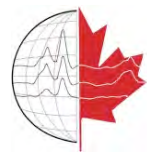


Till Geochemistry and Indicator Mineral Methods for Exploration in Glaciated Terrain

M. Beth McClenaghan
Geological Survey of Canada

Exploration 07 Workshop 2
Exploration Geochemistry: Basic Principles and Concepts
September 8, 2007



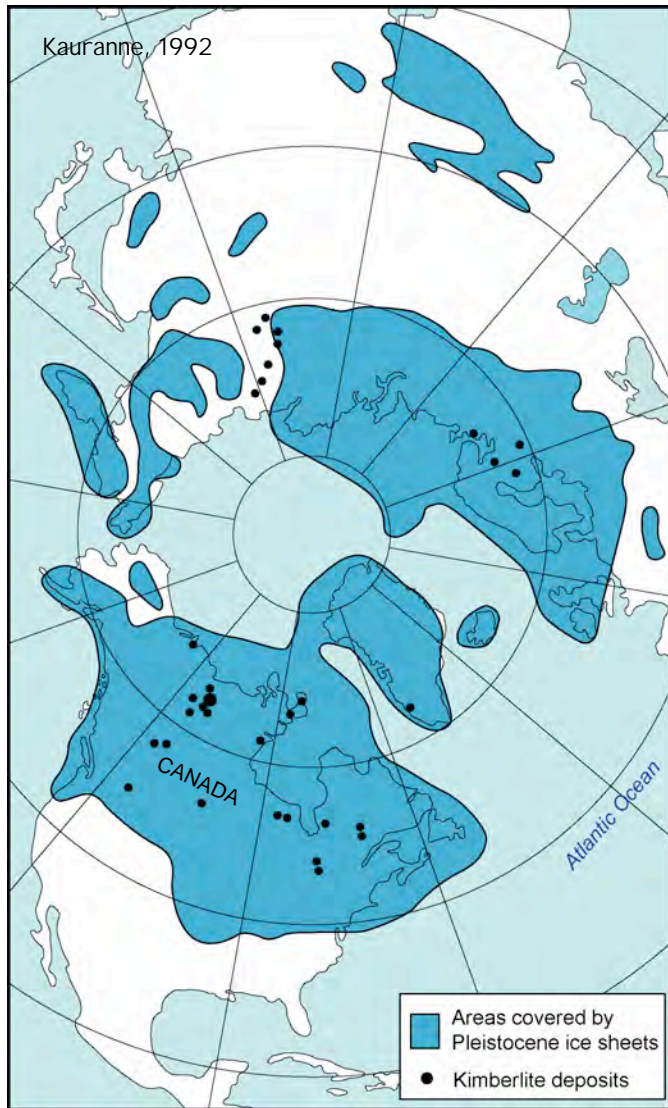
Exploration07



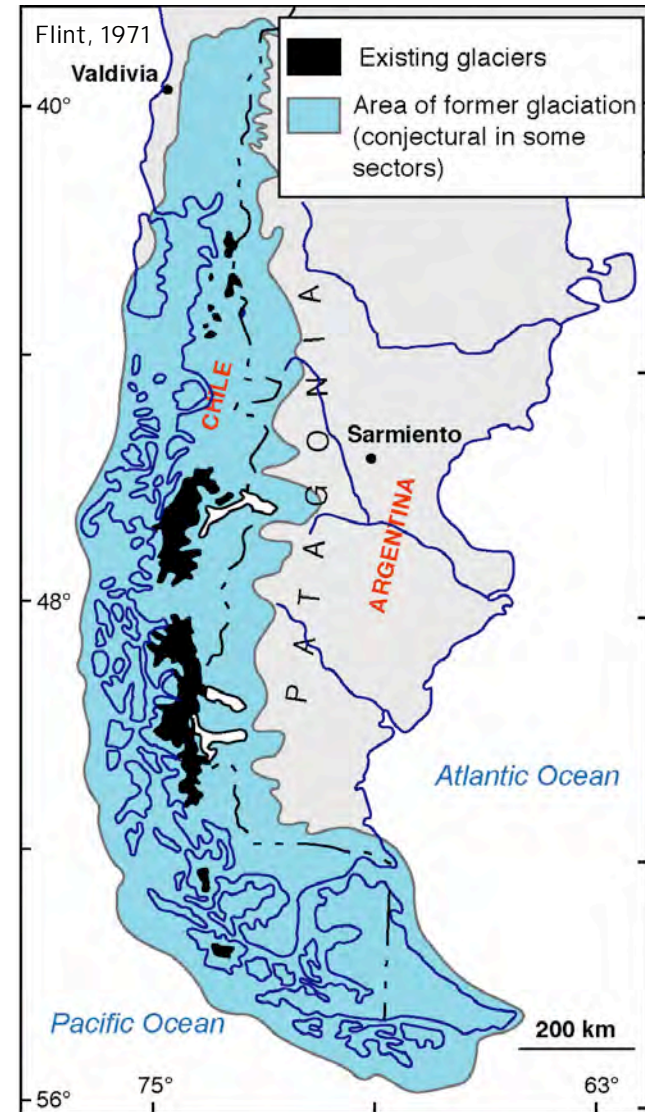
GLACIATED TERRAIN

- Drift prospecting is a common mineral exploration method in glaciated terrain
- Method dates back to observations of boulder transport in 1700s
- In the 20th century, method has contributed to significant discoveries including base metals deposits at Outokumpu, Finland, the Buchans and Bathurst VMS camps, U deposits in the Athabasa Basin, Au deposits in the Abitibi Greenstone Belt and diamond deposits in northern Canada
- Multiple glaciations the Quaternary period (last 1.9 Ma)
- Deposits sampled for mineral exploration are largely Late Wisconsinan (100,000 yrs)
- Late Glacial Maximum (LGM): 18k – 20k yrs BP

GLACIATED TERRAIN



Northern hemisphere



South America

GLACIATION



Alpine Glaciers

- Mountainous terrains
- e.g. North & South American Cordillera



Continental Glaciers

- Moderate relief terrains
- e.g. Central & Eastern North America, Fennoscandia

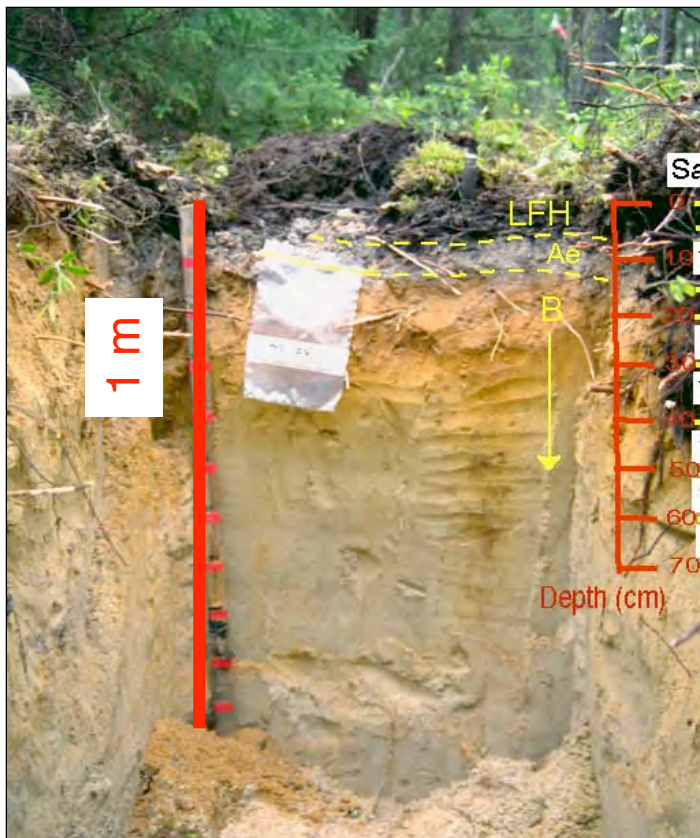
SAMPLE MEDIA IN GLACIATED TERRAIN

- Till:
 - geochemistry and indicator minerals
 - reconnaissance to local scale
- Stream sediments:
 - geochemistry, indicator minerals, water
 - reworked glacial sediments (shield), glacial seds+ bedrock (Cordillera)
 - reconnaissance to local scale
- Modern lake sediments:
 - geochemistry
 - organic lake sediments, water
 - reconnaissance to regional scale
- Soils:
 - selective leach analytical methods
 - for thick drift areas with no till
 - Scale depends on size of target
- Vegetation:
 - geochemistry
 - local scale only

GLACIATED VS UNGLACIATED REGIONS

GLACIATED

- Soil development shallow ~1 m



Northern Ontario, Canada

UNGLACIATED

- Soils can be developed to depth >100 m (regolith)



Western Australia

(Shilts, in Menzies, 1996)

GLACIATED VS UNGLACIATED REGIONS

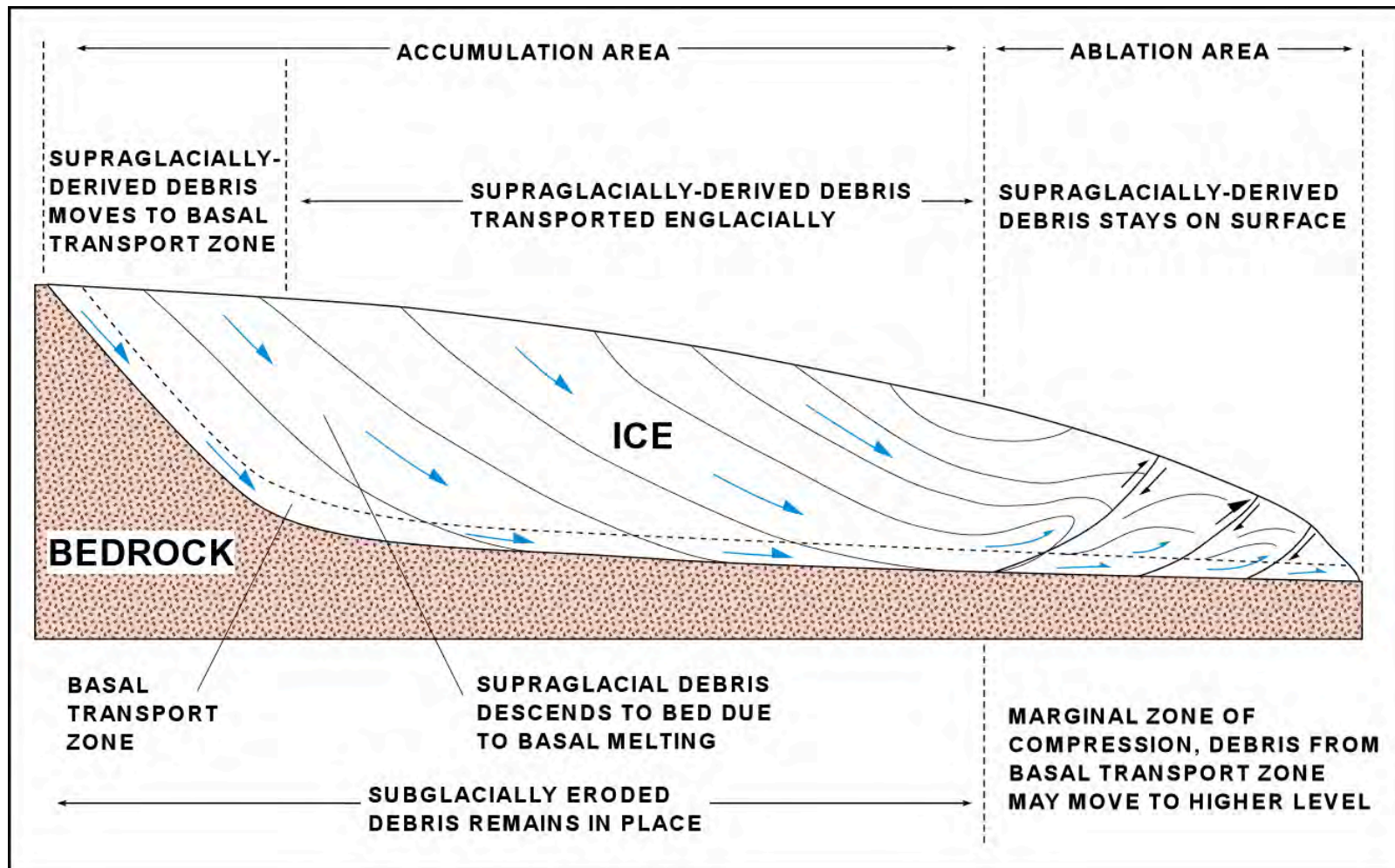
GLACIATED

- Material dispersed by glacial processes (mechanical processes)
- Dispersal patterns **not** confined to a drainage basin except in mountainous regions with valley
- Minerals of different bedrock sources can be intermixed in glacial sediments (e.g. ultramafic & granitic)
- Sediments still contain minerals that are usually broken down in the first stage of weathering (e.g. carbonates, sulphides, olivine, pyroxene)

UNGLACIATED

- Material in situ or remobilized by fluvial, eolian, or chemical processes
- Dispersal confined to a drainage basin
- More likely to have minerals of a single bedrock source
- Most of these minerals have been destroyed by soil forming processes and weathering

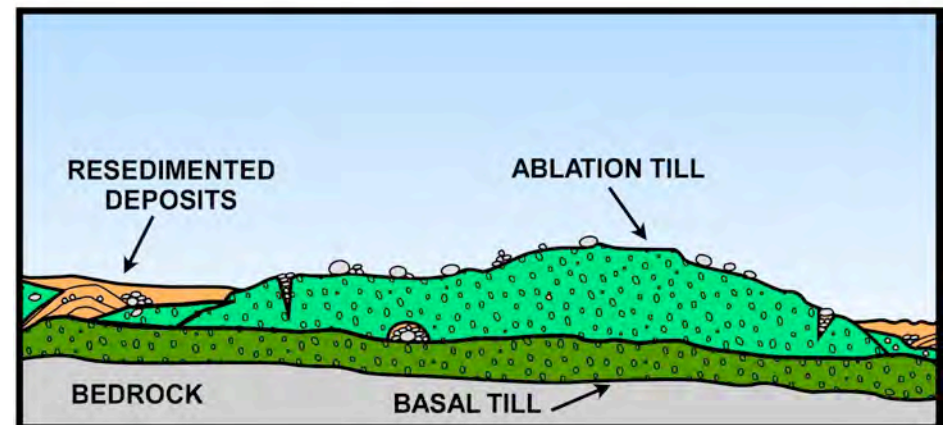
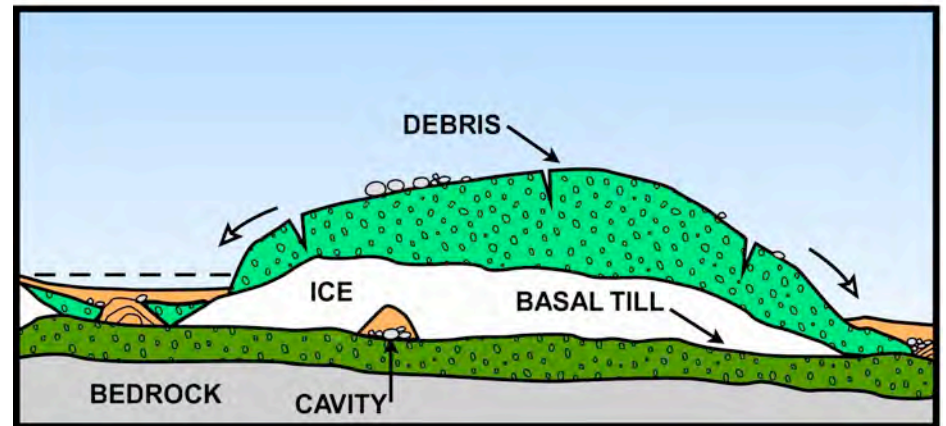
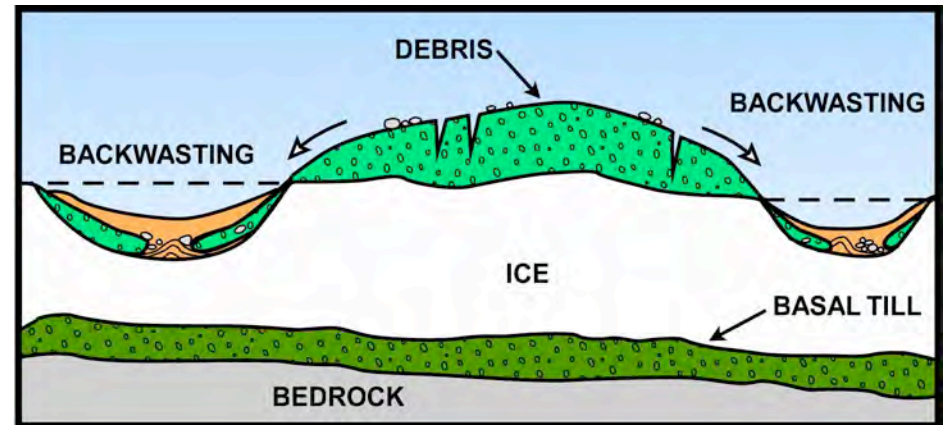
GLACIAL TRANSPORT



(Boulton 1996)

TILL DEPOSITION

- Lodgement
- Meltout
- Deformation
- Sublimation

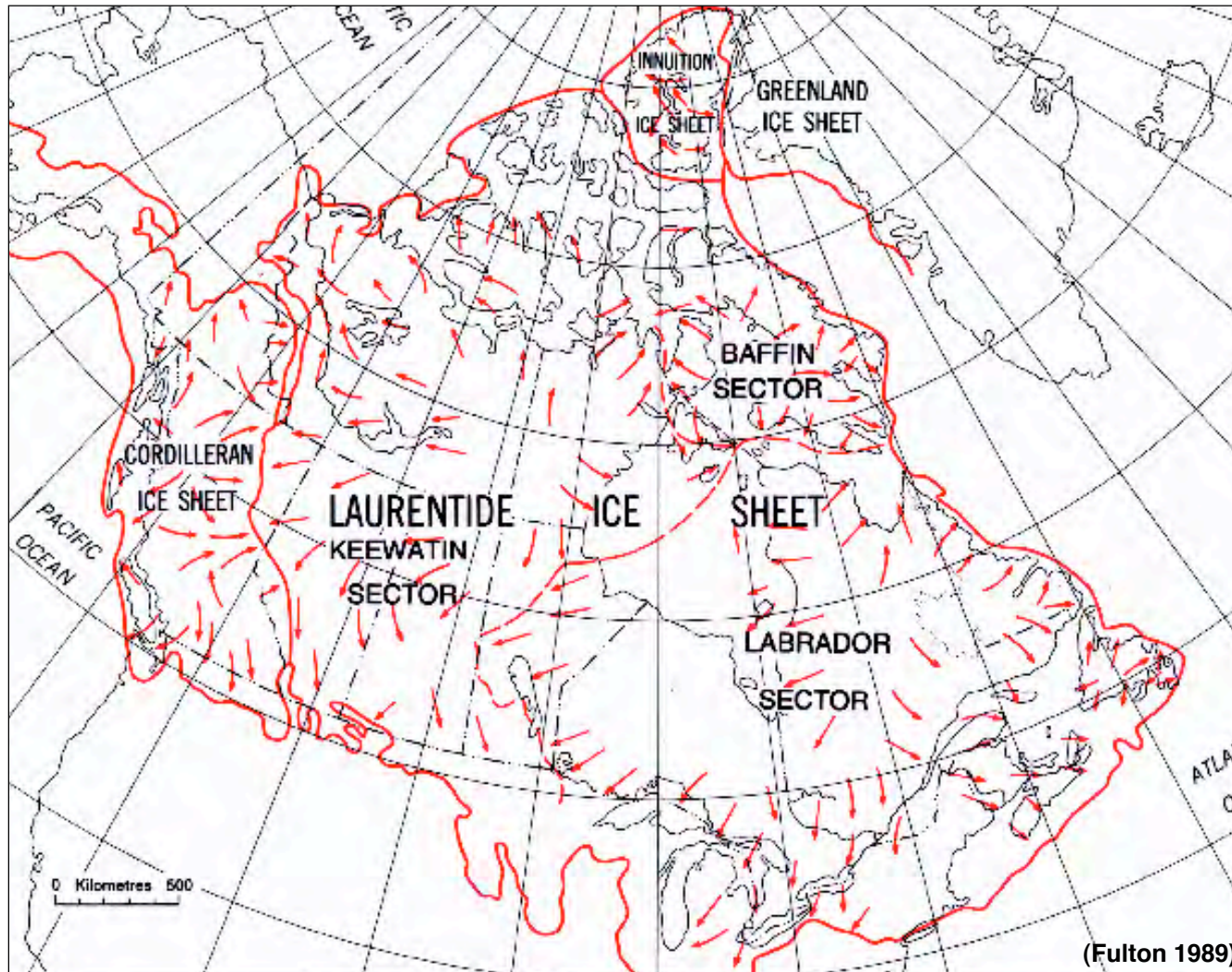


TILL

- Sediment deposited directly by ice
- Very poorly sorted
- Clay to boulder sized material
- Texture reflects source material bedrock, recycled preglacial and/or glacial sediments
- Transport distance, few m to 100 km



VARIATIONS IN ICE FLOW PATTERNS



Probable directions of ice flow at the Late Wisconsin glacial maximum

INDICATORS OF ICE FLOW DIRECTION

Erosional

- Roches moutonnées
- Whalebacks
- Rock drumlins
- Flutings
- Grooves
- Striations

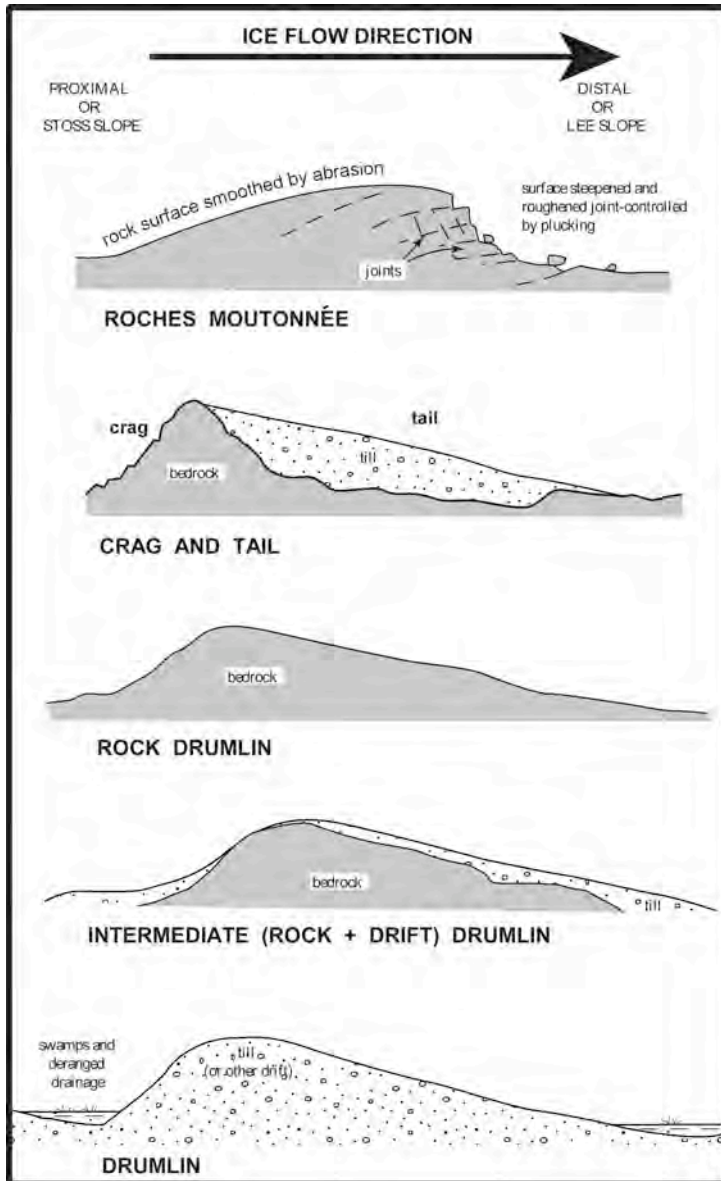
Depositional

- Drumlin ridges
- Fluted till plain
- Till clast fabric
- Dispersal train

Combined

- Crag and tail
- Bullet-shaped boulders
- Boulder pavements

LARGE ICE FLOW INDICATORS

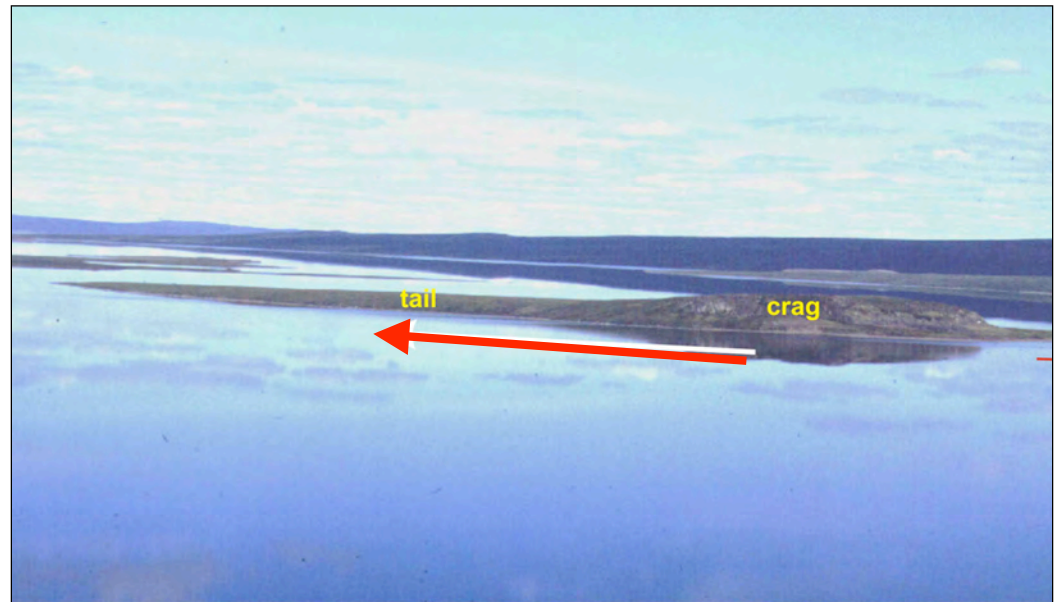


(Ryder, 1995)

- Oriented landforms visible on topographic and geological maps and air photographs
- Morphology strongly influenced by bedrock topography
- Typically occur in groups, showing a characteristic pattern on maps and air photographs
- Accentuated by vegetation and drainage
- Provides a general impression of regional flow directions

LARGE ICE FLOW INDICATORS

Crag and tail



I. McMartin

Till ridges



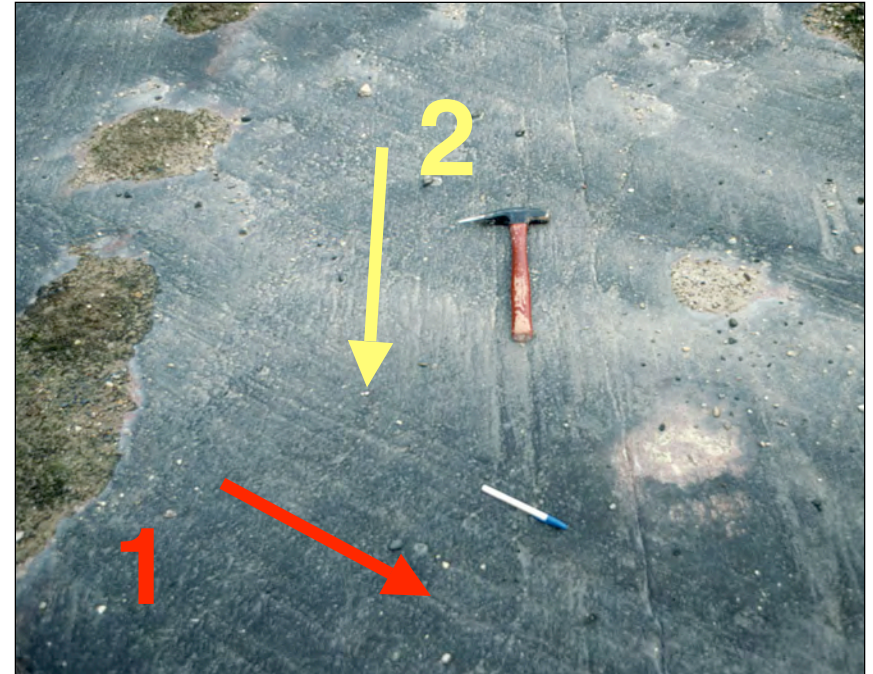
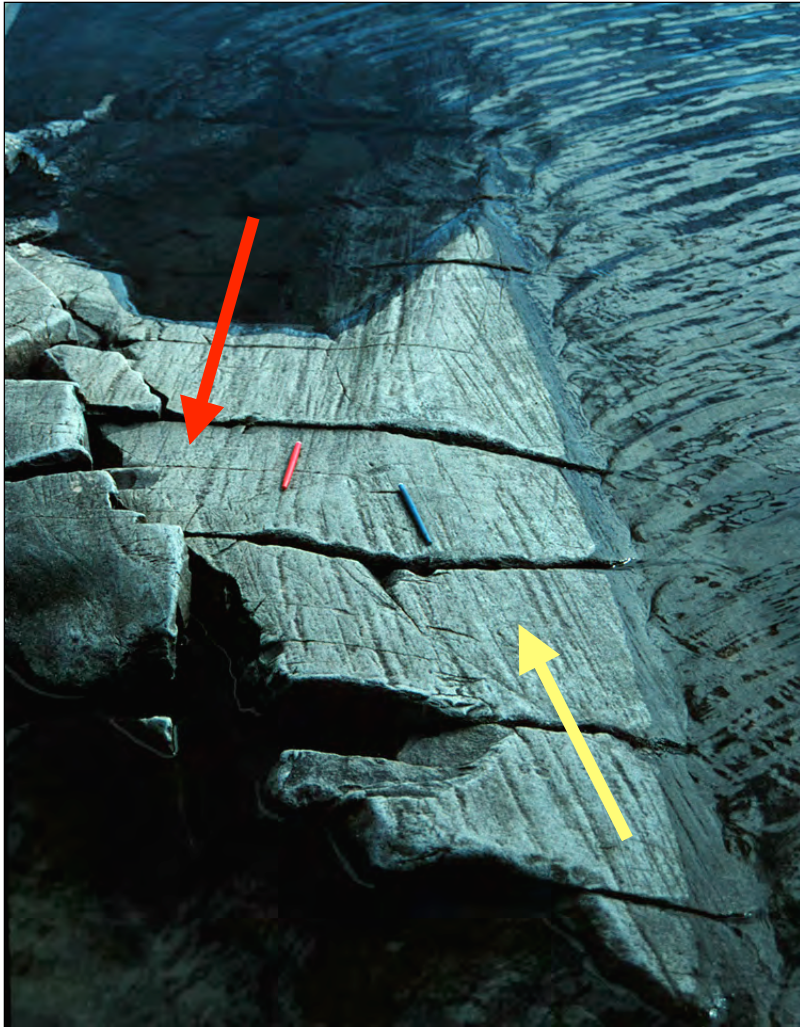
R. Paulen

Roche moutonnée



I. McMartin

STRIATIONS



I. McMartin

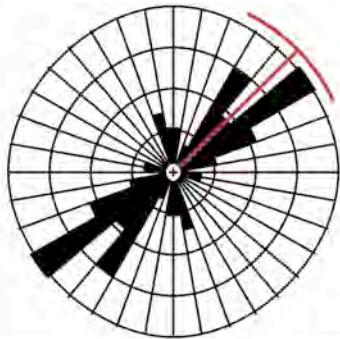
- Erosional marks on bedrock surface made by sole of glacier
- Most convenient and reliable means of determining ice-flow trends

CLAST ORIENTATION

R. Paulen

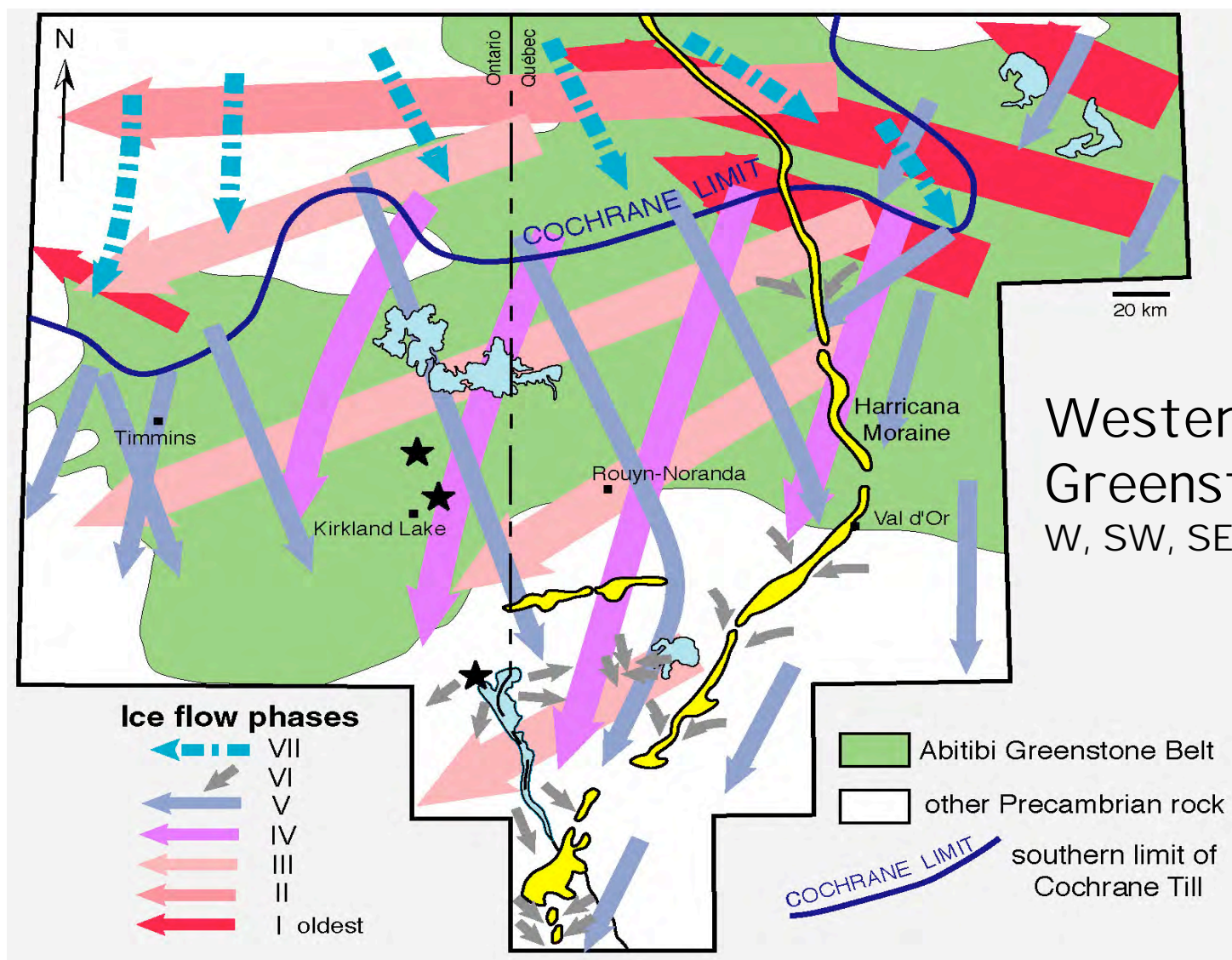


Elongated pebbles in till:
measure strike and dip (50-100)



Bullet shaped boulder in till:
measure boulder orientation & its striations

ICE FLOW RECONSTRUCTION

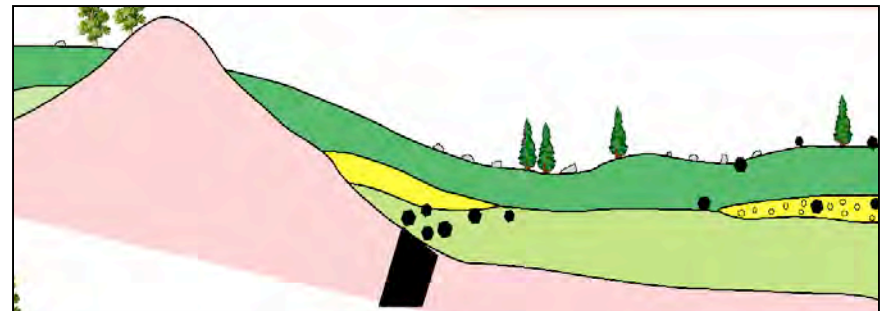
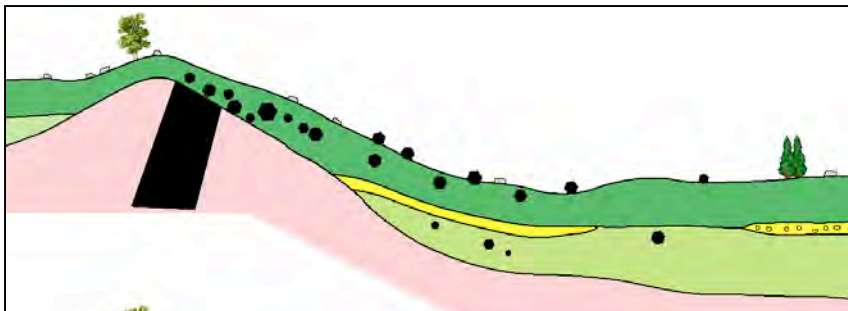


Western Abitibi
Greenstone belt:
W, SW, SE ice flow

(Veillette and McClenaghan, 1996)

GLACIAL DISPERSAL TRAINS

- Larger than their bedrock source, easier target to find
- Size and shape of train controlled by :
 - orientation of ice flow
 - size & erodibility of bedrock source
 - influence of topography on ice flow
 - till thickness, number of till units
- May be affected by post-depositional processes



MAPPING DISPERSAL



Clast fraction
(5+ mm)

- Boulders
- Cobbles
- Pebbles



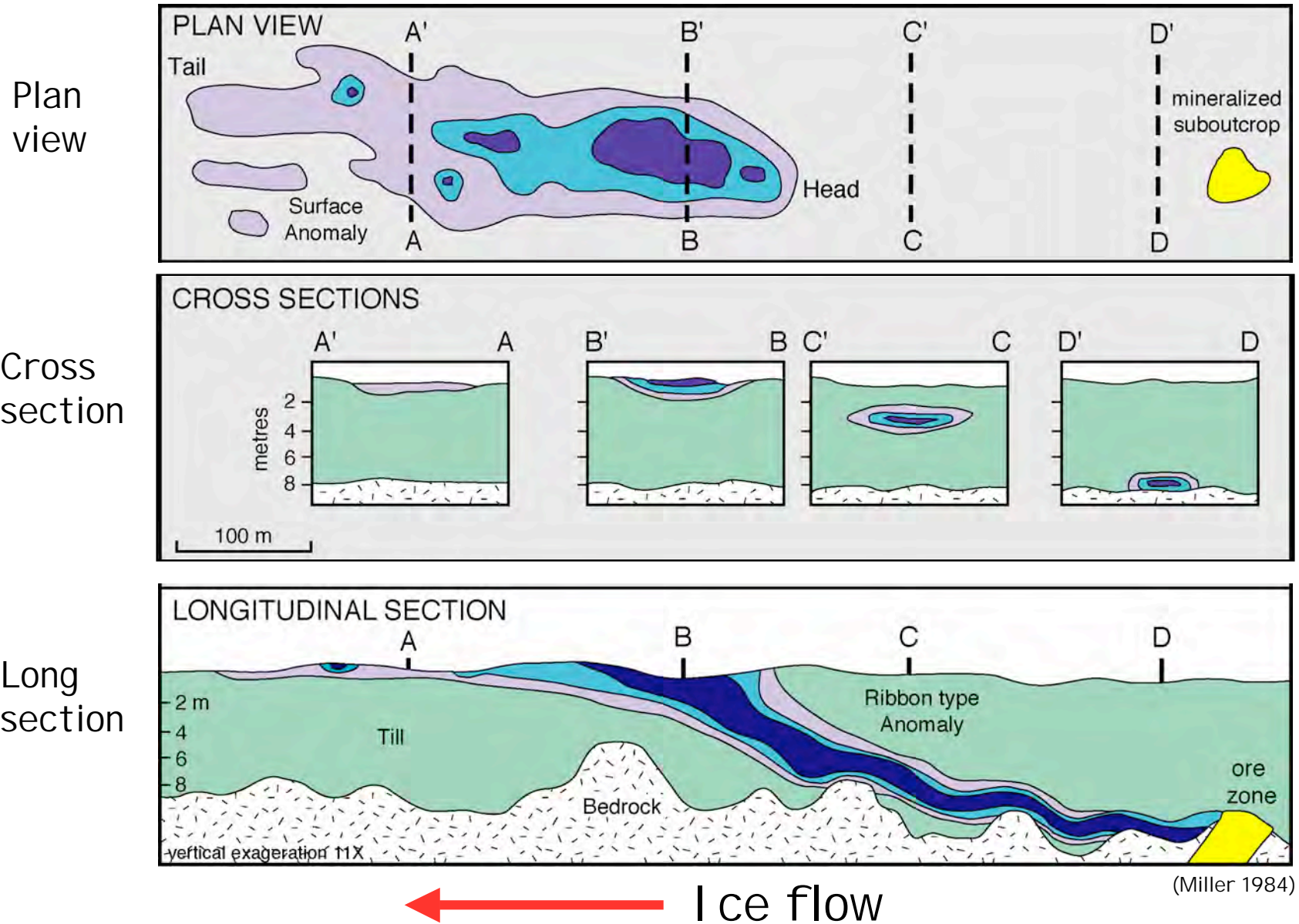
Heavy minerals
(0.25-2.0 mm)



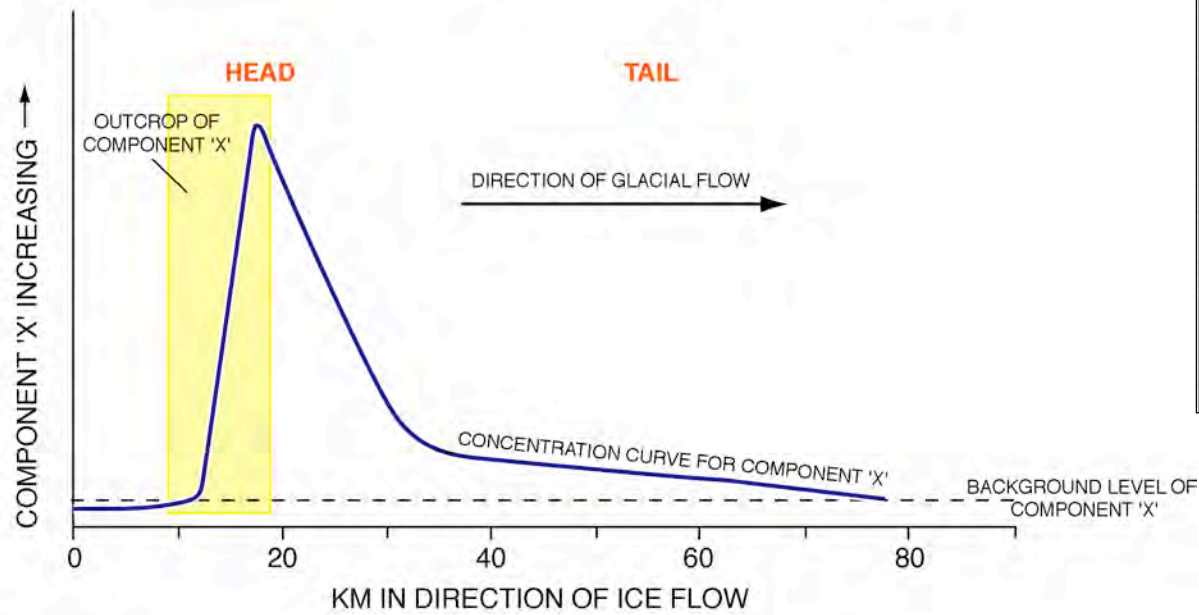
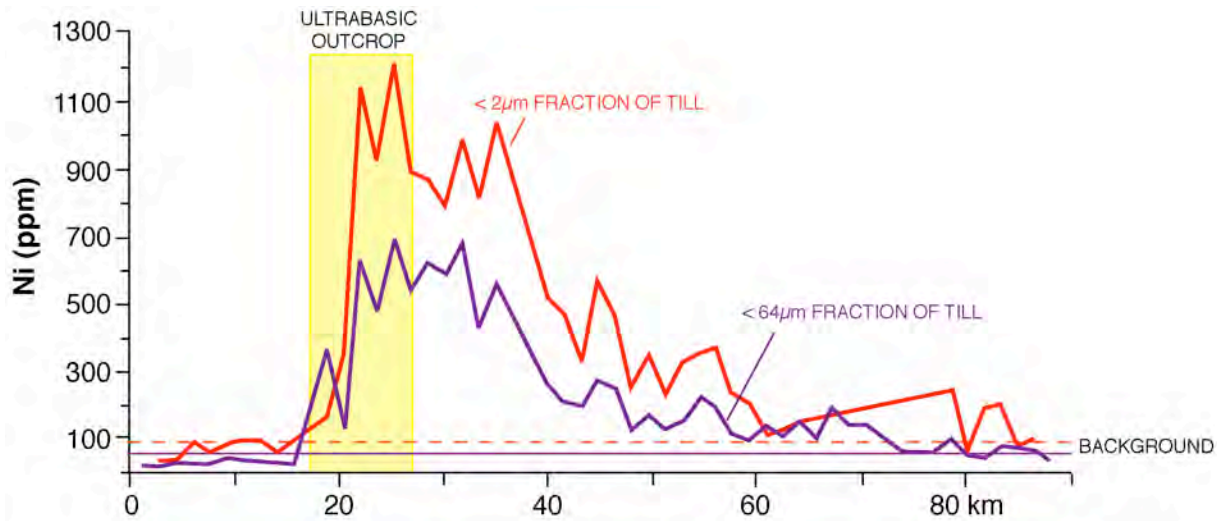
Till matrix
(<0.063 mm)

- Geochemistry
for specific elements

IDEAL MODEL OF GLACIAL DISPERSAL TRAIN

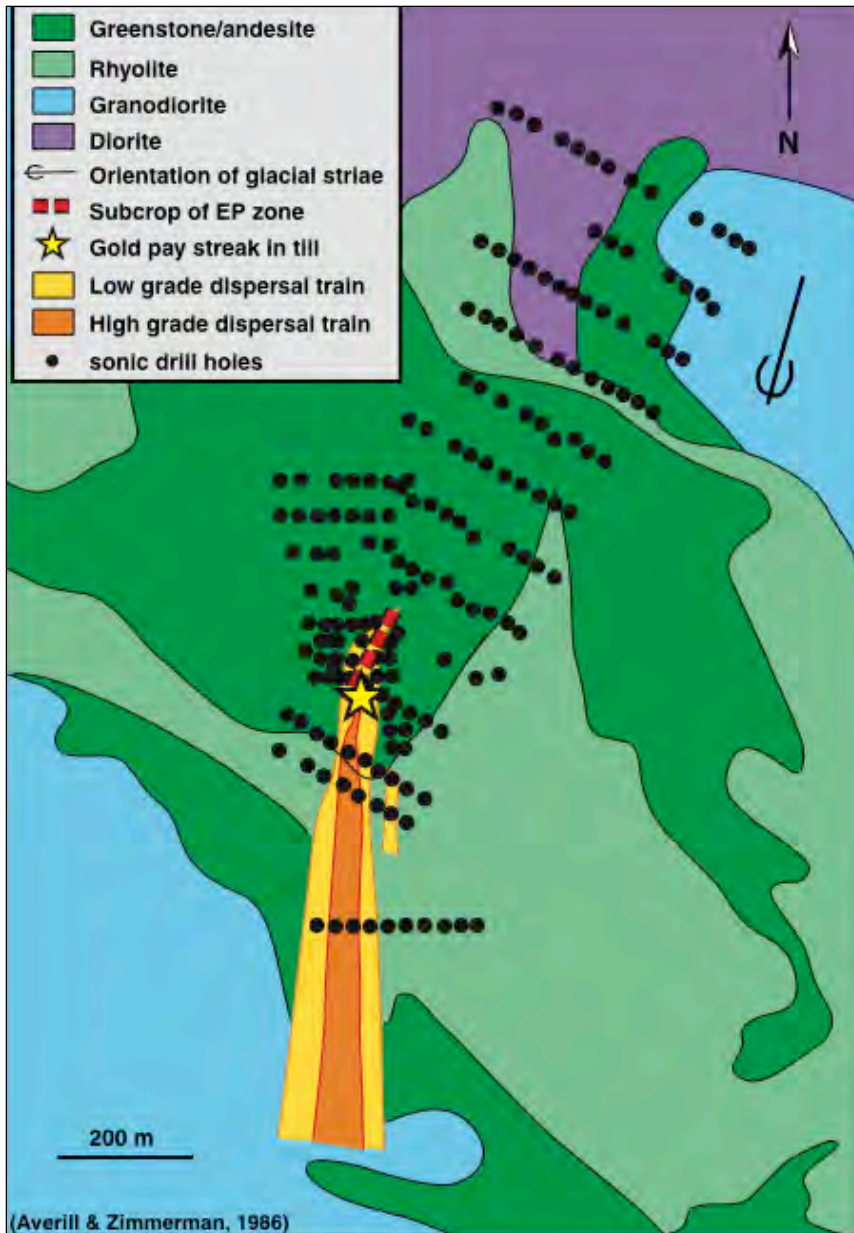


MODEL OF GLACIAL DISPERSAL TRAIN

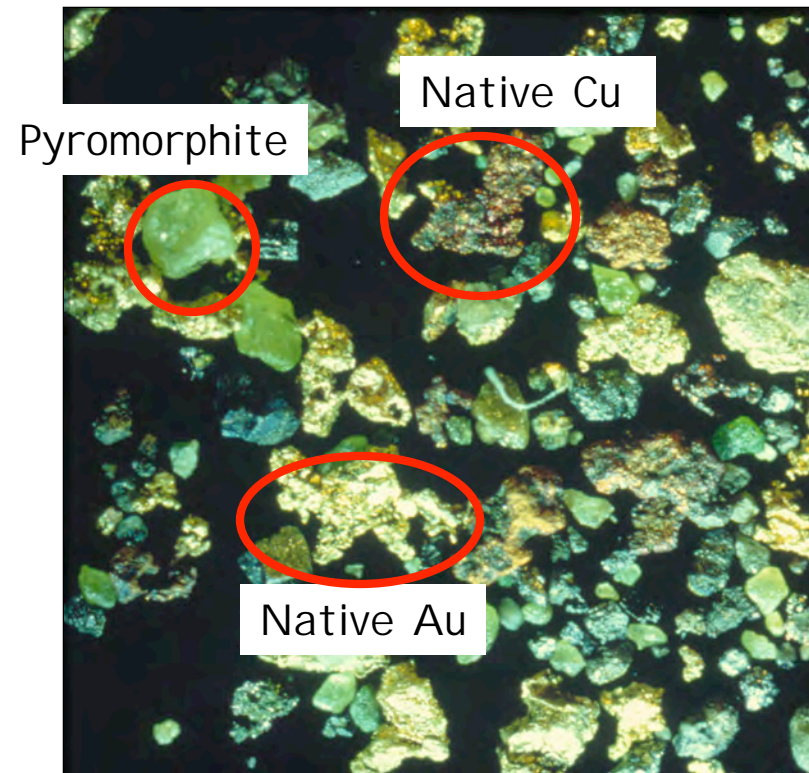


(Shilts, 1976)

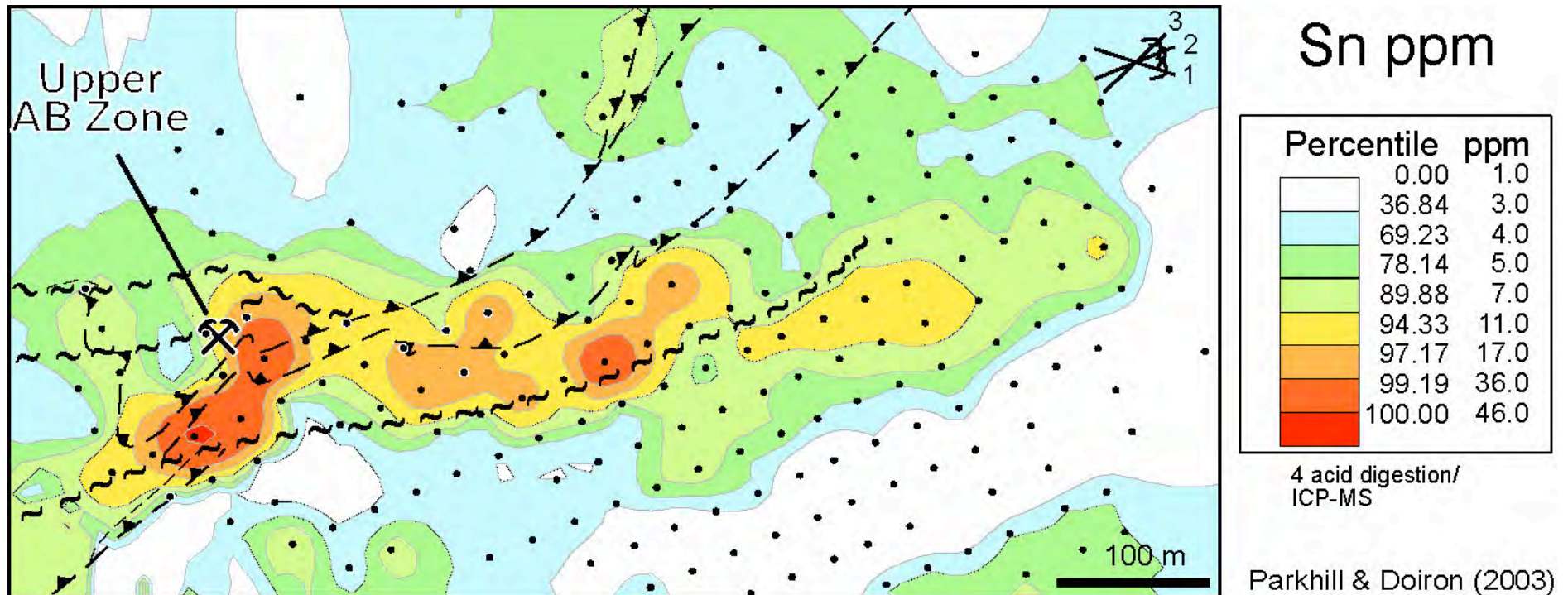
WADDY LAKE, SASKATCHEWAN



- Archean volcanic-hosted Au deposit
- Ribbon-shaped train
- Indicator minerals: pyromorphite (Pb-PO_4), gold and native grains
- Dispersal distance >500 m

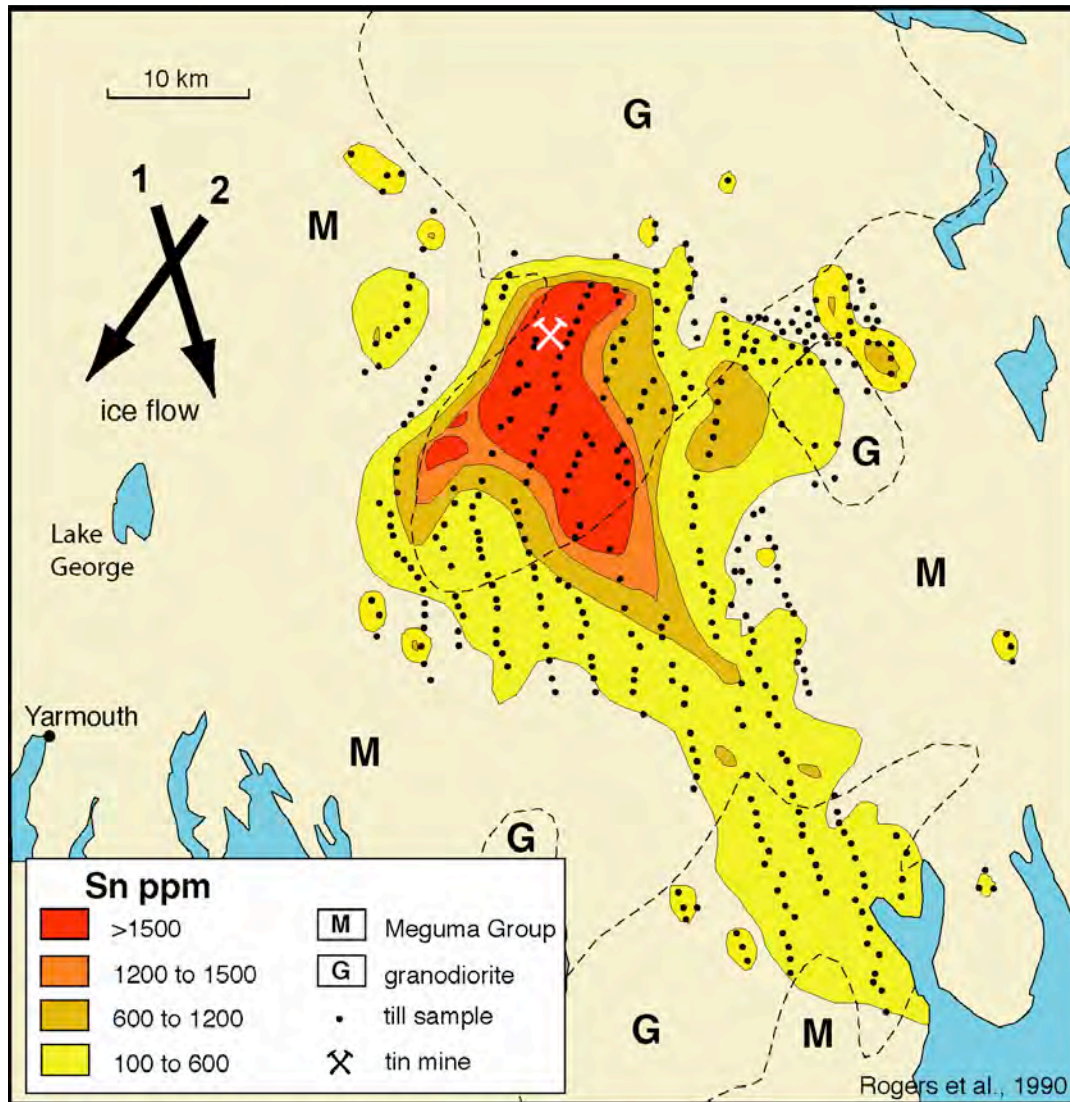


HALFMILE LAKE ZN-PB-CU DEPOSIT, BATHURST, NEW BRUNSWICK



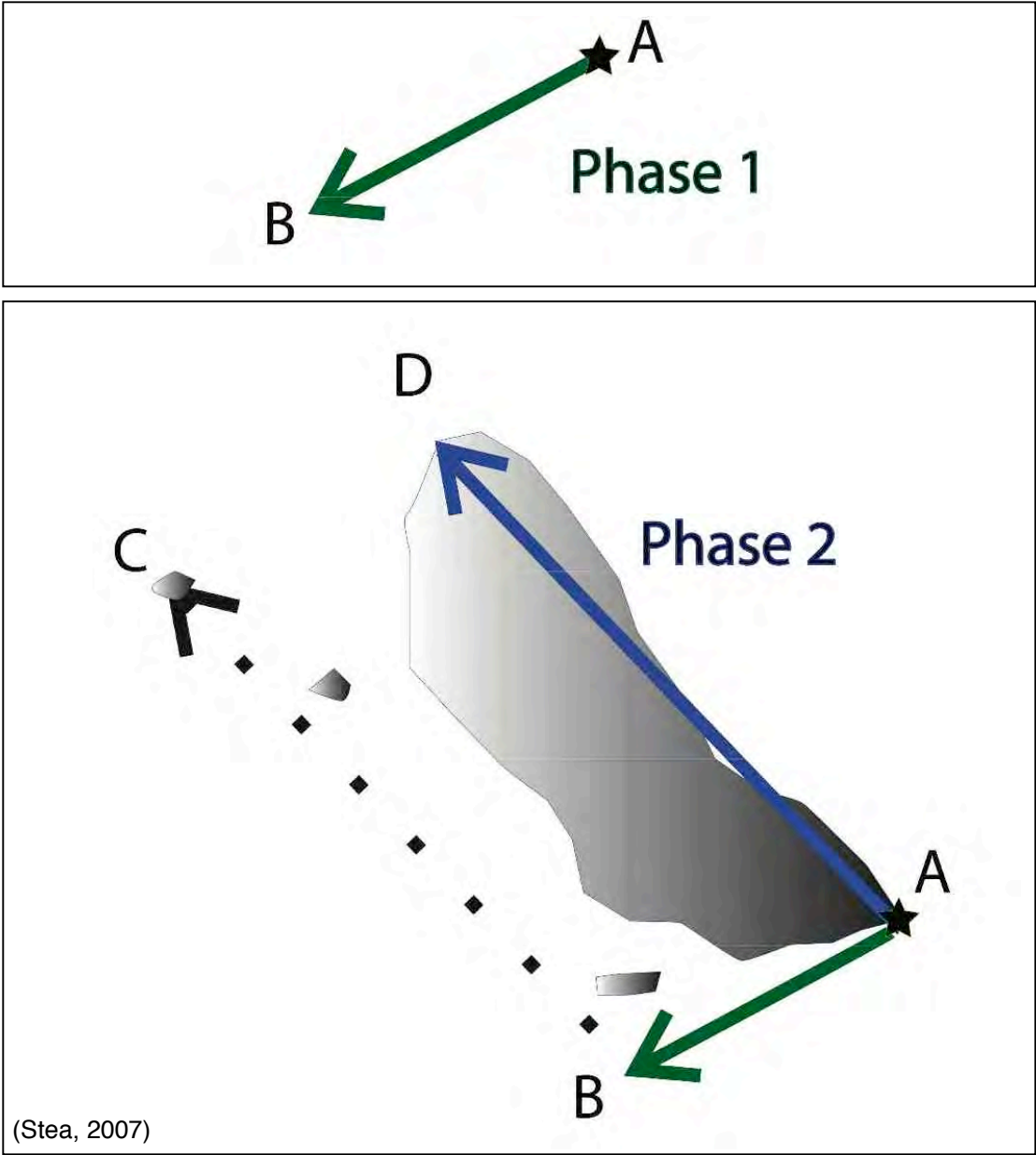
- VHMS Cu-Pb-Zn deposit
- Ribbon-shaped train, ENE ice flow
- Matrix geochemistry: Sn <0.063 mm fraction
- Dispersal distance ~500 m

EAST KEMPTVILLE TIN MINE, NOVA SCOTIA

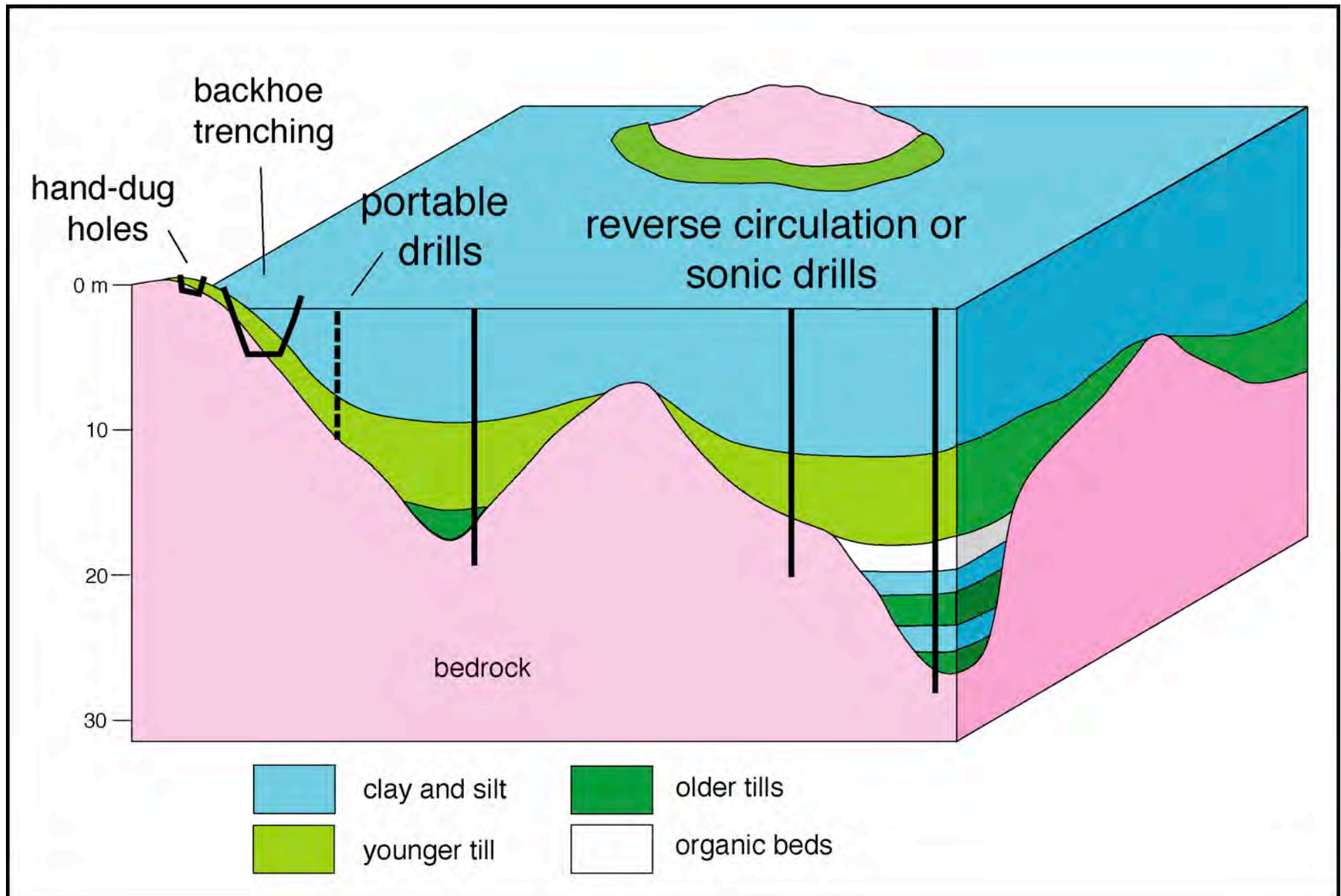


- Tin deposit hosted in granite
- Fan-shaped dispersal train
- Two ice flow phases, SE, SW
- Matrix geochemistry:
Sn < 0.063 mm
- Dispersal distance > 50 km

MODEL OF MULTI-PHASE GLACIAL DISPERSAL



TILL SAMPLING STRATEGIES

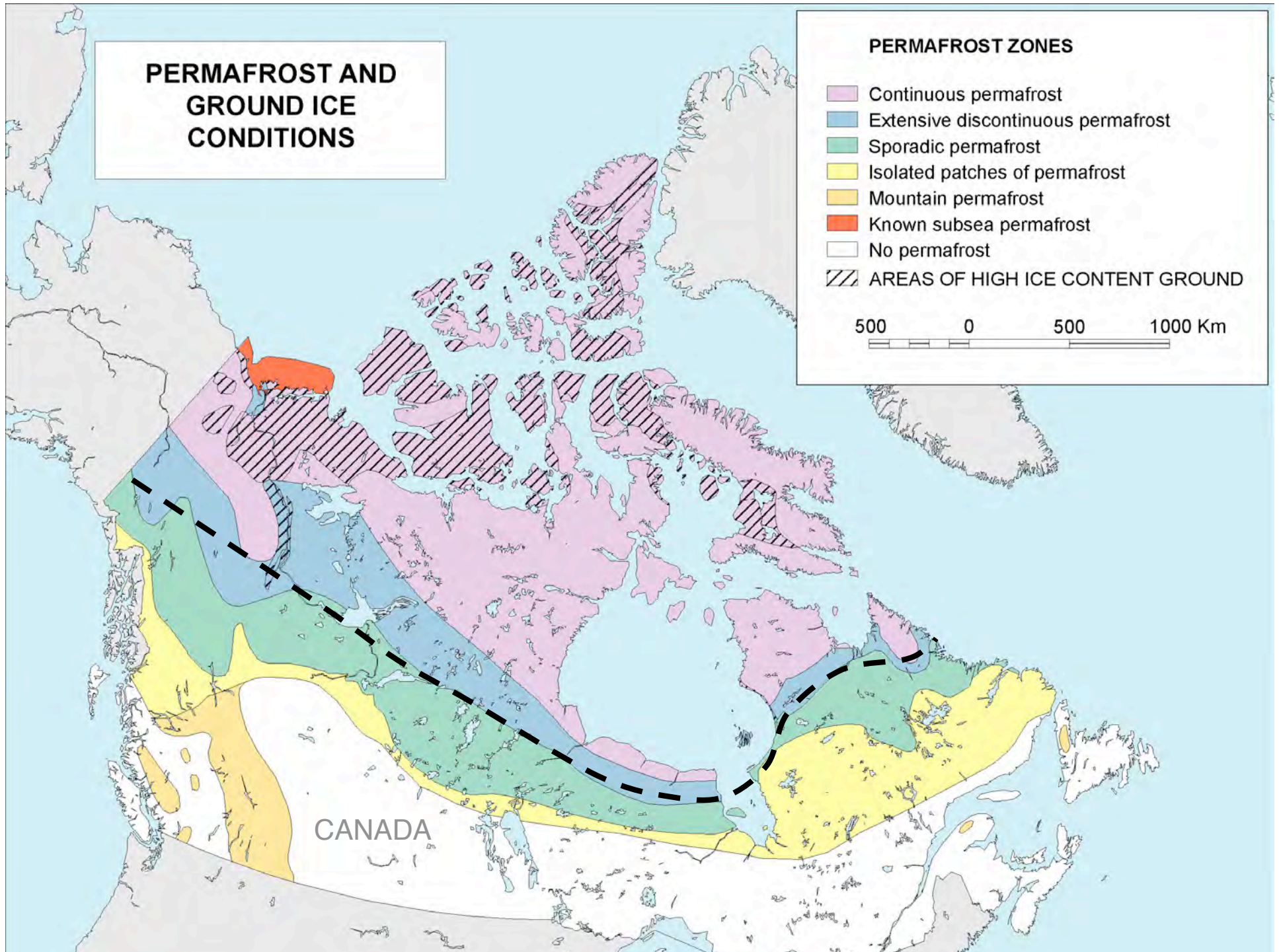


PERMAFROST AND GROUND ICE CONDITIONS

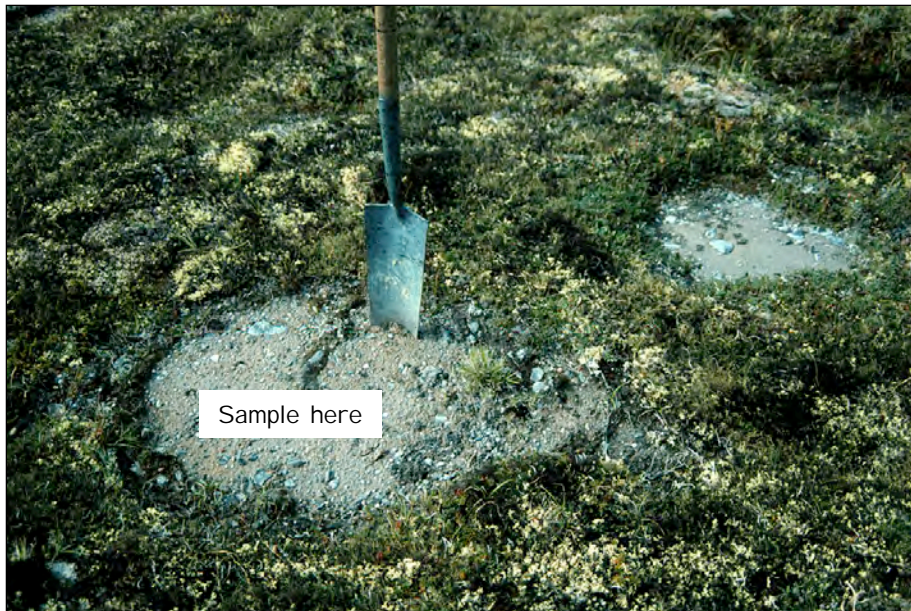
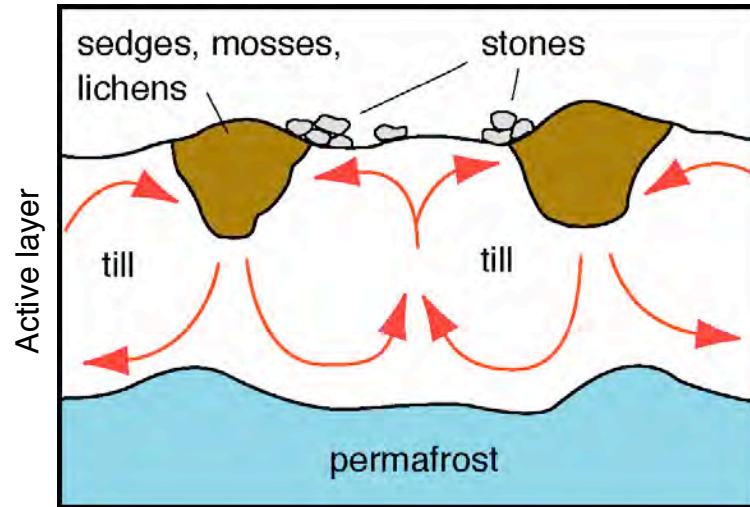
PERMAFROST ZONES

- Continuous permafrost
- Extensive discontinuous permafrost
- Sporadic permafrost
- Isolated patches of permafrost
- Mountain permafrost
- Known subsea permafrost
- No permafrost
- AREAS OF HIGH ICE CONTENT GROUND

500 0 500 1000 Km



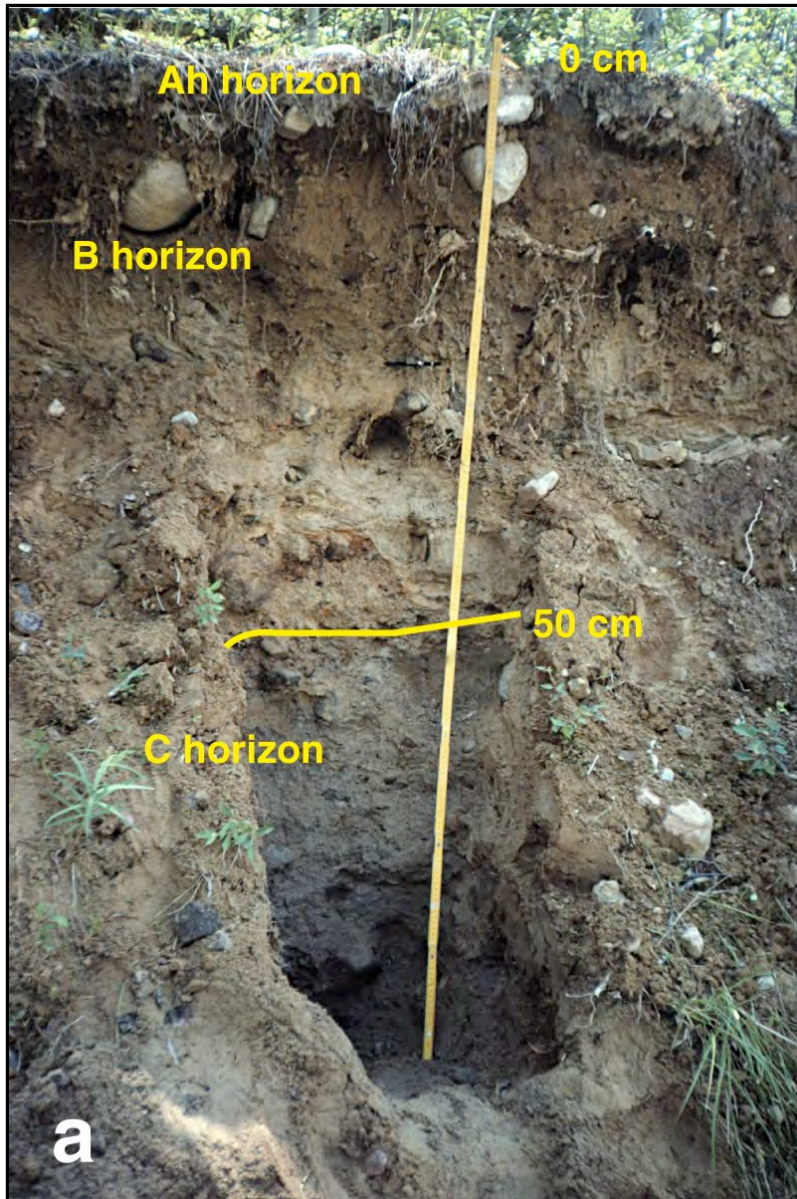
PERMAFROST TERRAIN: MUDBOILS



I. McMartin



FORESTED AREAS



Black-brown organic mineral soil

Orange-brown, highly oxidized
Fe & Mn-rich B horizon

Grey, unoxidized C horizon

HAND EXCAVATION

- Till at surface
- Flanks of bedrock outcrop
- Road cut exposures
- Lake, river exposures along shorelines



I. McMartin



I. McMartin

TRENCHING



PORTABLE SOLID STEM AUGER



R. Paulen



R. Paulen

HOLLOW-STEM AUGER



R. Paulen

WET-ROTARY DRILL



R. Paulen

ROTASONIC DRILL



- overburden 10 to 125 m thick
- stony/bouldery till
- detailed stratigraphy
- continuous 9 cm core
- high costs



REVERSE CIRCULATION DRILL

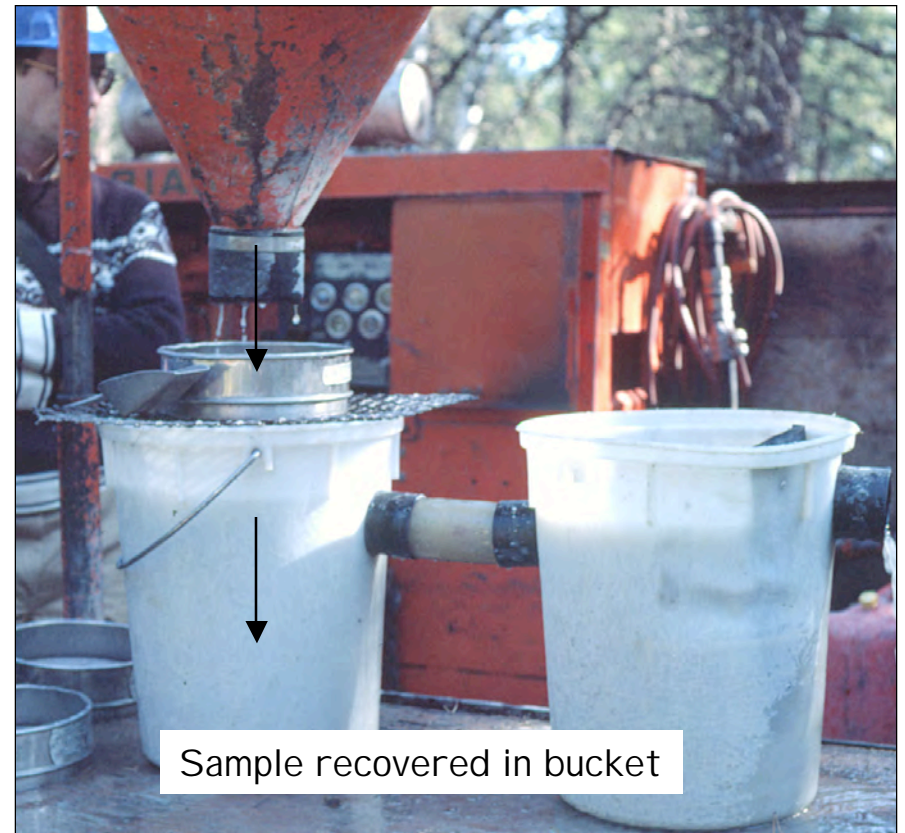
- Overburden 10 to 125 m thick
- Stony/bouldery till
- Tricone bit
- Mud and chip slurry
- Clay-sized material lost



Tricone bit



+10 mesh on screen for logging



Sample recovered in bucket

TILL SAMPLE WEIGHT

Sample weight depends on analytical methods:

- Till geochemistry - 2 to 5 kg
- Indicator minerals - 10 to 50 kg
 - Clay-rich till, sand content <20%, 25 to 50 kg sample
 - Sandy-till, sand content >30%, 10 to 25 kg sample

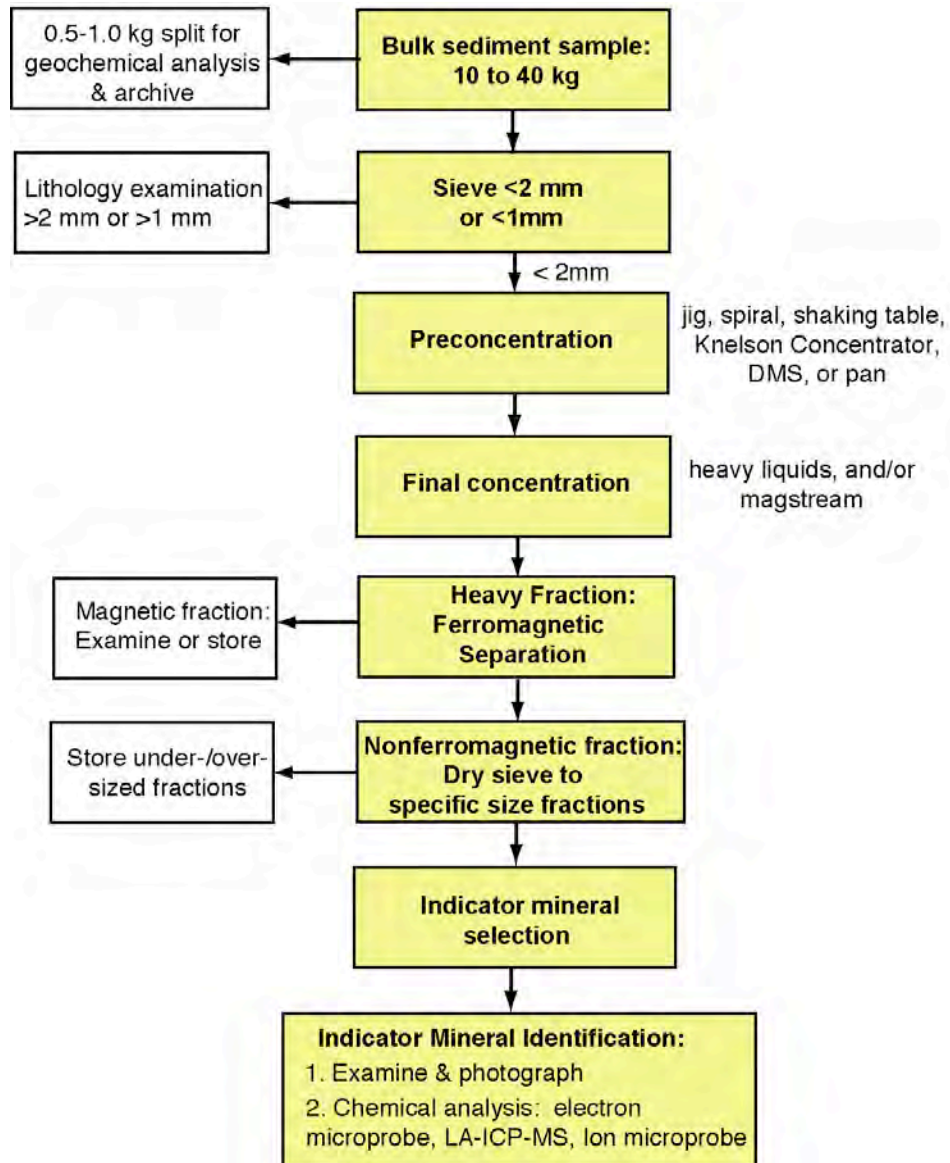
40 kg sample



10 kg sample



SAMPLE PROCESSING & ANALYSIS FLOWSHEET



B. Coker

INDICATOR MINERALS

Definition: Mineral that suggests the presence of a deposit, alteration or lithology

Physical Characteristics:

- Occur mainly in host rock
- Visually and chemically distinct
- Moderate to high density
- Silt to medium sand-sized (0.10 to 2.0 mm)
- Survive weathering
- Survive clastic transport

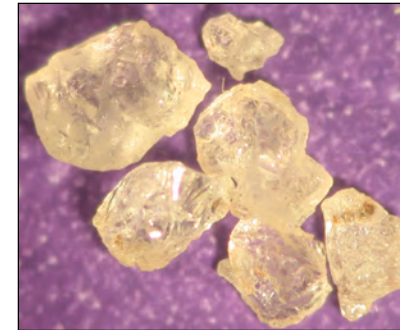


COMMON INDICATOR MINERALS

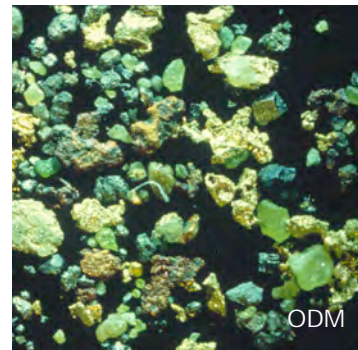
- Gold grains (Au)
- Native copper (Cu)
- Kimberlite indicator minerals
- Platinum Group minerals (PGM)
- Sulphide minerals
- Metamorphosed massive sulphide minerals- e.g. gahnite
- Magmatic Ni-Cu-PGE minerals
- Scheelite (W)
- Cassiterite (Sn)
- Cinnabar (Hg)
- Fluorite, topaz (F)
- Uranium minerals
- Rare earth element (REE) minerals



Kimberlite indicator minerals



Topaz



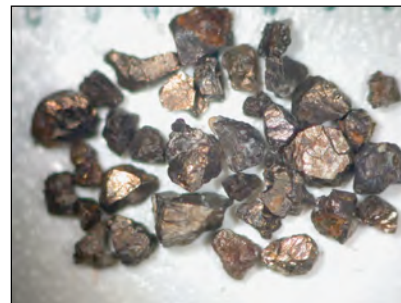
Gold, native copper, pyromorphite



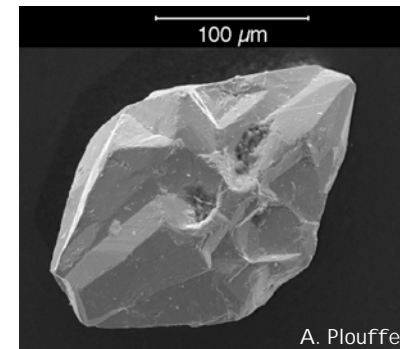
Gahnite

ODM

- May be recovered from same heavy mineral concentrate, depends on processing methods used
- Selected from sample all at same time, or during re-examination



Pentlandite



Cinnabar

A. Plouffe

SAMPLE PROCESSING

- Reduce sample volume
- Recover heavy mineral fraction
- Reduce volume of heavy mineral fraction to examine
- Recover & analyze indicator minerals



10 to 40 kg sample



10s to 1000s indicator mineral grains

STEP 1

Disaggregate
& homogenize



Cement mixer

STEP 2

Screen off gravel fraction

- >4 mm (5 mesh)
- >2 mm (10 mesh)
- >1 mm (20 mesh)
- Retain gravel for pebble counts



Stainless steel sieves

STEP 3: PRECONCENTRATION

Size Screening

- silt to very coarse sand (0.1 to 2.0 mm)

• Density Separation

- Jig, pan, spiral, wheel
- Dense media separator (DMS)
- Shaking table (Wilfley table)
- Knelson Concentrator

• Magnetic Separation

- Separate ferromagnetic fraction



B. Coker

Dense media separator



Shaking Table



Spiral concentrator



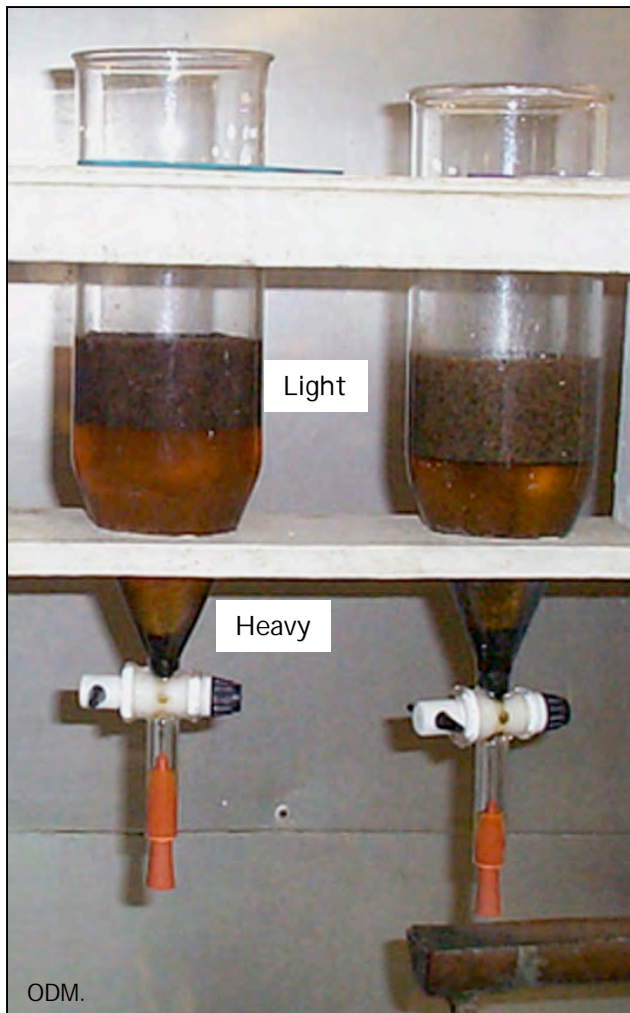
P. Sarala

Knelson concentrator



M. Lehtonen

STEP 4: FINAL CONCENTRATION



- Preconcentrate (step 3) further processed using heavy liquid
- Exact separation at a specific density, light minerals float, heavy minerals sink
- Heavy liquids commonly used:
 - Methylene iodide (MI) SG=3.3
 - Diluted MI SG=3.2
 - Tetrabromoethane (TBE) SG=2.96
 - Na-polytungstate SG 2.82-2.95
- Lower limit for kimberlite indicator minerals is SG 3.2, to include Cr-diopside and forsteritic olivine

STEP 5: REMOVAL OF FERROMAGNETIC MINERALS

Purpose: reduce volume of material to examine for indicator minerals



Hand magnet



Magnetic separator

STEP 6: ADDITIONAL PROCESSING

Purpose: reduce picking volume & time

- Sizing, e.g. 0.25-0.5 mm; 0.5-2.0 mm
- Magnetic susceptibility (paramagnetic separation)
- Magstream



Carpco magnetic separator

STEP 7: INDICATOR MINERAL SELECTION

- Visual identification of possible & probable indicator minerals using binocular microscope
- Grain morphology & surface textures: binocular microscope, SEM
- Examine entire HMC or portion (normalize to full weight HMC)
- Select indicator minerals for chemical analysis



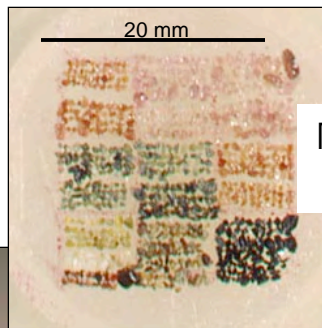
ODM



KIM Dynamics

STEP 8: MINERAL CHEMISTRY

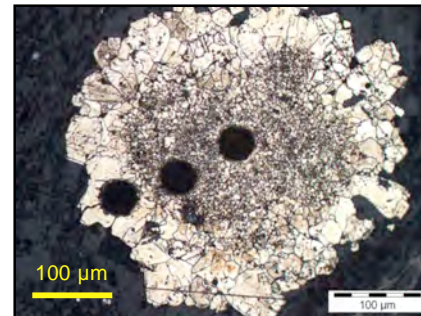
- Quantitative major & trace element analysis
- Confirm visual mineral identification, evaluate deposit grade, deposit genesis & alteration
- e.g. kimberlitic chromite & Mg-ilmenite difficult to identify visually
- Mount & polish selected grains (25 mm epoxy mounts)
- SEM, EMP, LA-ICP-MS, SIMS



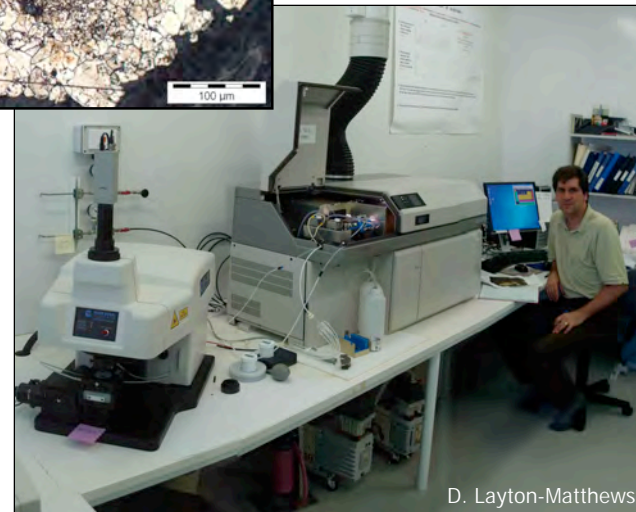
Mineral grains mounted for probe analysis



Electron microprobe (EMP)



Pyrite framboid with laser ablation pits

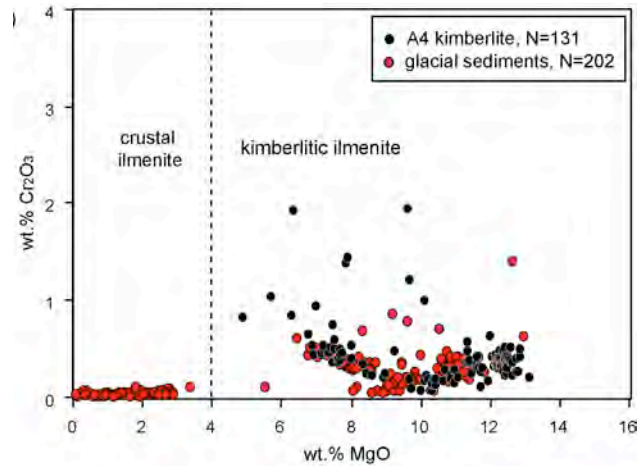


D. Layton-Matthews

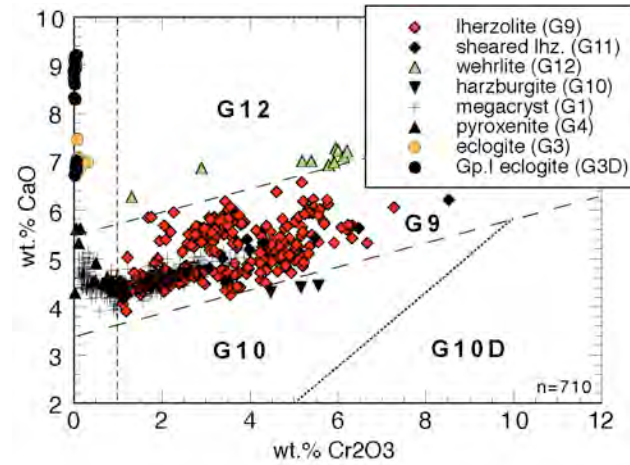
LA-ICP-MS, CODES

KIMBERLITE MINERAL CHEMISTRY

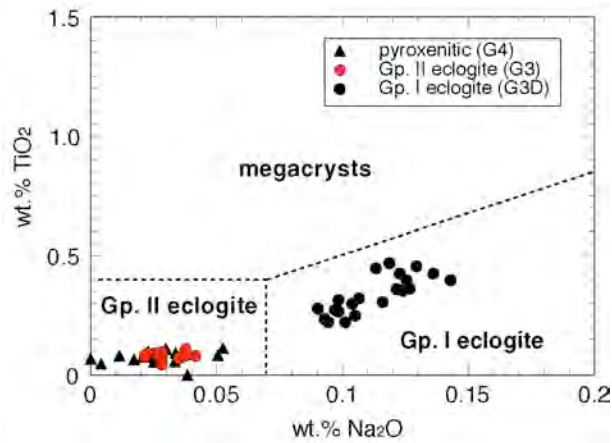
Mg-ilmenite



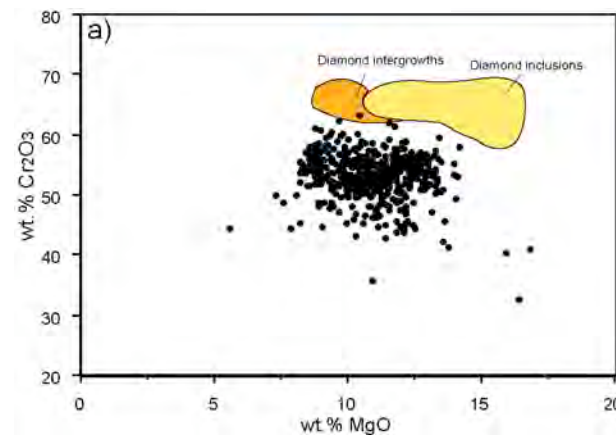
Garnets



Eclogitic garnets



Chromite



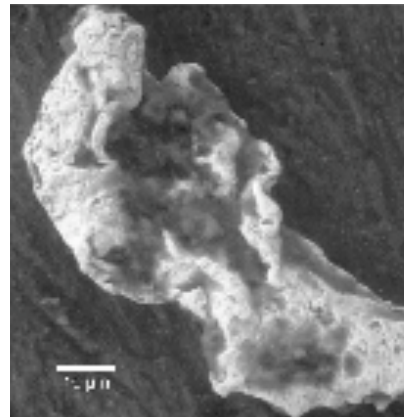
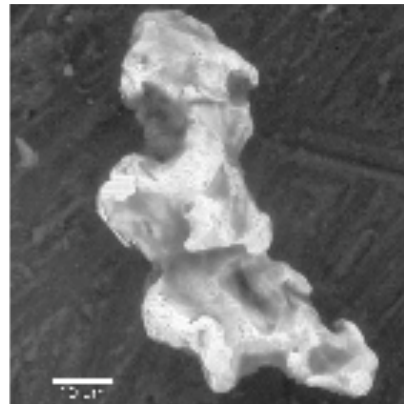
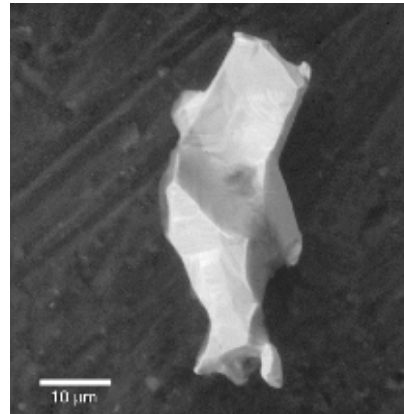
Also discrimination plots for olivine, Cr-diopside...

INDICATOR MINERALS

Surface Features



Kelyphite rims (k) on Cr-pyrope



Grain Shape

Pristine gold grains



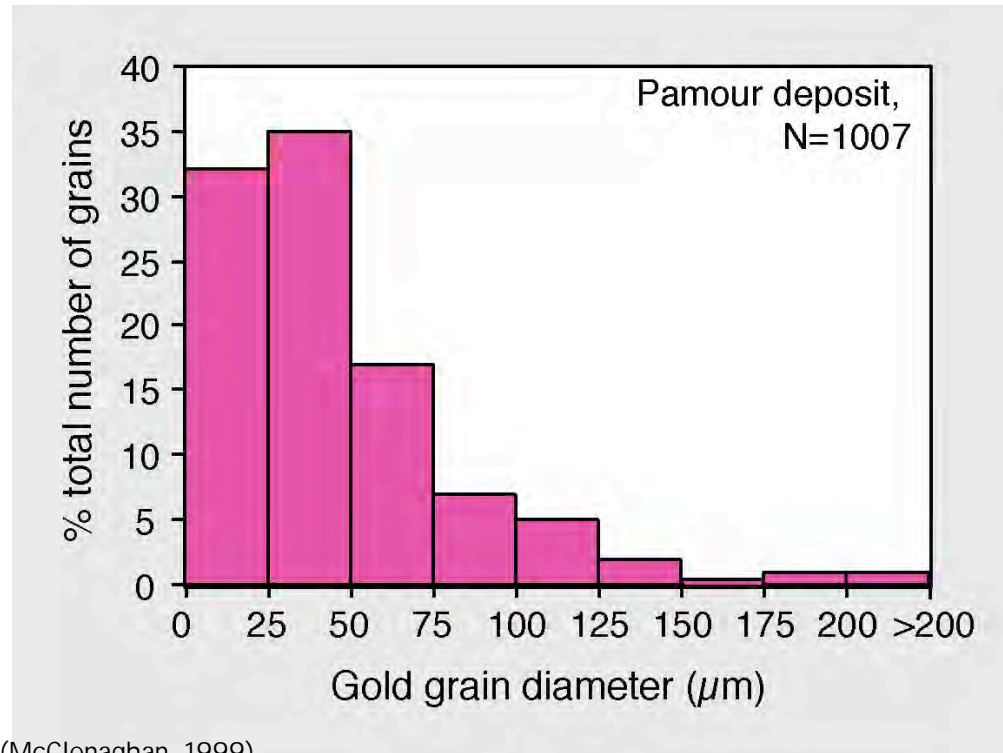
Modified gold grains



Reshaped gold grains

Increasing transport distance

INDICATOR MINERALS



Grain size

- Visible gold grains in till, Pamour Mine, No. 5 open pit, Timmins
- Grains fine sand to silt sized
- Most grains $<50 \mu\text{m}$
- Typical of Archean quartz vein-hosted lode gold deposit

QUALITY CONTROL

- QC program indicator mineral processing & analysis as outlined in “Mineral Exploration Best Practices Guidelines” in Canada
- Tour heavy mineral processing and picking labs
- Use blanks, field duplicates, spiked samples, repick ~5-10%
- Use same/similar labs for duration of project to allow comparison of results over several batches/years
- Report raw counts, as well as normalized counts
- Report indicator mineral abundances with respect to sample weight for interpretations on maps, figures etc..., e.g. 100 grains/10 kg

Mineral Exploration Best Practices Guidelines

Sampling Methods

- Appropriate, sufficient material collected
- Drill logs/field notes
- Photographic record

Sample security

- Secure storage, and shipping

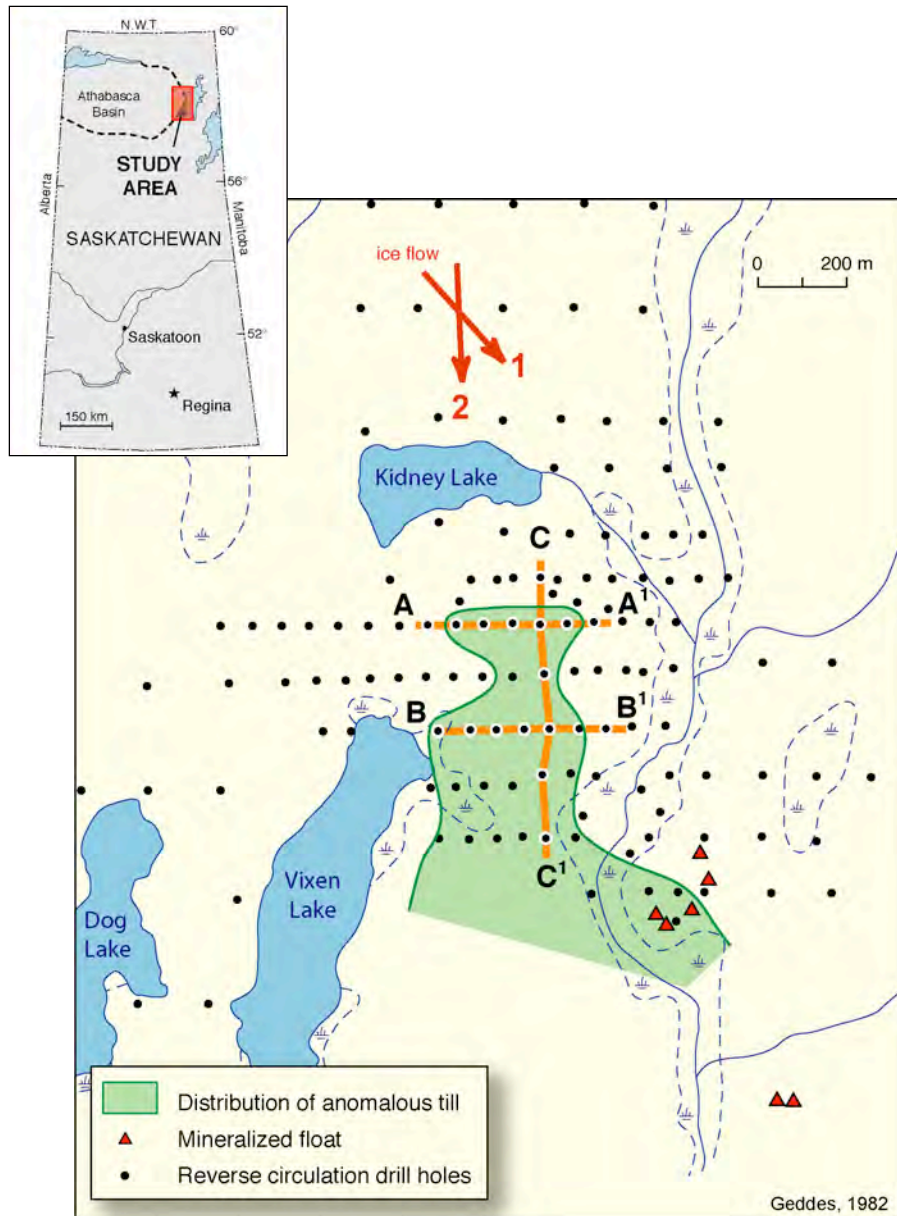
Sample preparation

- Till matrix geochemistry- sieving
- Indicator mineral processing & recovery of heavy minerals
- Indicator mineral selection
- Methods appropriate, quality control monitored

Analysis & Testing

- Till matrix - geochemical analysis
- Mineral chemistry analysis
- Methods appropriate, quality control monitored

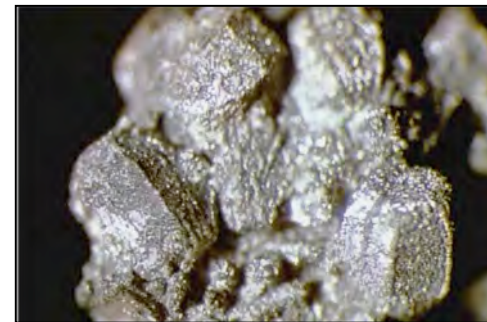
ATHABASCA BASIN, SASKATCHEWAN



Key Lake area, uranium deposits

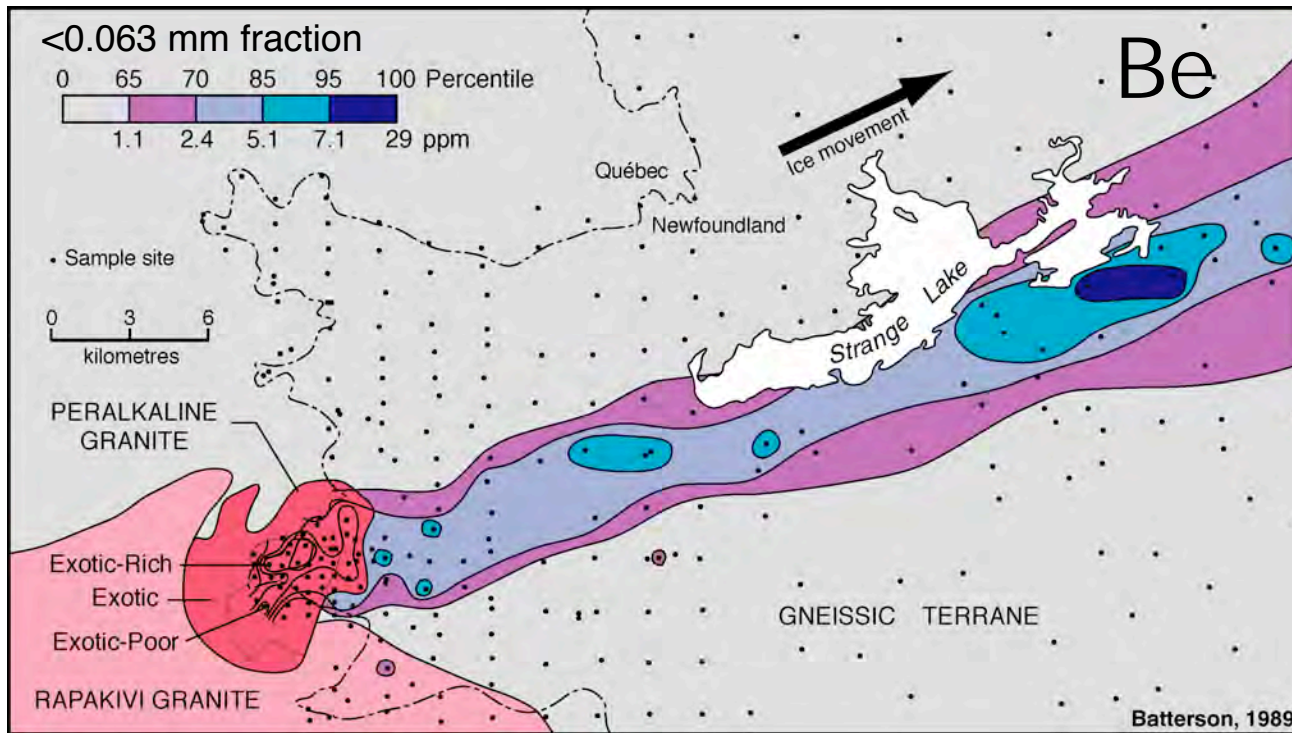
- Fan shaped dispersal train defined by boulders, till geochemistry & indicator minerals
- Train separated by 13 km gap from bedrock source
- Indicator minerals: niccolite (NiAs), hematite
- Till Geochemistry: U, Ni, As

Niccolite



(Webmineral.com)

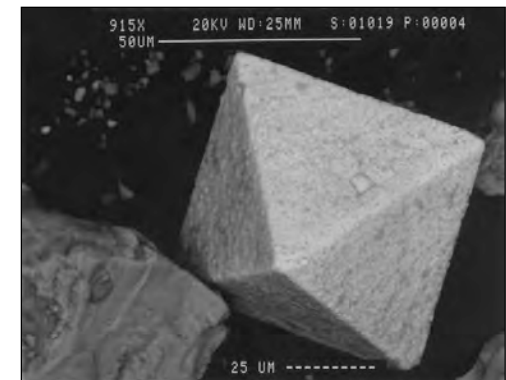
STRANGE LAKE, LABRADOR



Pyrochlore (Nb, F)



(www.Webmineral.com)



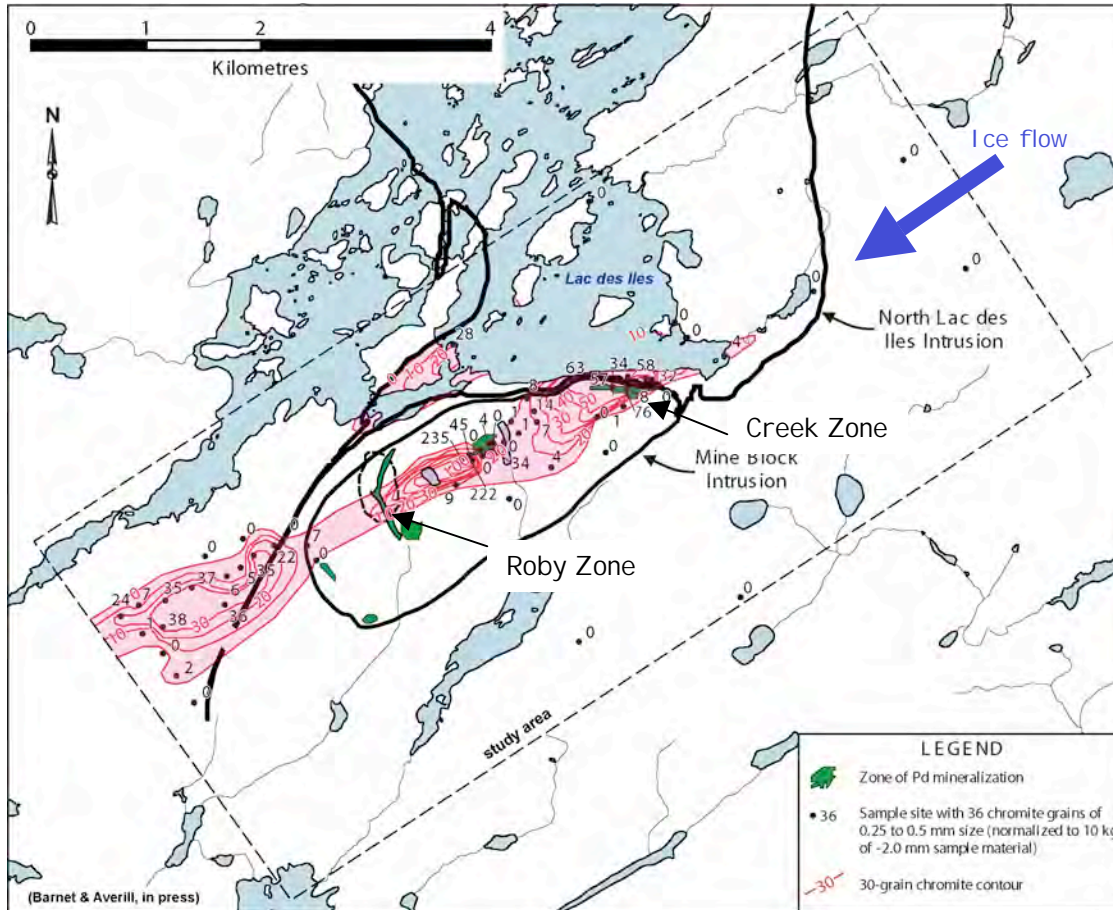
(DiLabio, 1982)

Strange Lake peralkaline granite, F-rich phases

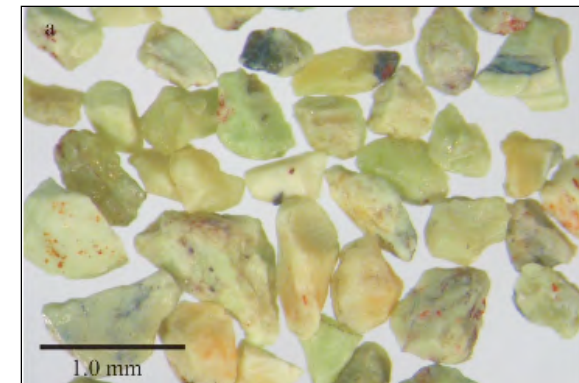
- >40 km ribbon-shaped dispersal train defined by till geochemistry
- Indicator minerals: F, Nb, Ta, REE-rich minerals
e.g. fluorite, pyrochlore, zirconosilicates, monazite
- Till geochemistry: Be, La, Nb, Pb, Th, U, Y, Zr

LAC DES ILES, NW ONTARIO

Chromite in 0.25-0.5 mm fraction

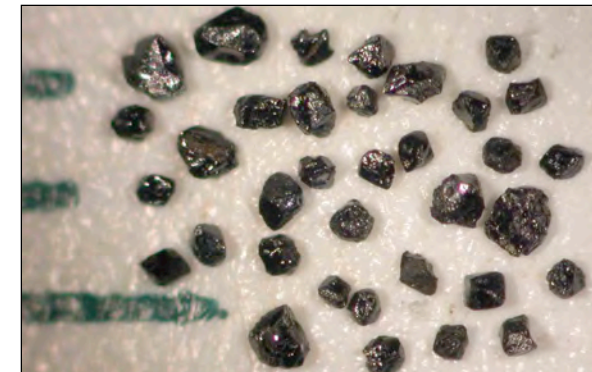


Cr-andradite (Cr-bearing garnet)



(Averill, 2007)

Chromite

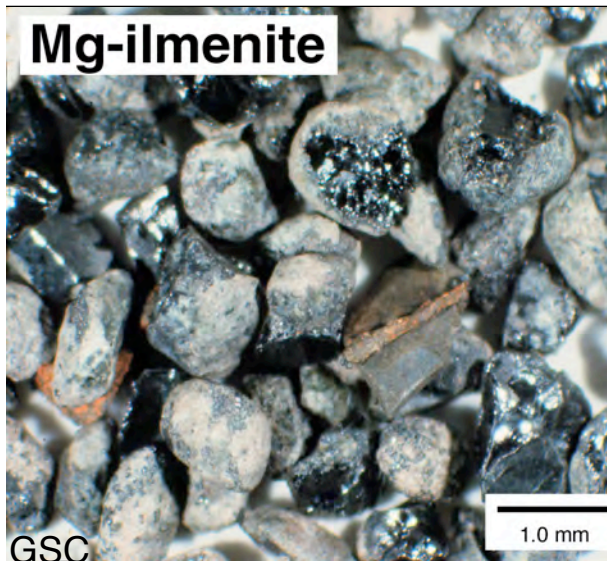
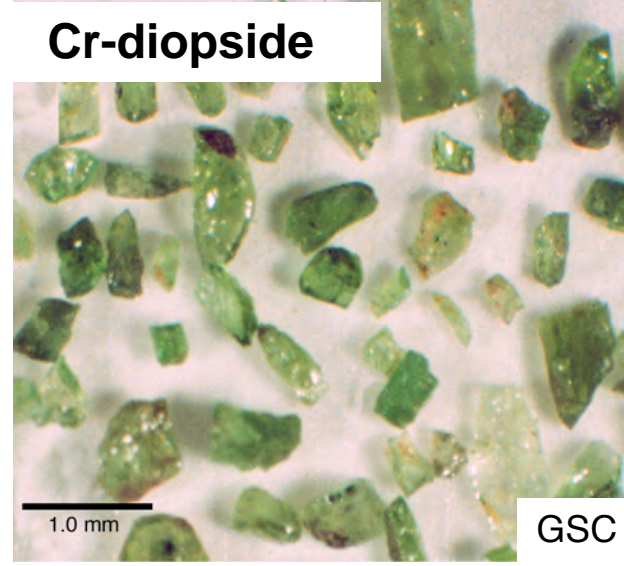


Lac des Iles Platinum mine

- >5 km ribbon-shaped dispersal train defined by till geochemistry & indicator minerals
- Indicator minerals: Cr-andradite, chromite, PGM minerals

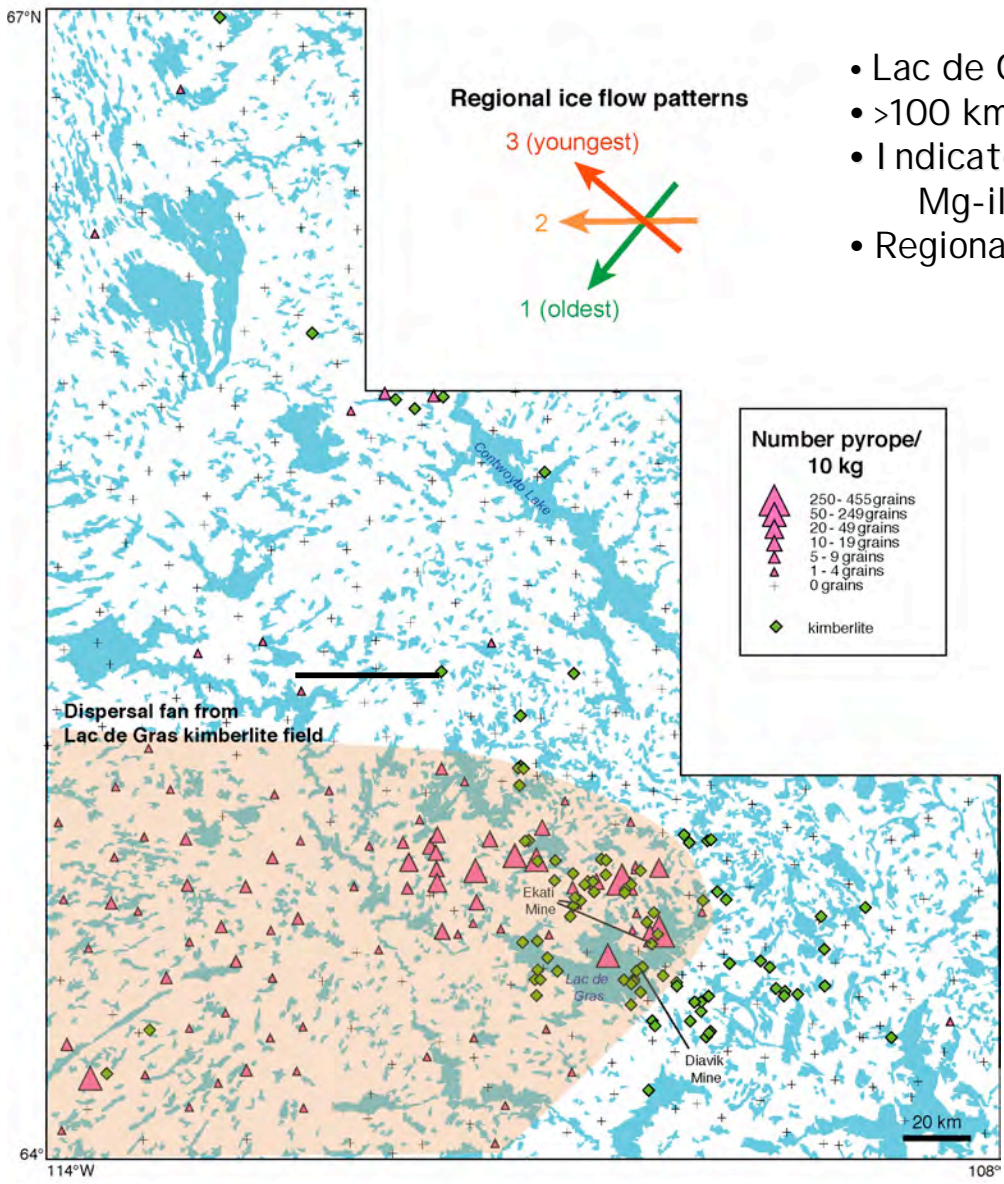
(Barnet & Averill, in press)

KIMBERLITE INDICATOR MINERALS

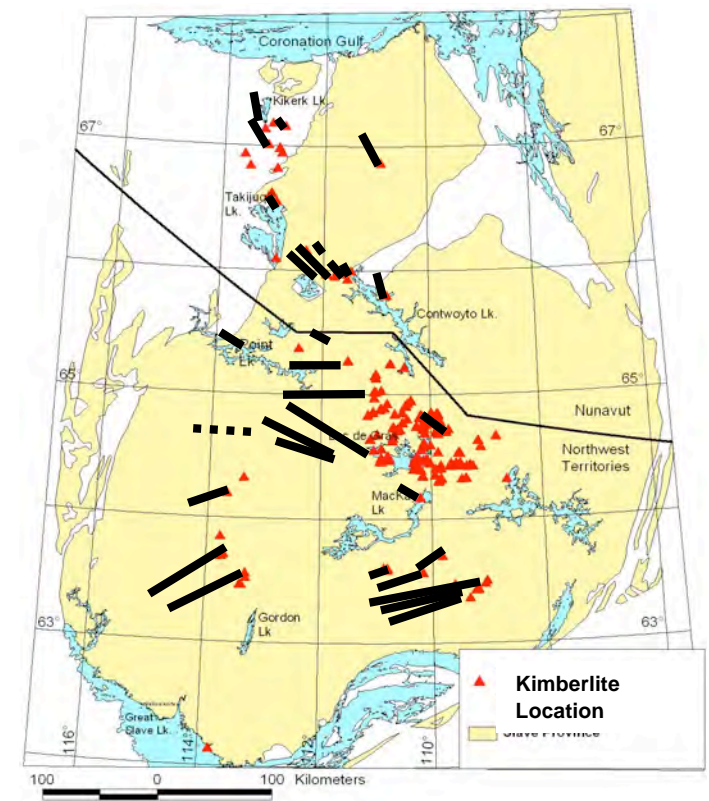


LAC DE GRAS, NWT

- Lac de Gras kimberlite field
- >100 km dispersal fan defined by indicator minerals in till
- Indicator minerals: Cr-pyrope, Cr-diopside, chromite, Mg-ilmenite, olivine, and diamond
- Regional survey, 10 to 15 km spacing

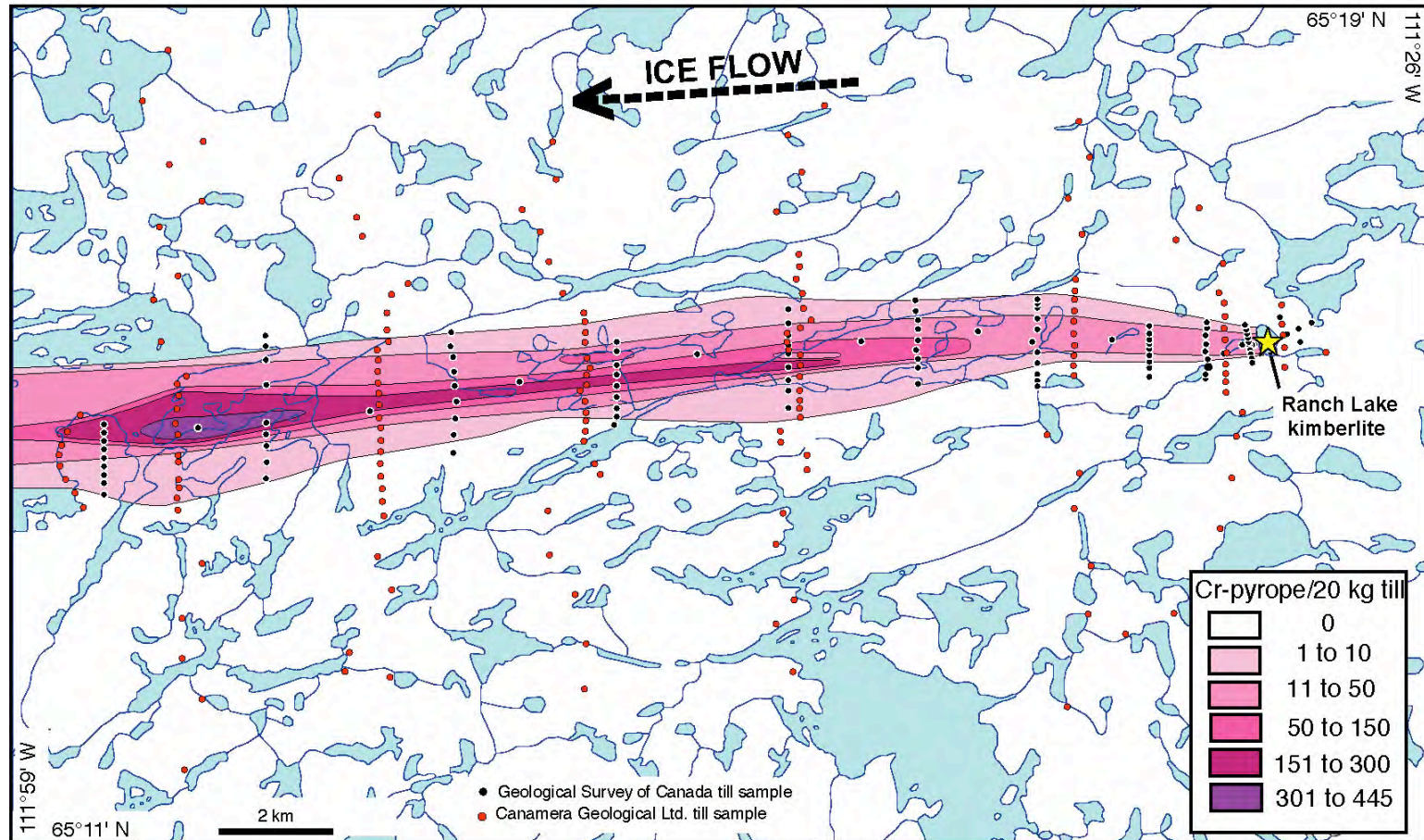


(Kerr, 2000)



(Armstrong, 2003)

RANCH LAKE, NWT



(McClenaghan et al., 2002)

- Ranch Lake kimberlite
- ~70 km dispersal train defined by indicator minerals in till
- Indicator minerals: Cr-pyrope, Cr-diopside, olivine, chromite

SUMMARY

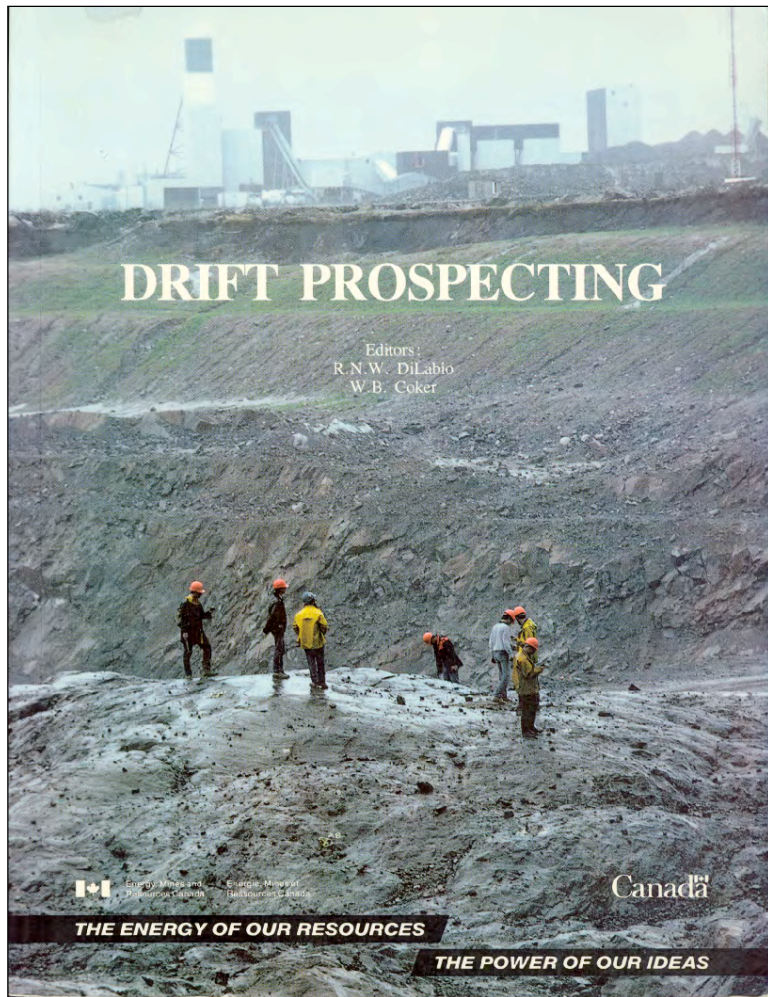
- Ice flow mapping and reconstruction of ice flow history key part of till sampling program, local or regional scale
- Glacial dispersal mapped using different size fractions: ore boulders or distinct lithology; indicator minerals; till matrix geochemistry
- Dispersal train shape reflects net result of all ice flow events; train may initially be intersected anywhere along its length, may not be complete, concentrations not always highest at head
- Indicator minerals are rugged, easily recovered heavy minerals. Recovery methods exploit mineral size, density and magnetic characteristics
- Various processing methods available, methods used will depend on: cost, number of samples, survey location, time frame to obtain results
- Mineral abundance, chemistry, shape, surface features may provide important information about bedrock source, including style of mineralization, host lithology, alteration, or grade, as well as distance of glacial transport
- Broad range of indicator mineral species can now be recovered, allowing exploration for a wide range of deposit types using the same samples
- Commercial labs now offer a range of analytical methods for till matrix geochemistry as well as indicator mineral processing, selection and analysis
- Optimal approach is to use both till geochemistry and indicator minerals methods

ACKNOWLEDGMENTS

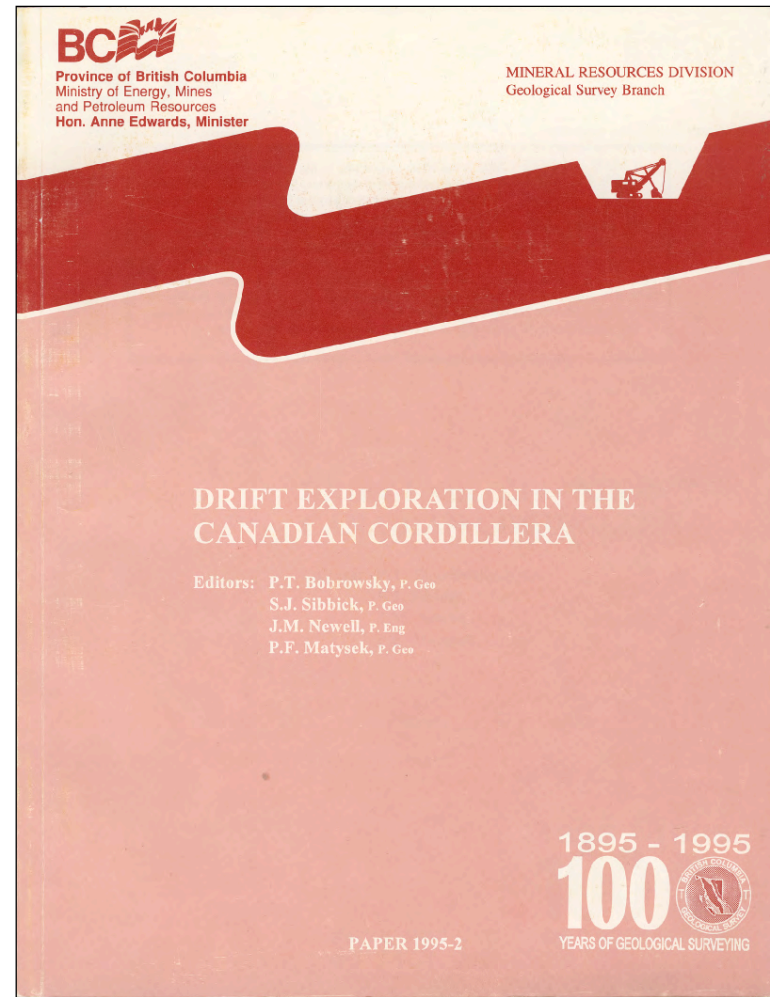
- Stu Averill, *Overburden Drilling Management Ltd.*
- Chris Benn, Bill Coker, *BHP Billiton Exploration*
- Marja Lehtonen, *Geological Survey of Finland*
- Isabelle McMartin, *Geological Survey of Canada*
- Roger Paulen, *Alberta Geological Survey*
- Alain Plouffe, *Geological Survey of Canada*
- Pertti Sarala, *Geological Survey of Finland*
- R. Stea, *Consultant*
- Pam Strand, *Shear Minerals*
- Harvey Thorliefson, *Minnesota Geological Survey*



FURTHER READING: DRIFT PROSPECTING

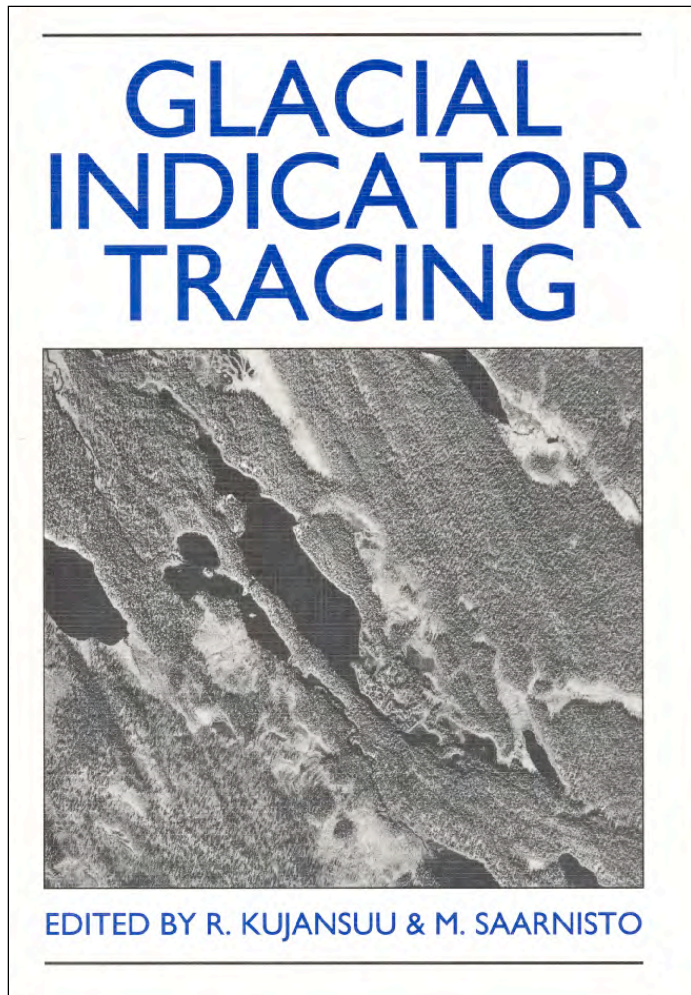


Drift Prospecting
(DiLabio and Coker 1989)

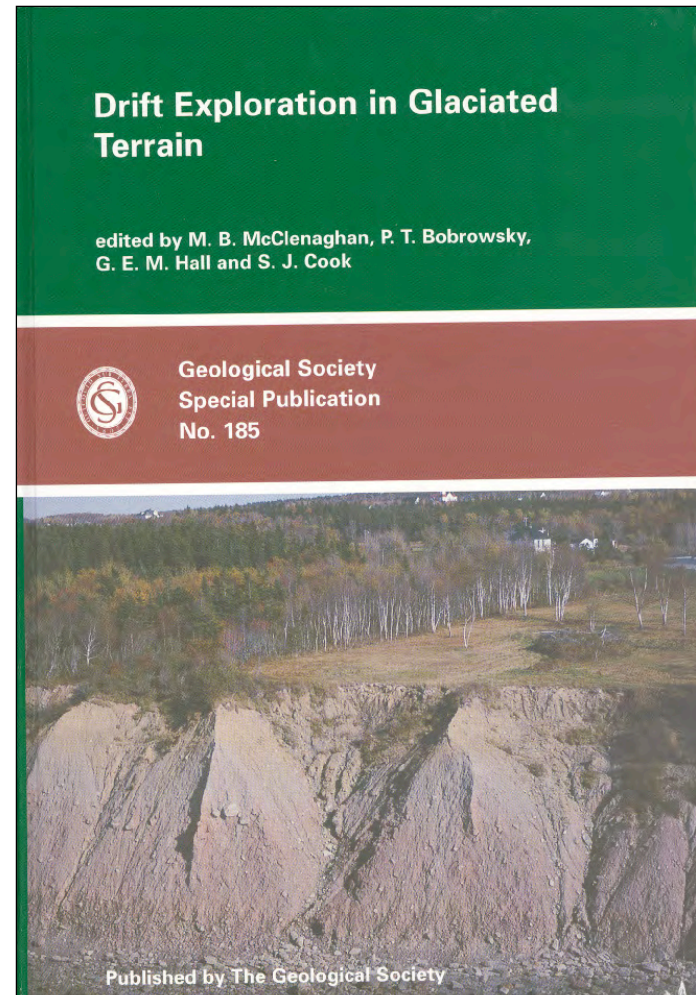


Drift Exploration in the Canadian
Cordillera (Bobrowsky et al. 1995)

FURTHER READING: DRIFT PROSPECTING



Glacial Indicator Tracing
(Kujansuu and Saarnisto 1990)



Drift Exploration in Glaciated Terrain
(McClenaghan et al. 2001)