olivine diabase of Sudbury dike swarm; and 52 (blue) quartz diabase. Mines (purple circles) and showings (purple hexagons): 105–Lady Violet showing, 108–Elsie Mine, 109–Murray Mine, 110–original discovery site, 111–McKim Mine, 113 and 114–unnamed showings.

The Murray deposit is a classic South Range footwall contact deposit hosted in a 2 km wide by 0.3 km deep, northwest-plunging embayment along the Sudbury Igneous Complex basal contact, approximately 2.5 km northeast of the Copper Cliff funnel. The crosshatch pattern in Figure 5 shows the surface projection of the mineralization envelope. It is terminated down the 45° dip of the footwall contact by the South Range Shear Zone.

Description

The peripheral part of the Murray mineralization envelope is exposed in the current railway cut approximately 50 m down a path from the northeast end of the parking lot. Photo 6 illustrates some of the features observed at Stop 2. The following sequence is exposed from southeast (stratigraphically lowest) to northwest (stratigraphically highest) along the railroad cut (*see* Figure 4).

- **Stobie Formation**, which in this locality comprises greenschist facies mafic metavolcanic rocks that have been contact metamorphosed by the overlying Sudbury Igneous Complex, is exposed to the right (southeast) of the access path. The contact with overlying Sublayer Norite is obscured by the access path.

- **Sublayer Norite** (discontinuous lowermost unit of the Sudbury Igneous Complex), comprising greater than 50% subrounded, orange-brown (weathered) mafic fragments in a heavily oxidized noritic matrix containing 10 to 50% disseminated Fe-Ni-Cu sulfides (pyrrhotite with lesser pentlandite and chalcopyrite), is exposed to the left (northwest) of the access path. In a few places, enough of the oxidized surface on the sulfides has been hammered away to expose partially decomposed sulfides. The abundance of sulfide and inclusions appears to decrease northwest (stratigraphically upward) over several metres. The contact with overlying South Range Norite is completely gradational.
- **South Range Norite**, containing at least seven 2 to 5 cm wide layers of 5 to 10% coarse disseminated (blebby) sulfides, oxidized to orange-brown goethite, separated by almost sulfide-free norite. The sulfide layers and many joints appear to dip northwest, subparallel to the footwall contact. The mineralogy of the norite is very clear on weathered surfaces: plagioclase is white, clinopyroxene is green, and orthopyroxene (subordinate) is brown.
- **South Range Norite**, coarse- to medium-grained, with decreasing amounts (<2%) of fine disseminated sulfides.

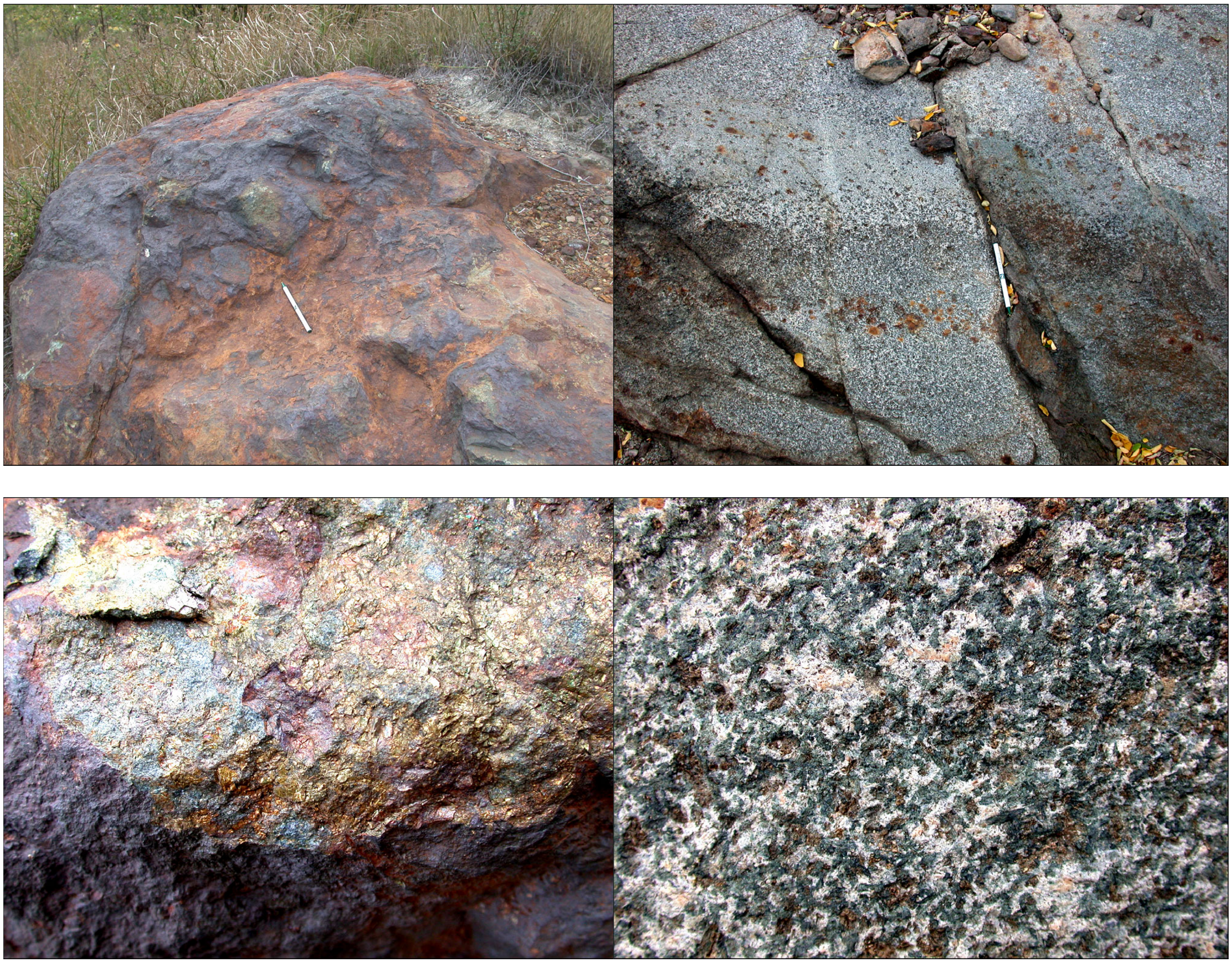

Photo 6. Photographs of rocks from Stop 2. **Upper left.** Sublayer inclusions with massive sulfide matrix. Pen in centre of photo is ~12 cm long. **Lower left.** Massive sulfide. Field of view is ~20 cm high. **Upper right.** Disseminated sulfide forming layers in Sublayer norite. Pen in centre of photo is ~12 cm long. **Lower right.** Close-up of Sublayer norite showing 1 to 2 mm brown orthopyroxene, green clinopyroxene, white plagioclase, and pinkish granophyre.

STOP 3. SHEARED MINERALIZED SUBLAYER AT THE VICTORIA WEST MINE (J.P. GOLIGHTLY)

Location

This stop is located near the Victoria West Mine, at 469794E and 5141470N (Zone 17, WGS84). From Sudbury drive approximately 34.5 km west on Highway 17 (junction with Hwy. 69) to Fairbank Lake Road (Regional Road 4). Turn right (north) and drive approximately 2.5 km north and then west to the Crean Hill Road turnoff, the site of the former Victoria Mine smelter (in operation 1900–1913). Turn right (north) and drive approximately 2.07 km to the fork in the road. Take the left fork, Fairbank Road, and drive approximately 2.5 km northwest to near 469998E and 5141420N (Zone 17, WGS84). Park along the side of the road near the outcrops, making sure that your vehicle can be seen by traffic coming from the north and south.

History

The Victoria Mine comprised several high-grade massive sulfide orebodies, one underlying the site described here in a footwall embayment and the other near the junction of the upper parts of the Victoria Offset and a larger embayment. The capped shaft lies in the latter location east of the road south of Victoria Lake. Total historical production from the Victoria mine was 1,400,000 tonnes grading on average 2.26% Cu and 1.57% Ni plus PGEs. The Mond Nickel Company mined 620,000 tons from 1900 to 1913 (Charbonneau 2003). Inco mined 589,000 tonnes of ore averaging 1.26% Cu, 0.83% Ni and 2.3g/t PGE between 1973 and 1978 (Fort Knox Resources Inc. 2001). Quadra FNX Mining, who currently hold the property, explored the footwall contact environment in the early 2000s and reported an *indicated* resource of 10.23 million tons grading 0.50% Ni and 0.51% Cu and an *inferred* resource of 16.97 million tons of 0.46% Ni and 0.45% Cu. Quadra FNX is actively exploring the Victoria Offset dike complex well south of the historic mine and very recently has announced some success.

Background

The footwall rocks (metabasalt of the Stobie Formation) in the Victoria West area are cut by a horsetail pattern of east- to northeast-trending, south-dipping ductile shear zones, including

- the near-vertical east-trending Victoria (Main) shear,
- two east-northeast-trending minor shears 80 and 350 m north of the Victoria West Mine,
- and the northeast-trending Flett shear, which curves eastward to join the east-northeast-trending South Range Shear Zone (Figure 6).

All exhibit south-side-up with lesser sinistral oblique senses of displacement, ranging from approximately 3 km for the Flett shear through approximately 1 km for the Victoria (Main) shear to progressively much less for the other shears. There is also a shear along the northward-dipping Sudbury Igneous Complex-footwall contact with a north-side-up (reverse) sense of displacement. The shears contain an earlier assemblage dominated by green to black amphibole that is cut by a later assemblage of chlorite, sericite, and ferroan carbonate.

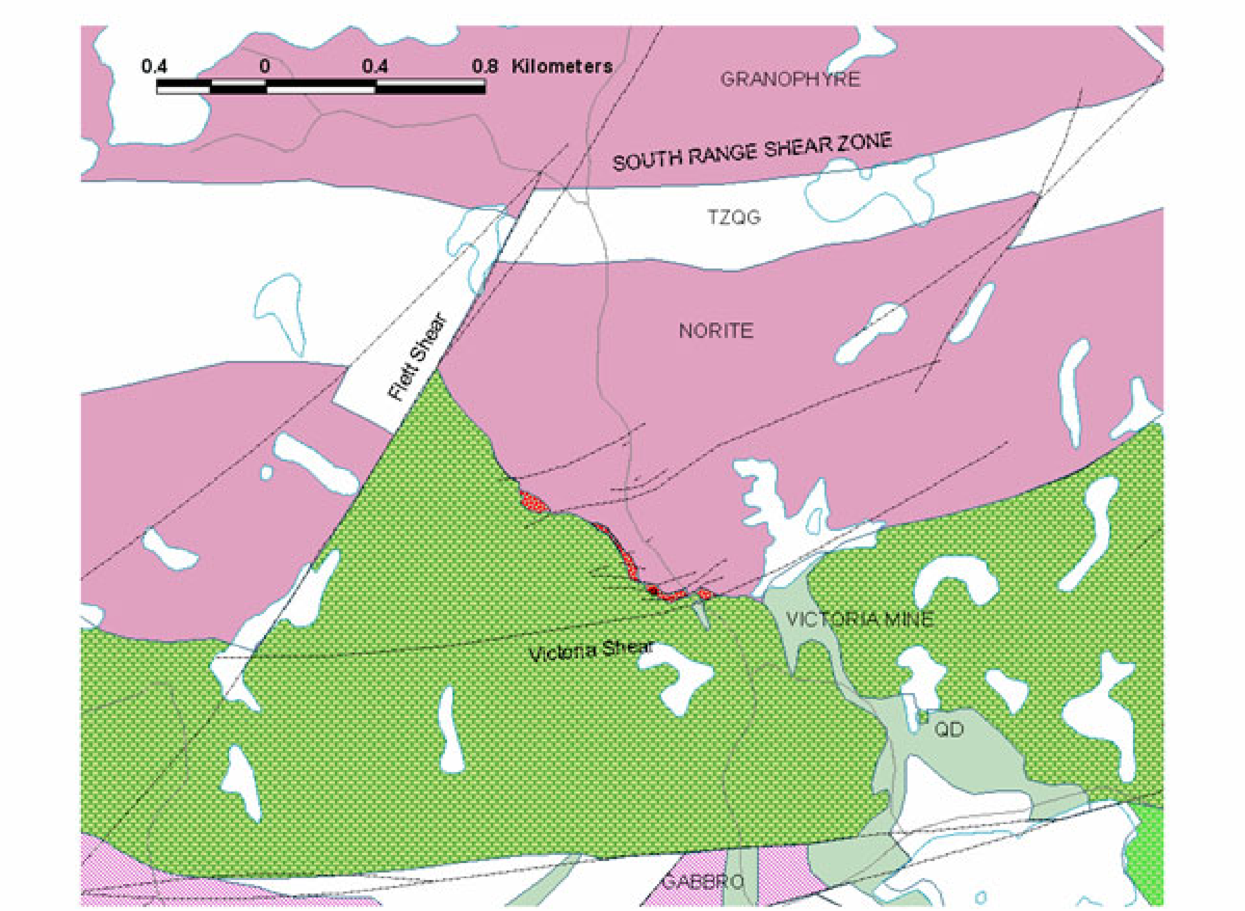

Figure 6. Geological map of the Victoria Mine area showing the locations of the Victoria Mine, Victoria Shear, and Flett Shear.

The mined-out Victoria West #2 orebody (mined by Inco in the 1970s) of the old Victoria Mine occurs almost directly down plunge from the contact shear. It was a long, narrow, steeply plunging body with much structural complexity. The long axis was subparallel to the displacement vector on the shears, but it appears to have been deformed and elongated by the shear movements. The upper and lower portions of the orebody apparently were deformed by the footwall contact-parallel shear, whereas one of the Victoria shears deformed the middle portion.

Description

The Victoria (Main) shear and Victoria 80 shear are exposed in the metabasaltic footwall rocks along the east (Victoria Main) and west (Victoria 80) sides of the road at 469998E and 5141420N and 469906E and 5141506N (Zone 17, WGS 84), respectively. Approximately 100 m west of the road, walk up the north side of the outcrop at the latter locality, along the norite ridge to the Sublayer and follow the obvious footwall contact shear north-northwest a few metres to a rocky knoll at 469794E and 5141470N (Zone 17, WGS84 (Photo 7). At the top of the knoll, relatively undeformed mineralized Sublayer dominated by abundant xenoliths and a somewhat sheared, sulfidic matrix (Photo 8) overlies a west-northwest-striking, north-northeast-dipping footwall contact-parallel shear best exposed in a small pit on the southeast side of the knoll. The contact shear has an Sudbury Igneous Complex-up (reverse) sense of movement (Photo 8). An old trench along the northernmost of these east-trending shears at the north edge of the knoll follows the Victoria 80 shear. Judging from a few gossanous relicts, it appears to have contained a lens of massive sulfide and quartz veining.

Although the footwall rocks in this area are almost exclusively mafic volcanic rocks, the Sublayer contains abundant ultramafic and anorthositic fragments (Photo 9). The source for the latter may be anorthositic rocks (Chicago Mine anorthosite) that have been mapped several kilometres to the west. The plagioclase in this anorthosite south of the Chicago Mine is porcellanous white and completely recrystallized. It may represent devitrified maskelynite (shock-melted feldspar).

Photo 7. Features exposed on the knoll at 469794E and 5141470N, Zone 17, WGS84. Footwall contact shears, A and B, are exposed in the small pit on the southeast side of the knoll, looking west-northwest. North-side-up sense of displacement on the shear. Field of view is about 1 m wide.

Photo 8. Ultramafic and mafic inclusions in sulfide-rich sublayer matrix at Victoria West. Scale is the same as in Photo 9.

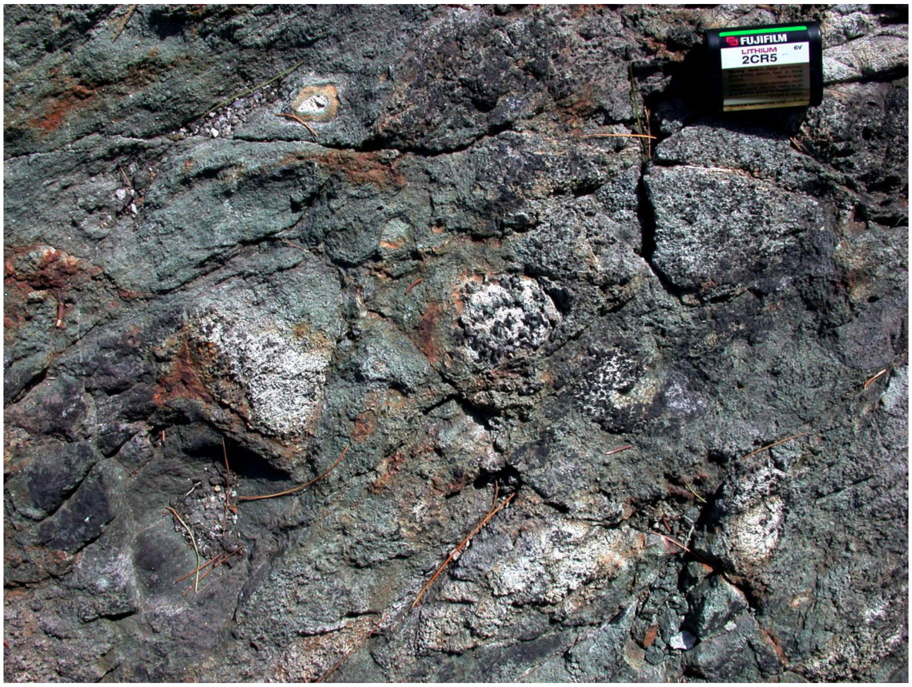

Photo 9. Mafic volcanic and anorthosite inclusions in footwall breccia at Victoria West. Battery pack is approximately 3 cm long.

STOP 4. WORTHINGTON OFFSET (J.P. GOLIGHTLY)

Location

This stop is located on the site of the old Worthington Mine, which is adjacent to the Totten Mine on the Worthington Offset. From Sudbury drive approximately 34.5 km (from junction with Hwy. 69) west on Highway 17 to Fairbank Lake Road (Regional Road 4). Turn right (north) and drive 8.3 km north and west to a small road on the south side at UTM 465319E, 5136841N, Zone 17, WGS84, which is 420 m east of the Totten Mine road and 550 m east of Worthington Store. Drive 107 m west to a junction with a disused driveway at 465689E, 5137018N, Zone 17, WGS84. The first group of occurrences (**Stop 4a**) are located on a 10 m high, 170 m long, southwest-trending, pine-forested ridge lying 85 m south of this intersection. A second group of occurrences (**Stop 4b**) are at the site of the Worthington #2 Mine 500 m to the northeast. To reach it from the first parking spot, return to Fairbank Lake Road and drive 495 m east and park at the gate on the north side at 466092E, 5137309N, Zone 17, WGS84.

Table 2. GPS locations (Zone 17, WGS84) for features seen at Stop 4, Sites 4a and 4b.

Worthington Site 4a (Photos 10 to 14)	**Photo number**	**Easting**	**Northing**
Example of quartz diorite type QD2		465600	5136850
Two types of quartz diorite and inclusions	10, 11, 12	465601	5136853
East Contact with sandstone, also spherulitic textures	13	465614	5136836
Pit with massive sulfide		465620	5136883
Quartz diorite with large inclusions	14	465688	5136940
Worthington Site 4b (Photo 15)			
Inclusion-filled quartz diorite (QD1)	15	466073	5137316
Amphibolite		466089	5137357
Quartz diorite		466108	5137373

History

The Worthington and Totten Mine properties are owned by Vale Inco Ltd. Worthington Mine was originally operated by the Mond Nickel Company from 1919 to 1927 producing about 630,000 tons of 3.03% Cu and 2.62% Ni. "Activities came to a violent end at 6 AM on October 4, 1927, when the underground works collapsed (from the 500 foot level) and the surface subsided" to form a pond (Jackson 2007). The small lake southwest of Site 4a is the former site of the mine. A water-filled tunnel, readily visible from the main road west of Site 5, passes northwest to southeast under the ridge. The Totten Mine was re-opened by Inco from 1966–72 and more recently in the 21st Century by Vale-Inco Ltd.

Description

The Worthington Offset quartz diorite (QD) dike is generally about 100 m wide and trends southwest at an acute angle to the Sudbury Igneous Complex footwall contact. It forms a continuous dike for at least 9.6 km and appears to narrow to the southwest. The connection to the Sudbury Igneous Complex footwall is not exposed and is complicated by faulting and a complex geometry, but may be connected via the wider north-trending Victoria Mine Offset. There are many small deposits identified within this dike system, but only the Victoria Mine #4 orebody at the Sudbury Igneous Complex footwall and the Worthington and Totten Mines, about 7 km from the Sudbury Igneous Complex, have been economically significant. Amongst radial offset dikes, the Worthington Offset ranks a distant second in economic importance to the Copper Cliff Offset.

The Worthington and Totten deposits lie in the quartz diorite (QD) dike where it cuts lower Huronian sandstones, southwest of an amphibolite or Sudbury Gabbro body in the country rock which is in contact with the QD at the northeastern (Site 5a, *see* Stop 5) locality. The dike contains scattered 5 to 100 cm sized angular xenoliths of amphibolite that seem to derive from the amphibolite at **Stop 4b**. This is consistent with movement of the QD away from the main mass of the Sudbury Igneous Complex 1.1 km northeast.

The quart diorite has 2 phases: 1) a nonmineralized phase, QD1, which tends to occur adjacent to the dike contacts or as 5 to 10 cm inclusions in the later mineralized QD2. The mineralized QD2 is not noticeably chilled against QD1, indicating no significant time gap between the 2 intrusions. QD2 is usually sparsely mineralized grading locally to massive sulfide. QD2 tends to have inclusions of both QD1 and country rock, most notably amphibolite or Sudbury Gabbro. QD2 occurs as lenses up to 75% of the width of the dike, usually approximately centred in the dike. The amphibolite wallrock unit at stop 4b is thought to have played a role in localizing the Worthingon and Totten deposits.

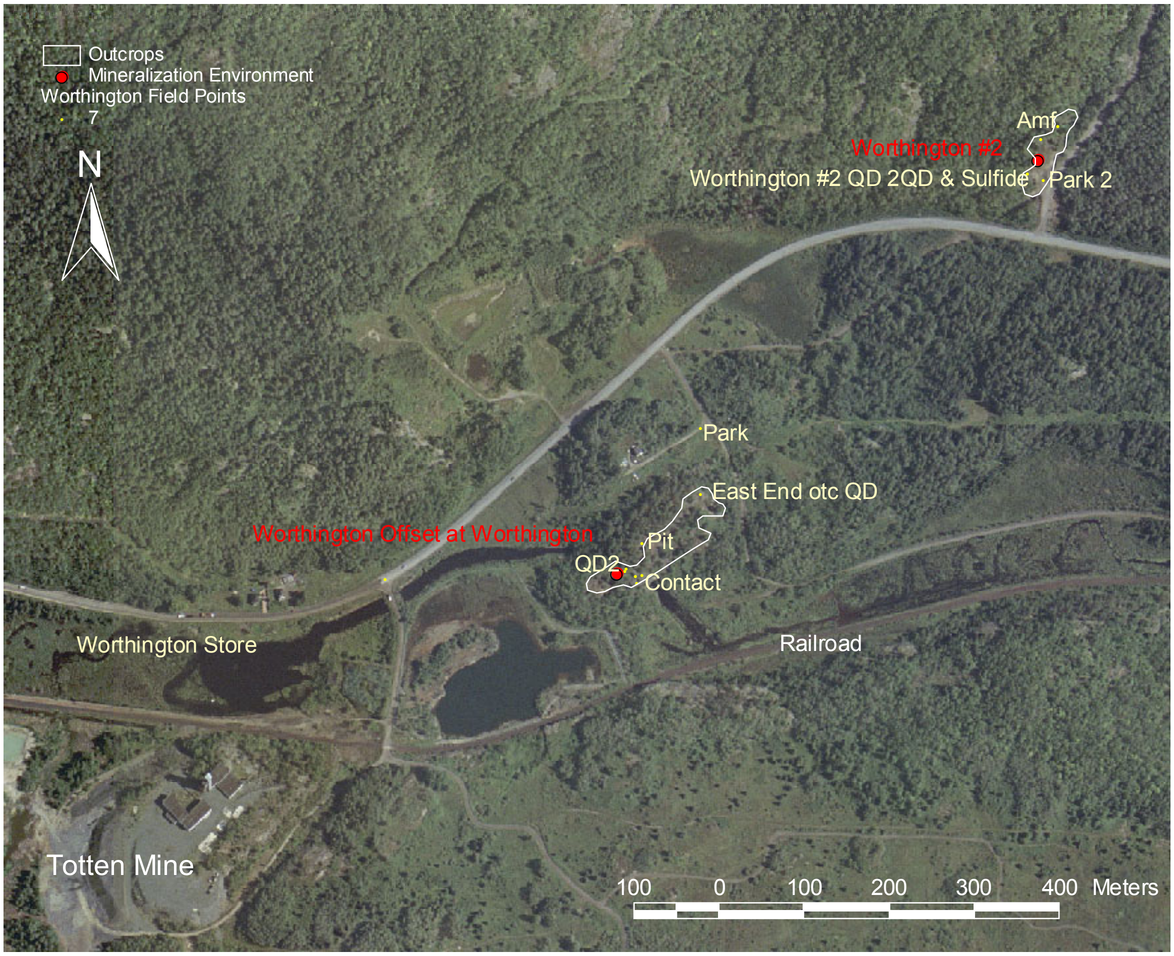

Figure 7. Aerial view of the Worthington–Totten Mine area. The house shown at the centre of the photo, 80 m west-southwest of the parking spot, no longer exists. The pond southwest of the mapped outcrop is the water-filled pit, site of the mine collapse. Note the river that passes under the outcrop through a tunnel.

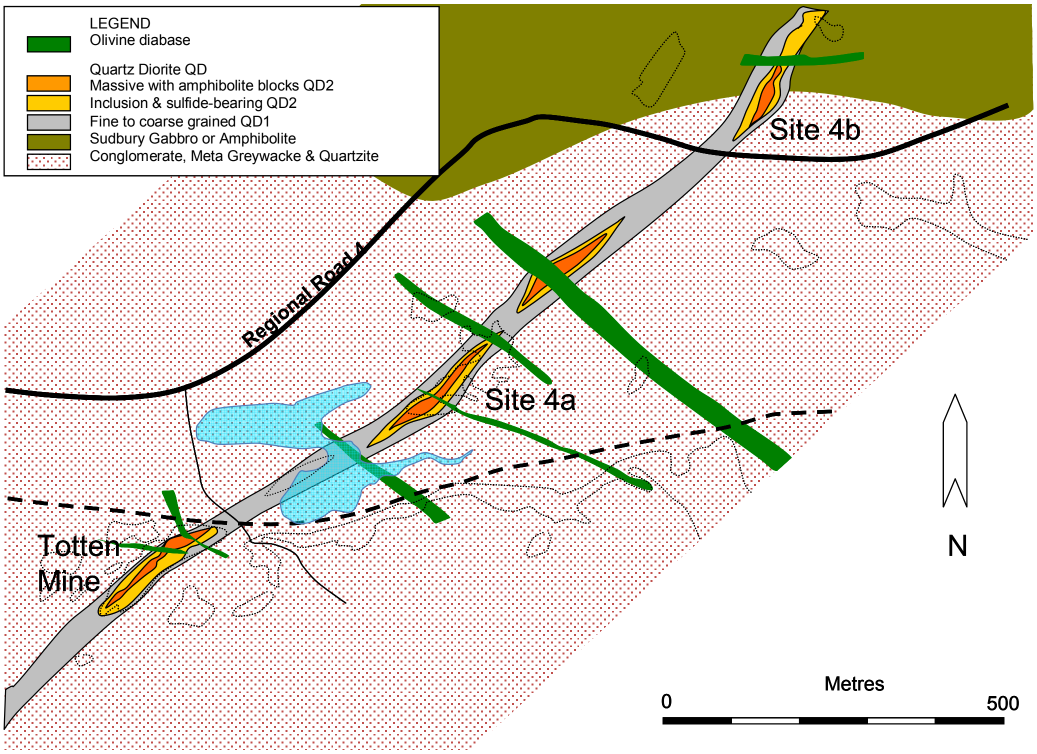

Figure 8. Geology of sites 4a and 4b, Worthington–Totten Mine area. Cut and redrafted *from* Map 9, Lightfoot et al. (1997). Blue area is water.

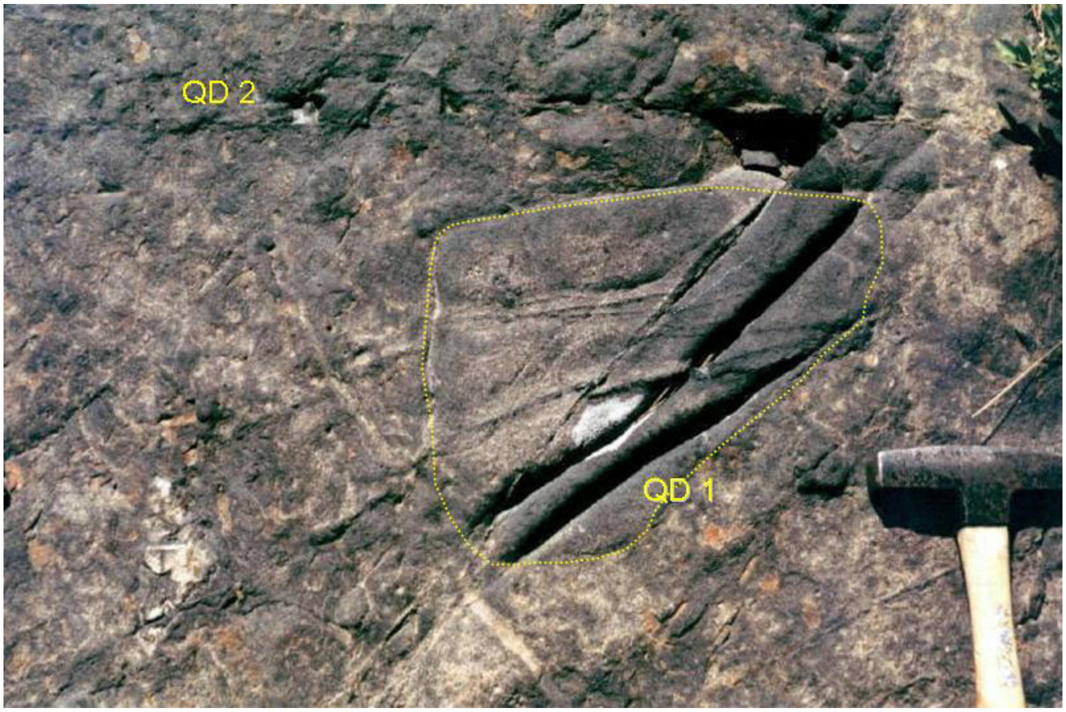

Photo 10. Site 4a. Barren quartz diorite inclusion (QD1) in mineralized quartz diorite (QD2) near Worthington Mine. UTM 465601E, 5136853N, Zone 17, WGS84.

Photo 11. Site 4a. Chill fabric comprising approximately 0.5 cm long acicular crystals referred to as spherulitic. UTM 465601E, 5136853N, Zone 17, WGS84.

Photo 12. Site 4a. Amphibolite (also known as Sudbury Gabbro) fragments in mineralized quartz diorite. UTM 465601E, 5136853N, Zone 17, WGS84.

Photo 13. Site 4a. Southeast contact (ctc) of quartz diorite (QD1) with Huronian sandstone (SS). Southeast is towards top of photograph. UTM 465614E, 5136836N, Zone 17, WGS84.

Photo 14. Site 4a. Large country rock blocks (SS = sandstone) in quartz diorite (QD) at northeast end of ridge looking northwest. UTM 465688E, 5136940N, Zone 17, WGS84.

Photo 15. Site 4b. Inclusion-filled QD1. UTM 466089E, 5137316N, Zone 17, WGS84.

STOP 5. TRILL OFFSET DEPOSIT (E.F. PATTISON)

Location and Directions

The Trill property is accessible by road and by all-terrain vehicle (ATV) trails. A four-wheel drive vehicle is advisable from the turnoff off of the Chicago Mine Road just past the Bailey Bridge shown in the inset on Figure 9. The last 1.5 km portion of the trail requires use of an all terrain vehicle or walking. **Warning.** Logging trucks sometimes use the Trill access road. In addition, sump trucks (hauling gravel) and logging trucks use both the Chicago Mine Road and Regional Road 4. They like to drive fast, so be prepared to avoid them.

Take Highway 17 west until the highway is no longer divided. Turn right onto Regional Road 4 to Worthington. Pass Vale Inco's Totten Mine, and at the Worthington "General" store turn right (following Regional Road 4). After approximately 5 minutes turn left onto Chicago Mine Road. Pass the snow plow turn around and cross the Bailey Bridge. Take the first left past the bridge; this takes you onto a series of logging roads on the Trill property. (This portion of the route from Chicago Mine Road is enlarged on Figure 9.) At the first fork, take a left. Go over the hill and past a trail on the right. Take the next right which goes up a sandy/bouldery hill. From here follow the most dominant path which will take you past a storage container. At the green EMS sign, turn right. In approximately 350 m, near the edge of the clear cut, park in the more open area. The remaining approximately 1.5 km distance will be walked.

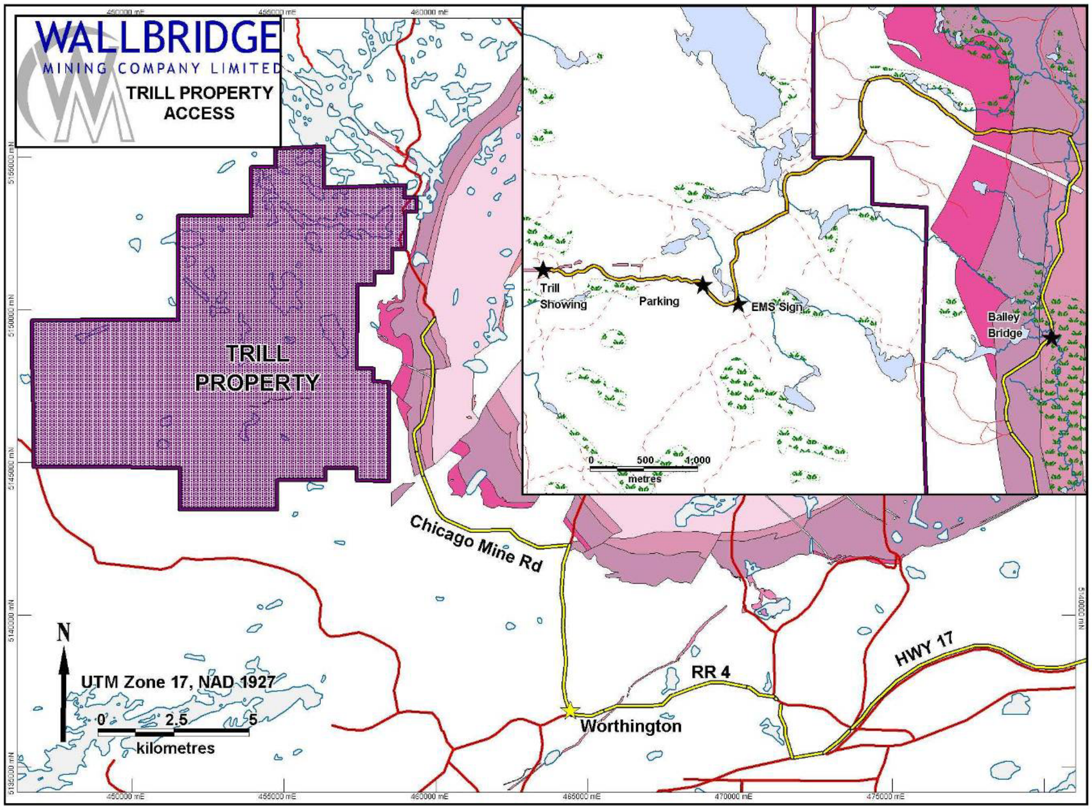

Figure 9. Directions to Stop 5, the Trill Offset occurrence. Figure courtesy of Wallbridge Mining. Note map is in UTM Zone 17, NAD27.

The deposit can also be accessed from the north by taking Old Cartier Road from Highway 144 at Windy Lake and travelling west and south through Cascaden Township. This road is long and tortuous and is not recommended.

Note that in this section of the guidebook, UTM co-ordinates are given in NAD27, not NAD83 or WGS84, in order to be consistent with the co-ordinates shown on Figures 9, 10, 11 and 12.

Description

The Trill property is located on the North Range of the Sudbury Igneous Complex (Figure 10). The east boundary of the Trill property is located 200 to 800 m west of the western edge of the Sudbury Igneous Complex contact (*see* Figure 10). The oldest rocks at the Trill property are monzogranitic and tonalitic gneisses, with lesser amounts of intermediate and mafic gneisses of the Archean Levack Gneiss Complex (2700–2640 Ma), found around Armstrong Lake and East Totten Lake in the northern part of the Trill property. These gneisses are intruded by slightly deformed, felsic to intermediate granitoid rocks of the Cartier granite (2642 Ma; Meldrum et al. 1997). Matachewan swarm diabase dikes (2473 Ma; Heaman 1997) and Sudbury Swarm olivine diabase dikes (*circa* 1240 Ma; Krogh et al. 1987) cut both the granites and gneisses. Nipissing gabbro intrusions and Sudbury Breccia are also present.

The most economically important rock type of the area is quartz diorite (QD), of which all Offset dikes of the Sudbury Igneous Complex are composed. Outcrops of this rock type were mapped for the first time during the fall of 2004 as part of ground follow-up of an AeroTEM anomaly. Only a small area was exposed at that time. The exposed area has been increased by trenching and stripping and the discovery of new outcrops (Figure 11). The dike has been traced over an east-trending distance of 1.85 km, centred on the discovery showing. The silicate components comprise euhedral plagioclase and amphibole, with minor amounts of biotite, titanite, apatite, and characteristic, granophyric intergrowths of quartz and feldspar. The texture is varied; very fine-grained chill margins are sometimes found along the wallrock contacts, and stellate or acicular amphibole crystal aggregates (after pyroxene) characterize the fine-grained sections of the dike, with coarser, interlocking igneous textures typifying the core of the dike. Xenoliths of various rock types, including amphibolite, anorthosite, and granite, are found in some parts of the dike, in which case this rock type is called inclusion quartz diorite (IQD). The inclusions range in size from a few centimetres to almost a metre. Their compositions have not been studied in detail. On the outer edges of the QD corridor there are centimetre-scale glassy or spherulitic-textured quartz diorite dikes that do not have the typical QD textures but are composed of devitrified glass; however, they have a similar lithogeochemical signature to the QD and are hereafter referred to as spherulitic quartz diorite (SQD) by Wallbridge. In 2007, a Sudbury Breccia-like variation of the IQD was discovered. This IQD generally has smaller but more plentiful inclusions of granitoids, gabbro-anorthosite, and marginal, inclusion-free, quartz diorite. This version of inclusion quartz diorite is not associated with massive mineralization. In the area of the showing, the dike appears to widen and split into branches, possibly encircling large monzonite xenoliths. The mineralization is found along the southern branch of the dike. The contact between the dike and the wallrock at that point may be either chilled or coarse grained with small pieces of wallrock being spalled off into the dike. The Offset dike generally trends eastward, but is cut in several places by crosscutting faults which may displace it by several tens of metres.

Mineralization in the Trill Offset dike occurs as a sulfide and inclusion-rich core zone flanked by marginal sulfide and inclusion-poor quartz diorite on both sides. This is a very typical geometric arrangement of mineralization associated with quartz diorite offsets in the Sudbury area. The mineralization extends for approximately 60 m, and ranges from 2.0 to 5.2 m in width. The sulfide mineralogy of the showing is typical of a sulfide-rich Sudbury mineral deposit. Major economic minerals include, but are not limited to, pentlandite and chalcopyrite. Violarite occurs as an oxidation product of pentlandite. Merenskyite and michenerite were identified as PGE-bearing phases using electron microprobe analysis. Gangue minerals associated with the mineralization are pyrrhotite, pyrite, magnetite and a variety of silicate minerals.

The mineralization in the showing is crudely zoned. The core contains massive or inclusion-bearing, nickel-rich sulfide. The flanks contain copper-rich, vein- and disseminated-style mineralization. The margins of the quartz diorite dike are not mineralized. The mineralization is defined on the basis of borehole intersections, channel samples and surface mapping (Figure 12). Average grade is estimated at about: 1.2% Ni, 1% Cu, 2g/t Pt, 5g/t Pd, 0.4g/t Au, and 4.3g/t Ag. The mineralization is contained in a zone that is approximately 65 m long, 5 m wide, and dips steeply to the north.

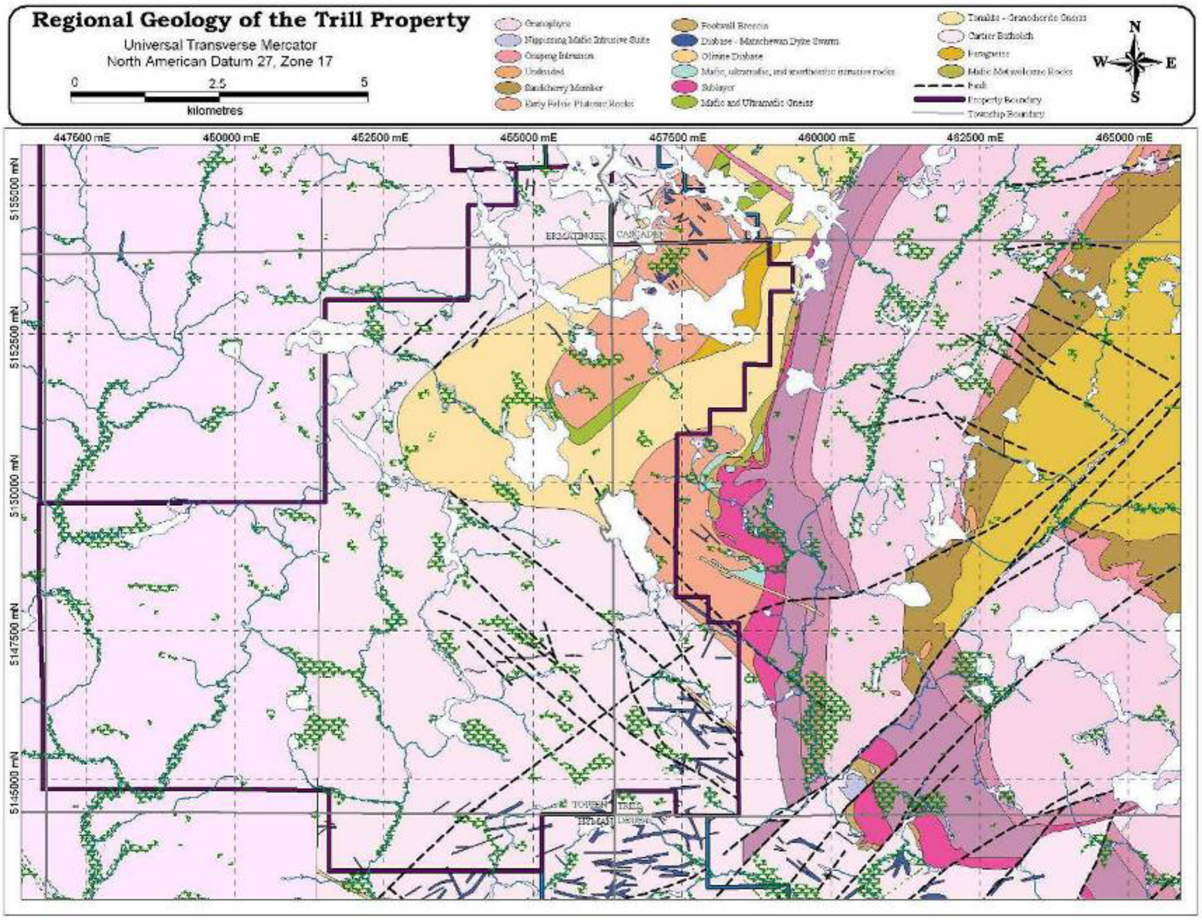

Figure 10. Geology of the western end of the Sudbury Igneous Complex and adjacent footwall rocks. Figure courtesy of Wallbridge Mining. Note map is in UTM Zone 17, NAD27.

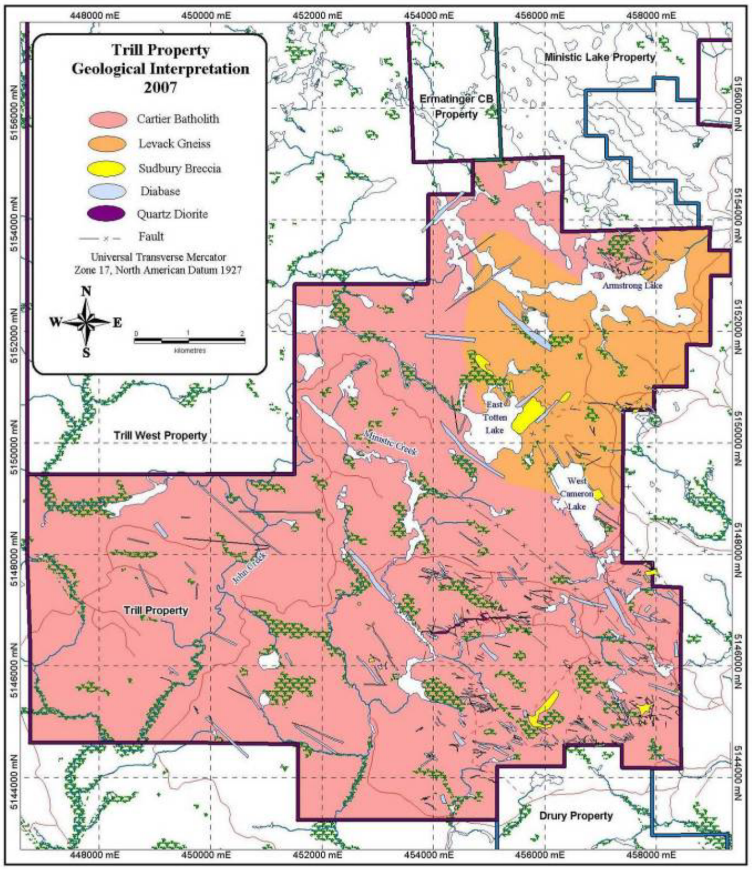

Figure 11. Simplified geology of the Wallbridge Trill property showing the location and mapped extent of the Trill Offset dike. Figure courtesy of Wallbridge Miniing. Note map is in UTM Zone 17, NAD27.

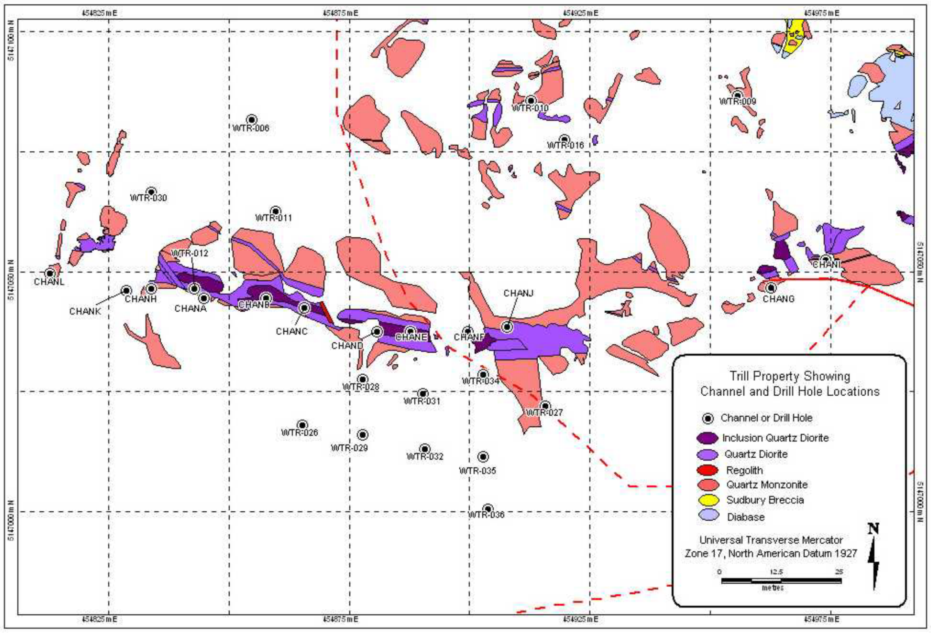

Figure 12. Detailed geology of the Trill Cu-Ni-PGE occurrence. The "regolith" unit is oxidized overburden in the vicinity of the sulfide occurrence, Site 5c. Figure courtesy of Wallbridge Miniing. Note map is in UTM Zone 17, NAD27.

Site 5a, Stop 5. Unmineralized QD and IQD Trench

This trench (UTM 455300E, 5147090N, Zone 17, NAD27) was excavated in 2007, and is located due east of the main Trill showing. The trench is dominated by a Sudbury Breccia (SDBX)-like inclusion quartz diorite (IQD) (over 16 m) that is flanked by typical quartz diorite (QD) on the north and south contacts. You can see the characteristic pink hue of the nonmagnetic QD and the acicular amphibole. Note that the QD does not chill against the host granite, whereas the IQD chills against the QD. The IQD has a variety of clasts (granite, diabase, gabbro to anorthosite) that range in size from millimetres to approximately 1 m. The occurrence of 'exotic' (gabbro to anorthosite) clasts is important to get an idea of the size of the system. The nearest known gabbro-anorthosite is the Drury anorthosite, located approximately 8 km to the southeast, compared to the granite and diabase clasts that are local. At this location we are roughly 3 km from the Sudbury Igneous Complex.

Site 5b, Stop 5. Barren QD and IQD Pit

Warning. Please use caution when climbing down and up and be careful not to dislodge any rocks; they may slide down and hit someone. The rocks in the pit can be slippery.

This trench (UTM 454988E, 5147082N, Zone 17, NAD27) is quite similar to the previous one, with a core of SDBX-like IQD, and QD margins. At this locality reaction rims can be observed around resorbed quartz clasts in the QD. Rims are also observed in the host granite along the gradational contact with the QD. Most importantly, note the occurrence of an approximately 25 cm inclusion of QD in the IQD along the northern contact. Features visible at this site are illustrated in Photos 16, 17, and 18.

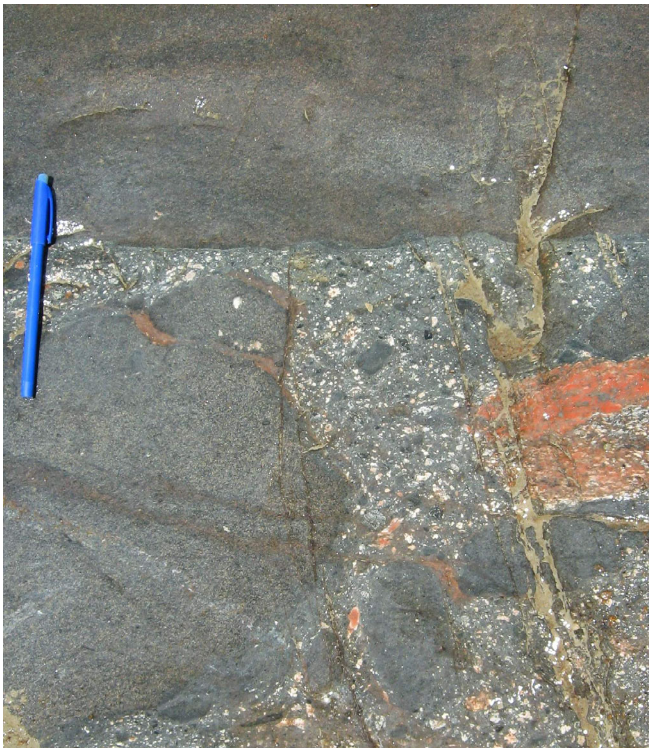

Photo 16. Site 5b. Inclusion of quartz diorite (QD) in matrix of fine-grained, inclusion-rich quartz diorite (IQD).

Photo 17. Site 5b. Gradational contact between quartz diorite (QD) and quartz monzonite of the Cartier granite.

Photo 18. Site 5b. Sharp quartz diorite (QD) contact showing abundant resorbed quartz xenocrysts.

Site 5c, Stop 5. Mineralized showing

An excellent exposure of the central mineralized zone flanked on both margins by barren quartz diorite (QD) is visible along the length of this large stripped area (Photo 19) (UTM 454860E, 5147050N, Zone 17, NAD27). Approximately mid-way along the north contact, a 25 cm wide dike of barren quartz diorite (QD) splits off from the dike and intrudes the host quartz monzonite.

The mineralization associated with the Trill Offset, in common with mineralized zones in other offset dikes, is associated with the core IQD phase of the dike. A variety of inclusion types are present within the IQD, including locally derived granitoid and “exotic” ultramafic lithologies (Photo 20). Most obviously, portions of the mineralized zone are characterized by concentrations of zoned, euhedral to lobate, zoned plagioclase crystals (Photo 21). These are most likely portions of disaggregated xenoliths of an East Bull Lake intrusive suite body, such as the Drury anorthosite.

Major economic minerals include, but are not limited to, pentlandite and chalcopyrite. Violarite occurs as a probable oxidation product of pentlandite. Merenskyite ($(Pd,Pt)(Te,Bi)_2$) and michenerite ($(Pd,Pt)BiTe$) have been identified as PGE-bearing phases. Gangue minerals associated with the mineralization are pyrrhotite, pyrite, magnetite and a variety of silicate minerals. The mineralization in the showing is crudely zoned. The core contains massive or inclusion-bearing, nickel-rich sulfide, whereas the flanks contain copper-rich, vein- and disseminated-style mineralization. The margins of the quartz diorite dike tend not to be mineralized. The average grade of the Trill lens is estimated to be 1.2% Ni, 1% Cu, 2g/t Pt, 5g/t Pd, 0.4g/t Au, and 4.3g/t Ag.

Photo 19. Site 5c. The main trench at Trill showing the rusty central core of mineralized inclusion quartz diorite (IQD) flanked on both sides by barren quartz diorite (QD).

Photo 20. Site 5c. Weakly mineralized inclusion quartz diorite (IQD) from the main trench containing a variety of local and "exotic" inclusion types.

Photo 21. Site 5c. Euhedral to subhedral plagioclase xenocrysts in inclusion quartz diorite (IQD).

Site 5d, Stop 5. Glassy and spherulitic phases of quartz diorite

Proceed up the hill to an area that is north of the showing area (UTM 454915E, 5147098N, Zone 17, NAD27). Near the hill top there are small (up to 10 cm) dikes that have spherulitic-like quench textures, or are glassy and have no macroscopic indications of quenching. Although not visible in hand specimen, the black glassy dikes generally have microscopic indications of quenching (Photo 22, 23). Geochemically these dikes are identical to the QD, and tend to occur along the margins of the interpreted QD lens. Locally, spherulitic textures occur along the margins of the main dike.

Photo 22. Site 5d**.** Spherulitic devitrification(?) texture in a glassy quartz diorite (QD) dikelet north of the main trench.

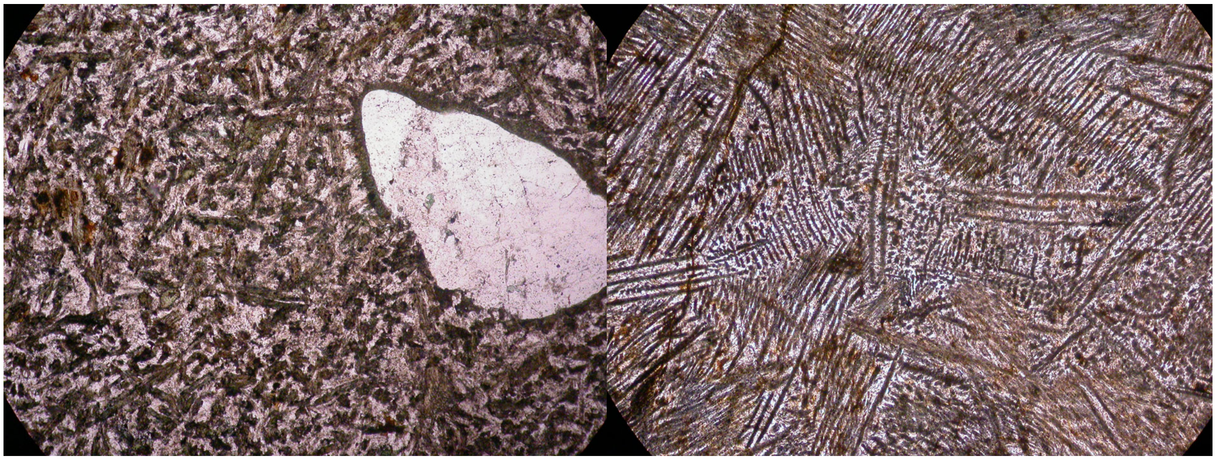

Photo 23. Site 5d. Photomicrographs of fine-grained quartz diorite (QD) with xenocryst of quartz with thin reaction rim (left) and quenched quartz diorite (QD) with feathery skeletal pyroxene(?) crystals (right) in a thin aphanitic dike.

References

Ames, D., Davidson, A., Buckle, J.L. and Card, K.D. 2005. Geology, Sudbury bedrock compilation, Ontario; Geological Survey of Canada, Open File 4570, scale 1:50 000.

Ames, D., Golightly, P., Lightfoot, P. and Gibson, H. 2002. Vitric compositions in the Onaping Formation and their relationship to the Sudbury Igneous Complex, Sudbury Structure; Economic Geology, v.97, p.1541-1562.

Ames, D., Stoness, J.A. and Rousell, D.H. 2009. Whitewater Group; *in* A Field Guide to the Geology of Sudbury, Ontario Geological Survey, Open File Report 6243, p.37-44.

Bennett, G., Dressler, B.O. and Robertson, J.A. 1991. The Huronian Supergroup and associated intrusive rocks; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.549-591.

Carr, S.D., Easton, R.M., Jamieson, R.A. and Culshaw, N.G. 2000. Geologic transect across the Grenville Orogen of Ontario and New York; Canadian Journal of Earth Sciences, v.37, p.193-216.

Charbonneau, Y. 2003. Victoria Mines, http://www.ghosttownpix.com/ontario/towns/victoria.html (last accessed on May 2, 2010).

Cochrane, L.B. 1984. Ore deposits of the Copper Cliff Offset; *in* the Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.327-346.

Corfu, F. and Andrews, A.J. 1986. A U-Pb age for mineralized Nipissing diabase, Gowganda, Ontario; Canadian Journal of Earth Sciences, v.23, p.107-109.

Davis, D.W. 2008. Sub-million-year age resolution of Precambrian igneous events by thermal extraction–thermal ionization mass spectrometer Pb dating of zircon: Application to crystallization of the Sudbury impact melt sheet; Geology, v.36, p.383-386.

Dressler, B.O., Gupta, V.K. and Muir, T.L. 1991. The Sudbury Structure; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.593-625.

Fedorowich, J.S., Golightly, J.P. and Rousell, D.H. 2009. Breccias in the Footwall; *in* A Field Guide to the Geology of Sudbury, Ontario Geological Survey, Open File Report 6243, p.45-55.

Fort Knox Resources Inc. 2001. Update on Fort Knox/Dynatec proposed acquisition of five Inco Sudbury Basin Properties, July 2, 2001, http://www.marketwire.com/press-release/Fort-Knox-Gold-Resources-Inc-452860.html. (last accessed on May 2, 2010).

Golightly, J.P. 1994. The Sudbury Igneous Complex as an impact melt: Evolution and ore genesis; *in* Proceedings of the Sudbury–Noril'sk Symposium, Ontario Geological Survey, Special Volume 5, p.105-117.

Heaman, L.M. 1997. Global magmatism at 2.45 Ga: Remnants of an ancient large igneous province?; Geology, v.25, p.299-302.

Holm, D.K., Schneider, D.A., O'Boyle, C., Hamilton, M.A., Jercinovic, M.J. and Williams, M.L. 2001. Direct timing constraints on Paleoproterozoic metamorphism, southern Lake Superior region: Results from SHRIMP and EMP U-Pb dating of metamorphic monazites; Geological Society of America, Abstracts with Program, v.33, no.6, p.A-401.

Jackson, B. 2007. With a future, appropriate to shed light on Worthington's past, http://www.northernlife.ca/News/Opinions/2007/05-09-07-jackson.pdf, (last accessed on May 2, 2010).

Krogh, T.E., Davis, D.W. and Corfu, F. 1984. Precise U-Pb zircon and baddelyite ages for the Sudbury Structure; *in* Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.431-446.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenough, J.D. and Nakamura, E. 1987. Precise U-Pb isotopic ages of diabase dykes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon; *in* Mafic Dyke Swarms, Geological Association of Canada, Special Paper 34, p.147-152.

Krogh, T.E., Kamo, S.L. and Bohor, B.F. 1996. Shock metamorphosed zircons with correlated U-Pb discordance and melt rocks with concordant protolith ages indicate an impact origin for the Sudbury structure; *in* Earth Processes: Reading the Isotopic Code, American Geophysical Union, Geophysical Monograph 95, p.343-353.

Lesher, C.M., Golightly, J.P., Gregory, S.K. and Stout, A.E. 2009. Dynamic remelting and zone refining of Ni-Cu-PGE mineralization in the Sudbury Igneous Complex, Ontario, Canada; *in* Proceedings of the Xi'an International Ni-Cu-(Pt) Symposium, Northwestern Geology, v.42, p.157-160.

Lightfoot, P.C., Doherty, W., Farrell, K., Keays, R.R., Moore, M. and Pekeski, P. 1997. Geochemistry of the Main Mass, Sublayer, Offsets and inclusions from the Sudbury Igneous Complex; Ontario Geological Survey, Open File Report 5959, 231p.

Meldrum, A., Abdel-Rahman, A.-F.M., Martin, R.F. and Wodicka, N. 1997. The nature, age and petrogenesis of the Cartier batholith, northern flank of the Sudbury Structure, Ontario, Canada; Precambrian Research, v.82, p.265-285.

Mourre, G.A. 2000. Geological relationships at discontinuties in the Copper Cliff quartz diorite offset: An investigation into offset dikes and the relationship to the Sudbury Igneous Complex, Ontario; unpublished MSc thesis, Laurentian University, Sudbury, Ontario, 255p.

Noble, S.R. and Lightfoot, P.C. 1992. U-Pb baddeleyite ages of the Kerns and Triangle Mountain intrusions, Nipissing diabase, Ontario; Canadian Journal of Earth Sciences, v.29, p.1424-1429.

Pattison, E. 2009. Sudbury Igneous Complex; *in* A Field Guide to the Geology of Sudbury, Ontario Geological Survey, Open File Report 6243, p.56-74.

Piercey, P., Schneider, D.A. and Holm, D.K. 2007. Geochronology of Proterozoic metamorphism in the deformed Southern Province, northern Lake Huron region, Canada; Precambrian Research, v.157, p.127-143.

Rousell, D.H. and Brown, G.H. 2009. Part 2 – Self-guided field trip; *in* A Field Guide to the Geology of Sudbury, Ontario Geological Survey, Open File Report 6243, p.141-180.

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

ISSN 0826-9580 [print]
ISBN 978-1-4435-3971-5 [print]

ISSN 1916-6117 [online]
ISBN 978-1-4435-3972-2 [PDF]