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"The rocks are the final court of appeal" Francis Pettijohn

PRECAMBRIAN RESEARCH CENTER PROFESSIONAL WORKSHOP SERIES

Field, Petrographic, and Mineralization Characteristics of Mafic Layered Intrusions

October 4 – 10, 2009

***University of Minnesota Duluth
Duluth, Minnesota***

Sponsored by:
Precambrian Research Center
Department of Geological Science
Natural Resources Research Institute

www.d.umn.edu/prc/workshops

About the Workshop

The workshop is designed for professional geologists and graduate students working with and/or interested in field and drill core studies of mafic layered intrusions (MLI), which host sulfide and oxide mineralization. The focus of the workshop will be mostly on descriptive aspects of MLI, but with some discussion about genetic interpretations of MLI features. The goal of the workshop is to familiarize participants in the nomenclature and methodologies that lead to thorough descriptions of the mineralogical, textural, structural, and mineralization attributes of MLI in the field, in drill core, and under the microscope.

The workshop includes three days of short course lectures and labs and three days of field excursions. The short course, which will be conducted at the University of Minnesota Duluth, involves topical lectures, virtual powerpoint tours of well documented mafic layered intrusions, and hands-on studies of hand samples, drill core, and thin sections profiling these intrusions. The field excursions will visit two mafic layered intrusions of the Duluth Complex and will view drill core profiling different MLI in Minnesota. The primary goal of these excursions is to highlight mapping and core logging techniques that lead to a robust understanding of the igneous stratigraphy of mafic layered intrusions.

Tentative Schedule

Sunday, October 4

6-9 PM Welcoming Reception (Inn on Lake Superior, Canal Park); Introductions

Monday, October 5

8:00 Transport participants to UMD
8:30-9:30 **Lecture 1:** Stratigraphic Nomenclature (*Scoates & Scoates*)
9:30-10:00 Coffee Break
10:00-11:00 **Lecture 2:** Layering and Other Structures (*Cooper*)
11:30-12:30 Lunch at UMD
1:00-2:30 **Lab 1:** Skaergaard Intrusion (*Miller and Severson*)
2:30-3:00 Break
3:00-4:30 **Lab 2:** Stillwater Complex (*Cooper*)
5:00 Return participants to motels

Tuesday, October 6

7:30 Transport participants to UMD
8:00-9:00 **Lecture 3:** Silicate/Oxide Mineralogy and Textures (*Li*)
9:00-9:30 Coffee Break
9:30-10:30 **Lecture 4:** Sulfide Mineralogy and Texture (*Ripley*)
10:30-11:30 **Lecture 5:** Deuteric Alteration and Metamorphism (*Easton*)
11:30-12:30 Lunch at UMD
12:30-2:00 **Lab 3:** Voisey's Bay (*Li and Ripley*)
2:00-3:30 **Lab 4:** Duke Island (*Ripley and Li*)
3:30-4:00 Break
4:00-5:30 **Lab 5:** East Bull Lake Intrusive Suite (*Easton*)
5:45 Return participants to motels

Wednesday, October 7

8:00-5:00 **Field Trip 1** – Igneous Stratigraphy of the Duluth Layered Series (*Miller*)

Thursday, October 8

8:00 Transport participants to UMD
8:30-9:30 **Lecture 6:** Petrology of Mafic Layered Intrusions (*Marsh*)
9:30-10:00 Coffee Break
10:00-11:00 **Lecture 7:** Geochemistry of Mafic Layered Intrusions (*Miller*)
11:30-12:30 Lunch at UMD
1:00-2:30 **Lab 6:** Ferrar Sills (*Marsh*)
2:30-3:00 Break
3:00-4:30 **Lab 7:** Fox River and Bird River Sills (*Scoates & Scoates*)
4:45 Return participants to motels
6:00-9:00 Banquet at north shore restaurant

Friday, October 9

8:00-6:00 **Field Trip 2** – Drill Core Investigation of Mafic Layered Intrusions (Severson)

Saturday, October 10

8:00-6:00 **Field Trip 3** – Igneous Stratigraphy of the Sonju Lake Intrusion (Miller)

Workshop Instructors and Contributors

- **Roger Cooper** - Professor, Lamar University (PhD, Minnesota)
Research Interests: Ongoing research (1980-present) has focused primarily on the petrology, field geology and economic geology (Ni-Cu sulfide, chromite and PGE mineralization) of the Stillwater Complex, Montana. Prior to joining the Department of Geology at Lamar University in Beaumont, Texas in 1985, Roger worked as a staff geologist for Anaconda Minerals for five years where he conducted exploration projects for precious metal deposits in Precambrian terranes and their Phanerozoic analogues. Areas of emphasis included the Stillwater Complex, Montana; Archean greenstone belts of the Lake Superior region, Canada/USA and the Yilgarn Shield of Western Australia; and Precambrian and Paleozoic rift-related basins in the mid-continent of the US.
- **Michael Easton** – Geoscientist, Ontario Geological Survey (PhD, Memorial University, Newfoundland)
Research Interests: Since 1982, Dr. Michael Easton has been employed as a mapping geologist with the Ontario Geological Survey, studying the Proterozoic rocks of Ontario, in particular mafic layered intrusions located in the Sudbury and Nipigon areas of Ontario. His interest in MLIs focuses on their field relationships, metamorphism, geochemistry, and mineral potential. He is also an adjunct professor at both Laurentian and Carleton universities in Ontario.
- **Chusi Li** – Senior Scientist, Indiana University (PhD, Toronto)
Research Interests: Genesis of magmatic sulfide deposits associated with mafic-ultramafic rocks. In the last 30 years, Chusi has studied many world-class Ni-Cu-PGE deposits such as Jinchuan in China, Sudbury and Voisey's Bay in Canada, Noril'sk-Talnakh in Russia, the Merensky Reef of the Bushveld Complex in South Africa, and the J-M Reef of the Stillwater Complex in Montana, USA. He has served as a part-time consultant to several international mining companies and published more than 70 peer-reviewed papers to date.
- **Dick James** – Professor, Laurentian University (retired) (PhD, Manchester)
Research Interests: Current projects - Igneous stratigraphy, petrology and PGE mineralization in the River Valley Intrusion, central Ontario; Character and genesis of PGE-Cu-Ni mineralization and their host rocks in the Paleoproterozoic EBLI-type layered intrusions in central Ontario; Metamorphic, tectonic and geochronologic history of Paleoproterozoic intrusions and associated supracrustal rocks in the Grenville Front Tectonic Zone, central Ontario; and Metamorphism of banded iron formations and paragenesis of associated Au-pyrrhotite-arsenopyrite mineralization.
- **Bruce Marsh** – Professor, Johns Hopkins University (PhD, California Berkeley)
Research Interests: Understanding the production, transport and crystallization of magma within and onto the surface of Earth. Most recently, Bruce has focused his field and laboratory research on the Ferrar Dolerites of the McMurdo Dry Valleys, Antarctica in order to understand their role in the plumbing system of flood basalts. He has been a professor at Johns Hopkins University since 1974; he worked for Jones & Laughlin and Anaconda before doing his graduate work at the UC Berkeley. His principal field areas have been the Aleutian Islands, Iceland, Central Africa, Sudbury, and for the past fifteen years the McMurdo Dry Valleys.
- **Jim Miller** – Associate Professor, University of Minnesota Duluth (PhD, Minnesota)
Research Interests: Field, petrologic, and metallogenic studies of the igneous rocks of the 1.1 Ga Midcontinent Rift of the Lake Superior region with the goal of unraveling its tectonomagmatic evolution. In his 25 years as a senior geologist with the Minnesota Geologic Survey, Jim focused most of his research on detailed geologic mapping of the Duluth Complex and related intrusive terranes of the Midcontinent Rift in northeastern Minnesota. More topical research has focused on petrologic studies of various mafic intrusions within the Duluth Complex and evaluating their potential for economic mineralization, particularly PGE reefs. Jim left the MGS and joined the faculty at UMD in 2008.

- **Ed Ripley** – Professor, Indiana University (PhD, Penn State)

Research Interests: Isotope geochemistry of igneous systems and magmatic ore deposits. Specific research projects that Ed has recently been involved with include: the origin of sulfide mineralization in the Duke Island Complex, Alaska; the genesis of the Eagle Cu-Ni deposit, Michigan; Re-Os isotope studies of melt-country rock interaction, Duluth Complex – Animikie Group, Minnesota; geochemical studies of the Jinchuan Cu-Ni deposit, western China; isotopic variability in the Noril'sk – Talnakh intrusions, Siberia; stable isotopic studies of the Uitkomst and Kabanga Ni-Cu deposits, southern Africa; stable isotopic studies of the Sudbury melt sheet and footwall mineralization; geochemical and isotopic studies of the BIC (Michigan) and Tamarack (Minnesota) prospects; and S, O, and Re-Os isotopic systematic in high-T systems.

- **R.F. Jon Scoates** – Consulting Geologist, Nanaimo, BC (PhD, Manitoba)

Research Interests: The nature and origin of mafic/ultramafic complexes in Canada including layered intrusions (Fox River Sill, Bird River Sill, Manitoba; Muskox Intrusion, Nunavut; Rum Intrusion, Inner Hebrides, Scotland). Additionally, Jon has examined Duke Island, Alaska; Stillwater Complex, Montana; Skaergaard Intrusion, Greenland; parts of the Duluth Complex, Minnesota and the Platreef of the northern limb of the Bushveld Complex. After spending 35 years with the Manitoba Geological Survey and the Geological Survey of Canada he has spent the past 14 years as a consulting geologist. He has authored and co-authored more than eighty government reports and maps and other outside publications.

- **James S. Scoates** – Associate Professor, University of British Columbia (PhD, Wyoming)

Research Interests: Broadly focused on the differentiation processes in silicate magmas and how they affect magma compositional variability, magma dynamics, and mineralization potential using a combination of mapping, microscopy, experiments, geochemistry, and geochronology. All of James' projects involve a field-based component and his research has taken him across Canada from B.C. to Labrador and Nunavut, the U.S. (Wyoming, Montana, Alaska), Norway, France, and the Indian Ocean hotspot islands of Kerguelen and St. Paul. Current major projects address the evolution of a number of Phanerozoic oceanic islands and plateaus (Kerguelen, Hawaii, Wrangellia), the origin of Proterozoic massif anorthosites and associated magmatic Fe-Ti oxide ore deposits, and the formation and timing of emplacement of large layered mafic-ultramafic intrusions (Muskox, Stillwater, Bushveld).

- **Mark Severson** – Research Fellow, Natural Resources Research Institute-UMD (MS, Minnesota Duluth)

Research Interests: Economic geology of Minnesota, especially the Cu-Ni-PGE and Ti deposits of the Duluth Complex and other gabbroic intrusions, iron ore resources of the Mesabi Range, and the potential for sedimentary-hosted Pb-Zn deposits in Paleoproterozoic terranes. Mark has devoted most of his 20 years with the NRRI toward core logging and field mapping along of the Cu-Ni mineralized base of the Duluth Complex. To date, he has logged close to 1 million feet of Duluth Complex drill core. Prior to joining the NRRI in 1986, Mark worked as an exploration geologist for USX Corporation, Santa Fe Pacific, and Rhude-Fryberger.

Short Course Lectures

During three mornings of the short course, instructors will give Powerpoint lectures on a variety of topics related to mafic layered intrusions. Participants will be given printouts of the Powerpoint presentations for note-taking during the lectures and miscellaneous handouts in a ring-binder. After the course, participants will be sent electronic copies of each presentation on CD. The lecture topics, the instructors, and a short abstract of the lecture topics are given below.

Nomenclature and Classification – James Scoates and Jon Scoates

The overall nomenclature applied to layered intrusions will be reviewed (based on Irvine, 1982, with contributions from Wager, Brown and Wadsworth, 1960, Jackson, 1961, Wager and Brown, 1968, and other appropriate and more current references). The review will involve reference to various layered intrusions (Skaergaard, Bushveld, Stillwater, Muskox, Duluth Complex, as well as less well-known examples). The current understanding of layering processes, the relevance of fluid dynamics and the textures observed in these intrusions will be summarized. Reference to new ideas concerning textural maturity of cumulates will be introduced. The presentation will briefly address some controversial aspects of the terminology (e.g. appropriateness of the concepts and terminology of igneous cumulates). This segment will rely heavily on

field and petrographic observations, remembering that *good field (and petrographic) observations are hard to refute, whereas the fun begins with the interpretations* (with apologies to G.M. Brown).

Silicate/Oxide Mineralogy and Textures – Chusi Li

This lecture will review basic non-sulfide mineral assemblages encountered in mafic layered intrusions and terminology of mineral and whole rock textures. Special emphasis will be placed on the textural characteristics of rocks formed in dynamic magma conduits (e.g. Voisey's Bay and Eagle). Interpretations of textures representing cumulus processes, the formation of crystal mushes, xenolith-magma interaction, and subsolidus equilibration will be discussed.

Layering and other Internal Structures – Roger Cooper

Igneous layering is the most obvious feature of mafic layered intrusions, but the types of layering and ideas for their origin are incredibly diverse. Using examples mostly from the classic Stillwater Complex, this lecture will review the nomenclature that describes various types of layering and other structural features (e.g., foliation, lineation) commonly displayed by mafic layered intrusions. Layering features that have direct links to Cu-Ni sulfide or chromite mineralization will be particularly emphasized. In addition, the textural aspects of some layers and rocks, which seem to have strong implications for mineralization potential, will be highlighted. Various ideas for the primary or secondary origins of particular types of layering will also be briefly discussed.

Sulfide Mineralogy and Textures – Ed Ripley

Magmatic sulfide mineral assemblages found in mafic rocks will be reviewed, as well as commonly observed textures. Hydrothermal modification of magmatic assemblages and features of primary hydrothermal sulfide deposition will be discussed. Genetic inferences based on sulfide assemblages, texture, phase equilibria, and basic geochemical data will be evaluated.

Deuteric Alteration and Metamorphism – Michael Easton with Dick James

The lecture will provide a summary of alteration and metamorphic recrystallization processes that commonly affect primary igneous minerals in MLI, as well as a brief discussion on how these processes may influence precious metal tenor in MLI. The importance of corona textures in MLI will be discussed, as well as the use of geochemical methods to see through the effects of alteration and metamorphism. Examples from the East Bull Lake intrusive suite will be used to illustrate important processes and textures.

Petrology of Mafic Layered Intrusions – Bruce Marsh

The final nature of all intrusions is mainly the result of initial physical magmatic processes progressively buttressed by chemistry. It is of fundamental importance to realize how intrusions are built and how these initial conditions dictate the final outcome of the rock mass. A general method will be presented whereby the evolutionary origin of any intrusive body may be deciphered.

Geochemical Attributes – Jim Miller

Because most rocks comprising mafic layered intrusions are composed of various mixtures of primocryst minerals and a component of the solidified parental liquid, the chemistry of MLI rocks can be difficult to decipher. Commonly, whole rock analyses of MLI rocks are erroneously treated as if they represent liquid compositions. This lecture will discuss the utility and limitations of mineral chemistry data, whole rock analyses, and metal assays in understanding the emplacement, crystallization, and sulfide mineralization history of mafic layered intrusions.

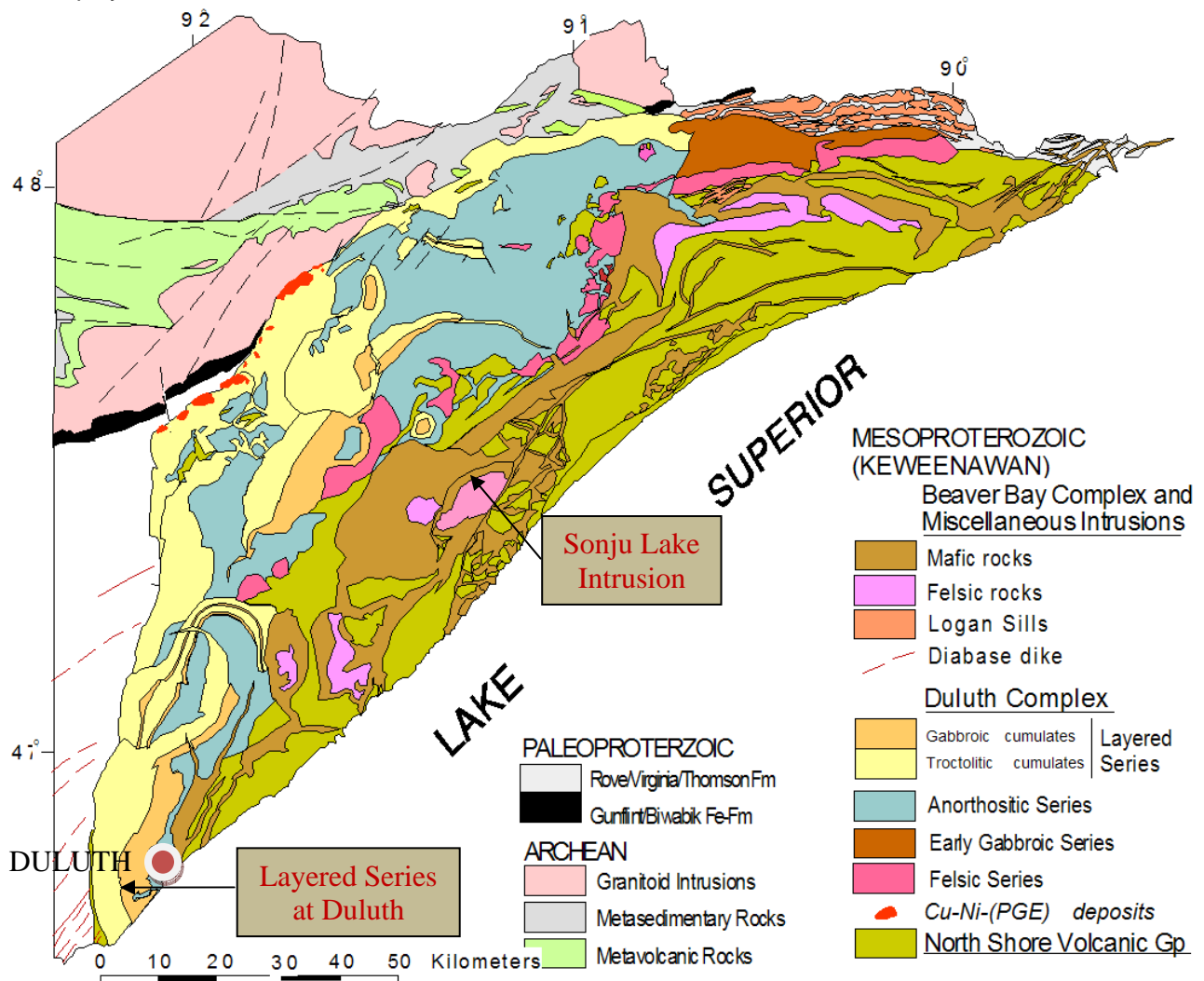
Virtual Field Trips and Sample Investigations

During three afternoons of the short course, instructors will give virtual Powerpoint tours that highlight the igneous stratigraphy and field relationship of some of the world's most notable mafic intrusions. These tours will be followed by a lab period that allows participants to view hand samples, drill core, and thin sections of representative samples that profile these intrusions. Powerpoint printouts for note-taking, sample lists, and miscellaneous handouts will be distributed to participants prior to the labs and CD copies of the powerpoint presentations will be distributed to participants after the workshop. The intrusions that are planned to be featured and the "tour" instructors are:

Skaergaard, Greenland (Severson and Miller)
 Stillwater, Montana (Cooper)
 Voisey's Bay, Labrador (Li and Ripley)
 Duke Island, Alaska (Ripley and Li)
 East Bull Lake Intrusive Suite, Ontario (Easton)
 Fox River and Bird River Sills, Manitoba (Scoates and Scoates)
 Ferrar Dolerites, Antarctica (Marsh).

Field Excursions and Exercises

Three days of the workshop will be devoted to field excursions on two layered intrusions in the greater Duluth Complex and to viewing drill core from various mafic intrusions in Minnesota. The primary goal of these excursions is to highlight mapping and core logging techniques that lead to a robust understanding of the igneous stratigraphy of mafic layered intrusions. During all three excursions, participants will conduct small mapping and core logging exercises that will emphasize the importance of recognizing stratigraphic variations in the mineralogy and textures of MLI rocks. The intrusions to be visited will be the Layered Series at Duluth and the Sonju Lake Intrusion (see figure). For the drill core excursion, the workshop will travel to the Minnesota Department of Natural Resources Drill Core Repository in Hibbing, MN. The core to be displayed will focus on sections of intrusions that contain Cu-Ni-PGE sulfide and Ti-oxide mineralization.



Generalized Geology of Northeastern Minnesota showing the Locations of the Field Excursions

Registration and Fees

Registration for this hands-on workshop is **limited to 22 participants** with preference given to PRC members*. Three slots at a discounted rate will be reserved for students enrolled in MS or PhD programs (see requirements below). All other participants will be accepted to the workshop on a first come – first serve basis contingent upon receipt of the registration form and full payment of the workshop fee.

*To learn about PRC membership, visit the website: www.d.umn.edu/prc/membership

Workshop Registration Fee: **\$1600** (Professional)
\$1100 (Graduate Student, limit 3, see below)
Late Registration Fee: **\$1800** (after Sept. 7, 2009)

The workshop fee includes:

- Short course volume of lecture notes, handouts, and reprints
- CD of Powerpoint lectures and virtual tours
- Copy of MGS Report of Investigations 58 (Geology and Mineral Potential of the Duluth Complex)
- Certificate of Attendance indicating contact hours
- Van transport between Downtown Duluth/Canal Park hotels and UMD
- Welcoming reception Sunday evening (10/4)
- Banquet dinner Thursday evening (10/8)
- Lunches and morning coffee breaks throughout workshop
- Field trip transportation (by 15 passenger van)

Participants will be responsible for all other meals not indicated above, as well as their hotel accommodations in Duluth and transportation to and from Duluth.

College Credits and Tuition

All registrants will receive a certificate of participation at the completion of the workshop that indicates involvement in 40 contact hours of instruction. Registrants also have the option of receiving 2.5 undergraduate credits from the University of Minnesota Duluth for participating in this workshop and submitting brief reports.

Course Name: GEOL 5095, Sec. 241 - Special Topics: Field, Petrographic, and Mineralization Characteristics of Mafic Layered Intrusions

Instructor of Record: Jim Miller, UMD Department of Geological Sciences

Tuition Fee: **\$225.25** (\$88/credit for tuition; \$5 for UMD Information Technology Systems and Services fee)

Requirements: To receive full credit for the course, participants must:

1. Participate in all aspects of the short course and field trip
2. Submit a 2- to 3-page reflection paper summarizing the main points expressed during the short course lectures
3. Complete a summary of the igneous stratigraphy and salient features of two mafic layered intrusions highlighted in this workshop (minimum of 2 pgs. of text for each intrusion report)
4. Complete a course evaluation form

Requirements 2-4 must be submitted to the instructor by Dec. 18, 2009 to receive Fall 09 credit.

Notice of Acceptance and Cancellation Policy

Upon receipt of a completed registration form and full payment, a preliminary notice of acceptance will be sent. If the course fills before the early registration deadline (Sept. 7), registrants can request to be put on a waiting list and your check held. Because a limited number of PRC members have priority for the course at any time before the early registration deadline, it is possible to be bumped from the workshop by a PRC member, especially for late registrants.

A full course refund will be given if notice of cancellation is received by Friday, **September 25**. Our program obligations make it necessary to assess a charge equal to one-half of the course fee for later cancellations. No course refund is possible after the course begins on October 4.

Graduate Student Registration

Up to three graduate students enrolled in accredited M.S. or Ph.D. programs in Canadian or US colleges during the 2008-2009 academic year may attend the workshop at a discounted registration rate of \$1100. Student registrations must be accompanied by:

- a letter by the student briefly describing how the workshop pertains to their thesis research and their career goals.
- a letter of recommendation from their thesis advisor commenting on the qualifications of the student and the usefulness of this workshop to the student's thesis research.

Student registrations do not initially require payment of fees. If more than 3 students register, the three most qualified students will be chosen and notified on **September 7th**. Upon notification of acceptance into the workshop, students will be expected to pay the registration fee (and tuition costs, if requested) by **September 28th**.

About Duluth

Duluth, the world's largest freshwater inland port, is located at the western tip of Lake Superior, midway between the Twin Cities of Minneapolis / St. Paul and the Canadian border. Nestled in the hills overlooking the largest of the Great Lakes, the city offers breathtaking scenery and serves as the gateway to abundant recreational opportunities

Persons desiring additional information about Duluth can call the Duluth Convention and Visitors Bureau at 1-800-4-DULUTH (438-5884) or visit their website (<http://www.visitduluth.com/>). For additional information about Minnesota, call the Minnesota Office of Tourism at 888-TOURISM (868-7476) or visit their website at <http://www.exploreminnesota.com/>.

Air and Ground Transportation to Duluth

Daily flights into Duluth International Airport (www.duluthairport.com/) are provided by Northwest Airlines with up eight flights daily arriving from Minneapolis-St. Paul and two from Detroit. Transportation from the airport to area hotels and motels is available by taxi at reasonable rates and some hotels provide shuttle service (check with your hotel). Rental cars may also be obtained at the airport from Alamo, Avis, Budget, Hertz, and National.

Hotel Accommodations

Participants are expected to reserve and pay for their own hotel accommodations for the duration of the workshop (7 nights). For ease of collecting and transporting people to and from UMD by van, participants should book accommodations in one of the Downtown/Canal Park area hotels listed below and shown on the attached map. Participants are encouraged to book rooms at the Inn on Lake Superior, where the welcoming reception will be held on Sunday (10/4). A total of 20 rooms have been reserved at a special rate of \$109 (good until 9/4). Request the "PRC rate" when making a reservation.

Downtown/Canal Park Hotels (see map)

Inn on Lake Superior	218/726-1111	888/668-4352	www
Canal Park Lodge	218/279-6000	800/777-8560	www
Hampton Inn	218/720-3000	800/426-7866	www
The Suites	218/727-4663	877/766-2665	www
Comfort Suites	218/727-1378	800/517-4000	www
Radisson	218/727-8981	800/333-3333	www
Holiday Inn	218/722-1202	800/477-7089	www



For More Information

Workshop Information - **Jim Miller** mille066@umn.edu

218-720-4355 (NRRI office) or 218-726-6582 (UMD office)

Registration, Lodging - **Julie Anne Heinz** jheinz@nrri.umn.edu

218-720-4272



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