Diamond Exploration in Western Canada

Short Course Notes - MEG - 2006

edited by

Dinu I. Pana

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Calgary Mining Forum

Diamond Exploration in Western Canada

Short Course - MEG - Calgary

April 28th, 2006

- 13:00-13:45 Diamond Sources in the Earth Mantle - Significance to Diamond Exploration
  Thomas Stachel (University of Alberta)
- 13:45-14:15 Overview of Glacial Processes in the Western Canada Sedimentary Basin
  Roger Paulen (Alberta Geological Survey/EUB)
- 14:15-14:45 Till Sampling for Kimberlite Exploration: Protocol for Success in Northern Alberta
  Roger Paulen (Alberta Geological Survey/EUB)

14:45-15:00 Coffee break

- 15:00-15:30 Stream Sediment Kimberlite-Indicator Minerals Prospecting in Northern Alberta
  Glen Prior (Alberta Geological Survey/EUB)
- 15:30-16:15 Quality Control and Quality Assurance Issues
  Michael McCubbing (Saskatchewan Research Council)
- 16:15-17:00 Geophysical Exploration Techniques
  Doug McConnel (FUGRO)

Cover photos are diamonds from Diavik mine, NWT (courtesy of Anetta Banas, APEX Geoscience Ltd.)

Diamond Sources in the Earth Mantle - Significance to Diamond Exploration

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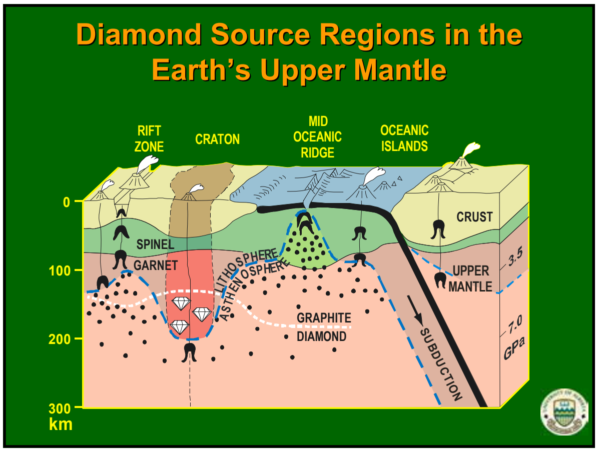
The dominant (~99%) primary source of diamonds is the subcratonic lithospheric mantle, where diamonds form at depth between 140 and 250 km in peridotitic and, less frequently, eclogitic lithologies. Based on studies of inclusions in diamonds chemical characteristics of diamondiferous lithosphere may be derived and then employed for indicator mineral assessment (e.g. Gurney 1984). The most useful mineral in this context is garnet of peridotitic and eclogitic paragenesis. The main focus of this presentation will be an evaluation of the most recent garnet classification (Grütter et al. 2004), combined with Cr in garnet barometry (Grütter et al 2006), employing a large inclusion in diamond data base (>1800 garnet inclusions).

Diamond Sources in the Earth's Mantle

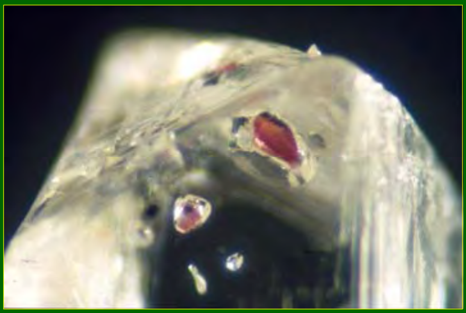
Photos: Anetta Banas, U of A

Clifford's Rule

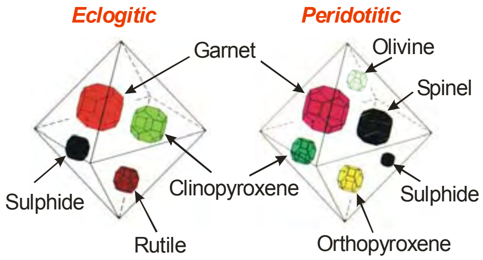


Diamond Source Regions in the Earth's Upper Mantle

Syngenetic Inclusions



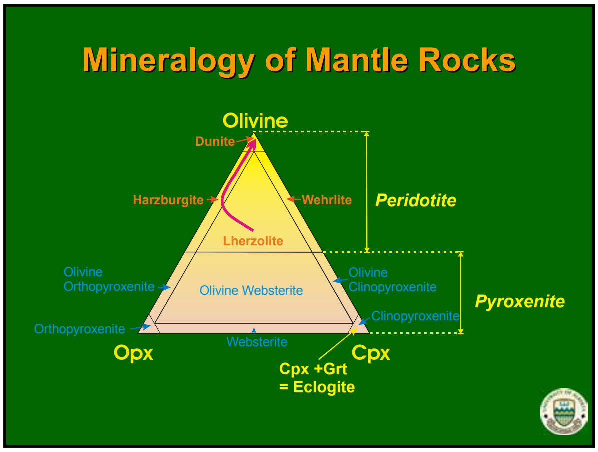
Inclusion Suites



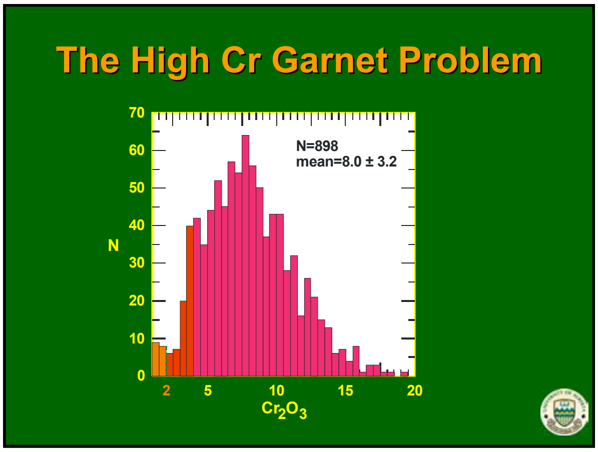
Peridotitic Diamonds

Common Inclusions:
- Olivine (Fo 91-95)
- Garnet (Knorringite-Pyrope)
- Opx (Enstatite >90)
- Cpx (Cr-Diopsid)
- Mg-Chromite
- Fe-Ni-Sulphide

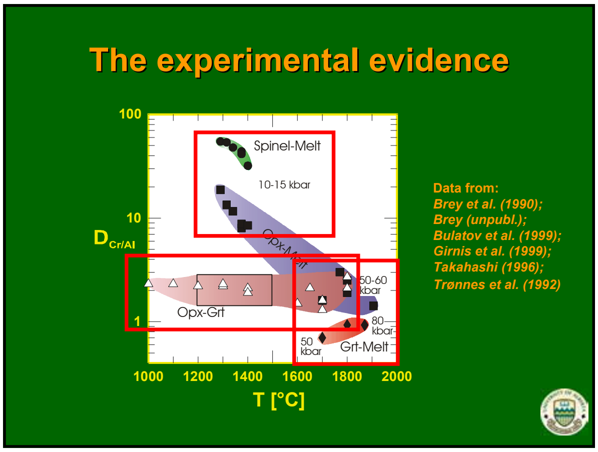
Rare Inclusions:
- Native Fe
- Mg-Ilmenite
- Zircon



Mineralogy of Mantle Rocks



The High Cr Garnet Problem



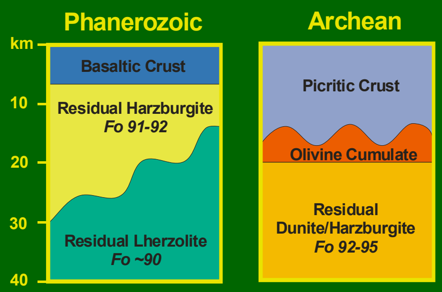
The experimental evidence

Data from:
Brey et al. (1990);
Brey (unpubl.);
Bulatov et al. (1999);
Girnis et al. (1999);
Takahashi (1996);
Trønnes et al. (1992)

Origin of Subcratonic Lithospheric Mantle

- SCLM residue of low P melt extraction
- High Mg# => high degree of partial melting
- Large volume => widespread process
- Archean MOR: 100-200 °C hotter => picritic

Origin of SCLM



e.g. Ringwood (1991)

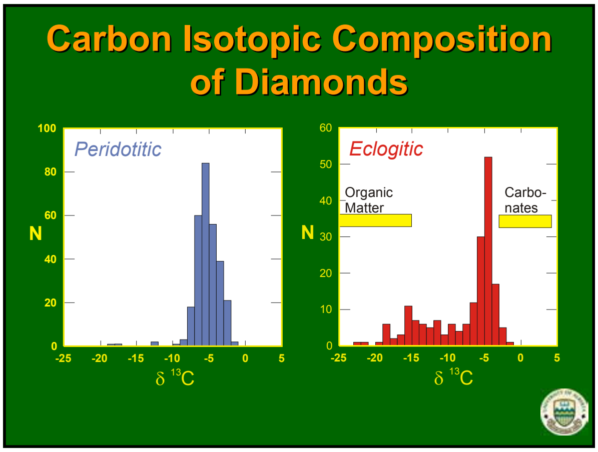
Eclogitic Diamonds

Common Inclusions:

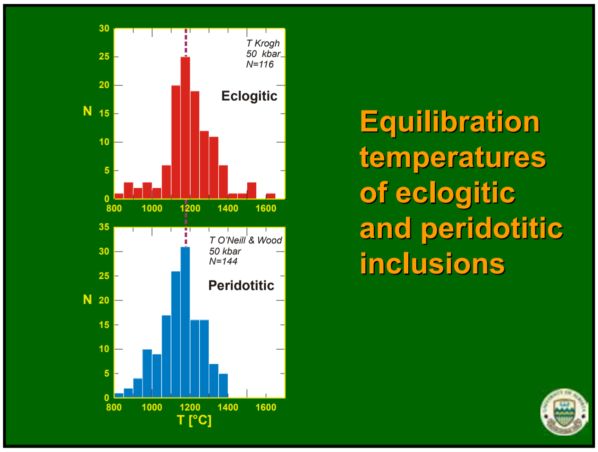
- **Grossular-Almandine-Pyrope**
- **Omphacitic Cpx**
- **Sulphide (Ni-poor)**

Rare Inclusions:

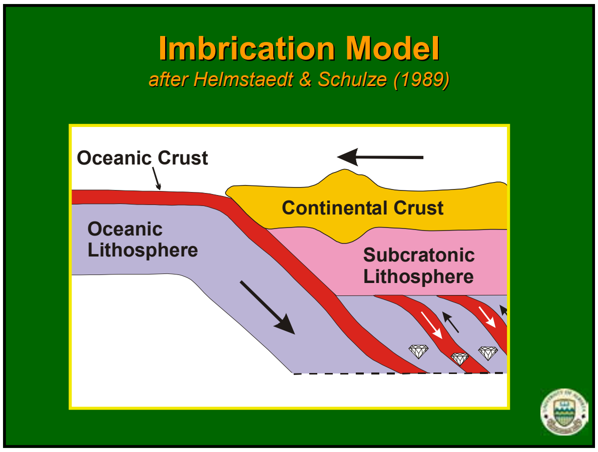
- Kyanite
- Sanidine
- Coesite
- Rutile
- Ruby
- Ilmenite



Carbon Isotopic Composition of Diamonds

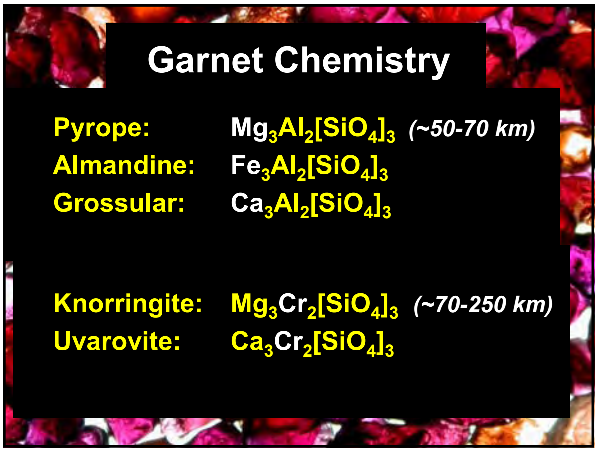


Equilibration temperatures of eclogitic and peridotitic inclusions



Imbrication Model

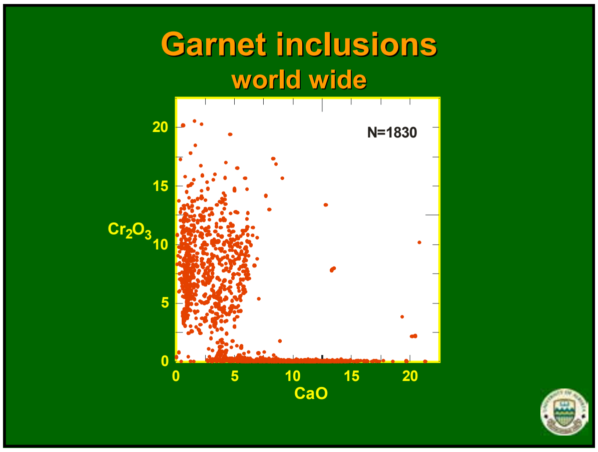
after Helmstaedt & Schulze (1989)



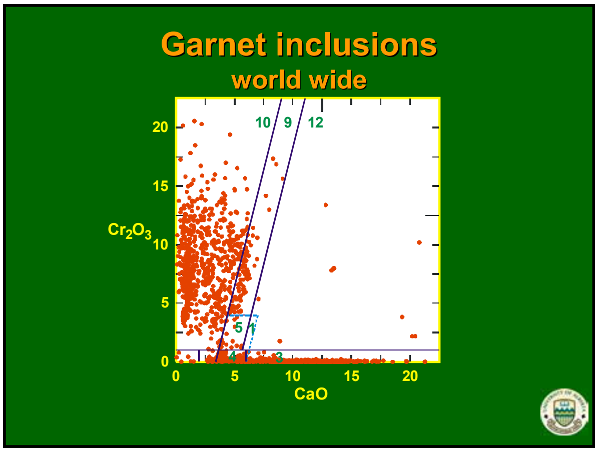
Garnet Chemistry

Pyrope: $Mg_3Al_2[SiO_4]_3$ *(~50-70 km)*
Almandine: $Fe_3Al_2[SiO_4]_3$
Grossular: $Ca_3Al_2[SiO_4]_3$

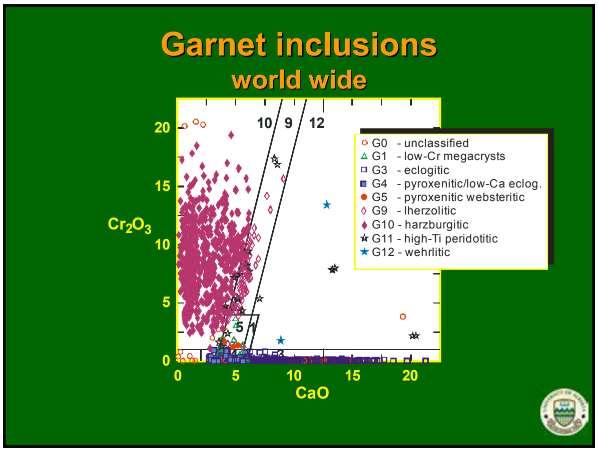
Knorringite: $Mg_3Cr_2[SiO_4]_3$ *(~70-250 km)*
Uvarovite: $Ca_3Cr_2[SiO_4]_3$



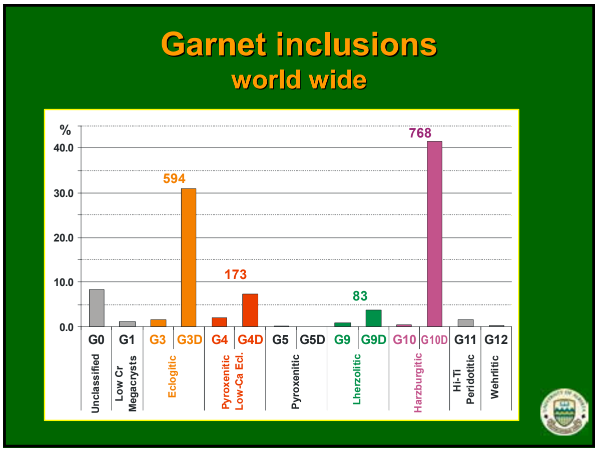
Garnet inclusions
world wide



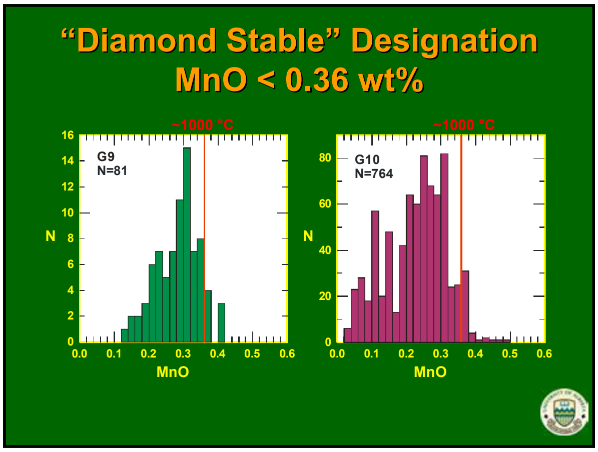
Garnet inclusions
world wide



Garnet inclusions
world wide

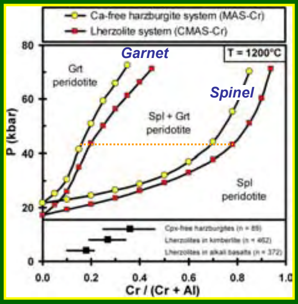


Garnet inclusions
world wide



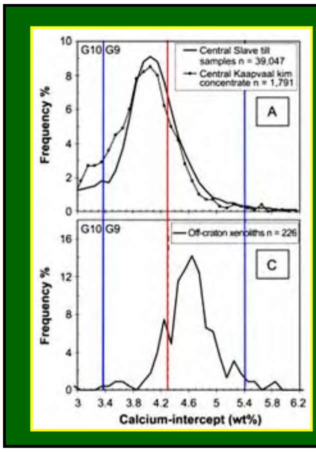
"Diamond Stable" Designation MnO < 0.36 wt%

Cr Barometry for Garnets



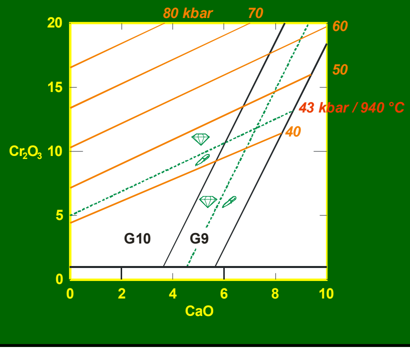
Grütter et al. (2006), J. Petrol.

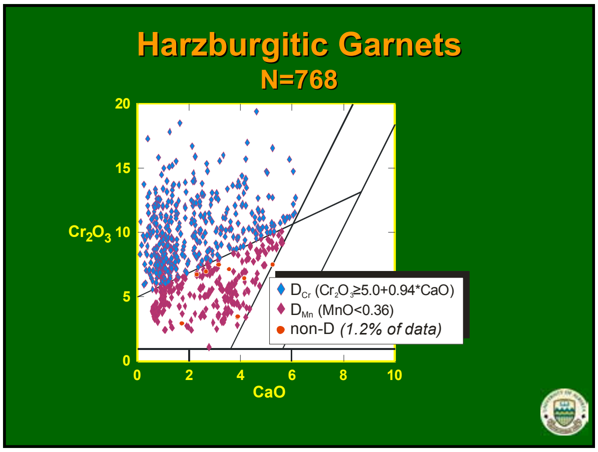
Ca Constraint for Diamond Facies Lherzolitic (G9) Garnets



Grütter et al. (2004), Lithos

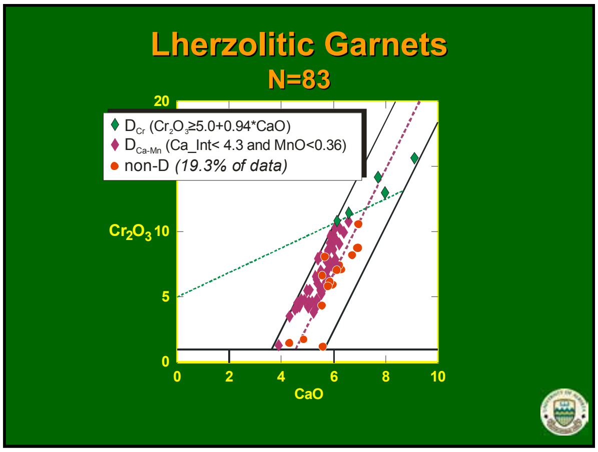
Cr-Ca plot with P_{38}





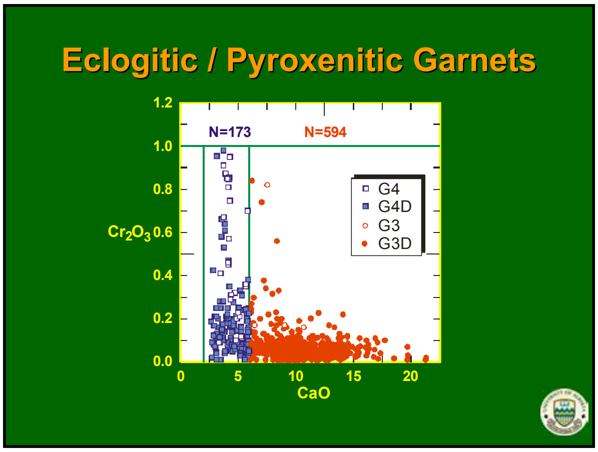
Harzburgitic Garnets

N=768

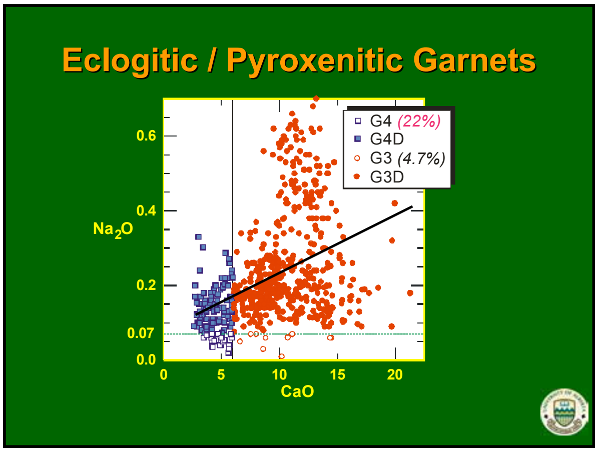


Lherzolitic Garnets

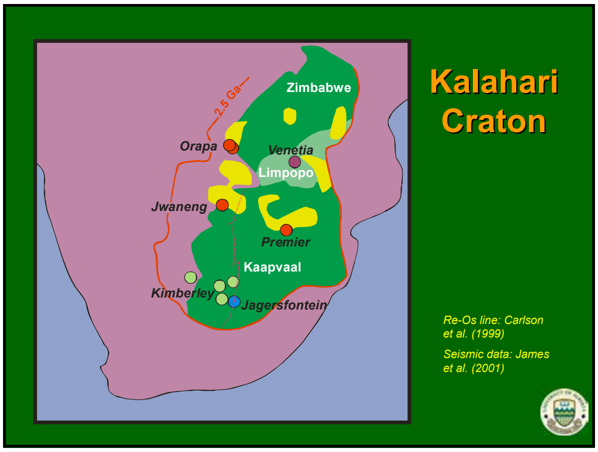
N=83



Eclogitic / Pyroxenitic Garnets



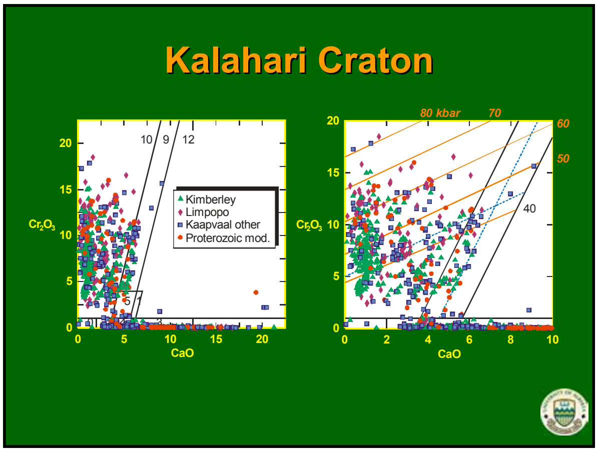
Eclogitic / Pyroxenitic Garnets



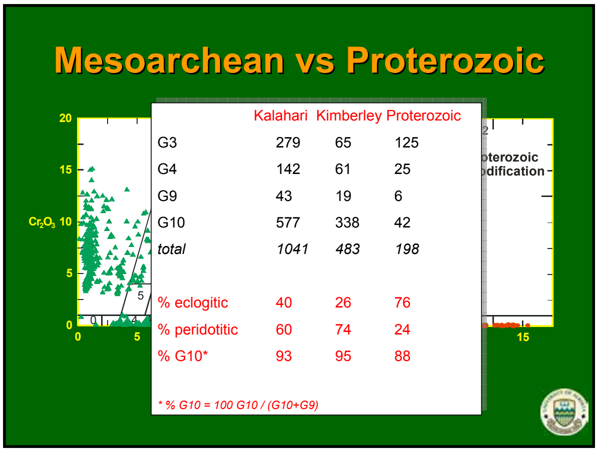
Kalahari Craton

Re-Os line: Carlson et al. (1999)

Seismic data: James et al. (2001)



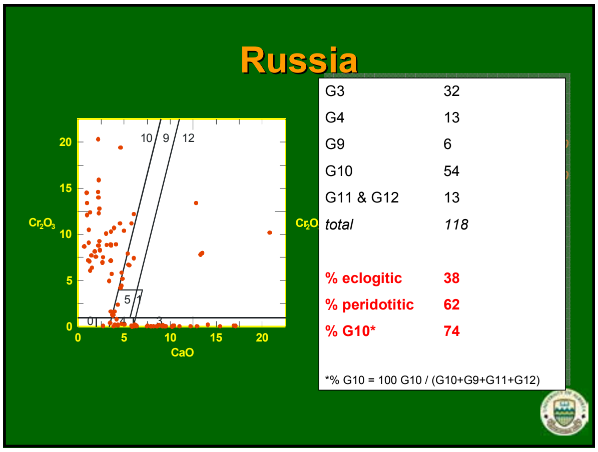
Kalahari Craton



Mesoarchean vs Proterozoic

	Kalahari	Kimberley	Proterozoic
G3	279	65	125
G4	142	61	25
G9	43	19	6
G10	577	338	42
total	*1041*	*483*	*198*
% eclogitic	40	26	76
% peridotitic	60	74	24
% G10*	93	95	88

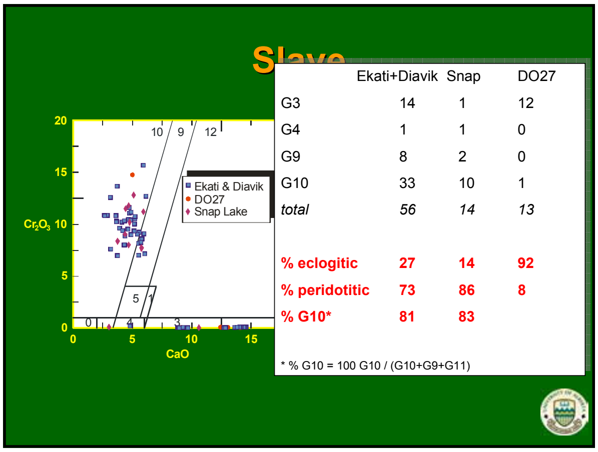
** % G10 = 100 G10 / (G10+G9)*



Russia

G3	32
G4	13
G9	6
G10	54
G11 & G12	13
total	*118*
% eclogitic	**38**
% peridotitic	**62**
% G10*	**74**

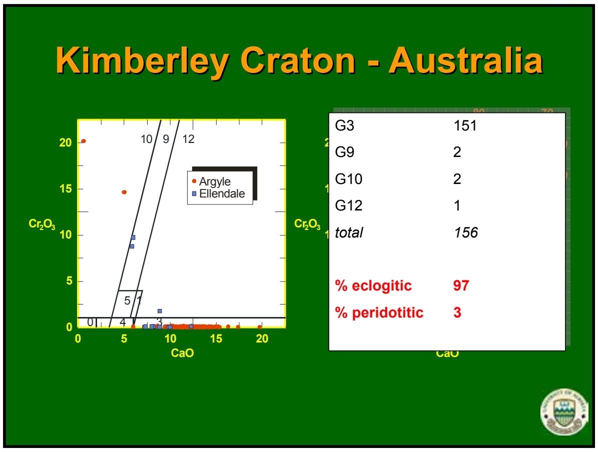
*% G10 = 100 G10 / (G10+G9+G11+G12)



Slave

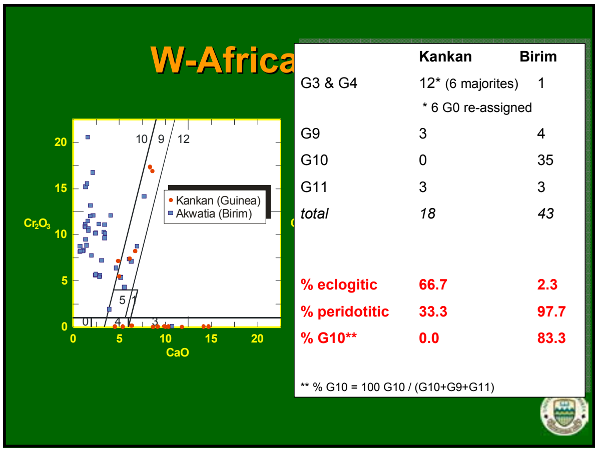
	Ekati+Diavik	Snap	DO27
G3	14	1	12
G4	1	1	0
G9	8	2	0
G10	33	10	1
total	*56*	*14*	*13*
% eclogitic	**27**	**14**	**92**
% peridotitic	**73**	**86**	**8**
% G10*	**81**	**83**	

* % G10 = 100 G10 / (G10+G9+G11)



Kimberley Craton - Australia

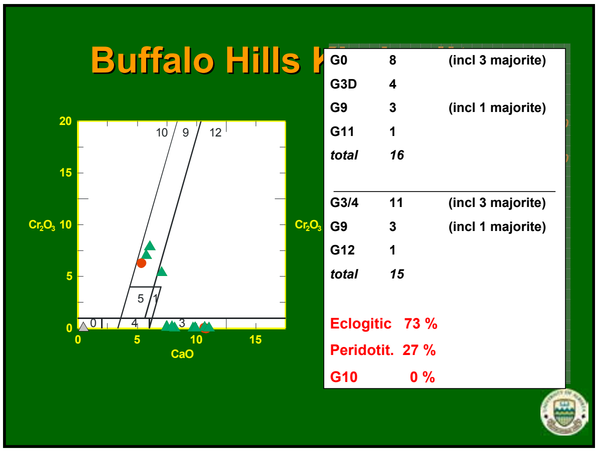
G3	151
G9	2
G10	2
G12	1
total	*156*
% eclogitic	**97**
% peridotitic	**3**



W-Africa

	Kankan	**Birim**
G3 & G4	12* (6 majorites) * 6 G0 re-assigned	1
G9	3	4
G10	0	35
G11	3	3
total	*18*	*43*
% eclogitic	**66.7**	**2.3**
% peridotitic	**33.3**	**97.7**
% G10**	**0.0**	**83.3**

** % G10 = 100 G10 / (G10+G9+G11)



Buffalo Hills K

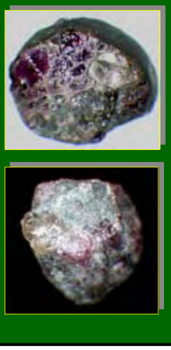
G0	**8**	**(incl 3 majorite)**
G3D	**4**	
G9	**3**	**(incl 1 majorite)**
G11	**1**	
total	***16***	
G3/4	**11**	**(incl 3 majorite)**
G9	**3**	**(incl 1 majorite)**
G12	**1**	
total	***15***	

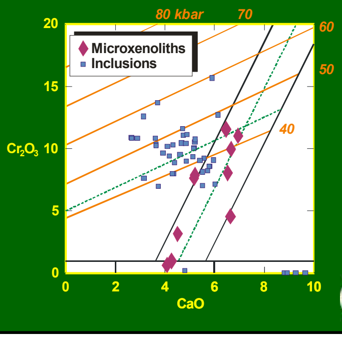
Eclogitic 73 %

Peridotit. 27 %

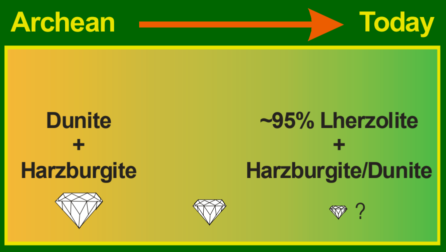
G10 0 %

Diamondiferous Microxenoliths from Diavik (A154)





Mantle Metasomatism

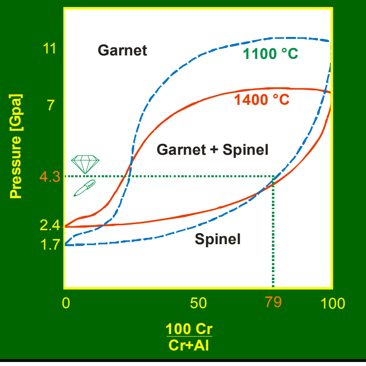


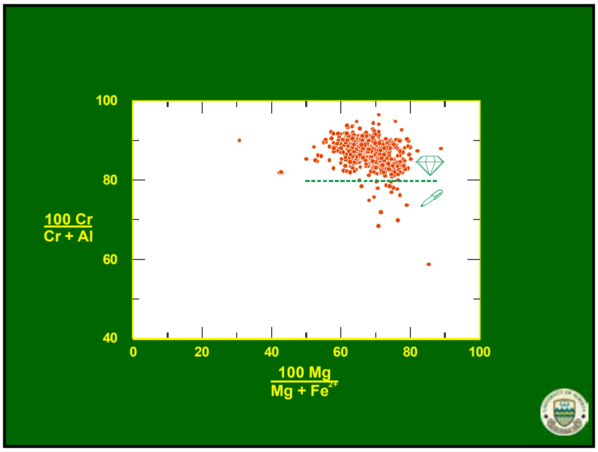
Archean → Today

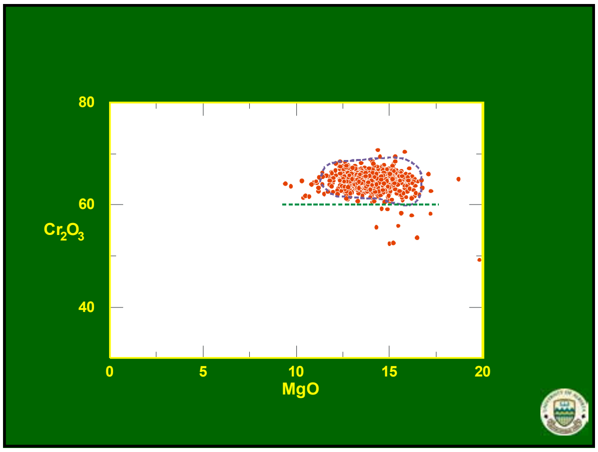
Dunite
+
Harzburgite

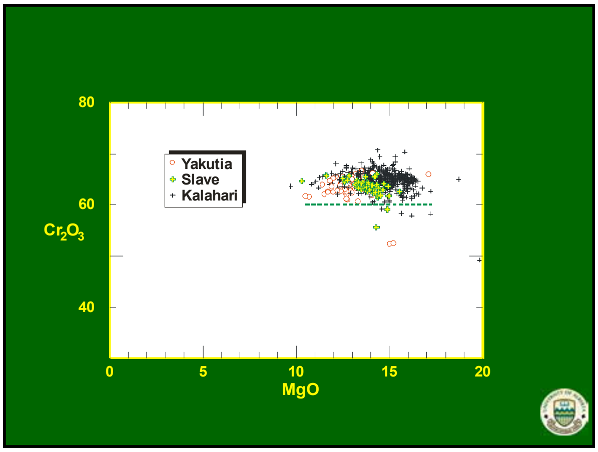
~95% Lherzolite
+
Harzburgite/Dunite

?




100
80
60
40
0
20
40
60
80
100
100 Cr / Cr + Al
100 Mg / Mg + Fe2+


80
60
40
0
5
10
15
20
Cr_2O_3
MgO


80
60
40
0
5
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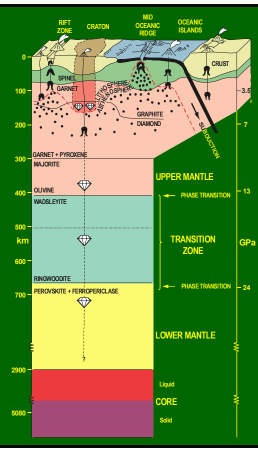
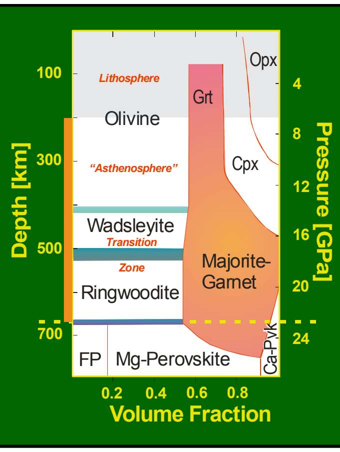
15
20
Yakutia
Slave
Kalahari
Cr_2O_3
MgO



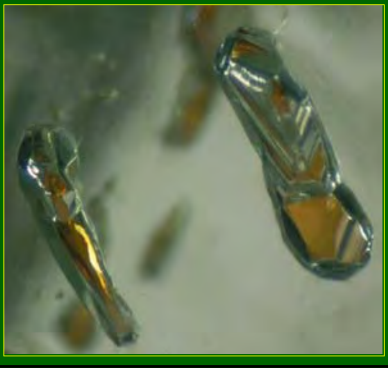
Inclusions in "ultra-deep" diamonds

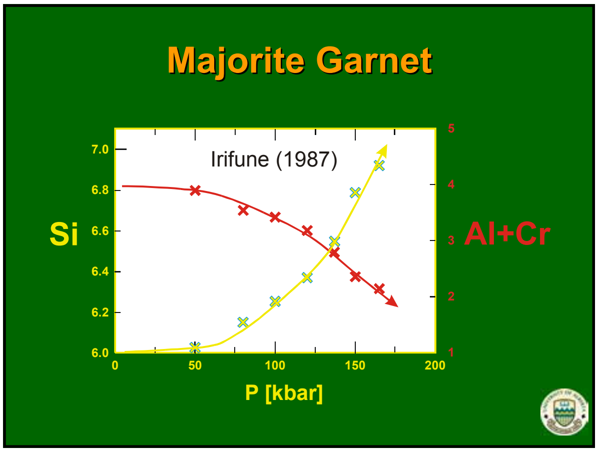


Phase Diagram for Pyrolite

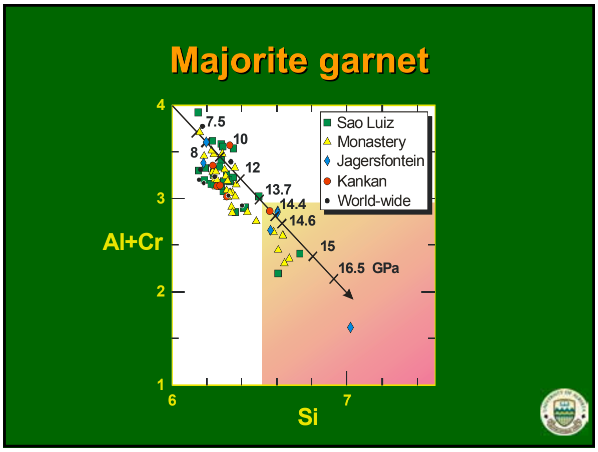
Ringwood (1991)
Wood (2000)

Majorite garnet





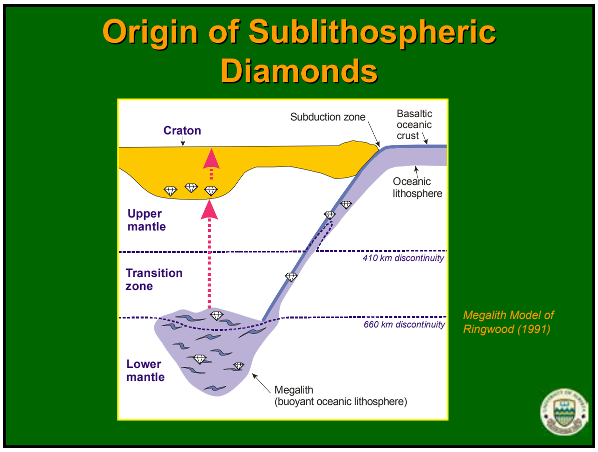
Majorite Garnet



Majorite garnet

Ferropericlase Inclusion

Diamond from Kankan (Guinea), field of view: 1mm



Origin of Sublithospheric Diamonds

Megalith Model of Ringwood (1991)

Glacial Processes: An Overview in the Western Canada Sedimentary Basin

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Effective and efficient diamond exploration in glaciated terrain calls for a thorough knowledge of the glacial geology of the area concerned. Drift prospecting relies on the identification of dispersal trains in glacial drift (*cf.* DiLabio and Coker 1989; Kujansuu 1990; Bobrowsky *et al.* 1995; McClenaghan *et al.* 2001). Kimberlite exploration in the Western Canada Sedimentary Basin is hampered by a highly variable overburden thickness, paucity of outcrop and a complex glacial and deglacial history, with more than one glacial event affecting most of Alberta. Glacial ice has played the principal role in the transportation of indicator minerals. Tills containing these trains occur in a range of thin deposits, less than 5 m thick, generally deposited in a straight-line trajectory derived from local bedrock, or in thick deposits, tens of metres thick, with a complex history of reworking.

Over the last two decades the basis for drift prospecting in western Canada has significantly improved through the continued development of ice sheets models, the acquisition of empirical evidence for ice flow, drift composition and glacial history through an improved understanding of glacial processes. During the last decade, a considerable amount of research has taken place in northern Alberta. Particular attention has been paid to the unique geological setting of northern Alberta's Quaternary history and the challenges of drift prospecting for diamonds here, relative to known methodologies that are well established within the Canadian Shield. The kimberlite fields of northern Alberta differ from other Canadian kimberlite fields (e.g. Central Slave) in various ways from the perspective of drift prospecting in glaciated terrain. Such factors include the bedrock geology, glacial history, physiography and drift thickness (Fenton et al. 2003 – a copy this overview is provided here).

The erosional and depositional records of ice flow are formed beneath the ice sheet at different times, in different locations, and by different processes. Thus, although occurring together in the modern landscape, they represent spatially and temporally distinct aspects of glacial history (e.g. Boulton 1996; Klassen 2001). From theoretical models, subglacial processes are most active in marginal zones where ice flow velocities are greatest. In those zones, erosion occurs during expansion, whereas either during or subsequent to the glacial maximum depositional processes are dominant (Slide #10). The changes from erosional to depositional regimes reflect change in basal ice conditions. Thus the type, definition, provenance and relative age of the geological record, including streamlined landforms, reflect their geographic and glaciological context in the former ice sheet, and they cannot be weighed equally for the interpretation of glacial dispersal patterns.

Till classifications (Slide #15) can reflect glacial processes (e.g. lodgment or deformation), position of transport with respect to the ice sheet (e.g. basal, englacial or supraglacial), and depositional environment (e.g. meltout or ablation). The definition and usage of these terms have been subject to long debate (e.g. Dreimanis 1990), reflecting the growth and sophistication of glacial sedimentology. Till is basically described as the net effect of glacial process. Vertical lithologic variations in till profiles can reflect either ice flow direction and provenance or distance of glacial transport associated with either change in ice flow velocity or in the position of debris in the ice, such as englacial versus basal (Boulton 1996). In exploration practice, however, sediments are typically recovered either from shallow pits or core. Consequently, although physical properties such as colour and texture can be recorded, sedimentary structures and stratigraphic relations required for till classification cannot be established readily. In northern Alberta, the geomorphology of the surficial units can provide some regional indications of depositional environment (e.g. doughtnut or hummocky moraine versus fluted moraine). Also evidence for sediment genesis and stratigraphic relationships can be obtained from regional examination of road cuts, borrow pits and stream sections, often well outside the localized exploration property; unfortunately this information is not routinely acquired during exploration.

Despite their importance to drift prospecting, the diverse fields comprising Quaternary studies – glaciology, glacial sedimentology, geochemistry, among others – are not widely known in the exploration community. The intent of this lecture is to succinctly highlight some of the processes and features specific to glacial materials derived, transported and deposited within the Western Canada Sedimentary Basin. Although this lecture reflects the author's experiences in drift prospecting and glacial geology, it also draws freely on the work of others, notably fellow researchers at the Alberta Geological Survey, principally Mark Fenton, and Beth McClenaghan of the Geological Survey of Canada. The content presented here is merely an overview, to serve merely as a guide for further investigation; the results of numerous, deserving studies have been omitted for lack of presentation time available. The message for exploration is that relations among bedrock, drift composition and ice flow history must be inferred in the wider context of the ice sheet and glacial history through recognition of the distinct character of the erosional and depositional records.

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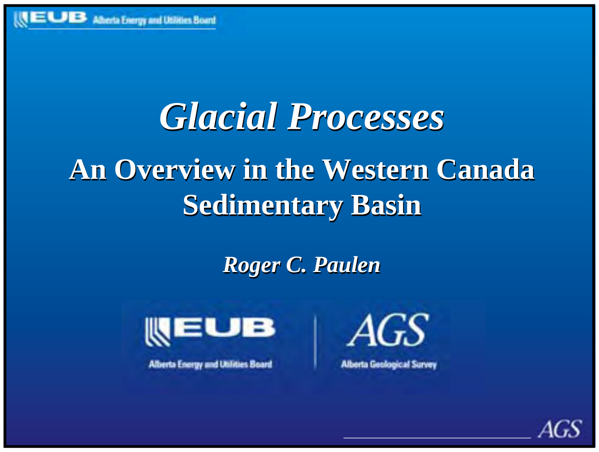


Glacial Processes

An Overview in the Western Canada Sedimentary Basin

Roger C. Paulen

EUB Alberta Energy and Utilities Board | AGS Alberta Geological Survey

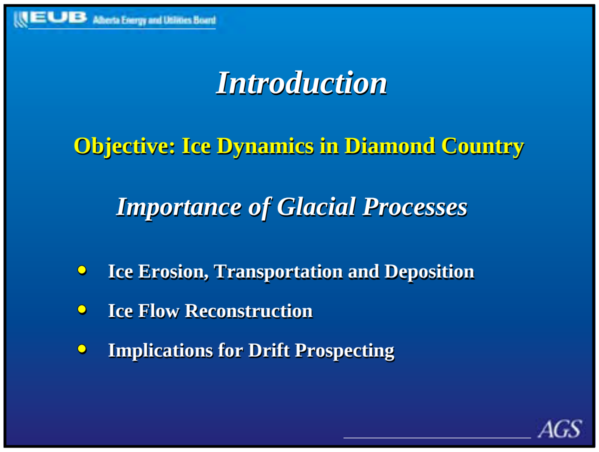
Why Study Glacial Processes?

Canada is now Diamond Country

(95% of Canada was glaciated during the Quaternary)

Drift Prospecting

- Led to the discovery of Slave Province kimberlites
- Now part of all kimberlite exploration programs

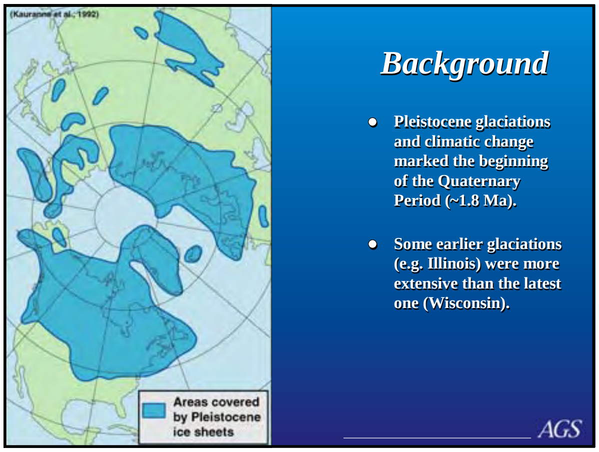


Introduction

Objective: Ice Dynamics in Diamond Country

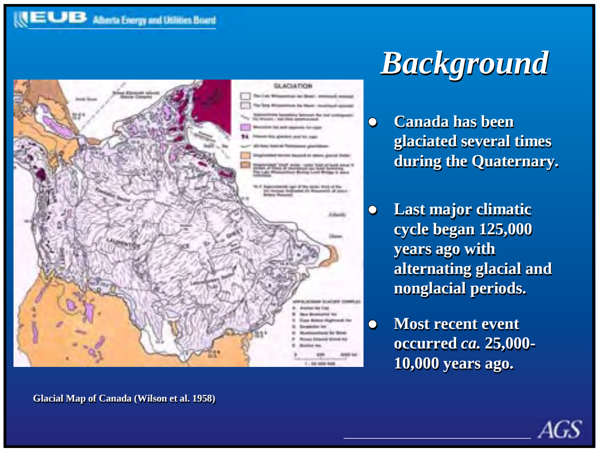
Importance of Glacial Processes

- Ice Erosion, Transportation and Deposition
- Ice Flow Reconstruction
- Implications for Drift Prospecting



Background

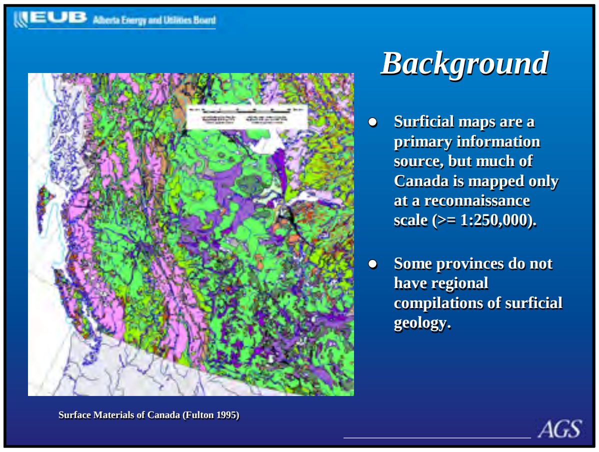
- Pleistocene glaciations and climatic change marked the beginning of the Quaternary Period (~1.8 Ma).
- Some earlier glaciations (e.g. Illinois) were more extensive than the latest one (Wisconsin).



Background

- Canada has been glaciated several times during the Quaternary.
- Last major climatic cycle began 125,000 years ago with alternating glacial and nonglacial periods.
- Most recent event occurred *ca.* 25,000-10,000 years ago.

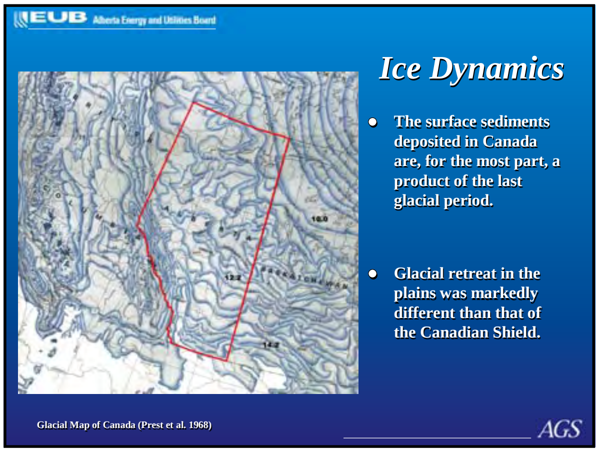
Glacial Map of Canada (Wilson et al. 1958)



Background

- Surficial maps are a primary information source, but much of Canada is mapped only at a reconnaissance scale (>= 1:250,000).
- Some provinces do not have regional compilations of surficial geology.

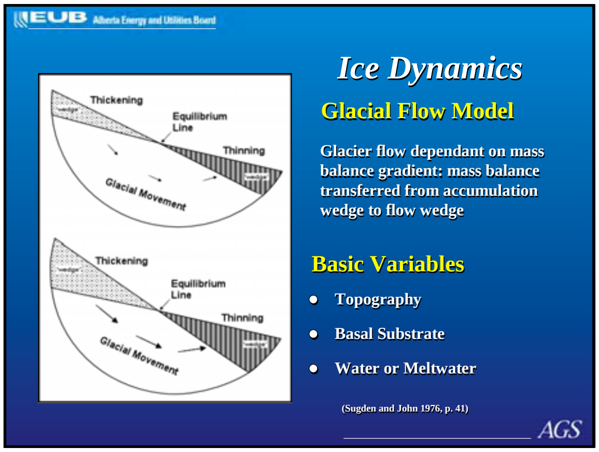
Surface Materials of Canada (Fulton 1995)



Ice Dynamics

- The surface sediments deposited in Canada are, for the most part, a product of the last glacial period.
- Glacial retreat in the plains was markedly different than that of the Canadian Shield.

Glacial Map of Canada (Prest et al. 1968)



Ice Dynamics

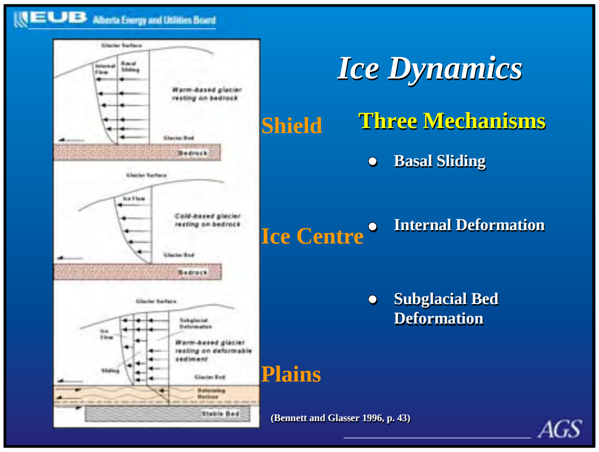
Glacial Flow Model

Glacier flow dependant on mass balance gradient: mass balance transferred from accumulation wedge to flow wedge

Basic Variables

- Topography
- Basal Substrate
- Water or Meltwater

(Sugden and John 1976, p. 41)

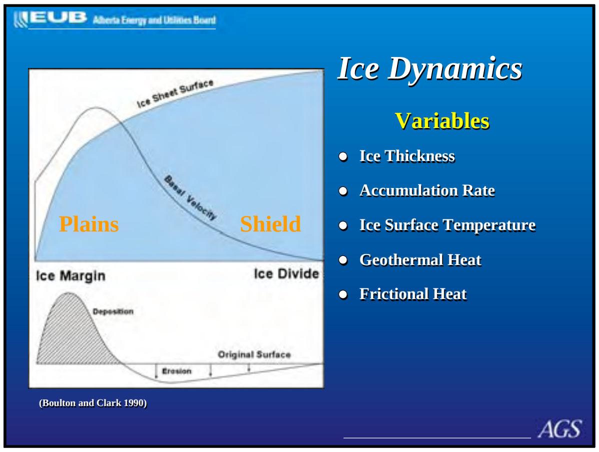


Ice Dynamics

Three Mechanisms

- Basal Sliding
- Internal Deformation
- Subglacial Bed Deformation

(Bennett and Glasser 1996, p. 43)

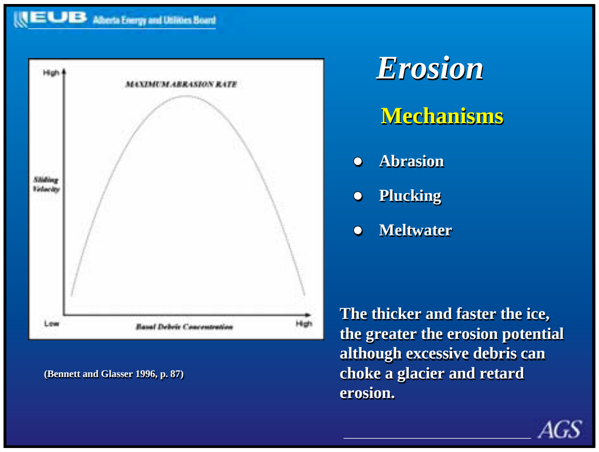


(Boulton and Clark 1990)

Ice Dynamics

Variables

- Ice Thickness
- Accumulation Rate
- Ice Surface Temperature
- Geothermal Heat
- Frictional Heat



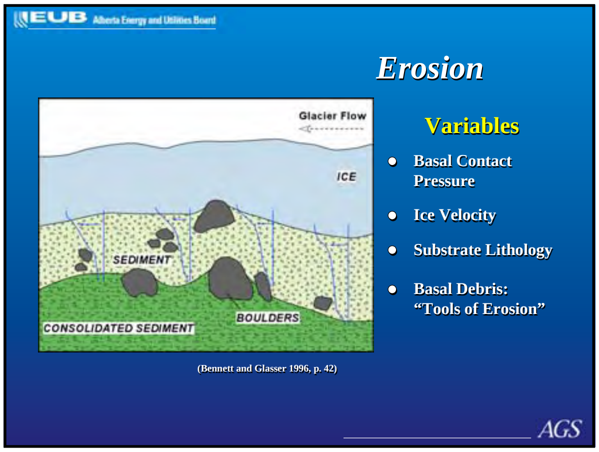
(Bennett and Glasser 1996, p. 87)

Erosion

Mechanisms

- Abrasion
- Plucking
- Meltwater

The thicker and faster the ice, the greater the erosion potential although excessive debris can choke a glacier and retard erosion.

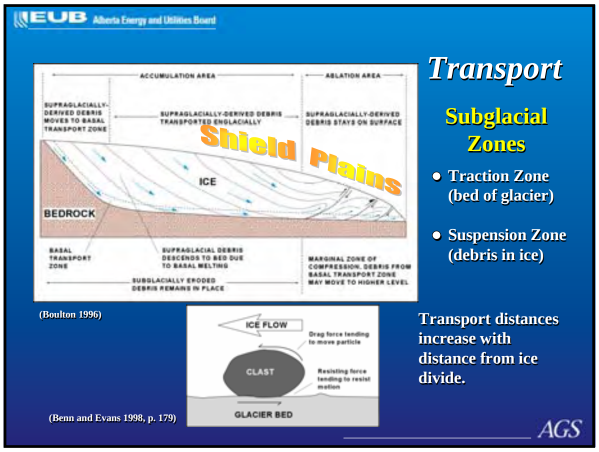


(Bennett and Glasser 1996, p. 42)

Erosion

Variables

- Basal Contact Pressure
- Ice Velocity
- Substrate Lithology
- Basal Debris: “Tools of Erosion”



Transport

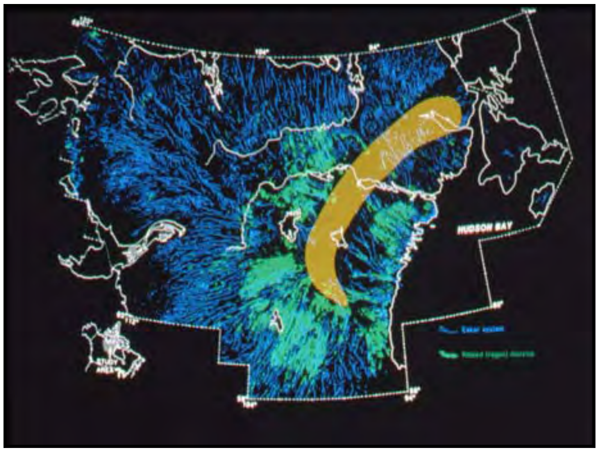
Subglacial Zones

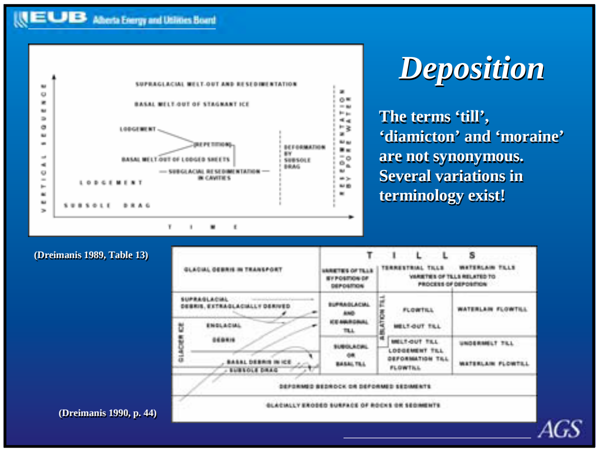
- Traction Zone (bed of glacier)
- Suspension Zone (debris in ice)

(Boulton 1996)

(Benn and Evans 1998, p. 179)

Transport distances increase with distance from ice divide.



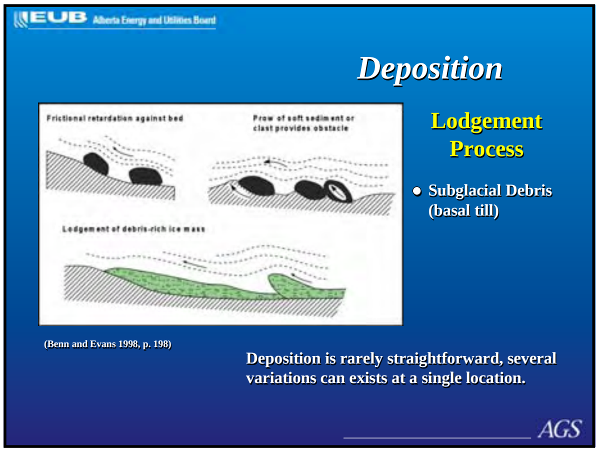


Deposition

The terms ‘till’, ‘diamicton’ and ‘moraine’ are not synonymous. Several variations in terminology exist!

(Dreimanis 1989, Table 13)

(Dreimanis 1990, p. 44)



Deposition

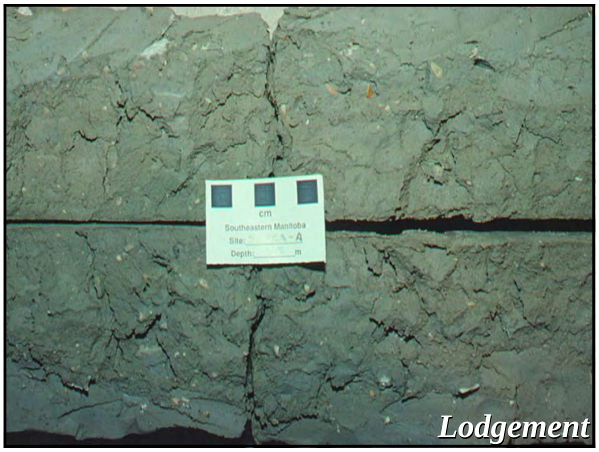
Lodgement Process

- Subglacial Debris (basal till)

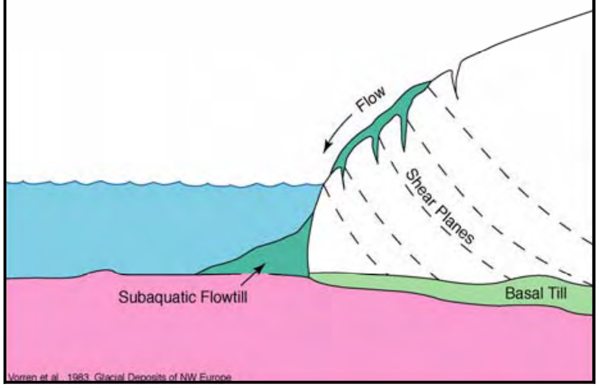
(Benn and Evans 1998, p. 198)

Deposition is rarely straightforward, several variations can exists at a single location.

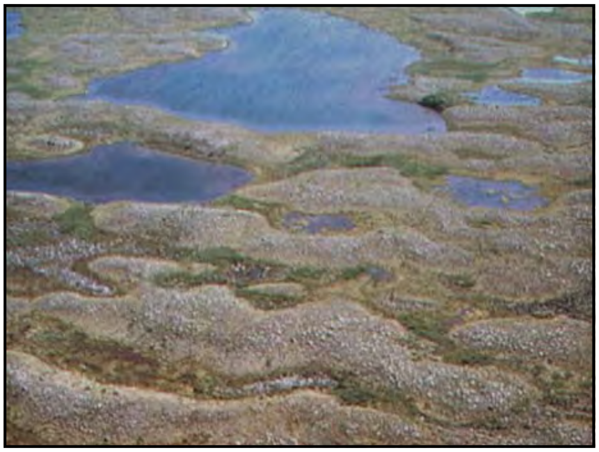

Lodgement


cm
Southeastern Manitoba
Site: -A
Depth: m
Lodgement

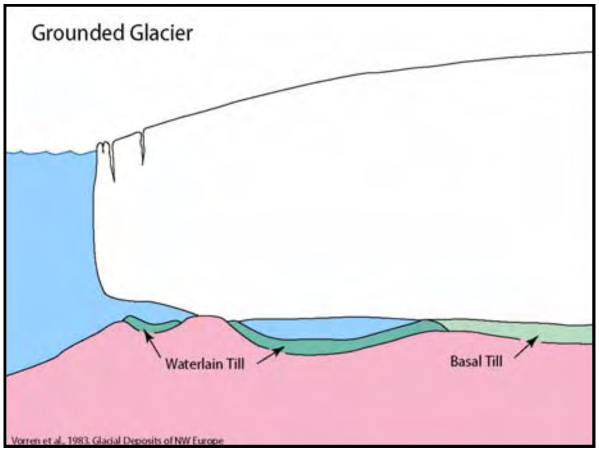
Grounded Glacier



Vorren et al., 1983, Glacial Deposits of NW Europe



Grounded Glacier



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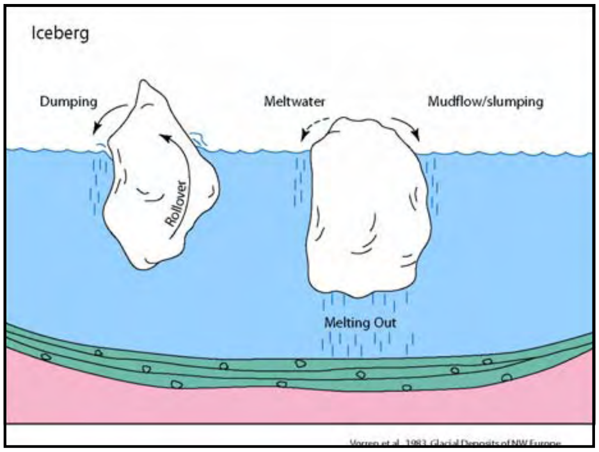
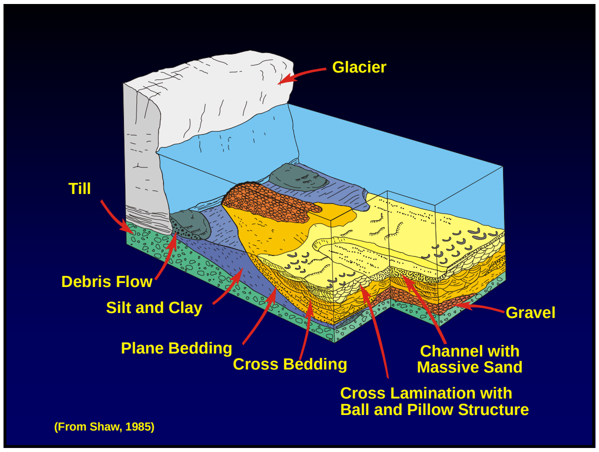
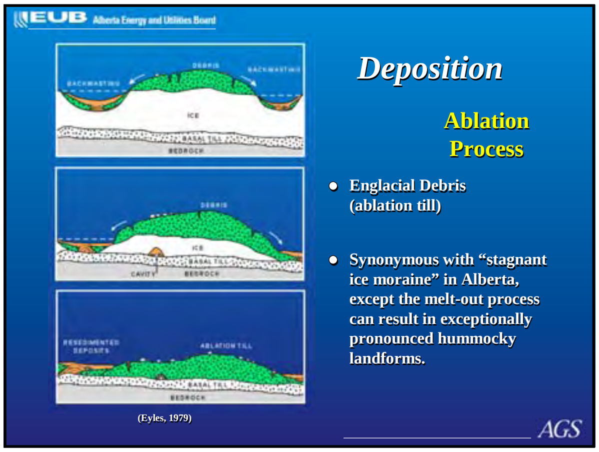


Vorren et al. 1983, Glacial Deposits of NW Europe

Waterlain



(From Shaw, 1985)



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Deposition

Ablation Process

- Englacial Debris (ablation till)
- Synonymous with "stagnant ice moraine" in Alberta, except the melt-out process can result in exceptionally pronounced hummocky landforms.

(Eyles, 1979)

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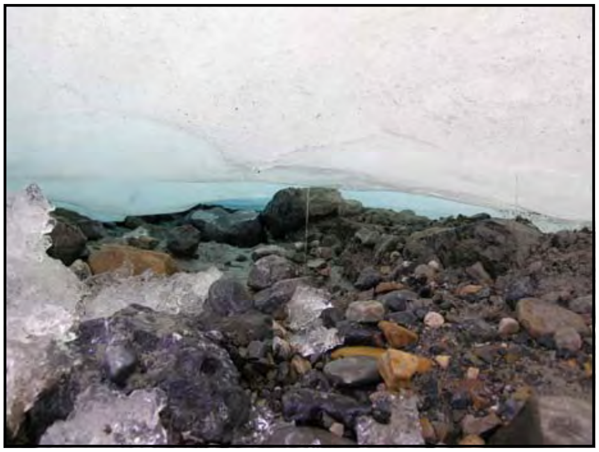
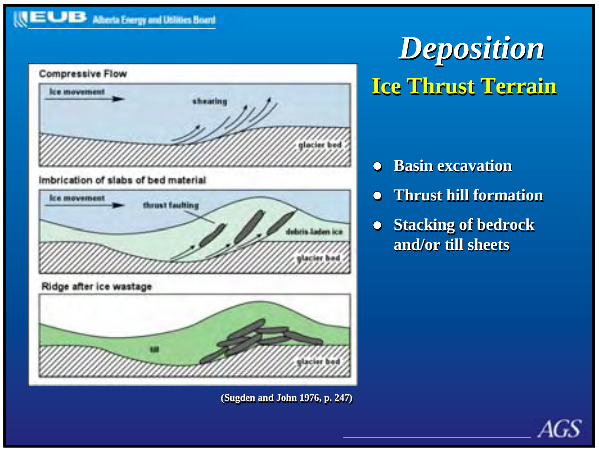


Ablation

Stagnant Ice Moraine



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Deposition

Ice Thrust Terrain

(Sugden and John 1976, p. 247)

- Basin excavation
- Thrust hill formation
- Stacking of bedrock and/or till sheets

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Deposition

Ice Thrust Terrain

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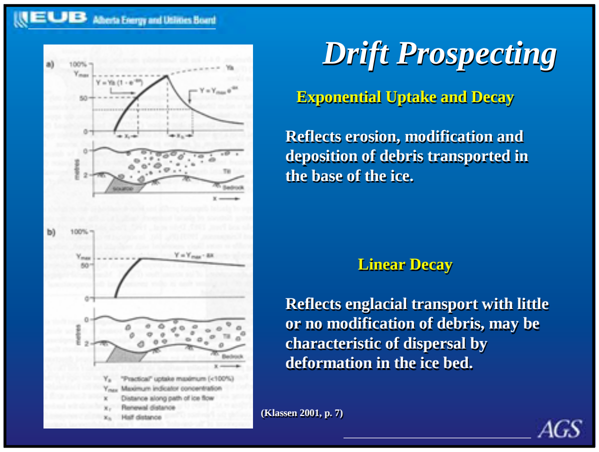
Transverse ice thrust ridges and flutes on the Peerless Highlands, AB.



Drift Prospecting

Exponential Uptake and Decay

Reflects erosion, modification and deposition of debris transported in the base of the ice.

Linear Decay

Reflects englacial transport with little or no modification of debris, may be characteristic of dispersal by deformation in the ice bed.

(Klassen 2001, p. 7)

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Further Reading: Drift Prospecting

DRIFT PROSPECTING

Drift Prospecting (DiLabio and Coker 1989)

DRIFT EXPLORATION IN THE CANADIAN CORDILLERA

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

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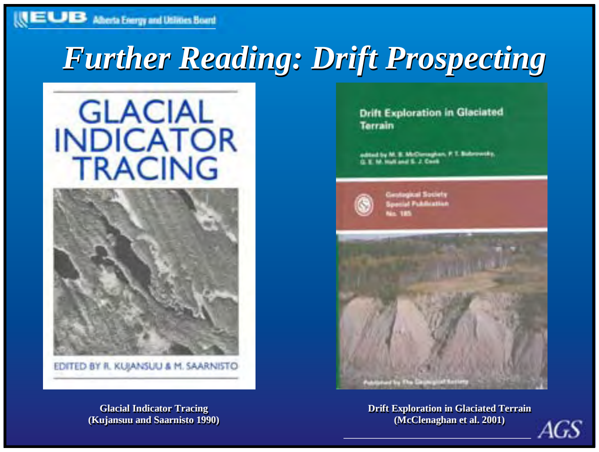

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Further Reading: Drift Prospecting

GLACIAL INDICATOR TRACING

EDITED BY R. KUJANSUU & M. SAARNISTO

Glacial Indicator Tracing
(Kujansuu and Saarnisto 1990)

Drift Exploration in Glaciated Terrain

Geological Society Special Publication No. 185

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

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NEW

Surficial Mapping Webpage on the AGS Website:

http://www.ags.gov.ab.ca/activities/surficial_mapping/surficial_mapping.html

Contains information on the surficial mapping program of northern Alberta, glacial stratigraphy, ice flow history and relevant research in drift prospecting.

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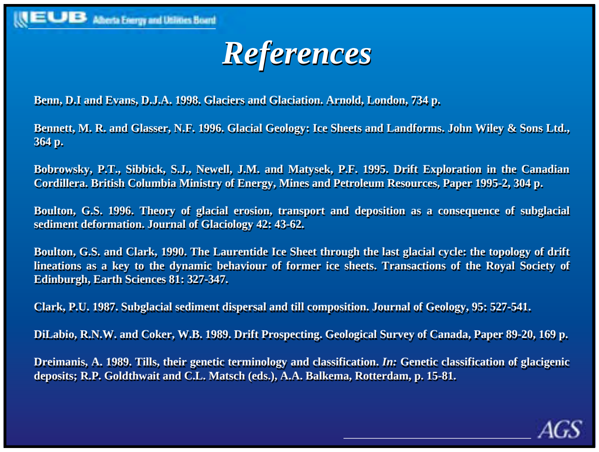
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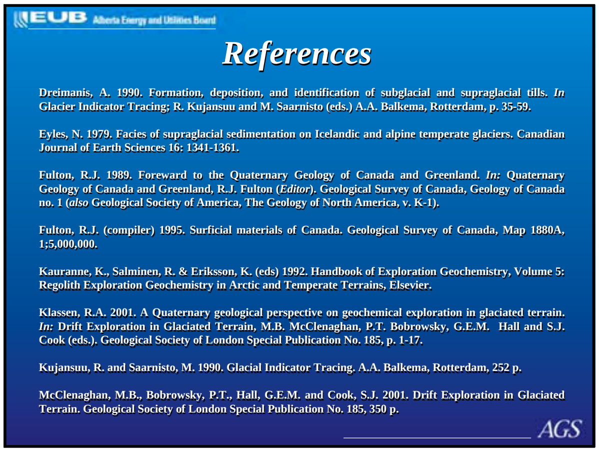
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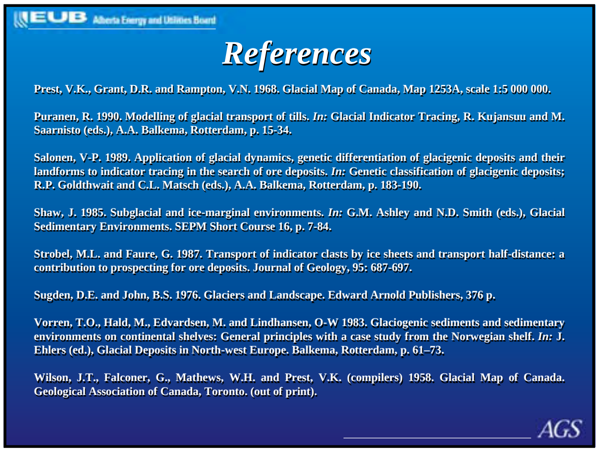

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Till Sampling for Kimberlite Exploration: Protocol for Success in Northern Alberta

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Materials having an intimate relation to their source are the most suitable for exploration (Rose et al. 1979). In glaciated terrain, drift prospecting is an integral part of diamond exploration in Canada because of the widespread nature of the glacial deposits, especially till which is a first-order sediment - directly deposited by glacier ice (Klassen 1997). Till is composed of freshly crushed bedrock blended with reworked older unconsolidated sediments (glacial and nonglacial), and transported for a few metres to hundreds of kilometers along glacial flow paths. Thus till sampling, combined with boulder tracing and ice-flow indicator mapping, has become an important tool in the tracing of diamond deposits.

Results from till sampling surveys are likely to be far less variable than those from associated glaciofluvial sediments (second-order) or post-glacial stream sediments (third-order). Till, however, is more difficult to sample and must be sampled in greater quantity to obtain a desired amount of sand-sized material. In order to obtain an adequate number of indicator mineral grains, a sample must contain an average of 5 to 10 kg of sand (Averill 2001). In the Western Canada Sedimentary Basin, samples collected by the GSC (e.g. Thorleifson and Garrett 1997) and AGS (e.g. Fenton and Pawlowicz 1993; Prior et al. 2005) tend to be roughly 25 to 30 kg in weight (30 litres) which contain an average of 1 kg of gravel-sized material and 5-8 kg of sand. Sample size is in part a function of signal to noise ratio; in regions with elevated background value, larger samples may be necessary.

In simple situations where only one till occurs, indicator concentrations are typically greatest at the base of the deposit, directly over and down-ice of the source, and it is commonly observed that the dispersal train rises in a down ice direction within the till sheet at a low angle of inclination (e.g. DiLabio 1990; Paulen 2001; Bobrowsky et al. 2003). Therefore, there can be separation (offset) between the bedrock source and the first occurrence of mineralized debris at the surface, and this distance tends to increase with till thickness (Slides #44-45). In exploration, this gap between the head of the dispersal train and its bedrock occurrence must be prospected in the subsurface by trenching or drilling. Zones of separation, or non-deposition, can also occur along the path of ice flow (Finck and Stea 1995).

In diamond exploration, recent research has shown that the nature of the kimberlitic source is one of the main factors that control dispersion of kimberlite indicator minerals (McClenaghan et al. 2004). Kimberlite exposed to prolonged preglacial weathering forms a regolith; the kimberlite bedrock is soft and easily eroded by tools carried within the sole of a glacier. Indicator minerals are easily plucked and released from the kimberlitic regolith and strongly defined dispersal trains form at the source (Slides #21-22). Kimberlite protected from preglacial or interglacial weathering is quite resistant to erosion by glaciers; the resultant dispersal train of indicator minerals is not formed until the solid kimberlitic fragments are eroded under the glacier and the indicator minerals freed from the kimberlitic host rock (i.e. plucking, transport, comminution and deposition). This can lead to offset dispersal trains that are only detected several or even tens of kilometers down-ice from the source (e.g. McClenaghan et al. 1999, 2000, 2004).

Despite the importance of site-specific relevant data, most sampling programs neglect to properly document some basic information on the sample site itself (e.g. texture, structure and the character of the sediment sampled) and its context within the regional glacial depositional history (e.g. collected next to an esker or within a drumlin field). Pictures do speak one thousand words and often a photo of every sample site is invaluable, especially now where digital memory is quite cheap. The intent of this lecture is to provide many examples from till sampling surveys in northern Alberta, with specific examples on till facies identification and sampling protocol. Although this lecture reflects the author's experiences in drift prospecting and till sampling surveys, it also draws freely on the work of others, notably fellow researchers Alberta Geological Survey (Mark Fenton, John Pawlowicz and Glen Prior). The message for exploration is that with proper care and documentation, drift prospecting for diamonds can be successfully applied in northern Alberta.

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Till Sampling for Kimberlite Exploration

Protocol for Success in Northern Alberta

Roger C. Paulen

EUB
Alberta Energy and Utilities Board
AGS
Alberta Geological Survey

Introduction

Till Sampling in Western Canada

- Sources of information and advice
- Regional till surveys and information available
- Locating and identifying sample media

Background

Northern Miner 1987-2001 (CD-ROM) Statistics (Diamond Exploration)

- Till + Sampling: 526
- Glacial + Till: 289
- Basal + Till: 31
- Surficial + Mapping: 7
- Drift Prospecting: 6
- Up-ice source: 83
- Ice flow, ice direction: 27
- Glacial + Studies: 23
- Surficial + Studies: 4

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Information

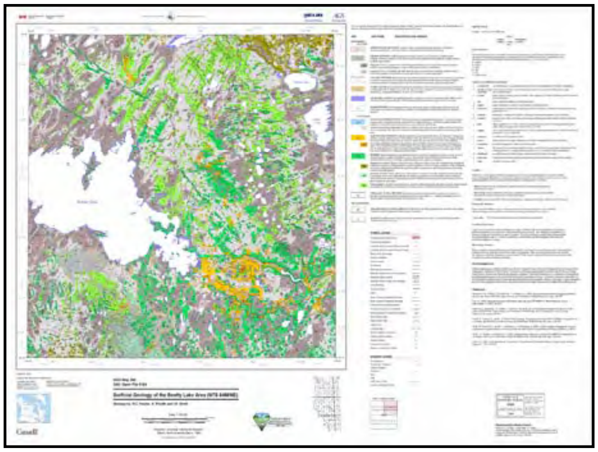
Surficial Maps (GSC or Provincial Surveys)

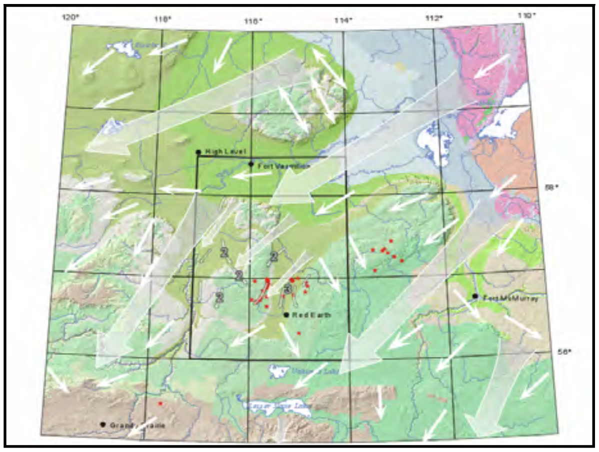
- Mapped till units
- Information on ice flow
- Relatively low cost

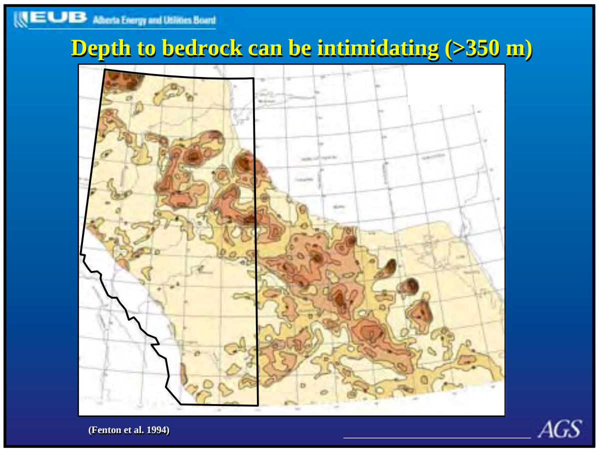
Previous Reports

- Assessment files
- Federal or Provincial survey reports
- Published literature

AGS







Depth to bedrock can be intimidating (>350 m)

(Fenton et al. 1994)

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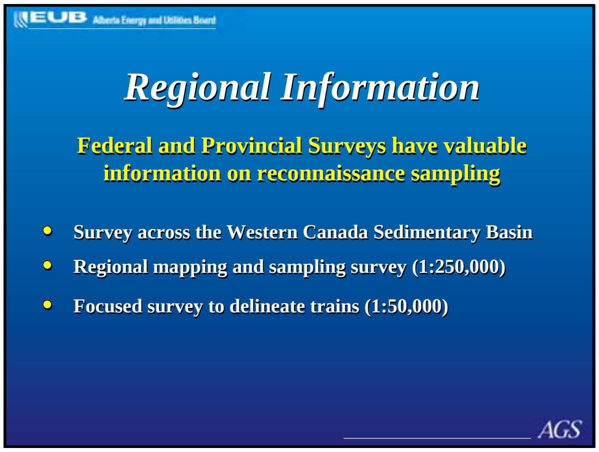

Regional Information

Federal and Provincial Surveys have valuable information on reconnaissance sampling

- Survey across the Western Canada Sedimentary Basin
- Regional mapping and sampling survey (1:250,000)
- Focused survey to delineate trains (1:50,000)

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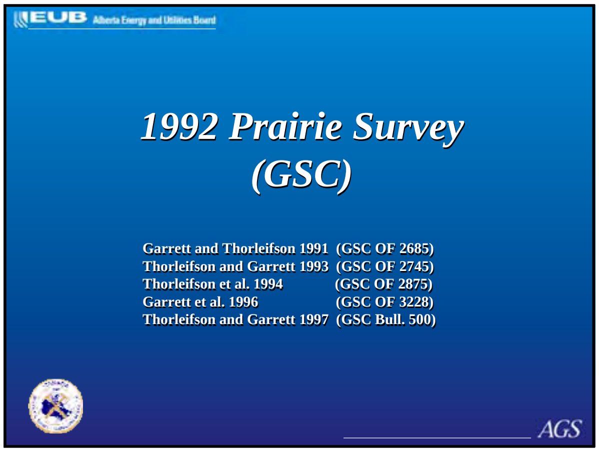
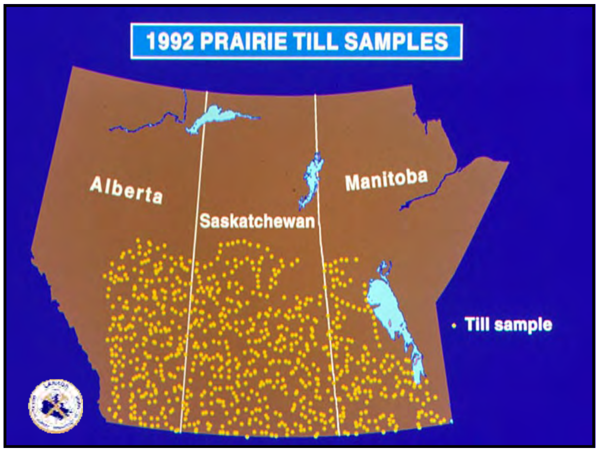


1992 Prairie Survey (GSC)

Garrett and Thorleifson 1991	(GSC OF 2685)
Thorleifson and Garrett 1993	(GSC OF 2745)
Thorleifson et al. 1994	(GSC OF 2875)
Garrett et al. 1996	(GSC OF 3228)
Thorleifson and Garrett 1997	(GSC Bull. 500)

AGS



1992 PRAIRIE TILL SAMPLES

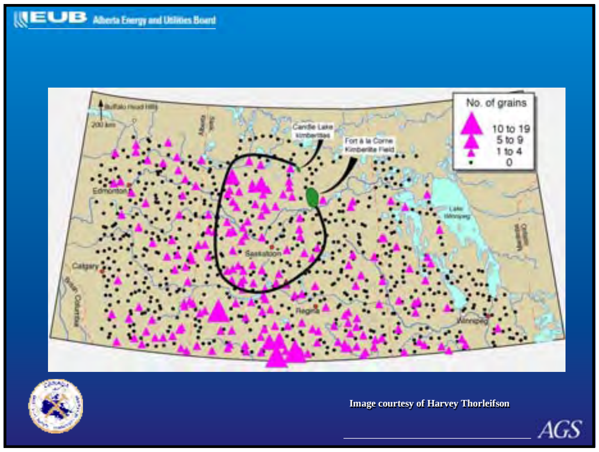
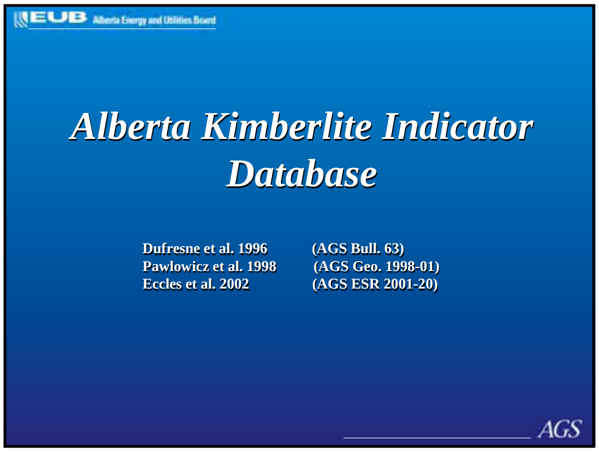
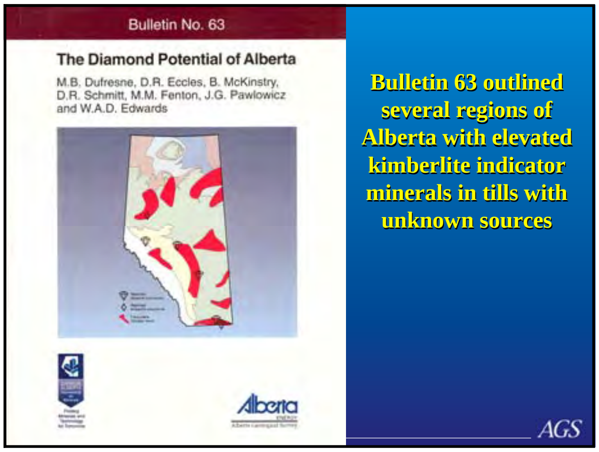


Image courtesy of Harvey Thorleifson



Alberta Kimberlite Indicator Database

Dufresne et al. 1996	(AGS Bull. 63)
Pawlowicz et al. 1998	(AGS Geo. 1998-01)
Eccles et al. 2002	(AGS ESR 2001-20)

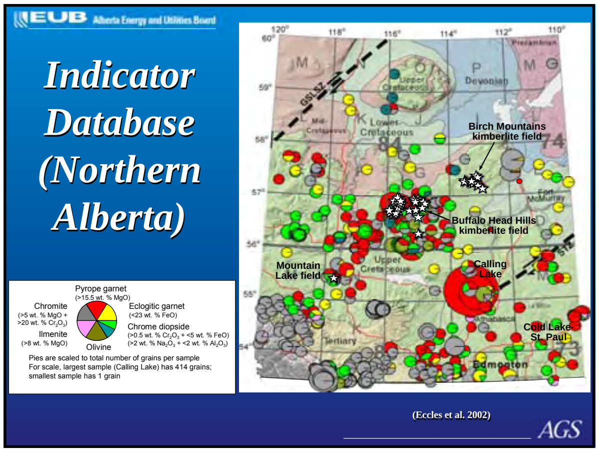


Bulletin No. 63

The Diamond Potential of Alberta

M.B. Dufresne, D.R. Eccles, B. McKinstry, D.R. Schmitt, M.M. Fenton, J.G. Pawlowicz and W.A.D. Edwards

Bulletin 63 outlined several regions of Alberta with elevated kimberlite indicator minerals in tills with unknown sources



Indicator Database (Northern Alberta)

Pyrope garnet (>15.5 wt. % MgO)

Chromite (>5 wt. % MgO + >20 wt. % Cr_2O_3)

Eclogitic garnet (<23 wt. % FeO)

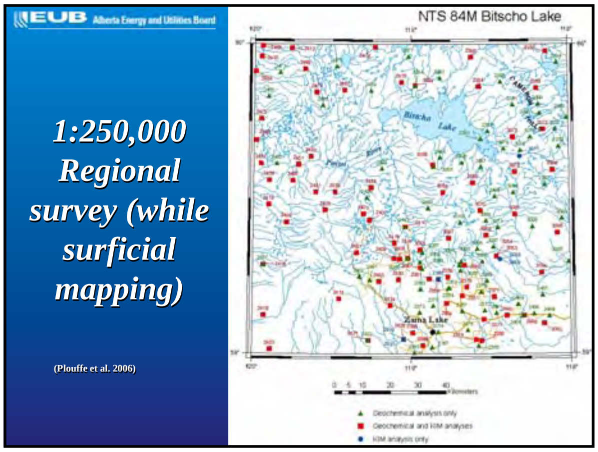
Chrome diopside (>0.5 wt. % Cr_2O_3 + <5 wt. % FeO) (>2 wt. % Na_2O_3 + <2 wt. % Al_2O_3)

Ilmenite (>8 wt. % MgO)

Olivine

Pies are scaled to total number of grains per sample
For scale, largest sample (Calling Lake) has 414 grains;
smallest sample has 1 grain

(Eccles et al. 2002)

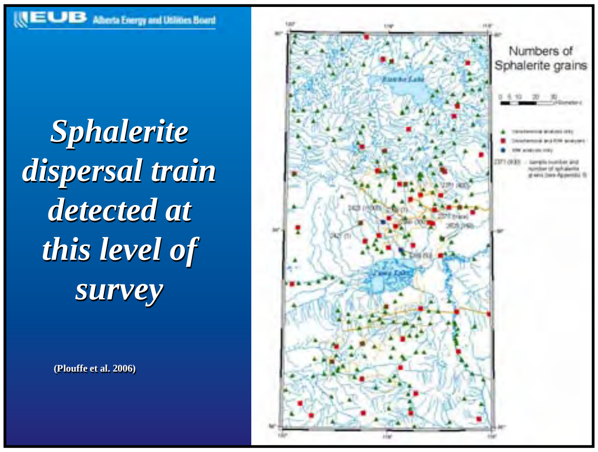


1:250,000 Regional survey (while surficial mapping)

(Plouffe et al. 2006)

NTS 84M Bitscho Lake

Geochemical analysis only
Geochemical and KIM analyses
KIM analysis only



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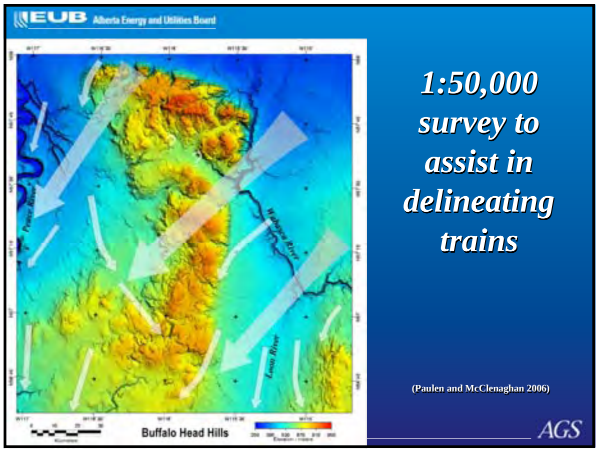
Sphalerite dispersal train detected at this level of survey

(Plouffe et al. 2006)



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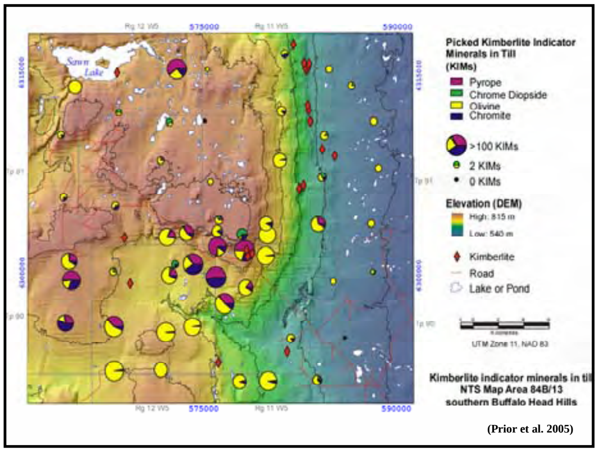
1:50,000 survey to assist in delineating trains

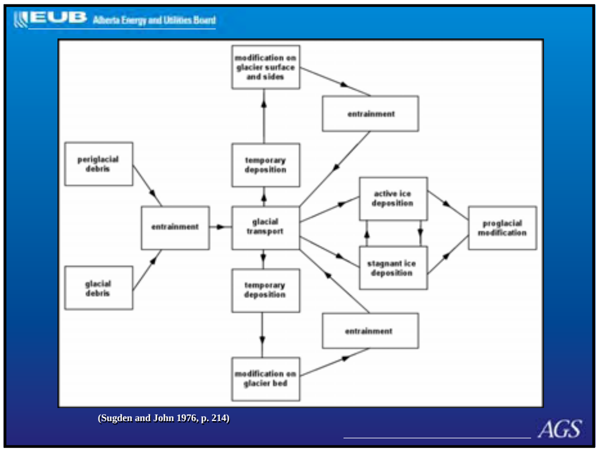
(Paulen and McClenaghan 2006)

AGS

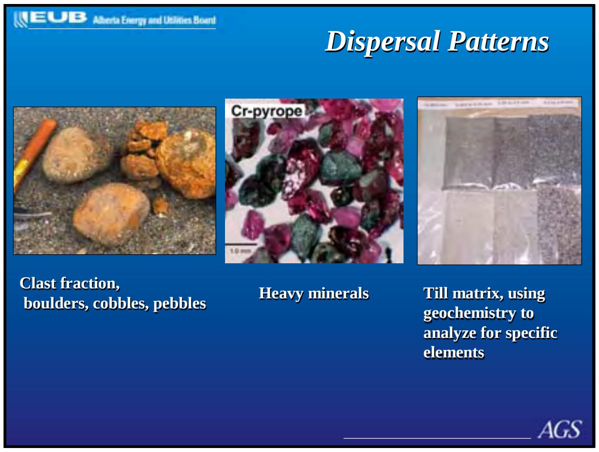


Kimberlite indicator minerals in til
NTS Map Area 84B/13
southern Buffalo Head Hills

(Prior et al. 2005)



(Sugden and John 1976, p. 214)

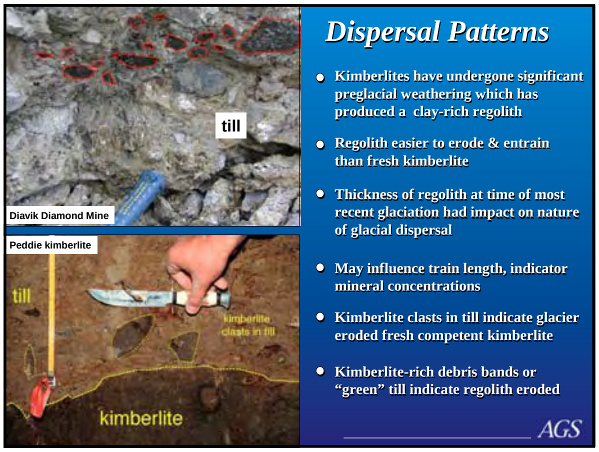


Dispersal Patterns

Clast fraction, boulders, cobbles, pebbles

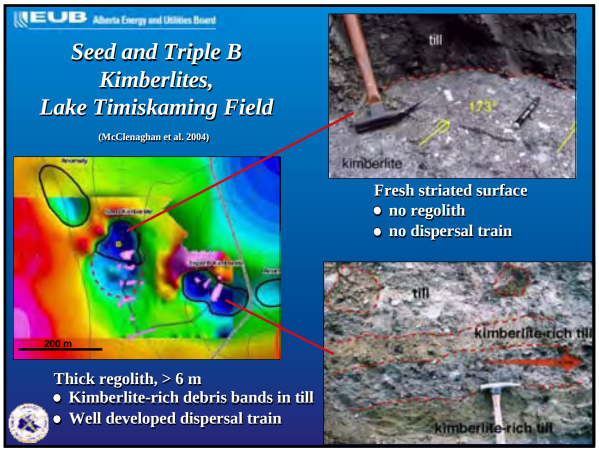
Heavy minerals

Till matrix, using geochemistry to analyze for specific elements



Dispersal Patterns

- Kimberlites have undergone significant preglacial weathering which has produced a clay-rich regolith
- Regolith easier to erode & entrain than fresh kimberlite
- Thickness of regolith at time of most recent glaciation had impact on nature of glacial dispersal
- May influence train length, indicator mineral concentrations
- Kimberlite clasts in till indicate glacier eroded fresh competent kimberlite
- Kimberlite-rich debris bands or “green” till indicate regolith eroded

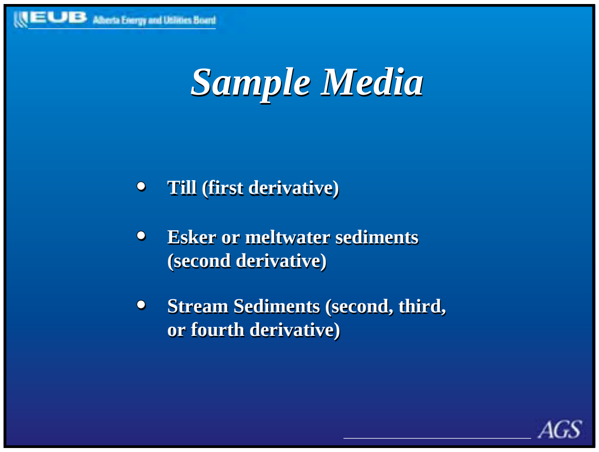


Seed and Triple B Kimberlites, Lake Timiskaming Field

(McClenaghan et al. 2004)

Fresh striated surface
- no regolith
- no dispersal train

Thick regolith, > 6 m
- Kimberlite-rich debris bands in till
- Well developed dispersal train

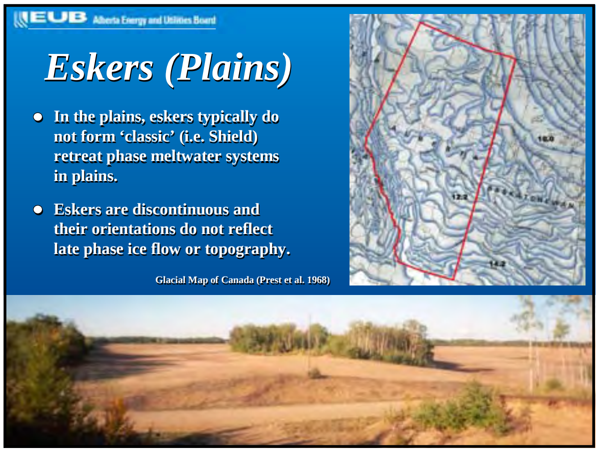


Sample Media

- Till (first derivative)
- Esker or meltwater sediments (second derivative)
- Stream Sediments (second, third, or fourth derivative)

Eskers (Shield)

- Esker orientations generally follow retreat phase of ice flow.
- Provenance of sediment can vary from <1 km to >200 km.
- The uppermost coarse lag is the “last gasp” of meltwater in the glaciofluvial system and is likely derived from washing of local (<25 km) tills or previously deposited ice-contact sediments.
- Poorly sorted, coarser material is also required to sample heavy mineral layers.



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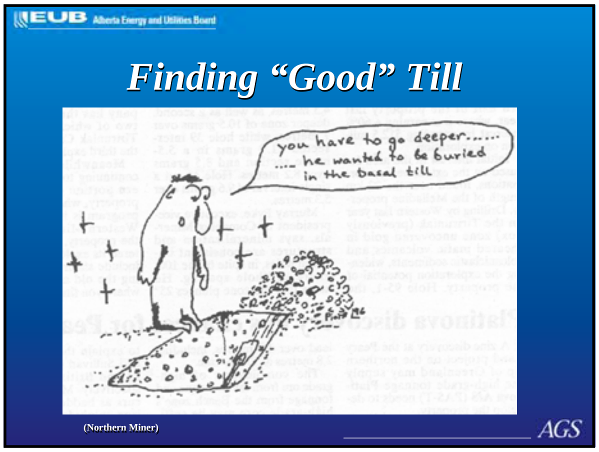
Eskers (Plains)

- In the plains, eskers typically do not form 'classic' (i.e. Shield) retreat phase meltwater systems in plains.
- Eskers are discontinuous and their orientations do not reflect late phase ice flow or topography.

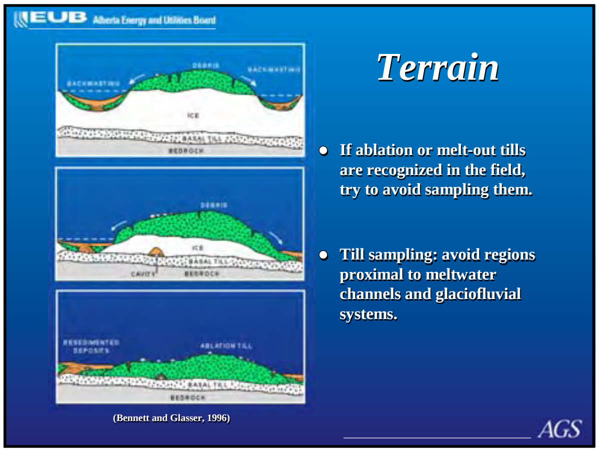
Glacial Map of Canada (Prest et al. 1968)



Finding “Good” Till

(Northern Miner)

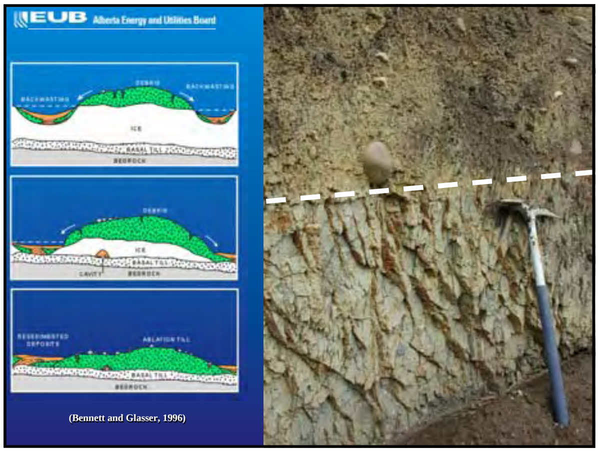
C-Horizon Till



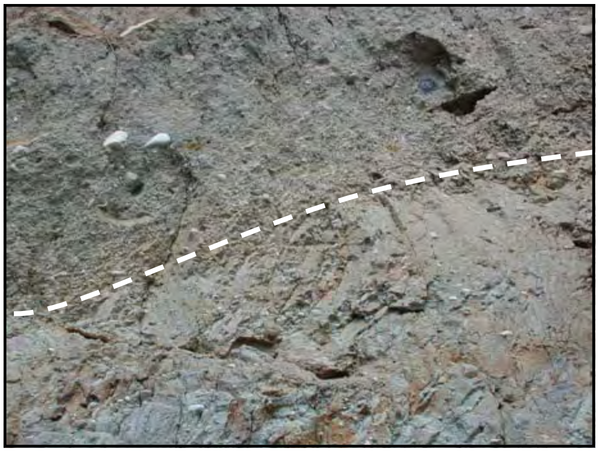
Terrain

- If ablation or melt-out tills are recognized in the field, try to avoid sampling them.
- Till sampling: avoid regions proximal to meltwater channels and glaciofluvial systems.

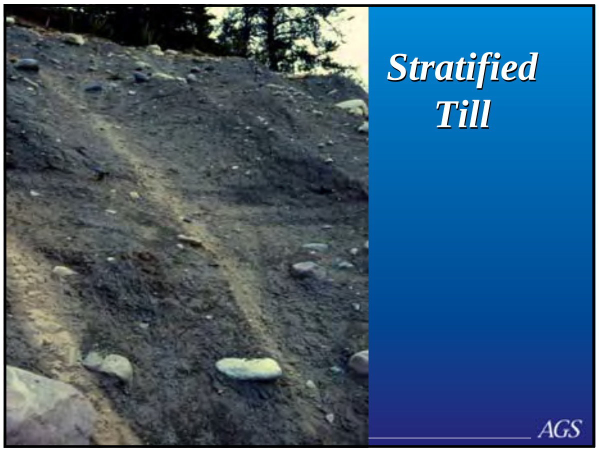
(Bennett and Glasser, 1996)



(Bennett and Glasser, 1996)



Variable Till Textures



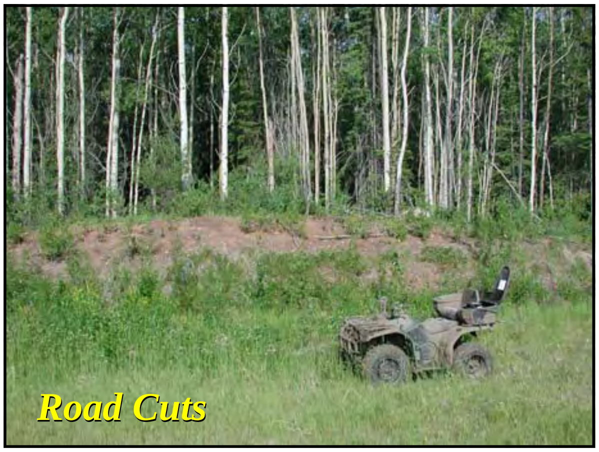
Stratified Till

Glaciotectonism

Stony Till

Clayey Till

Till Sampling

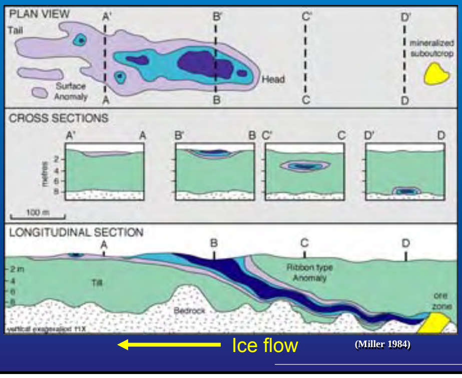

Road Cuts


Borrow Pits


River
Exposures

Sample lowermost part of exposure

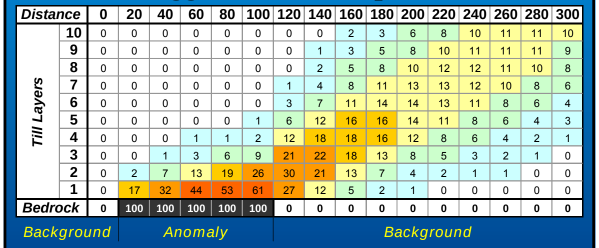
Ideal Model of Dispersal Train



Ice flow

(Miller 1984)

Aggradational Dispersion Model

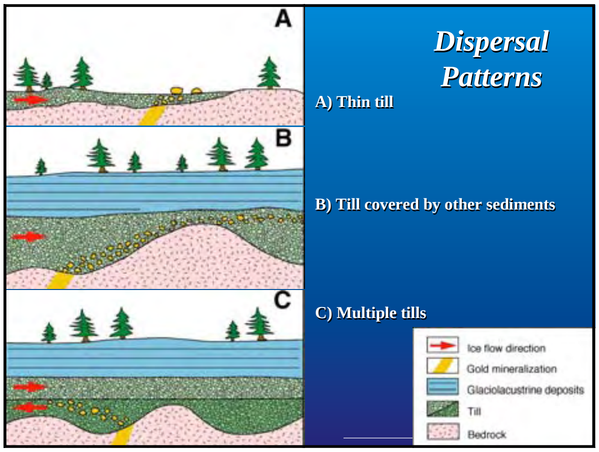


Distance		0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300
Till Layers	10	0	0	0	0	0	0	0	0	2	3	6	8	10	11	11	10
	9	0	0	0	0	0	0	0	1	3	5	8	10	11	11	11	9
	8	0	0	0	0	0	0	0	2	5	8	10	12	12	11	10	8
	7	0	0	0	0	0	0	1	4	8	11	13	13	12	10	8	6
	6	0	0	0	0	0	0	3	7	11	14	14	13	11	8	6	4
	5	0	0	0	0	0	1	6	12	16	16	14	11	8	6	4	3
	4	0	0	0	1	1	2	12	18	18	16	12	8	6	4	2	1
	3	0	0	1	3	6	9	21	22	18	13	8	5	3	2	1	0
	2	0	2	7	13	19	26	30	21	13	7	4	2	1	1	0	0
	1	0	17	32	44	53	61	27	12	5	2	1	0	0	0	0	0
Bedrock		0	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0

Background Anomaly Background

- anomalous material is smeared down-ice
- width of the anomaly increases down-ice
- concentrations of most anomalous material decrease down-ice (diluted by mixing)

(Stanley 2003)

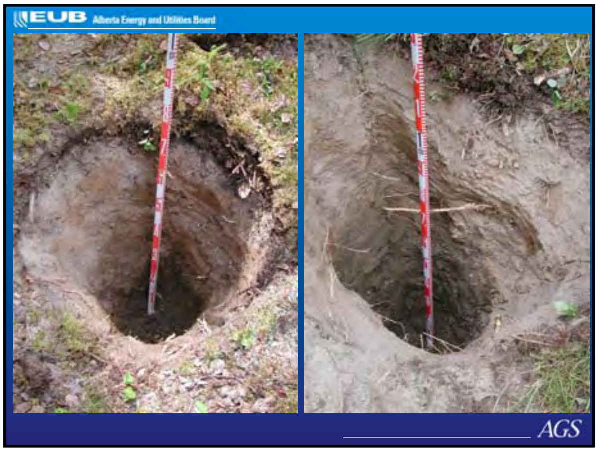


Dispersal Patterns

A) Thin till

B) Till covered by other sediments

C) Multiple tills

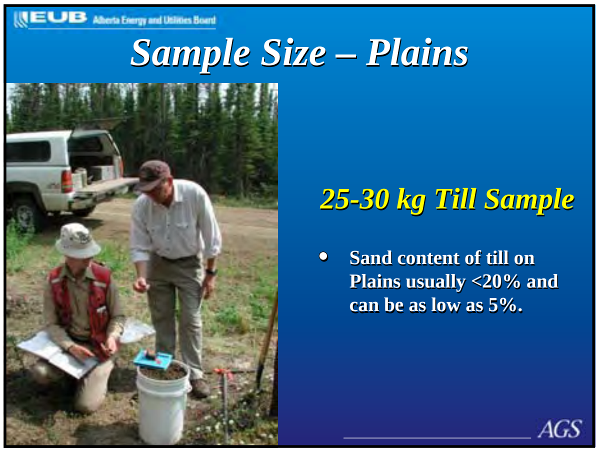


Sample Size – Shield

10-15 kg Till Sample

- Sand content of Shield-derived till usually >35% and can exceed 90%.

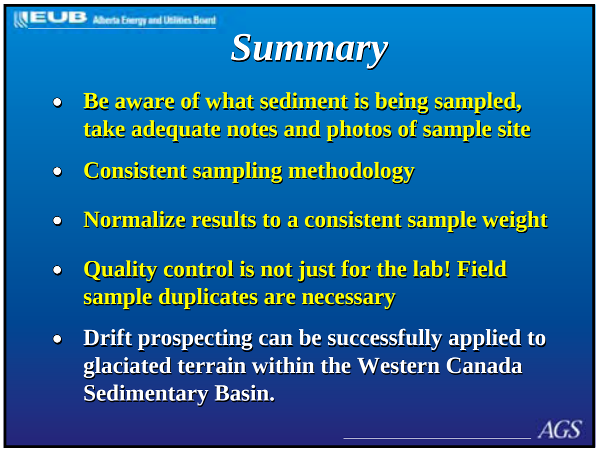
Photo courtesy of Beth McClenaghan



Sample Size – Plains

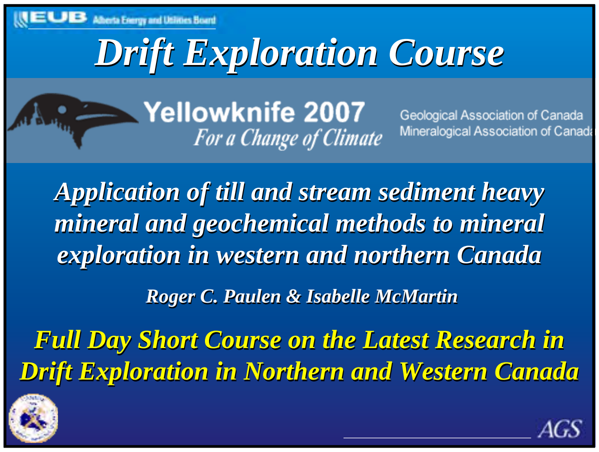
25-30 kg Till Sample

- Sand content of till on Plains usually <20% and can be as low as 5%.



Summary

- Be aware of what sediment is being sampled, take adequate notes and photos of sample site
- Consistent sampling methodology
- Normalize results to a consistent sample weight
- Quality control is not just for the lab! Field sample duplicates are necessary
- Drift prospecting can be successfully applied to glaciated terrain within the Western Canada Sedimentary Basin.



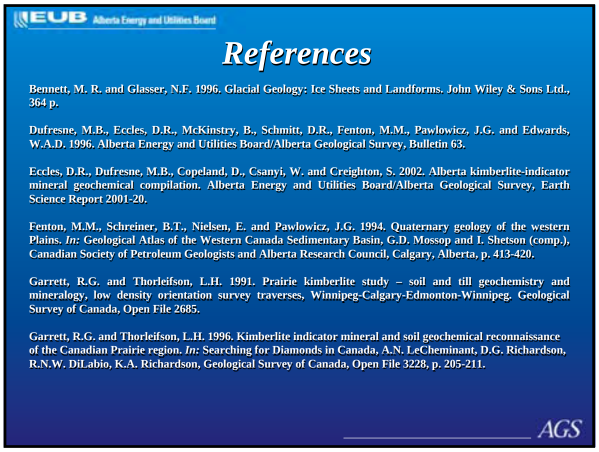
Drift Exploration Course

Yellowknife 2007
For a Change of Climate
Geological Association of Canada
Mineralogical Association of Canad

Application of till and stream sediment heavy mineral and geochemical methods to mineral exploration in western and northern Canada

Roger C. Paulen & Isabelle McMartin

Full Day Short Course on the Latest Research in Drift Exploration in Northern and Western Canada



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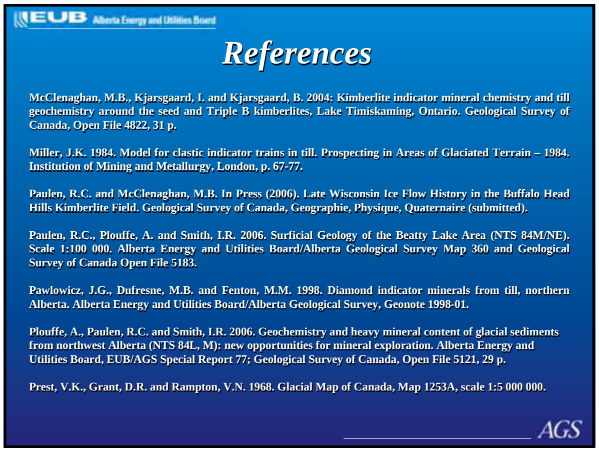

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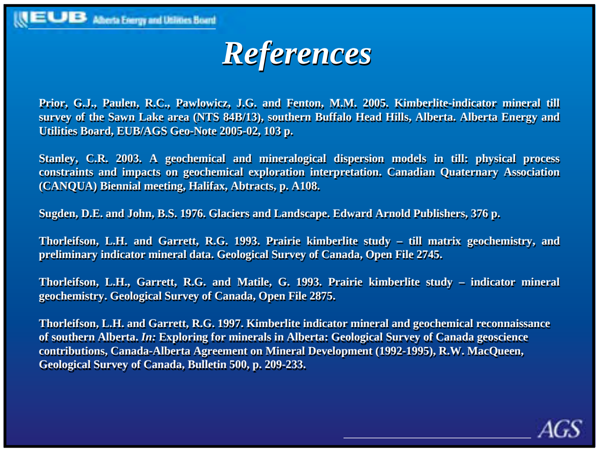

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QUATERNARY GEOLOGY OF NORTHERN ALBERTA: IMPLICATIONS FOR KIMBERLITE EXPLORATION

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INTRODUCTION

During the last decade, a considerable amount of research has taken place in northern Alberta. Particular attention has been paid to the unique geological setting of northern Alberta's Quaternary history and the challenges of drift prospecting for diamonds here, relative to known methodologies that are well established within the Canadian Shield. Currently, 47 ultramafic diatremes have been discovered in three separate areas within the Western Canada Sedimentary Basin of northern Alberta: 2 non-kimberlitic pipes at Mountain Lake, 37 kimberlite pipes in the Buffalo Head Hills area and 8 kimberlite pipes in the Birch Mountains area. The kimberlite fields of northern Alberta differ from other Canadian kimberlite fields (e.g. Lac de Gras) in various ways from the perspective of drift prospecting in glaciated terrain. Such factors include the bedrock geology, glacial history, physiography and drift thickness.

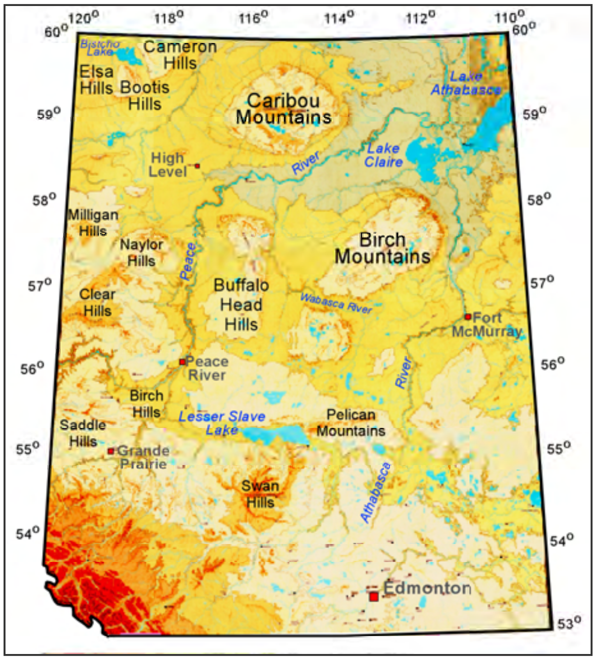

Figure 1. Relief and physiography of northern Alberta

Quaternary deposits are the surface materials and form the local landforms over virtually all of northern Alberta. Bedrock, which controls the broad elements of the physiography, rarely crops out. Most of the surficial deposits that occur were deposited during the Pleistocene glaciations. For the most part, the surficial materials and present-day landforms are a result of the last glacial event during the Late Wisconsin (25-12 ka BP).

The physiography of northern Alberta (Figure 1) consists of a number of highlands: the Swan Hills, Pelican Mountains, Saddle Hills, Clear Hills, Naylor Hills, Milligan Hills, Buffalo Head Hills, Birch Mountains, Caribou Mountains, Cameron Hills, Bootis Hills and Elsa Hills. Separating these highlands are major drainage ways such as the Peace, Wabasca and Athabasca rivers (Pettapiece, 1986).

BEDROCK GEOLOGY

The Mountain Lake pipes occur within the Upper Cretaceous Wapiti Formation, which is composed mainly of non-marine sandstone. The kimberlites of the Buffalo Head Hills and Birch Mountain fields are hosted by a Cretaceous succession composed dominantly of marine shales of the Shaftesbury Formation and Smoky Group, which are separated by deltaic to marine sandstones of the Dunvegan Formation (Hamilton et al., 1999). This differs considerably from other prospective regions in Canada where exploration focuses on the Archean craton (e.g. Slave Province). There, exploration targets usually lie beneath small round lakes; this is generally a product of differential erosional as kimberlitic bedrock is considerably softer than rocks of the Canadian Shield that surround them. In Alberta, however, several of the kimberlites form topographic and/or bedrock highs due to their greater resistance to weathering and glacial erosion relative to the enclosing soft Cretaceous sedimentary rocks.

BEDROCK TOPOGRAPHY

The bedrock topography (Figure 2) is the result of erosion during the Tertiary and probably at least the early Quaternary (Fenton et al. 1994). The bedrock topography generally resembles the surface topography/physiography to some degree, with the high and lows in the bedrock surface being reflected in the surface topography. Two basic topographic elements are evident: the broad generally northward and eastward trending valleys, and intervening uplands formed by eroded bedrock remnants. Note however, that in the vicinity of the Cameron, Bootis and Elsa Hills in northwestern Alberta, the bedrock elevation is considerably lower and than the surface expression of these hills, hence the high topography reflects an accumulation of thick surficial deposits.

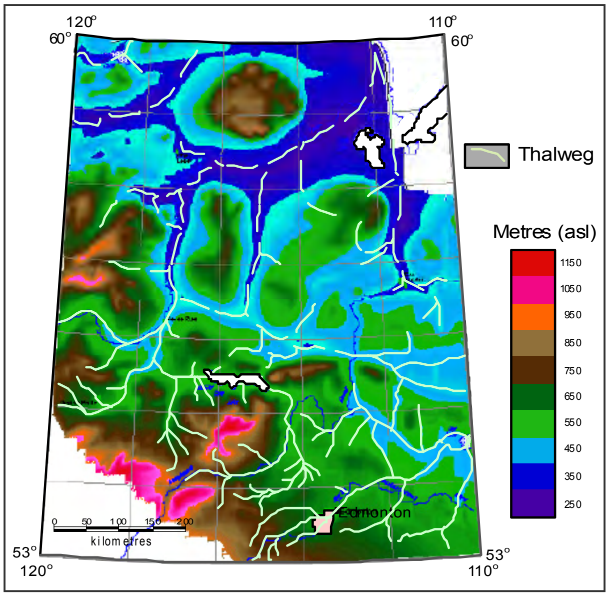

Figure 2. Bedrock topography of northern Alberta (modified from Pawlowicz and Fenton, 1995a)

The bedrock topographic lows in northern Alberta are primarily the major preglacial valleys. Most of these valleys were likely eroded prior to the first glacial advance to reach the region. However, the existence of preglacial sediment at the base of these valleys is needed to confirm this assumption. Preglacial sediment in northern Alberta consists of coarse sediment, predominantly quartzite clasts, derived from the Cordillera.

DRIFT THICKNESS

The thickness of unconsolidated sediment overlying the bedrock, including sediment of both Late Tertiary and Quaternary age, is shown in Figure 3. The Tertiary sediment is confined largely to the lower portions of the preglacial channels. The drift thickness varies from 0 m in a few areas to 300 m in the Wiau channel which extends westward from the Saskatchewan boarder, north of latitude 55°N. The drift is generally thick in these channels, but in places it can also thicken on the uplands. The preglacial channels, for the most part, have been partially filled, thus lowering the local relief on the present land surface.

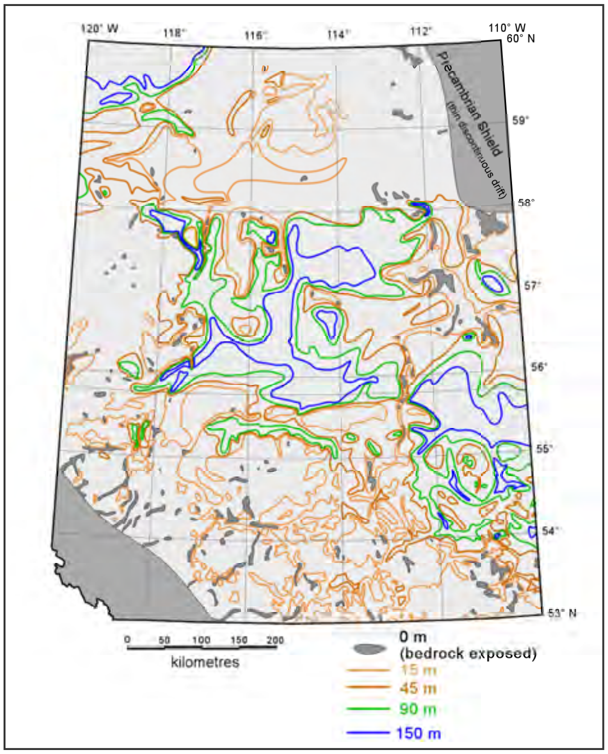

Figure 3. Drift thickness of northern Alberta (modified from Pawlowicz and Fenton, 1995b)

Deposition within these channels was more or less continuous from the close of the Tertiary into the Quaternary. The deposition of nonglacial fluvial sediment continued until the onset of glaciation. The ice sheets advanced into Alberta up-drainage, essentially blocking the preglacial drainage. The first stratigraphic marker positively identifying Quaternary sediment, at any particular site, is the stratigraphically lowest appearance of till, or other glacial stratified sediment, that contains exotic material transported westward and/or southward by the advancing Laurentide glaciers. Typically, this exotic material is from the Precambrian Shield and/or the adjacent Paleozoic carbonate outcrop belt.

Factors influencing the location of thick accumulations of sediment in northern Alberta are: (1) the preglacial valleys, (2) bedrock highlands and remnants, (3) areas of ice marginal still-stands and (4) bedrock contacts or scarps (Fenton et al, 1994). The preglacial valleys influenced deposition in a number of ways: (1) they acted as sediment traps, accumulating thick sequences of stratified sediment as the advancing or retreating glaciers dammed the eastward flowing streams; (2) they influenced glacial dynamics and contributed to the accumulation and preservation of comparatively thick sequences of till within them; (3) during the nonglacial intervals, they formed lows favorable to initial erosion and channel formation, and this led to subsequent infilling of these channels by nonglacial stratified sediment; and (4) because of their low position in the landscape, they tended to preserve the existing sediment from erosion during subsequent glacial advances (Fenton and Pawlowicz, 2000).

The effect of deposition at an ice marginal stillstand can be seen at the Cameron, Bootis and Elsa Hills regions in northwestern Alberta. The limited subsurface data indicates these uplands are composed primarily of a thick sequence of Quaternary sediment deposited during one or more intervals when the ice margin was stationary in the region long enough to deposit a substantial amount of sediment. Bedrock uplands may also include areas of thick drift accumulation. These areas may be the result of a thick, comparatively widespread, accumulation of glaciogenic sediment (till, and glaciofluvial and/or glaciolacustrine sediment) or the infilling of comparatively narrow preglacial or interglacial channels.

Bedrock contacts, buried channel margins and scarps are all areas where ice sheets have deformed the bedrock and drift to deposit comparatively thick accumulations of thrusted bedrock and glacial sediment. Minor glaciotectonic features have been recognized in many areas of northern Alberta and more are being discovered as the surficial mapping program moves into new areas (cf. Paulen 2002). Areas of known deformation include portions of the Birch Mountains, Pelican Mountain, northeastern flank of the Caribou Mountains, south of Rock Island Lake, at Fawcett Lake and Muskwa Lake, and in the Fort McMurray region. One example of glaciotectonism and transport is the Cooking Lake Erratic, a discontinuous mass of the Grand Rapids Sandstone that is exposed areally over a number of hectares east of Edmonton. It was thrusted into the Laurentide Ice Sheet and transported more or less intact about 300 km from its subcrops south of Fort McMurray. A detailed discussion of glacial tectonism can be found in Fenton and Pawlowicz (2000).

SEDIMENT AND STRATIGRAPHY

Glacial deposits in northern Alberta generally comprise till, glaciolacustrine and glaciofluvial sediments. The nature of these deposits reflects broad aspects of the bedrock lithologies and patterns of glacial and glaciofluvial transport. The soft poorly consolidated Mesozoic bedrock, together with the well developed relief, allowed the glaciers to incorporate considerable quantities of debris both as finely divided sediment and large masses incorporated through glaciotectonism. Clay and silt till is mainly derived from the fine-grained Cretaceous bedrock, with sand components from Cretaceous and Tertiary sandstones. Minor yet important components of the till come from bedrock of the Precambrian Shield, Paleozoic carbonates at the margin of the shield, and quartzites and other clastic rocks from the Cordillera.

The subsequent melting released this sediment to form a variety of landforms including streamlined terrain, hummocky stagnant ice terrain (Figure 4), deformation terrain, palimpsest terrain and low relief terrain, each of which contains different proportions of basal debris. The tills are generally much finer texture than those deposited on the Shield, which tend to be of a silty sand composition (Scott 1976; Vincent 1989). The till texture ranges from clayey silt to silty clay with less than 2 percent clasts of pebble size or larger. The exception in Northern Alberta is the sandy tills north of Fort McMurray and east of the Athabasca River.

Figure 4. Typical stagnant ice terrain (donut moraine) in northern Alberta (photo by R. Paulen).

Multiple glacial advances were documented in the Cold Lake region, with five tills recognized (Andriashek and Fenton 1989). Three lithologically distinct till sheets were recognized in the Cooking Lake moraine immediately east of Edmonton, with the upper till overlying organic remains dated to middle Wisconsin age (Andriashek and Fenton 1997). Their work also correlated these till sheets with those in the Cold Lake region. Recently, multiple tills have been identified in the Buffalo Head Hills kimberlite field. An older, oxidized till sheet was identified in boreholes and to the southwest in a deep burrow pit. Preliminary results from overburden drilling show that this older till (pre-middle Wisconsin) may have a higher concentration of kimberlite indicator minerals than the younger till (late Wisconsin) that overlies it. This may provide some insight on the difficulty of mapping kimberlite dispersal trains from samples collected at or near surface.

ICE FLOW HISTORY

Glacial advances in northern Alberta originated from the Laurentide Ice Sheet. The Laurentide Ice Sheet generally flowed across Alberta in a southwesterly direction (Dyke et al. 2002). The difficulty in piecing together the ice flow history in Alberta is the scarcity of erosional ice flow indicators, such as striations, roche moutonnées and sculpted bedrock forms. The soft Cretaceous bedrock was prone to intense erosion, glacial deformation and ice-thrusting. Distribution of erratics, streamlined landforms, and pebble fabrics can provide clues on regional ice movement (Fulton 1995; Klassen 1989). A preliminary ice flow history is presented in Figure 5.

DRIFT PROSPECTING

Indicator mineral surveys of near-surface till have been completed by the Alberta Geological Survey to document dispersal from kimberlites of the Buffalo Head Hills field (Dufresne et al. 1996; Fenton and Pawlowicz 1997; Pawlowicz et al. 1998; Eccles et al. 2001; Prior et al. 2003). In the southwestern Buffalo Head Hills an indicator mineral dispersal train, characterized by elevated counts of pyrope and chromite grains, is up to 6 km wide and extends for over 15 km (Prior et al. 2003). Overburden thickness in this area generally varies from about 2 m to >25 m. Therefore, despite the relative complexity of northern Alberta's Quaternary geology, drift prospecting is a viable exploration method in areas of thin to moderate overburden. However, as a consequence of the Quaternary history, indicator mineral dispersal trains from kimberlite sources may be palimpsest in nature.

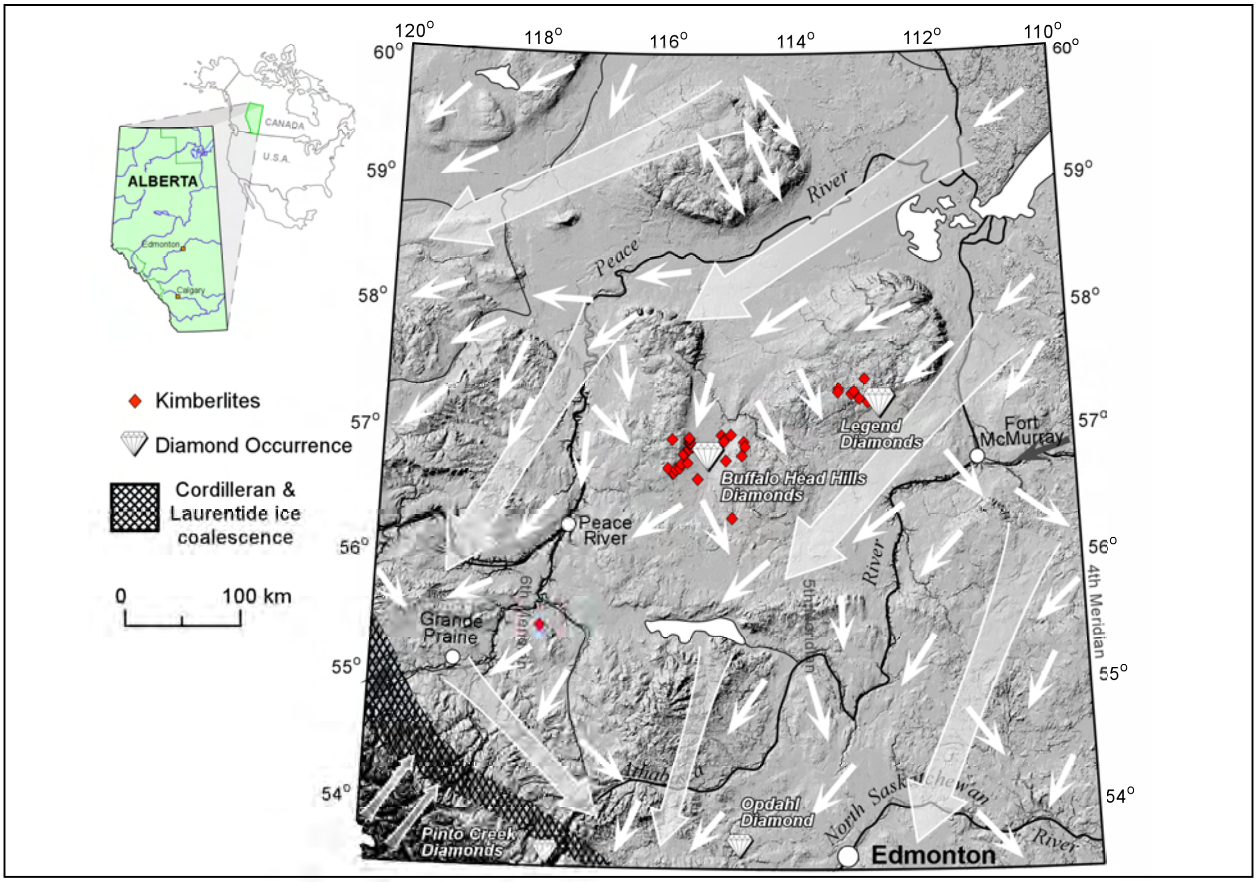

Figure 5. Ice flow of the Laurentide Ice Sheet during the Late Wisconsin. The large arrows indicate ice flow at glacial maximum (derived from Fulton 1989 and Prest et al. 1968). The smaller arrows indicate general flow directions of latest Late Wisconsin ice (Klassen 1989; Paulen et al. 2002)

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Stream Sediment Kimberlite Indicator Mineral Prospecting in Northern Alberta

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Sampling Methodology (from Prior et al., 2006)

Sample Collection

Material is collected from a single location where possible, or within close proximity otherwise. A 5-gallon (22.7 litre) plastic pail is lined with a heavy-duty polyethylene bag (18x24 inches, 4 Mil). Material is wet-sieved through a 12-mesh (1.68 mm) stainless steel sieve placed on top of the pail, until a sample weight of 10-15 kg is attained. The bag lining the pail was taped shut with black plastic (electrical) tape and placed into a second bag with a sample number and taped. Samples were shipped directly to a commercial lab for preparation and analysis. Figure 1 illustrates all the samples types collected at a typical bulk sediment site.

Figure 1. Pre-labelled Kraft paper bags and plastic bottles are used to collect samples of stream silts and stream waters. A bulk sample, for heavy mineral processing, is collected by wet-sieving coarse-grained stream sediment using a US Sieve Series 12-mesh (1.68 mm) sieve and collecting <12 mesh grains in a plastic pail lined with a polyethylene sample bag. The gold pan is used for adding water for wet sieving, not for heavy mineral concentrate panning. A sample composed of granules and pebbles, for archive, is collected at bulk sample sites by sieving >12 mesh material

through a US Sieve Series 2-mesh (10 mm) sieve and collecting the <10 mm material in a labelled Kraft paper bag. Flagging tape with a sample site number is used to mark sample sites. Field observations are noted on pre-printed water-resistant paper.

Sample Preparation

Bulk sediment samples are progressively reduced by different laboratory procedures to concentrate heavy minerals. Initially a 500-g character sample is taken and stored before a low-grade table concentrate is prepared from the remainder. Gold grains are observed at this stage and counted, measured and classified as to degree of wear (reflecting distance of transport). The table reject is re-tabled to scavenge possible unrecovered kimberlite indicator minerals and magmatic massive sulphide indicator minerals. The concentrate from both tabling runs is separated in methylene iodide diluted with acetone to S.G. 3.20 to recover heavy minerals including pyrope, Cr-diopside, forsterite and chromite. Magnetite is removed after the heavy liquid separation and the remaining concentrate cleaned with oxalic acid to remove limonite stains. The dried concentrate is sieved to separate it into several size fractions, (<0.25 mm, 0.25 to <0.5 mm, 0.5 mm to <1.0 mm, ≥ 1.0 mm to 2.0 mm). The <0.25 mm fraction is kept for chemical analysis and the 0.25 to 0.50 mm fraction is sorted with a Carpco® drum magnetic separator into strongly, moderately, weakly and non-paramagnetic fractions.

Analysis

Kimberlite indicator minerals (KIMs) are picked and identified from each of three size fractions (0.25-0.5 mm, 0.5 mm-1.0 mm, 1.0-2.0 mm). Fractions exceeding a 100 g threshold are characterized by a 100 g split and normalized to represent the total sample weight. Following removal of the kimberlite indicator minerals, 100 grains are randomly selected from each 0.25-0.5 mm fraction and identified. After identification these 100 grains are recombined with the source sample fraction. The 0.25-0.5 mm, 0.5-1.0 mm and 1.0-2.0 mm fractions (minus KIMs) are archived. The <0.25 mm fraction of the heavy mineral concentrate is sent to a commercial lab where it is ground in a ceramic mill and analyzed by a combination of ICP-MS, INAA and specific methods. Kimberlite indicator mineral grains undergo electron microprobe analysis for chemical characterization.

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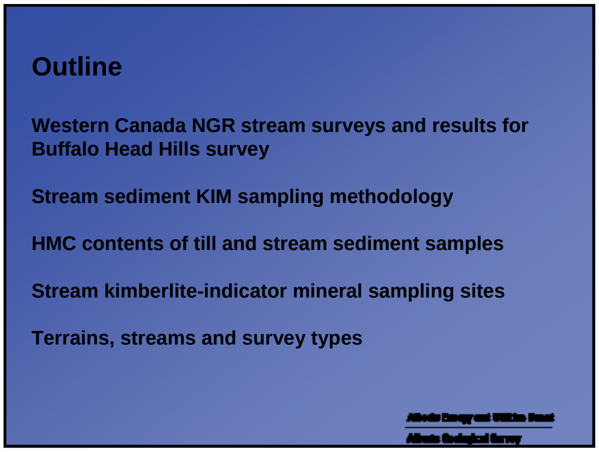
Prior, G.J., McCurdy, M.W., Friske, P.W.B., Pawlowicz, J.G., Day, S.J.A. and McNeil, R.J. (2006): Preliminary release of kimberlite indicator mineral data from National Geochemical Reconnaissance stream sediment samples in the Jackpine Lake area, (NTS 84C/15, 84C/16, 84F/01, 84F/02), southwest Buffalo Head Hills, Alberta; Alberta Energy and Utilities Board, EUB/AGS Special Report 78 and Geological Survey of Canada Open File 5267, 21 p.

Stream Sediment Kimberlite-Indicator Mineral Prospecting in Northern Alberta

Calgary Mineral Exploration Group 15th Calgary Mining Forum, 2006
Diamond Exploration in Western Canada Basin

Glen J. Prior, Peter W.B. Friske and Martin W. McCurdy

Alberta Energy and Utilities Board
Alberta Geological Survey



Outline

Western Canada NGR stream surveys and results for Buffalo Head Hills survey

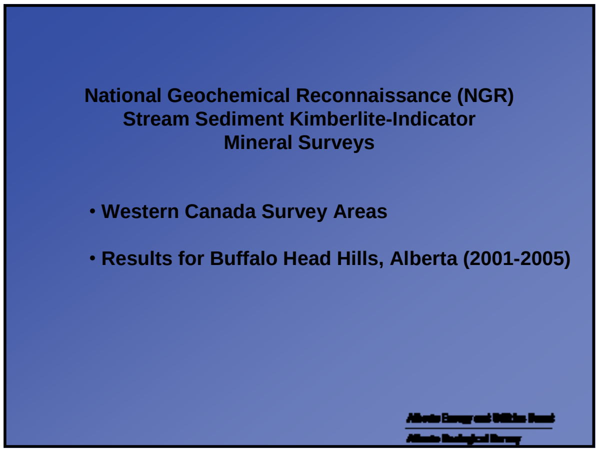
Stream sediment KIM sampling methodology

HMC contents of till and stream sediment samples

Stream kimberlite-indicator mineral sampling sites

Terrains, streams and survey types

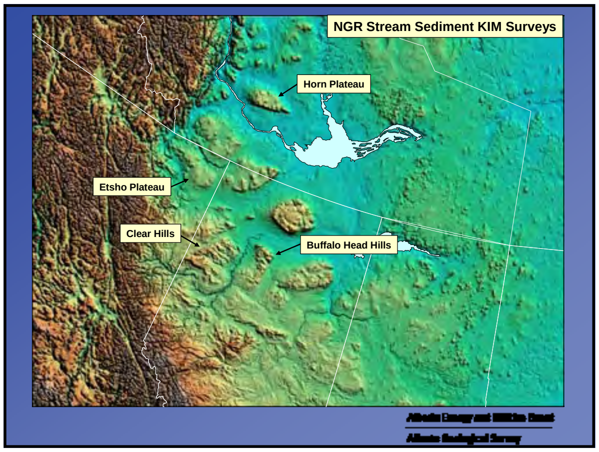
Alberta Energy and Utilities Board
Alberta Geological Survey



National Geochemical Reconnaissance (NGR) Stream Sediment Kimberlite-Indicator Mineral Surveys

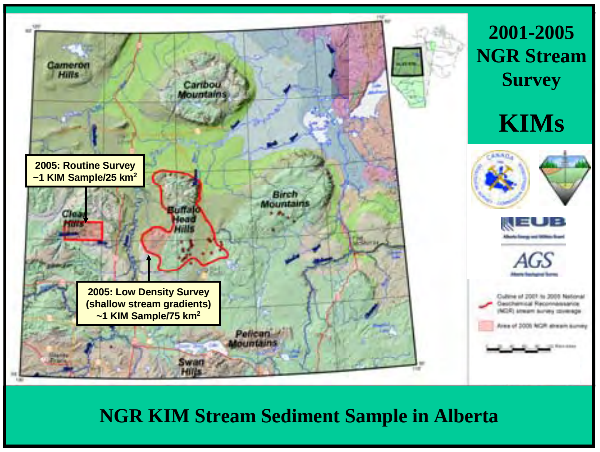
- Western Canada Survey Areas
- Results for Buffalo Head Hills, Alberta (2001-2005)

Alberta Energy and Utilities Board
Alberta Geological Survey



NGR Stream Sediment KIM Surveys

Alberta Energy and Utilities Board
Alberta Geological Survey



2001-2005 NGR Stream Survey

KIMs

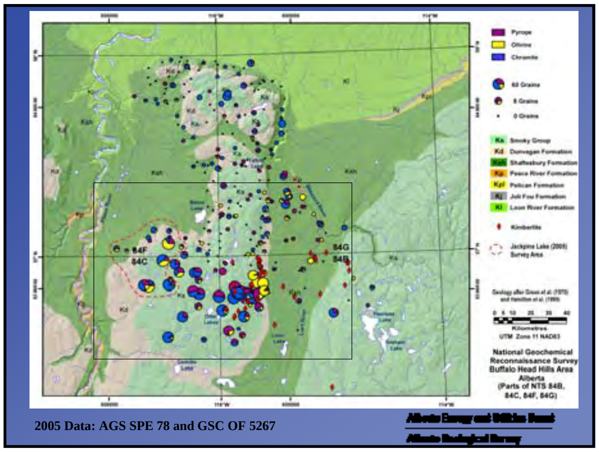
2005: Routine Survey
~1 KIM Sample/25 km^2

2005: Low Density Survey
(shallow stream gradients)
~1 KIM Sample/75 km^2

Outline of 2001 to 2005 National Geochemical Reconnaissance (NGR) stream survey coverage

Area of 2005 NGR stream survey

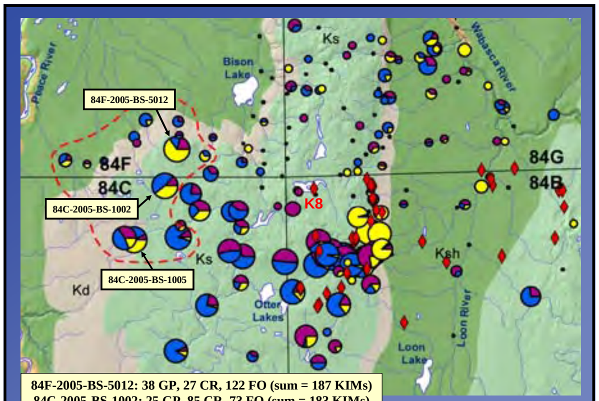
NGR KIM Stream Sediment Sample in Alberta



National Geochemical Reconnaissance Survey
Buffalo Head Hills Area
Alberta
(Parts of NTS 84B, 84C, 84F, 84G)

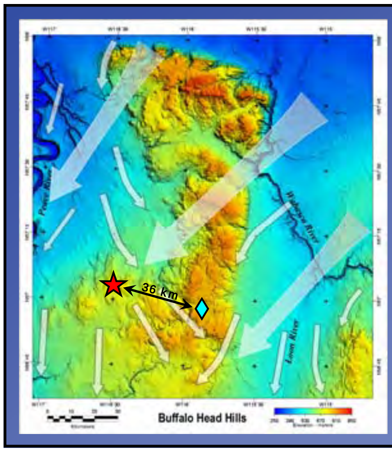
2005 Data: AGS SPE 78 and GSC OF 5267

Alberta Energy and Utilities Board
Alberta Geological Survey



84F-2005-BS-5012: 38 GP, 27 CR, 122 FO (sum = 187 KIMs)
84C-2005-BS-1002: 25 GP, 85 CR, 73 FO (sum = 183 KIMs)
84C-2005-BS-1005: 21 GP, 106 CR, 160 FO (sum = 287 KIMs)
AGS SPE 78 and GSC OF 5267

Ice Flow Reconstruction Shown on Digital Elevation Model



Paulen et al. (2005): AGS Information Series Report 132 (MEG 2005 Poster)

Paulen and McClenaghan (in press)

◆ Kimberlite K8

★ 84F-2005-BS-5012 (187 KIMs)

Stream Sediment KIM Sampling Methodology

1.7 mm (12 mesh) sieve

5 gallon (23 l) pail lined with polyethylene sample bag

Gold pan for adding water (not for panning)

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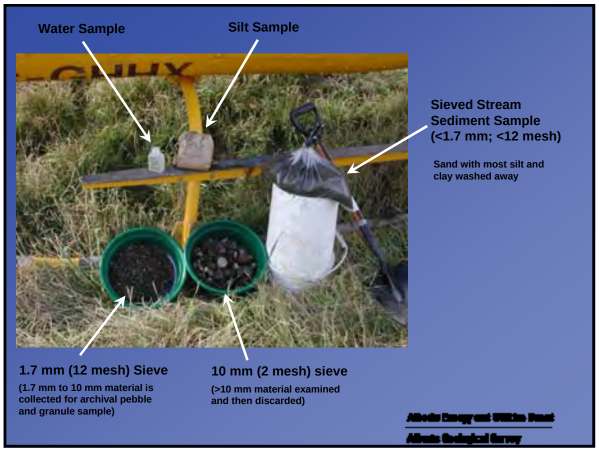

Water Sample

Silt Sample

Sieved Stream Sediment Sample (<1.7 mm; <12 mesh)

Sand with most silt and clay washed away

1.7 mm (12 mesh) Sieve

(1.7 mm to 10 mm material is collected for archival pebble and granule sample)

10 mm (2 mesh) sieve

(>10 mm material examined and then discarded)

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10 to 15 kg kimberlite-indicator mineral field sample
- nearly pure sand

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Field Data Sheet

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HMC Contents of Till and Stream Sediment Samples

- Differences
- Controlling Factors

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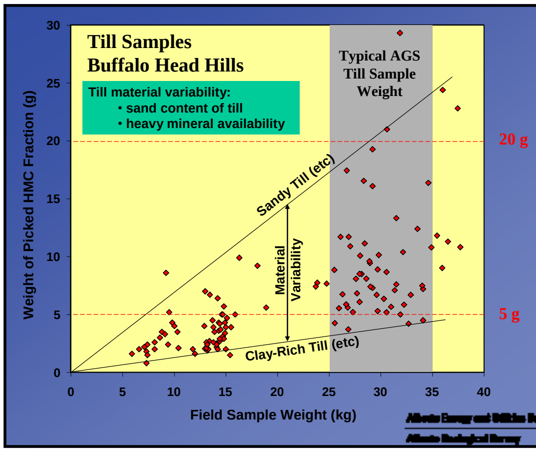

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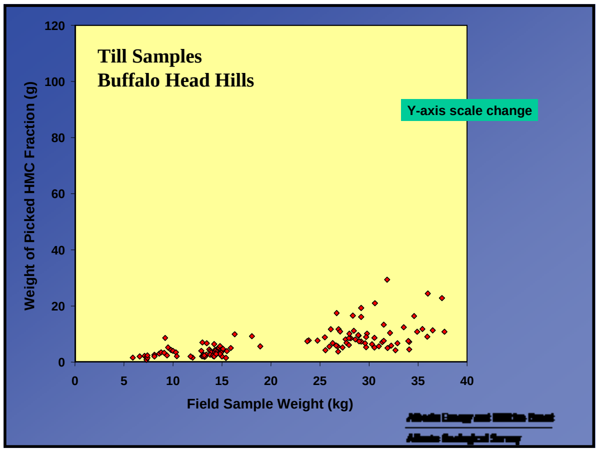
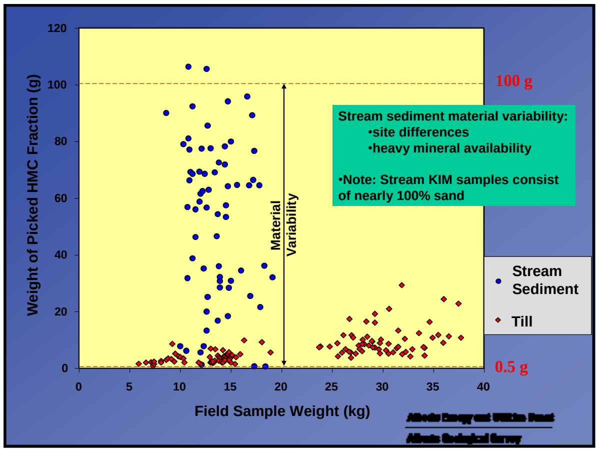
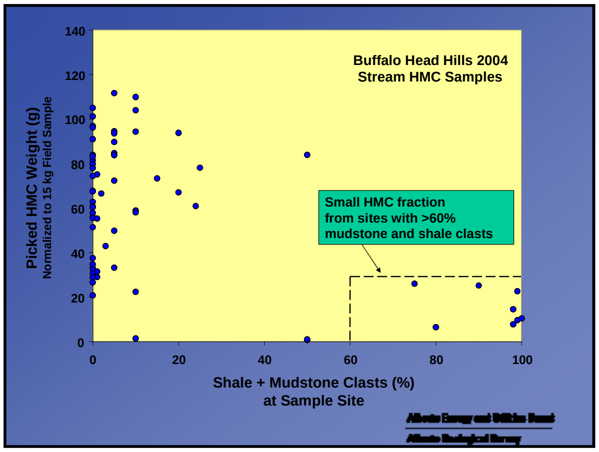


Y-axis scale change

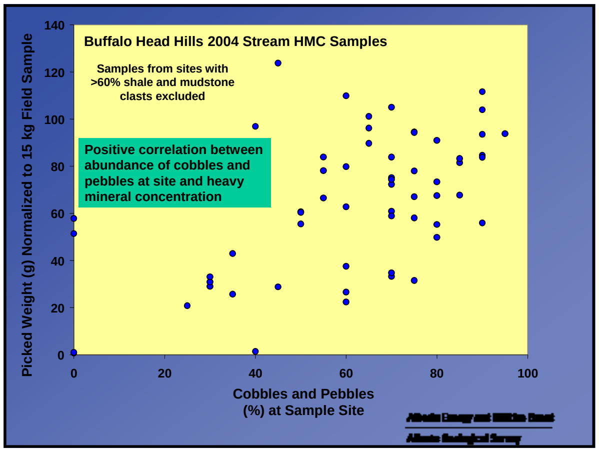


Stream sediment material variability:
- site differences
- heavy mineral availability

•Note: Stream KIM samples consist of nearly 100% sand



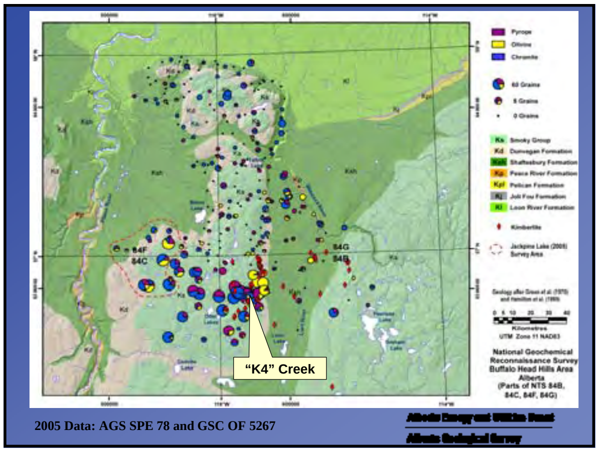
Small HMC fraction from sites with >60% mudstone and shale clasts



Buffalo Head Hills 2004 Stream HMC Samples

Samples from sites with >60% shale and mudstone clasts excluded

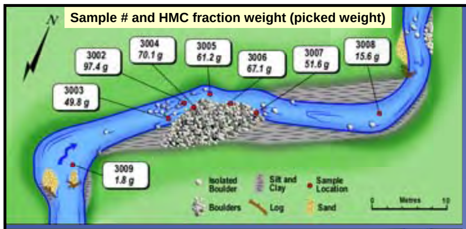
Positive correlation between abundance of cobbles and pebbles at site and heavy mineral concentration



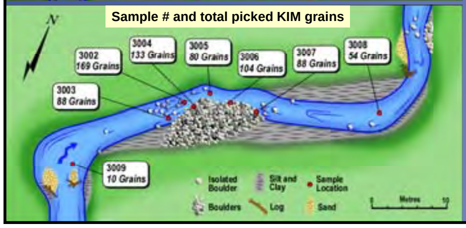
2005 Data: AGS SPE 78 and GSC OF 5267

"K4" Creek

Detailed Stream Sediment KIM Sampling



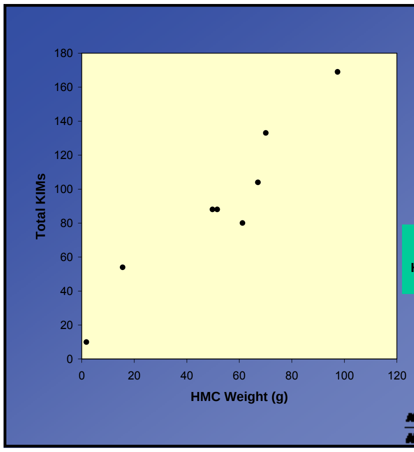
Sample # and HMC fraction weight (picked weight)



Sample # and total picked KIM grains

"K4" Creek

Detailed Stream
Sediment
KIM Sampling



"K4" Creek

Detailed Stream
Sediment
KIM Sampling

Better sample sites (e.g. boulder traps) yield larger HMC fractions to be picked for KIM grains

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Kimberlite-Indicator Mineral Stream Sampling Sites

the good, the bad and the ugly

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Upstream end of gravel and cobble bar

good

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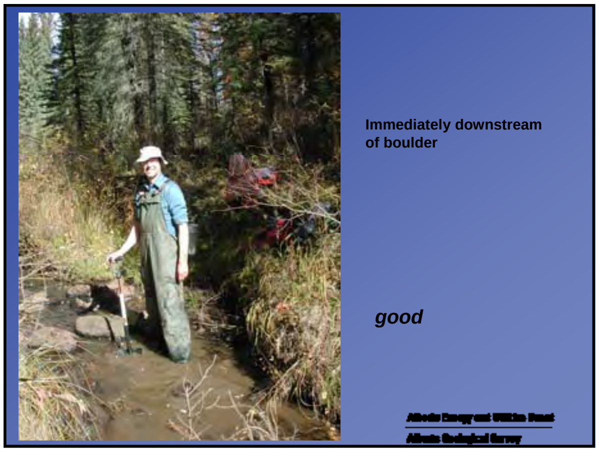

Immediately downstream of boulder

good

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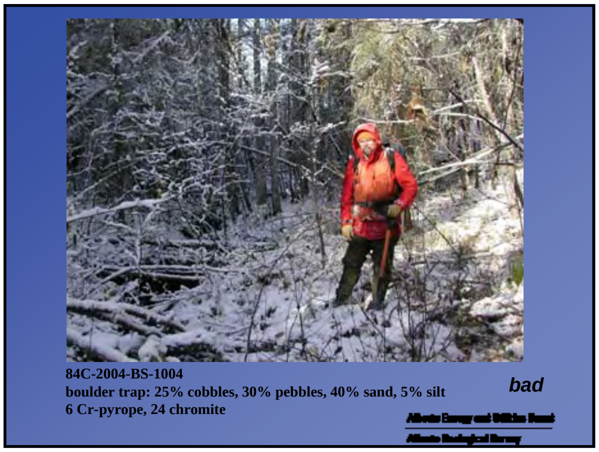

84C-2004-BS-1004
boulder trap: 25% cobbles, 30% pebbles, 40% sand, 5% silt
6 Cr-pyrope, 24 chromite

bad

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bad

84B-2002-BS-2027
74 olivine (forsterite) grains

Small area in stream bed of boulders, cobbles, pebbles and sand, possibly related to breaking of former beaver dams

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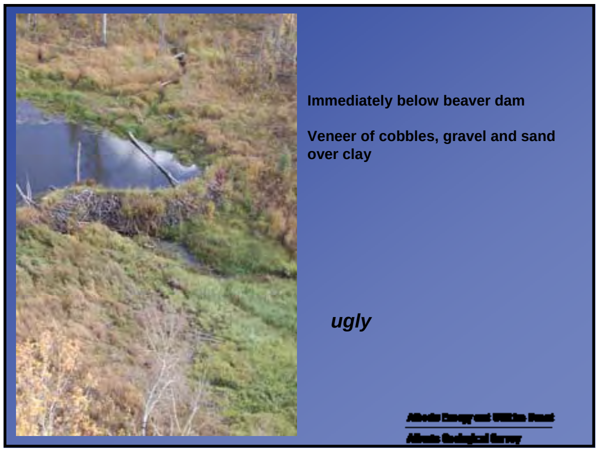

Immediately below beaver dam

Veneer of cobbles, gravel and sand over clay

ugly

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Terrains, Streams and Survey Types

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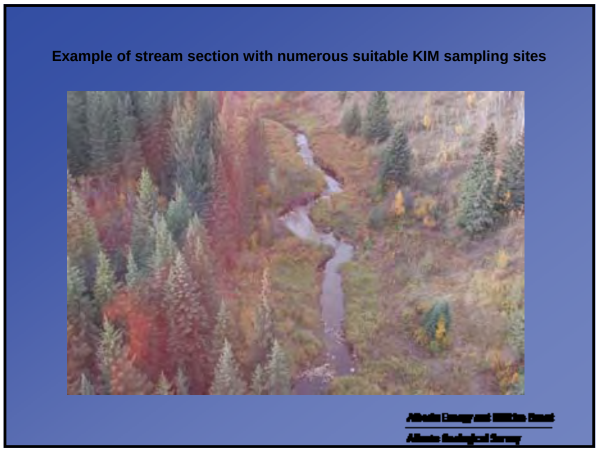
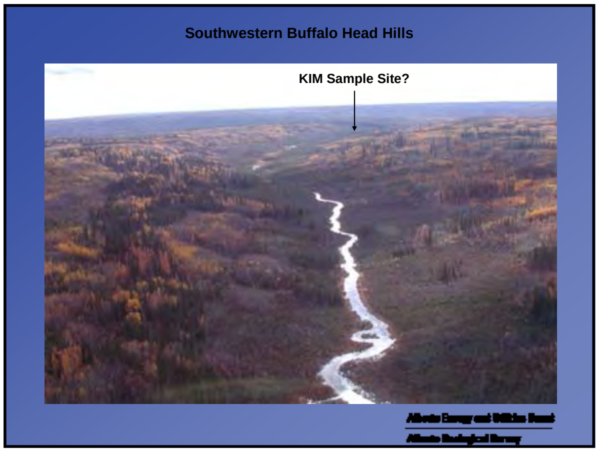
Alberta Geological Survey



Example of stream section with numerous suitable KIM sampling sites

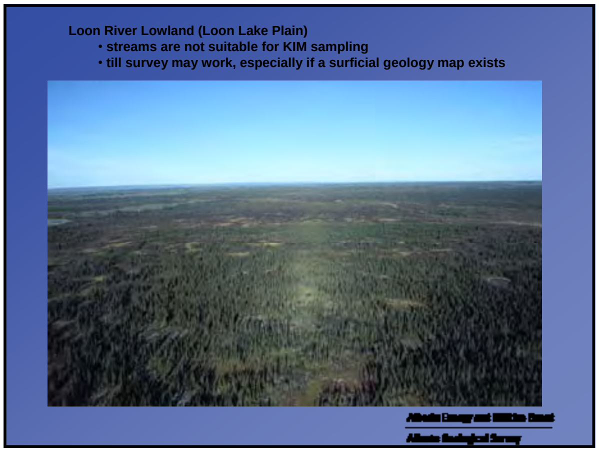
Buffalo River

Long stretches with no KIM sample sites but good sites do exist



Southwestern Buffalo Head Hills

KIM Sample Site?



Loon River Lowland (Loon Lake Plain)

- streams are not suitable for KIM sampling
- till survey may work, especially if a surficial geology map exists

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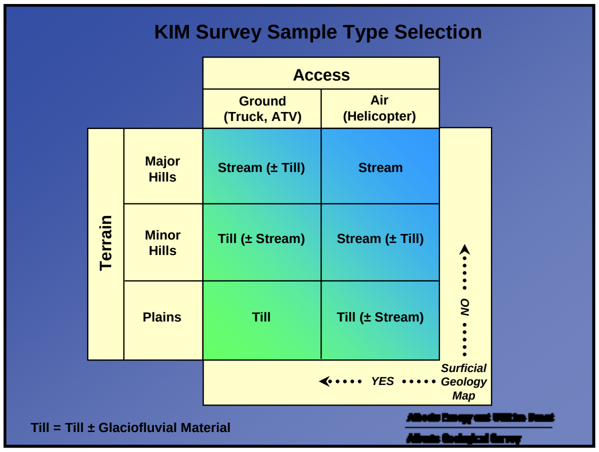

KIM Survey Sample Type Selection

		Access	
		Ground (Truck, ATV)	Air (Helicopter)
Terrain	Major Hills	Stream (± Till)	Stream
	Minor Hills	Till (± Stream)	Stream (± Till)
	Plains	Till	Till (± Stream)

Surficial Geology Map

NO

YES

Till = Till ± Glaciofluvial Material

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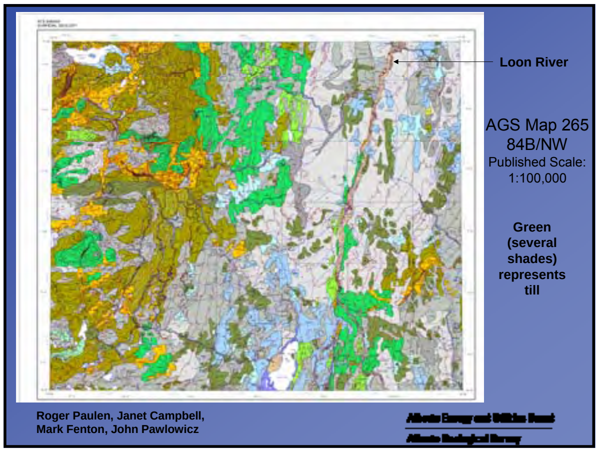

Loon River

AGS Map 265
84B/NW
Published Scale:
1:100,000

Green (several shades) represents till

Roger Paulen, Janet Campbell,
Mark Fenton, John Pawlowicz

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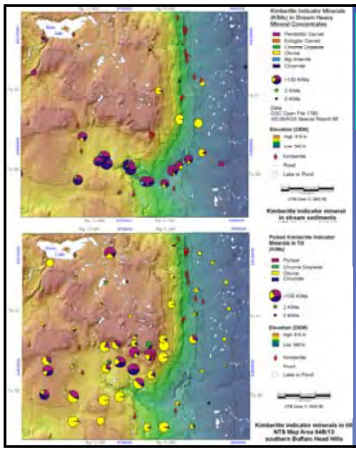

Sawn Lake (84B/13) Map Area

Similar KIM anomaly patterns from stream sediment and till surveys

Indicates that the two methods can be combined in exploration

Kimberlite Indicator Minerals in Stream Sediment, 84B/13

Kimberlite Indicator Minerals in Till, 84B/13

Alberta Energy and Utilities Board

Alberta Geological Survey

Quality Controls and Quality Assurance in Diamond Exploration

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Quality control and Quality assurance in diamond exploration covers a broad spectrum throughout the industry. Laboratory services are growing to support the exploration community. It is the intention of SRC to provide the local, national, and international mining and mineral exploration industry with independent, confidential, and the highest quality geochemical analyses and mineral processing services.

SRC is an ISO 17025 accredited laboratory on specific processes, we are continually audited by internal and external parties to ensure all facilities are adequate to carryout the services provided for the customer. All personnel are also adequately trained to be proficient in the activities they perform, or they are supervised by personnel until that time they meet training requirements. All staff is also under confidentiality agreements to ensure any sensitive data will not be exploited as well as undergoing an official criminal record check prior to the commencement of their first shift. We also ensure all customers sample management requirements have been met including the receipt, security/confidentiality, identification/labelling and processing of samples; verification of results and return shipment of residues.

When till samples are shipped from the field to the laboratory they will typically arrive in a poly sample bags with a tag or number for identification wrote directly on the bag. SRC will then assign an internal group number for which the set of samples will be referred to as for the entire process. This ensures client confidentiality within the processing facility. The bags are then inspected for flaws. Samples sometimes arrive at SRC with torn bags, open crates, etc. If there is a flaw in the bag or crate it will be photographed and noted in the file and issued with the chain of custody. Double bagged samples are good practice and often ensure the integrity of the sample but this is not always the case. The bags are then sorted into numerical order and then placed and sealed into a pre-labelled plastic 5-gallon pail. 90 percent of the time samples will arrive with some form of numbering system; this helps the flow of processing and makes the samples much easier to organize. If samples are received without a numbering system SRC will assign samples numbers in order to track them throughout processing. Once the samples have been received and recorded, a chain of custody is faxed to the client to confirm the sample shipment. A complete Chain of Custody should include a sample list, the date shipped, the date received, any assigned group numbers, the list of security seals used, method of transport, and the proposed method of processing as instructed by the customer. The customer then signs and approves the chain of custody and processing can begin.

Before any sample can be run on any piece of equipment SRC will ensure all equipment, supplies, and support services are functioning properly as so to meet Quality Standards required by the facility and /or the customer. This includes running preliminary standards, internal spiking and auditing, and data logging in order to monitor long term variation. All systems we have in place are geared to make the process as safe, accurate and efficient as possible. We continually audit the system to identify areas that can be made better with evolving technologies. Extensive testing and quality control protocols are completed on any new process before it enters the production system.

Micro Diamond analyses are another service Geoanalytical offers. This is done through caustic fusion. An exploration drill program can produce enough cores for micro diamond analyses to give a rough idea of the population of diamonds in a deposit without taking a large more costly bulk sample. Geoanalytical has the highest capacity micro diamond analyses facility in North America. We have increased capacity for 3 consecutive years to better serve the growing Canadian exploration industry by offering a faster turn-around. We intend to add an additional 36 kilns by March 2007 which will bring our total to 80 kilns. At this time Geoanalytical will be able to process 2 metric tonnes per week by caustic fusion. It will all be housed in a new state of the art, 60,000 square foot facility in Saskatoon. Our goal is to provide accurate, efficient results in hopes it will translate into many more successful mineral exploration projects in Canada.

Reporting of data is also carried out in a specific procedure which is all compliant with CIM guidelines and ISO 17025 certifications. All files are confidential and are treated as such. Upon completion, results will only be issued to the specified contact as stated on the chain of custody unless other authorization is offered by that contact. All results are issued electronically and hard copies are mailed the same day results are issued. Every process is signed off by a supervising geologist and certified as meeting all ISO qualifications. One of the overriding factors that is taken into consideration throughout the laboratory is safety. SRC provides every imaginable safety precaution if it is in our employees best interests. Laboratory environments are filled with hazards and if any process cannot be controlled with safe working practice that service will not be offered.

Calgary Mining Forum 2006

Diamond Exploration Short Course

Quality Control and Quality Assurance in Diamond Exploration

Michael McCubbing B. Sc.
Saskatchewan Research Council
Geoanalytical Laboratories

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Topics Covered:

- Quality Policy and Objectives
- ISO Certification
- Client Confidentiality
- Kimberlite Indicator Mineral and Micro Diamond processing:
  - Field Sample Preparation and Shipping
  - Chain of Custody
  - Spiking Techniques
  - Processing Procedure
  - Observation and Diagnostics
  - Reporting Guidelines
- Release, Storage, and Disposal of Results
- Health and Safety

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Quality Policy and Objectives

- It is the intention of SRC to provide the local, national, and international mining and mineral exploration industry with independent, confidential, and the highest quality geochemical analyses and mineral processing services.

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ISO 17025

- Internal and External Audits
- Specific Training Requirements
- Proper Documentation
- Confidentiality Agreements
- Criminal Record Checks
- Sample Management

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Contamination

- Inaccurate results
- Not trustworthy
- Additional sampling
- Extra costs
- Lengthens timeline

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Kimberlite Indicator Mineral Analyses

- Till sample shipping and receiving
- Receiving, Inspection, and Recording
- Internal group # is assigned
- Chain of Custody issued
- Processing begins
- Results are issued

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Received, Inspected, and Recorded

- Bags are inspected upon arrival.
- Samples are organized into numerical order.
- Chain of Custody is prepared
- Once a signed chain of custody is returned processing can commence.

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Sample Receiving

-All bags are inspected
-Double bagging prevents loss of sample

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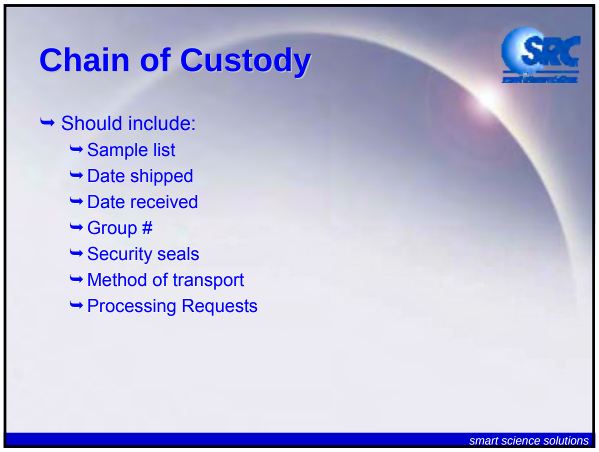

Chain of Custody

- Should include:
  - Sample list
  - Date shipped
  - Date received
  - Group #
  - Security seals
  - Method of transport
  - Processing Requests

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KIM External Spiking

- Insert a blank sample spiked with indicators.
- Number in the middle of processing stream to ensure uniformity.
- Photograph spike grains for verification upon recovery.

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KIM Processing

- Quality controls on all equipment daily prior to running any samples.
- Standards, internal spiking, process audits.
- All data should be logged to monitor long term variance.

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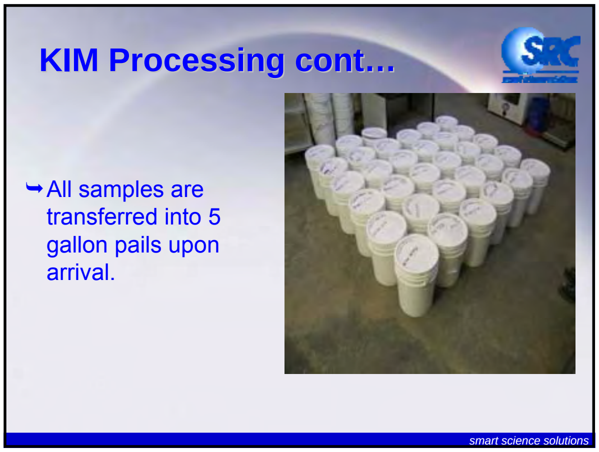

KIM Processing cont…

- All samples are transferred into 5 gallon pails upon arrival.

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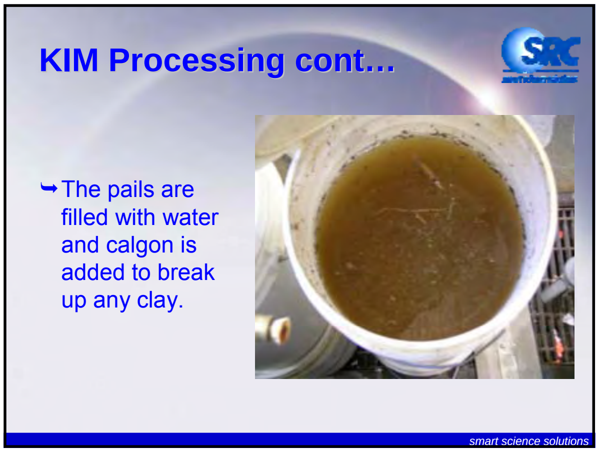

KIM Processing cont…

- The pails are filled with water and calgon is added to break up any clay.

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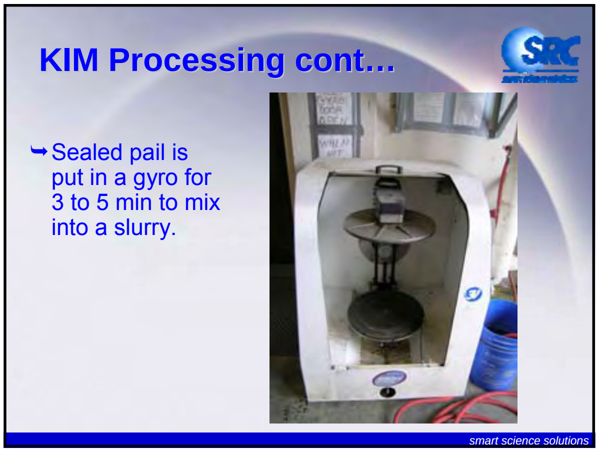

KIM Processing cont…

- Sealed pail is put in a gyro for 3 to 5 min to mix into a slurry.

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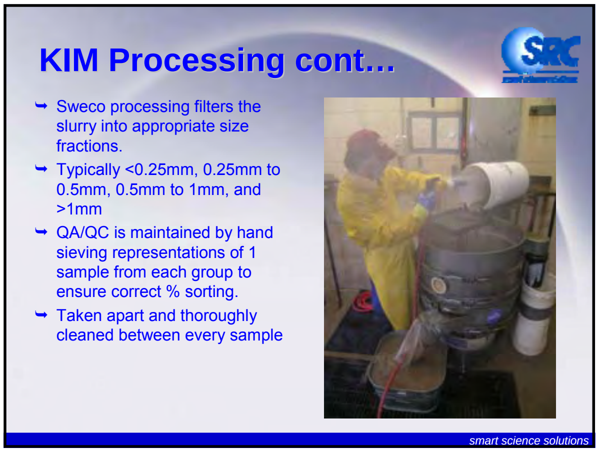

KIM Processing cont…

- Sweco processing filters the slurry into appropriate size fractions.
- Typically <0.25mm, 0.25mm to 0.5mm, 0.5mm to 1mm, and >1mm
- QA/QC is maintained by hand sieving representations of 1 sample from each group to ensure correct % sorting.
- Taken apart and thoroughly cleaned between every sample

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KIM Processing cont…

- <0.25mm and >1mm are bagged, tagged and stored.

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KIM Processing cont….

- 0.25mm to 1mm are transferred to pre-labeled stainless steel pans and placed in an oven to dry.

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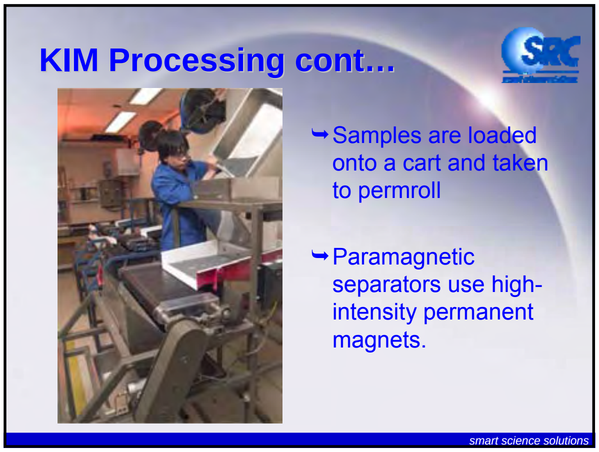

KIM Processing cont…

- Samples are loaded onto a cart and taken to permroll
- Paramagnetic separators use high-intensity permanent magnets.

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KIM Processing cont…

- Removes silica sand
- Reduces sample up to 90%
- Cleaned between every sample

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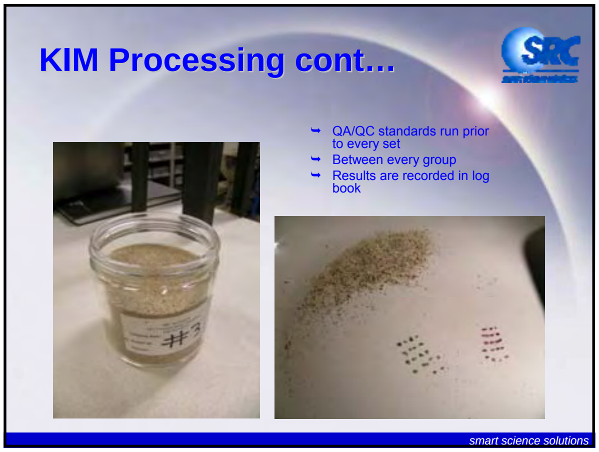

KIM Processing cont…

- QA/QC standards run prior to every set
- Between every group
- Results are recorded in log book

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KIM Processing cont…

- Magnetic fraction is transferred forward in a pre-labeled anti-static bag for heavy liquid separation
- Non-mag fraction is bagged, tagged, and stored

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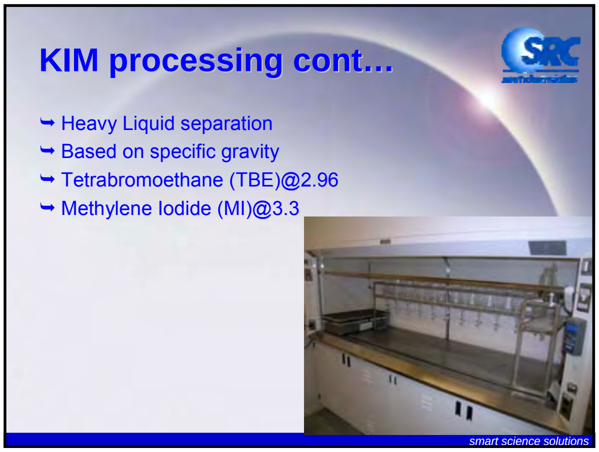

KIM processing cont…

- Heavy Liquid separation
- Based on specific gravity
- Tetrabromoethane (TBE)@2.96
- Methylene Iodide (MI)@3.3

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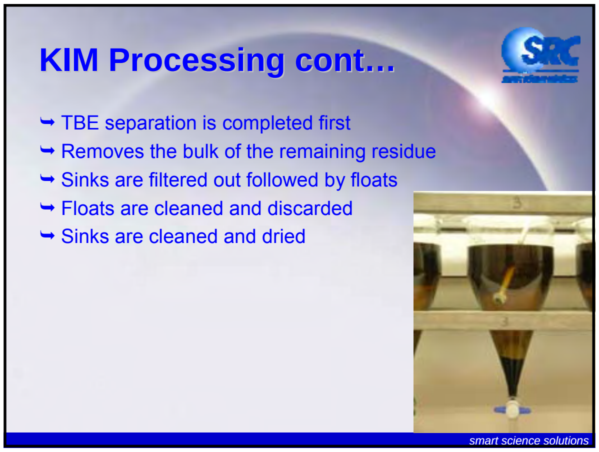

KIM Processing cont…

- TBE separation is completed first
- Removes the bulk of the remaining residue
- Sinks are filtered out followed by floats
- Floats are cleaned and discarded
- Sinks are cleaned and dried

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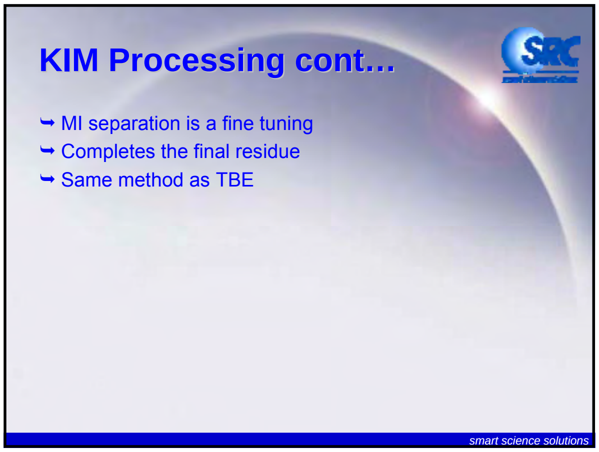

KIM Processing cont…

- MI separation is a fine tuning
- Completes the final residue
- Same method as TBE

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KIM Processing cont…

- TBE and MI are “older” organic heavy liquids
- Require fumehoods and repirators
- Neoplastigen and mutagen
- Phasing out TBE for LST (lithium heteropolytungstate)

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KIM Processing cont…

- LST is stable at a range of temperatures
- Can be safely handled without a fumehood
- Low toxicity
- Can reach densities up to 3.6g/ml at elevated temperatures

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KIM Processing cont…

- Final residue is passed over by a weak hand magnet to separate highly magnetic material
- This will be scanned in observation

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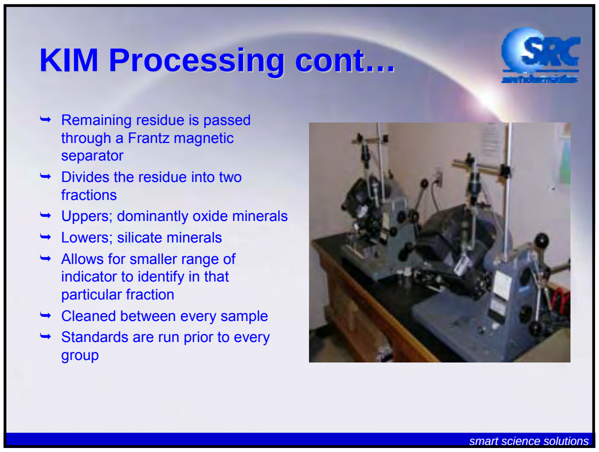

KIM Processing cont…

- Remaining residue is passed through a Frantz magnetic separator
- Divides the residue into two fractions
- Uppers; dominantly oxide minerals
- Lowers; silicate minerals
- Allows for smaller range of indicator to identify in that particular fraction
- Cleaned between every sample
- Standards are run prior to every group

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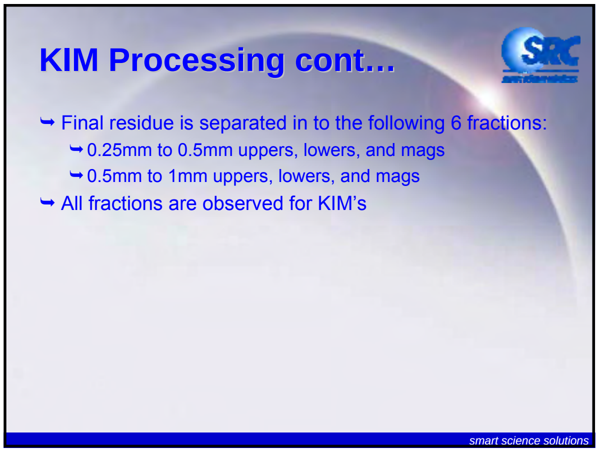

KIM Processing cont…

- Final residue is separated in to the following 6 fractions:
  - 0.25mm to 0.5mm uppers, lowers, and mags
  - 0.5mm to 1mm uppers, lowers, and mags
- All fractions are observed for KIM's

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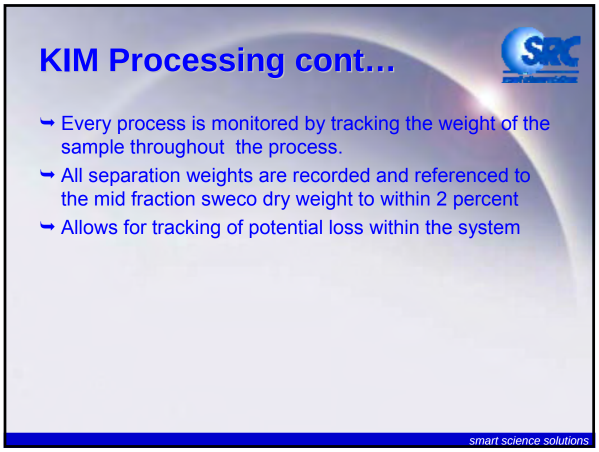

KIM Processing cont…

- Every process is monitored by tracking the weight of the sample throughout the process.
- All separation weights are recorded and referenced to the mid fraction sweco dry weight to within 2 percent
- Allows for tracking of potential loss within the system

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Kimberlite Processing for Indicators

- Obtaining indicators for mineral chemical data
- Crushed to 60% or -2mm
- Dry screened (Gilson)
- TBE (2.96)
- Floats are kept
- No perm roll or MI
- Separate circuit
- No possibility of contamination

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KIM Observation

- 15 observers
- Ranging in experience from 12 years to 5 months
- Extensive training
- Supervising mineralogist with over 15 years experience

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KIM Observation cont..

- Important to have uniform training
- Observation can be subjective
- Grain morphologies can tell a story of how that grain came to be where it was sampled
- Trained on colour, shape, angularity, and surface features.

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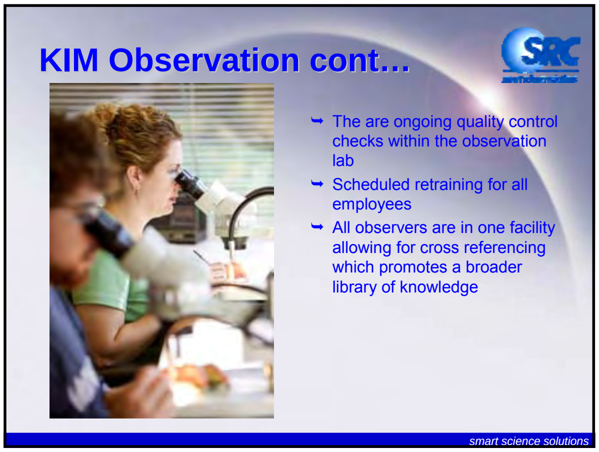

KIM Observation cont…

- The are ongoing quality control checks within the observation lab
- Scheduled retraining for all employees
- All observers are in one facility allowing for cross referencing which promotes a broader library of knowledge

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KIM Result Reporting

- The data provided by the lab consists of a summary of KIM grain counts, processing weights, and descriptions
- A percentage of the weight will be provided for the observed portion of large residues
- All removed grains are then sent to microprobe for verification and mineral chemistry

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KIM Processing Quality Assurance

- Safe
- Accurate
- Efficient
- Continuous audits
- Extensive training and testing

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Micro Diamond Analyses

- Caustic Fusion
  - Sodium Hydroxide (NaOH)
  - Strong Base
- 44 kilns
  - Over 1000Kg per week
- Largest in North America
- 25 employees
- Limited access facility

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MiDA cont…

- Secure facility
- All aspects of processing are done under one roof
- Controlled by magnetic key card access
- All exterior doors are monitored by 24 hour surveillance
- Security personnel on duty at all times
- Sorting room access limited to direct employees

smart science solutions

MiDA cont…

- Sample arrival
  - 5 gallon pails
- Received, Inspected, and Recorded
  - Security seals
    - Checked and recorded
- Internal group # is assigned
- Receive instructions
- Chain of Custody issued

smart science solutions

MiDA cont…

- Security seals
- Can be customized for client needs
- Added security for specific projects
- Require 4 weeks notice to supply
- Internal and external seals

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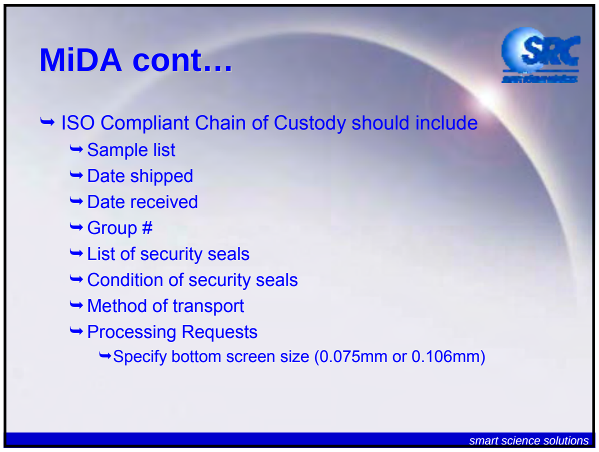


MiDA cont…

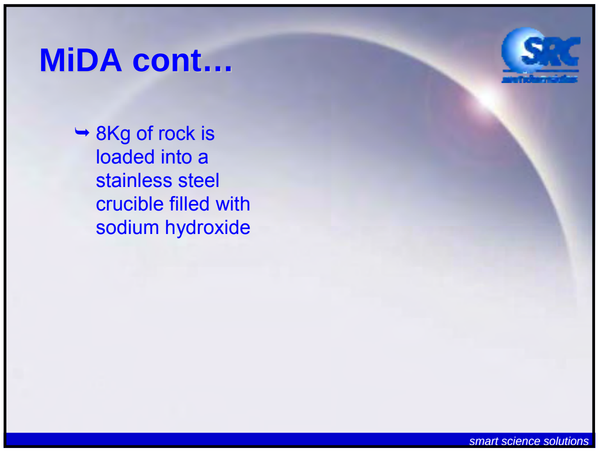
- ISO Compliant Chain of Custody should include
  - Sample list
  - Date shipped
  - Date received
  - Group #
  - List of security seals
  - Condition of security seals
  - Method of transport
  - Processing Requests
    - Specify bottom screen size (0.075mm or 0.106mm)

smart science solutions

MiDA cont…

- 8Kg batches
- Core, crush, rocks.
- Split into bags prior to shipment or in house

smart science solutions



MiDA cont…

- 8Kg of rock is loaded into a stainless steel crucible filled with sodium hydroxide

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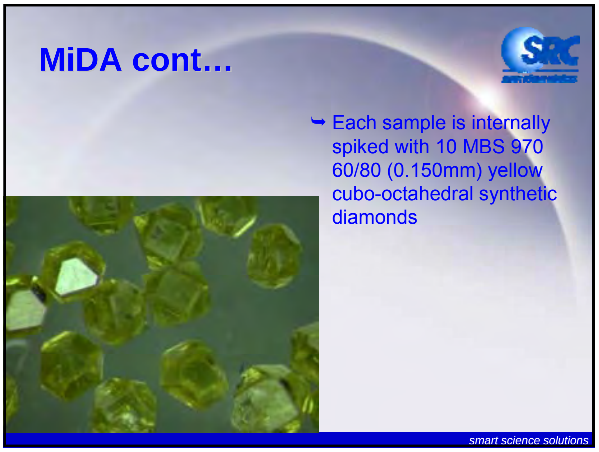

MiDA cont…

- Each sample is internally spiked with 10 MBS 970 60/80 (0.150mm) yellow cubo-octahedral synthetic diamonds

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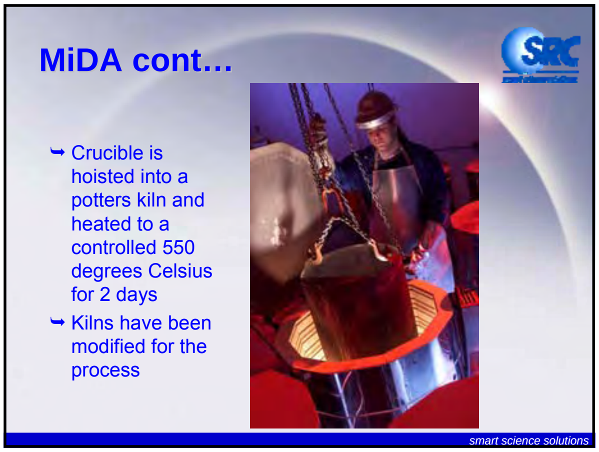
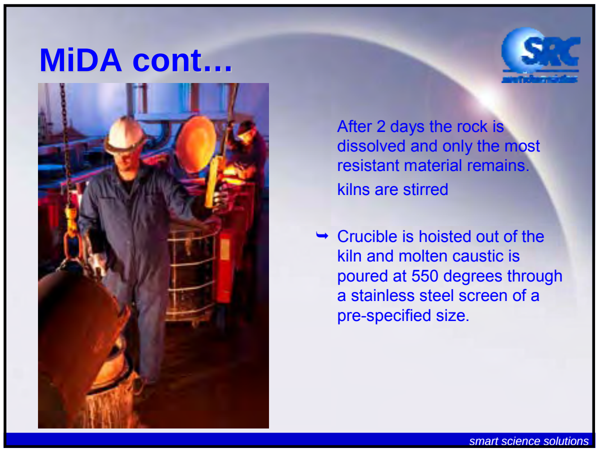


MiDA cont…

- Crucible is hoisted into a potters kiln and heated to a controlled 550 degrees Celsius for 2 days
- Kilns have been modified for the process

smart science solutions



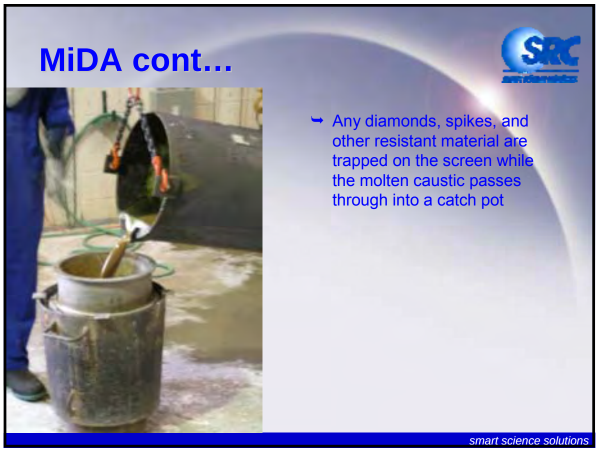
MiDA cont…

After 2 days the rock is dissolved and only the most resistant material remains.

kilns are stirred

- Crucible is hoisted out of the kiln and molten caustic is poured at 550 degrees through a stainless steel screen of a pre-specified size.

smart science solutions



MiDA cont…

- Any diamonds, spikes, and other resistant material are trapped on the screen while the molten caustic passes through into a catch pot

smart science solutions

MiDA cont…

- The catch pot is stored in a ventilated garage to cool overnight
- The caustic solidifies and is then stored in barrels

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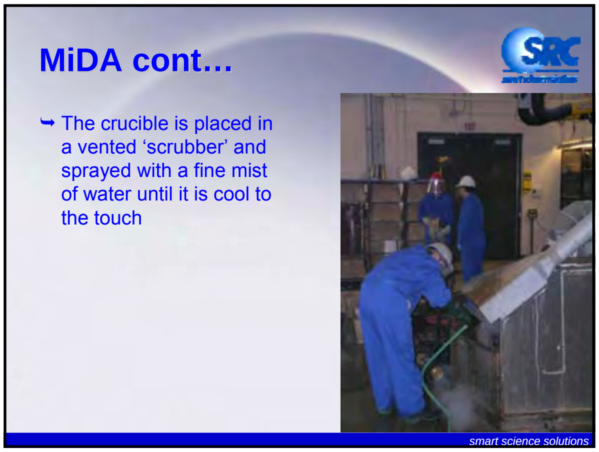

MiDA cont…

- The crucible is placed in a vented 'scrubber' and sprayed with a fine mist of water until it is cool to the touch

smart science solutions

MiDA cont…

- The remaining material from the cooled crucible is then rinsed through the screen

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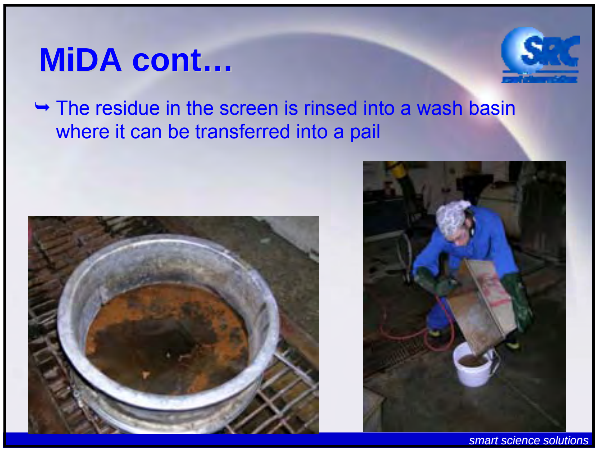

MiDA cont…

- The residue in the screen is rinsed into a wash basin where it can be transferred into a pail

smart science solutions

MiDA cont…

- All equipment are matched sets which eliminates cross contamination
- All crucibles, catch pots, wash basins, and pails are rigorously cleaned and inspected between every sample before being put back into processing.

smart science solutions

MiDA cont…

- Once the residue is in the pail it is spiked with an additional 10 synthetic diamonds of a larger 50/60 (>0.3mm) size
- Double spiking allows us to concentrate on a specific area in the case of a failure

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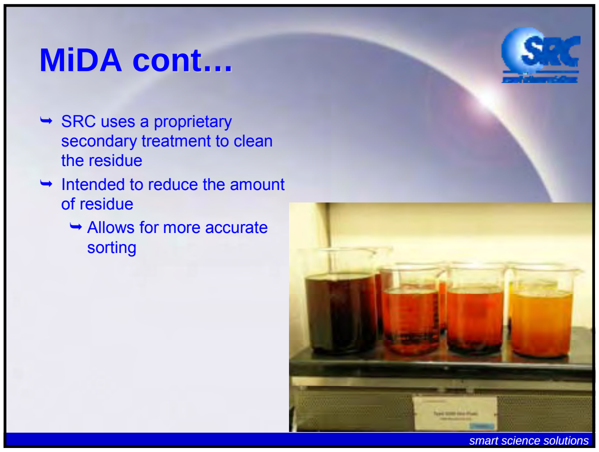


MiDA cont…

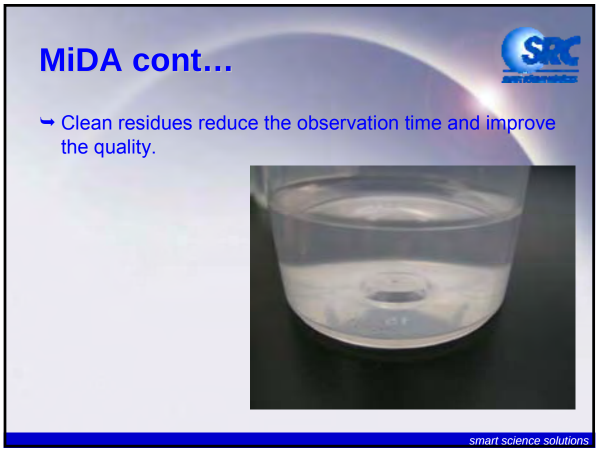
- SRC uses a proprietary secondary treatment to clean the residue
- Intended to reduce the amount of residue
  - Allows for more accurate sorting

smart science solutions

MiDA cont…

- Residues are often loaded with oxide minerals (ilmenite, chromite)
- Sorting large residues is time consuming and can often lead to inaccurate results

smart science solutions



MiDA cont…

- Clean residues reduce the observation time and improve the quality.

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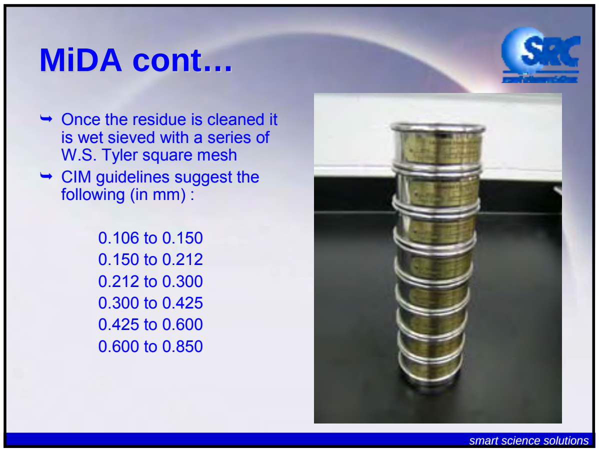


MiDA cont…

- Once the residue is cleaned it is wet sieved with a series of W.S. Tyler square mesh
- CIM guidelines suggest the following (in mm) :

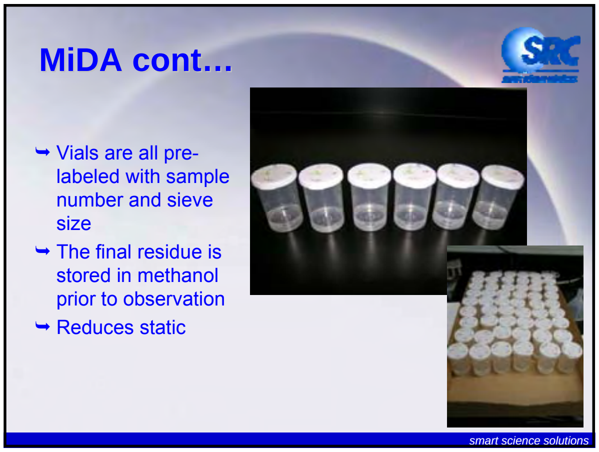
0.106 to 0.150
0.150 to 0.212
0.212 to 0.300
0.300 to 0.425
0.425 to 0.600
0.600 to 0.850

smart science solutions

MiDA cont…

- Sieves are sonically cleaned and inspected between every sample
- Every step within the facility is recorded and signed off as being done to ISO 17025 standard operating procedures by every employee
- Every client is issued a personal set of sieves

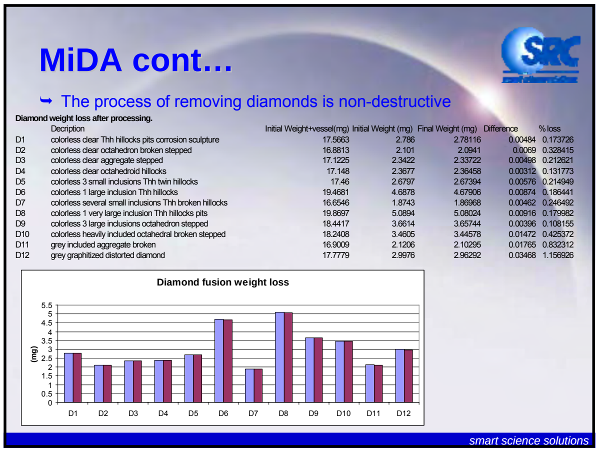
smart science solutions



MiDA cont…

- Vials are all pre-labeled with sample number and sieve size
- The final residue is stored in methanol prior to observation
- Reduces static

smart science solutions



MiDA cont…

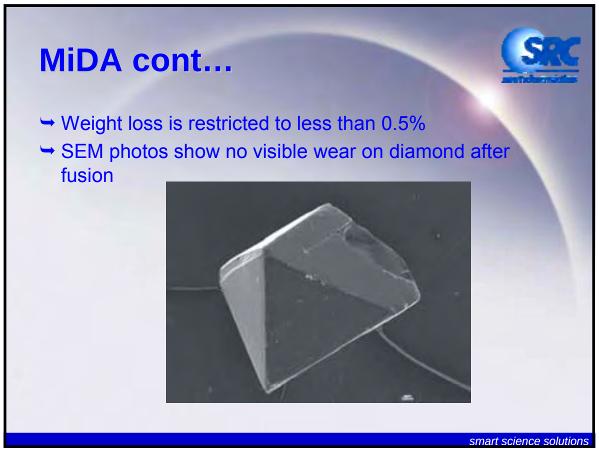
- The process of removing diamonds is non-destructive

Diamond weight loss after processing.

	Decription	Initial Weight+vessel(mg)	Initial Weight (mg)	Final Weight (mg)	Difference	% loss
D1	colorless clear Thh hillocks pits corrosion sculpture	17.5663	2.786	2.78116	0.00484	0.173726
D2	colorless clear octahedron broken stepped	16.8813	2.101	2.0941	0.0069	0.328415
D3	colorless clear aggregate stepped	17.1225	2.3422	2.33722	0.00498	0.212621
D4	colorless clear octahedroid hillocks	17.148	2.3677	2.36458	0.00312	0.131773
D5	colorless 3 small inclusions Thh twin hillocks	17.46	2.6797	2.67394	0.00576	0.214949
D6	colorless 1 large inclusion Thh hillocks	19.4681	4.6878	4.67906	0.00874	0.186441
D7	colorless several small inclusions Thh broken hillocks	16.6546	1.8743	1.86968	0.00462	0.246492
D8	colorless 1 very large inclusion Thh hillocks pits	19.8697	5.0894	5.08024	0.00916	0.179982
D9	colorless 3 large inclusions octahedron stepped	18.4417	3.6614	3.65744	0.00396	0.108155
D10	colorless heavily included octahedral broken stepped	18.2408	3.4605	3.44578	0.01472	0.425372
D11	grey included aggregate broken	16.9009	2.1206	2.10295	0.01765	0.832312
D12	grey graphitized distorted diamond	17.7779	2.9976	2.96292	0.03468	1.156926

Diamond fusion weight loss

smart science solutions



MiDA cont…

- Weight loss is restricted to less than 0.5%
- SEM photos show no visible wear on diamond after fusion

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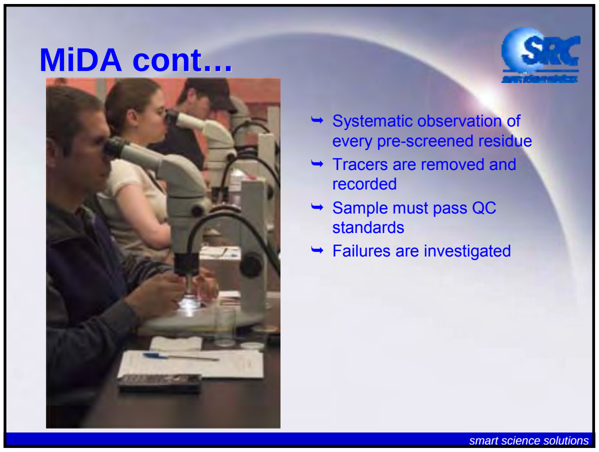


MiDA cont…

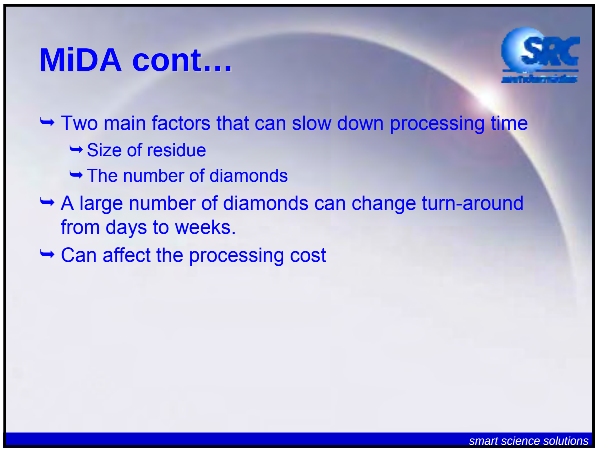
- Systematic observation of every pre-screened residue
- Tracers are removed and recorded
- Sample must pass QC standards
- Failures are investigated

smart science solutions

MiDA cont…

- Reporting procedure can be laid out prior to sorting
- Weights
- Descriptions
- Handling and Storage
- All can affect the amount of time required to complete

smart science solutions



MiDA cont…

- Two main factors that can slow down processing time
  - Size of residue
  - The number of diamonds
- A large number of diamonds can change turn-around from days to weeks.
- Can affect the processing cost

smart science solutions

MiDA cont…

- Diamonds are removed from the residue
- Diamonds are scratch tested on plates of corundum
- A polarizing lens can also be used to confirm

smart science solutions

MiDA cont…

- All stones are weighed on Mettler Toledo UMX2 ultramicrobalances.
  - Accurate to +/-0.5ug
- All balances are kept in atmospherically controlled room to increase reproducibility

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MiDA cont…

- All diamonds are handled one time once the residue is sorted
- Mounted on slides with one sided tape.
- Eliminates additional handling
- Reduces chance of losing grains

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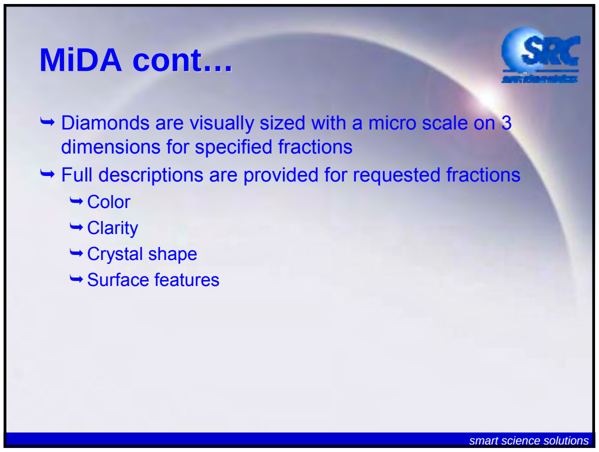

MiDA cont…

- Diamonds are visually sized with a micro scale on 3 dimensions for specified fractions
- Full descriptions are provided for requested fractions
  - Color
  - Clarity
  - Crystal shape
  - Surface features

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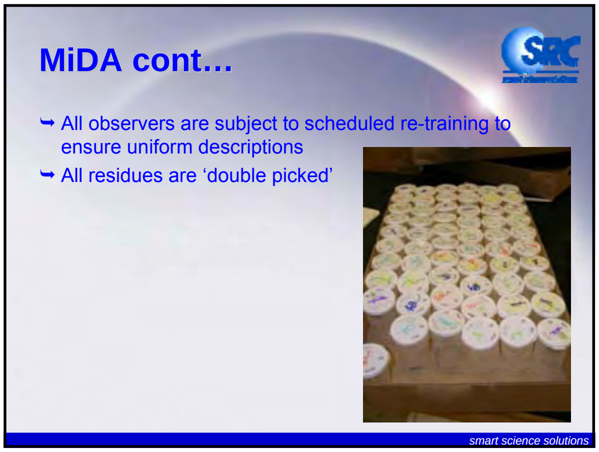

MiDA cont…

- All observers are subject to scheduled re-training to ensure uniform descriptions
- All residues are 'double picked'

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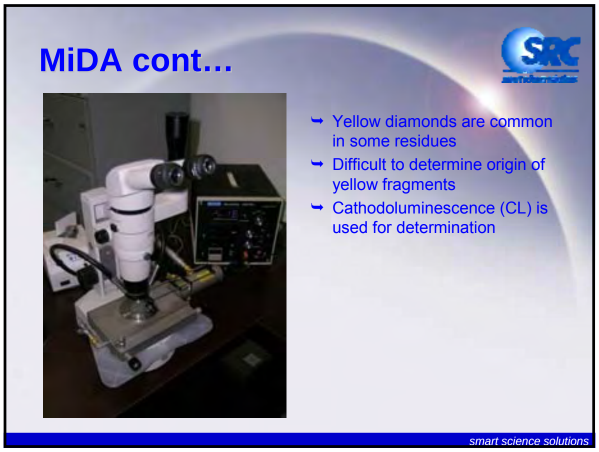


MiDA cont…

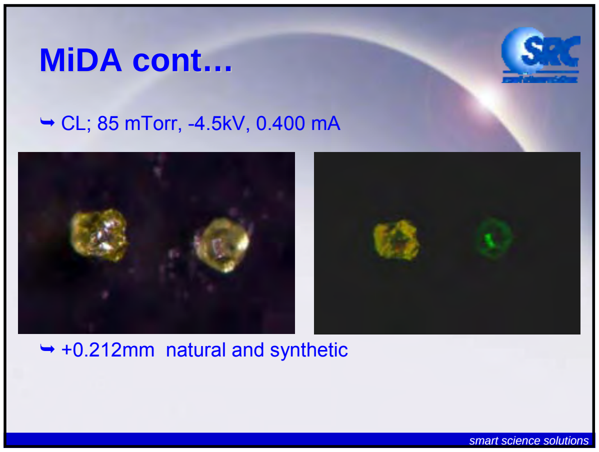
- Yellow diamonds are common in some residues
- Difficult to determine origin of yellow fragments
- Cathodoluminescence (CL) is used for determination

smart science solutions

MiDA cont…

- Cathodoluminescence
  - Bombardment of excited electrons onto a surface or mineral
  - Visible radiation or luminescence
  - Color and uniformity indicates origin
  - Fast process
  - Requires little setup

smart science solutions



MiDA cont…

- CL; 85 mTorr, -4.5kV, 0.400 mA
- +0.212mm natural and synthetic

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MiDA cont…

- Photomicrographs
  - Immediate feedback
  - Backup or reference
  - High detail
  - Promotional

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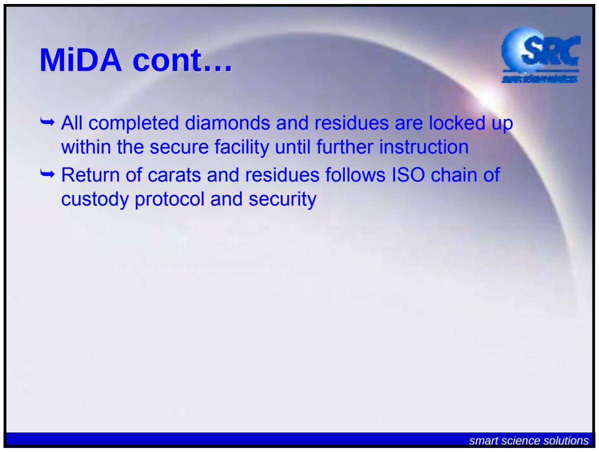

MiDA cont…

- All completed diamonds and residues are locked up within the secure facility until further instruction
- Return of carats and residues follows ISO chain of custody protocol and security

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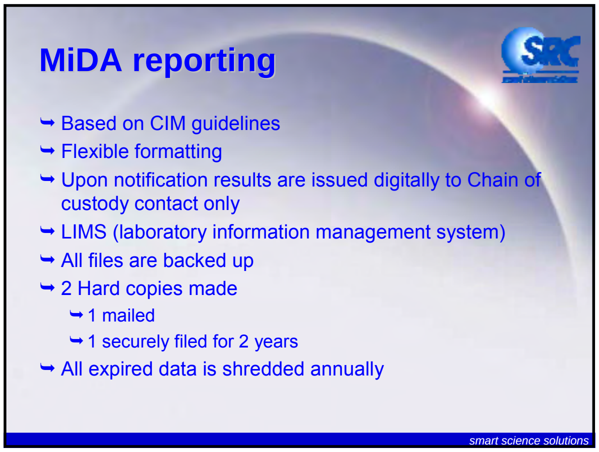

MiDA reporting

- Based on CIM guidelines
- Flexible formatting
- Upon notification results are issued digitally to Chain of custody contact only
- LIMS (laboratory information management system)
- All files are backed up
- 2 Hard copies made
  - 1 mailed
  - 1 securely filed for 2 years
- All expired data is shredded annually

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Health and Safety

- Laboratory environments provide many hazards
- Safety is highest priority at SRC
- Many processes require specialized personal protective equipment
- Translates into more efficient work environment

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Expansion

- SRC Geoanalytical Laboratories is moving
- March 2007
- Acquired over 60,000 sq ft
- North Saskatoon
- 80 kilns
  - 2 metric tonnes per week
- Planning for 10tph DMS
- Faster turn-around

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- Meeting industry demand
- U3O8 ISO certification
- 3 facilities for uranium analyses
  - Sandstone
  - Basement
  - Mineralized

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- Tours

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- The end

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Geophysical Tools and Examples;
Uranium and Diamond Exploration

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Introduction

These notes accompany two short presentations; 1. Geophysical methods for uranium exploration, 2. Geophysical Methods for Diamond Exploration. Although the information is of a general overview nature, most of the specific geophysical tools and examples are from airborne projects due to the author's background and experience. Most of the concepts here can be applied with similar equipment on the ground. Geophysics is a very broad subject. The intent of this short presentation is to compile some relevant examples and briefly discuss some appropriate technology.

Geophysics is the science of measuring the physical properties of the earth. The earth's magnetism, electrical properties, gravity and radioactive decay are the most commonly measured in mining geophysics. The measurements combined with reasonable assumptions and supporting geological information are turned into geological models. Only in rare cases can geophysics directly detect mineralization of economic interest, more often it is used to locate host rocks, associated mineralization, markers and structures of interest.

Contents

Geophysical Tools

Airborne Magnetic Surveys

Airborne magnetic measurements are an integral part of most mining related airborne geophysical surveys, serving as a valuable addition to all electromagnetic and radiometric surveys. By itself, magnetic measurements have moved far beyond target hunting and are now used for detailed geologic mapping of structure and lithology. The line spacing and flight altitude used on the survey controls the detail to which this mapping can be done.

Magnetometers

Cesium vapor magnetometers are the type most widely used for aeromagnetic surveys and for base stations, whenever the highest resolution and/or cycling rates for measurement of the earth's magnetic field is required.

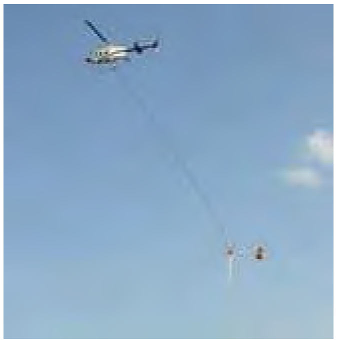
The output of a cesium sensor is essentially continuous in practice. Combined with the necessary electronics, it can operate at a resolution of up to 0.001 nT, at sampling rates of 10 readings per second or greater, throughout a range of 20,000 to 100,000 nT.

The magnetometers can be installed in fixed-wing aircraft or helicopters, in either "stinger" or "towed bird" configurations, and, in addition to measuring total magnetic field, can be used to make vertical, transverse and/or longitudinal gradient measurements by using two or more sensors.

A typical cesium magnetometer installation comprises some or all of the following subsystems:

- Sensor;
- Orienting Gimbal;
- Signal Processor and/or Compensator; and
- Airfoil.

Aircraft Motion and Attitude Sensors



The attitude and motion of the aircraft in flight, with respect to the Earth's magnetic field vector, is monitored by a three-component flux-gate magnetometer which is very sensitive to attitude changes. The outputs of this motion sensor are used to deconvolve the artificial anomalies created by the aircraft itself, from anomalies created by geologic variations.

With towed bird systems pitch, roll and yaw detectors are used in the bird to correct for geometric errors

created as the bird departs from its assumed ideal
flight orientation.

Navigation and Positioning

GPS brings a number of important benefits to aerial surveying. Firstly, the coordinates of the survey aircraft (horizontal and vertical) are provided on a continuous basis. This not only improves the quality of survey navigation and reduces its cost; it also simplifies data compilation and presentation by eliminating, to a large degree, the tedious and error-prone manual steps inherent in flight path recovery from film or video. Secondly, GPS provides a reusable positioning system. Surveys flown at different times in the same area may be precisely correlated in position, making it easy to repeat survey lines or to fly infill lines.

Airborne Gamma-Ray Spectrometry

Airborne gamma-ray spectrometry is an effective geological mapping tool in many different environments and has been applied to mineral, environmental, geothermal, hydrocarbon and even water investigations. The following are some of the most common applications for airborne gamma-ray spectrometry surveys:

- Mineral exploration: gold, mineral sands, uranium, rare earth elements;
- Geothermal exploration: potassic alteration;
- Hydrocarbon exploration: potassic/uranium alteration;
- Geological mapping: mineral, engineering and water exploration applications, paleodrainage systems;
- Contamination mapping and detection: military and industrial waste (eg. ^{137}Cs and ^{60}Co);
- Emergency response: fallout, nuclear contamination;
- Baseline surveys: for mining, nuclear reactor and industrial sites.

Method

An overall description of modern airborne gamma-ray spectrometry methods can be found in IAEA Technical Report 323 (Airborne Gamma-Ray Spectrometer Surveying), and in AGSO Record 1995/60 (A Guide to the Technical Specifications for Airborne Gamma-Ray Surveys).

Equipment

The Exploranium GR-820 gamma-ray spectrometer is probably the most commonly used.

The spectrometer features:

- Automatic Gain Control, which does not require operator adjustment or maintaining the crystals at a constant temperature;
- Accurate pulse-pile-up rejection;
- Internal shock mounting of sodium-iodide crystal detectors.

The Exploranium GR-820 is a self-stabilising, multi-channel (256 or 512) spectrometer that can be configured with up to 67.2 litres of sodium-iodide detector volume. It includes an upward-looking detector spectrometer which may be configured with up to 12.6 litres of detector volume. The GR-820 is a proven, rugged and reliable instrument.

The GR-820 is coupled to an acquisition system on a fixed wing or helicopter platform and is guided by real time differential global positioning system (DGPS) navigation. Radar altimeter, barometric and temperature sensors are also employed on airborne gamma-ray spectrometer surveys. Radiometrics surveys can be flown in conjunction with other airborne instruments such as EM, VLF and/or magnetometer systems. The lift capabilities of the aircraft and the weight of other geophysical systems on the same aircraft may limit the detector volume in some cases.

Processing

Airborne data is processed using spectral component analysis or similar methods to reduce statistical noise in airborne gamma-ray spectrometer survey data. These techniques utilise the complete 256 or 512 channel spectrum and are considerable advances in the radiometric data processing technique. The results are a more accurate measure of radioelement ground concentration, which improves considerably the discrimination between different geologic units with similar radioelement concentrations. This processing also results in improved discrimination of man-made radioactive sources from background.

Ternary presentation of the eU, eTh, K concentrations, Anti Atlas Region of Morocco.Data courtesy of the Ministry of Energy and Mines, Morocco and Fugro Airborne Surveys.

Gridding airborne gamma-ray data presents certain challenges because of the inherent statistical fluctuations in the data. Either the data must be smoothed and interpolated, or an average surface must be generated.

Products normally delivered for airborne gamma-ray spectrometer surveys include colour or contoured parameter maps reflecting the radioelements of interest, ratio maps, ternary maps and full spectrum and windowed digital data on a variety of media and formats.

General Overview of Airborne Electromagnetic Systems

Introduction

The primary objective of an airborne electromagnetic (EM) survey, whether time domain or frequency domain is to define the electrical conductivity (or its inverse - resistivity) distribution in the earth. In this sense, the primary objective is analogous to that of a magnetic survey, the goal of which is to define the magnetic susceptibility distribution in the earth. In many cases, however, the goals of an airborne EM or magnetic survey are more general, involving geological mapping of stratigraphy or soils.

The basic approach is to generate a primary electromagnetic field by means of a loop of wire carrying electric current (as per Ampere's law). This primary field propagates through the ground and induces secondary electric currents in the earth. These secondary currents flow in such a way that their electromagnetic field opposes the primary field inside the conductive region. The strength of the induced currents depends upon the resistivity of the ground and the frequency with which the primary field is alternating. In general, the currents are stronger when the resistivity is low and the frequency is high.

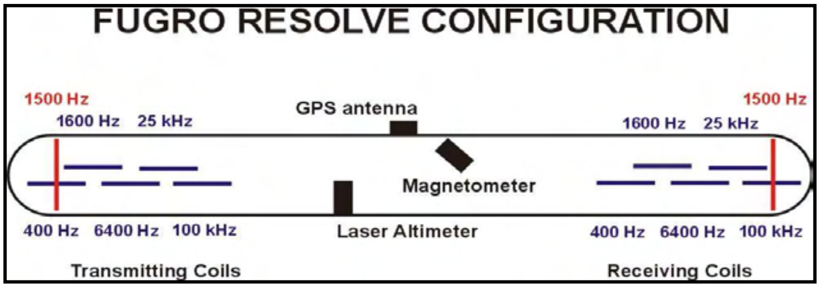
When the secondary field spreads out in space, it is "seen" by a measuring device (a coil receiver) and analysed either separately (as in most time domain techniques) or together with the primary field (as in all frequency domain techniques). The analysis results in products defining the conductivity distribution of the earth, which can be used to map geology.

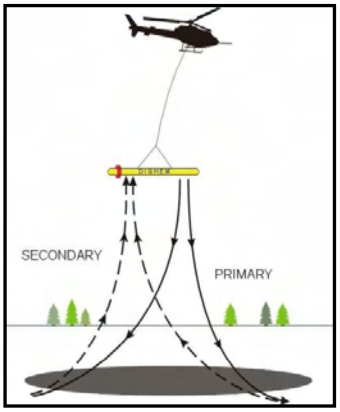
Frequency domain helicopter EM (HEM) systems (right, below) are inherently different than fixed wing time domain (FTEM) systems (above) or Helicopter time domain EM (HTEM) systems (left). The differences have less to do with the domain than with the coil array. The Laplace transform can yield frequency domain system output from time domain system input and vice-versa, even though the information provided by either system may not be complete enough to yield an accurate transform. The major difference in the systems currently in use, lies in the nature of the EM coil array. The potential user should determine which system is best suited to the target, as the target will probably favour one coil array more than the other.

.

Most EM surveys include a magnetometer in addition to an electromagnetic system. The compact symmetric transmitter-receiver system geometry in helicopter time domain and frequency domain systems produces simpler anomaly shapes in profile and plan, which are independent of flight direction. Helicopter EM is more efficient for small and irregularly shaped surveys, and a helicopter can follow terrain better in hilly to moderately rugged country. HEM and HTEM systems have better spatial resolution and are more effective for shallow or smaller targets. Transmitter and receiver coils are in a single large bird slung below a helicopter

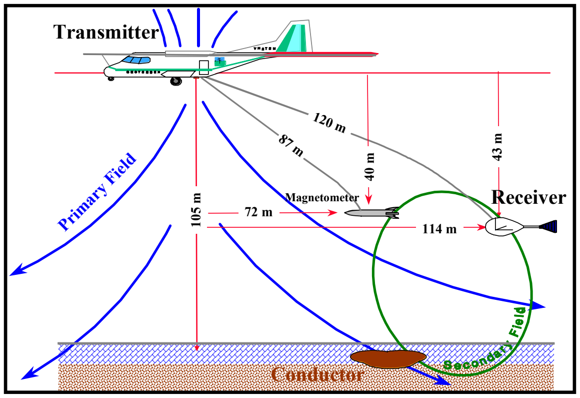
Time domain EM systems are able to generate much higher transmitter power than helicopter frequency domain systems. This power enables significantly deeper depth of resolution. Along with greater depth of resolution however comes an inherent lack of resolution near to the surface. The longer flights and higher airspeed of fixed wing systems allow for more efficient collection of data on larger projects.





Frequency Domain System Description

Helicopter frequency domain EM systems (left) are contained within a bird which is towed 30m beneath a helicopter at 30m above ground level. The bird contains a number of stand alone transmitting-receiving coil-pairs operating in the frequency domain. The secondary fields are sensed simultaneously by receiving coils that are maximum coupled to their respective transmitting coils (as shown at left). The system yields an inphase and a quadrature channel from each transmitting-receiving coil-pair. Up to six different frequencies are continuously operated allowing for the measurement of the earth's conductivity distribution at each sample point. The depth of exploration is inversely related to the conductivity of the ground. Depth penetration in excess of 125m is possible in highly resistive geological environments under ideal conditions, but is less in more conductive environments



Time Domain System Description

Fixed wing time domain EM systems employ a transmitter loop attached to the wings, tail and nose of the aircraft. The receiver coils are located in a "bird" towed on a 120m cable (see dimensions in following figure). Helicopter time domain EM systems employ a large diameter loop often 10 to 15 metres in diameter towed beneath a helicopter. Receiver position varies from a separate towed bird to some fixed location near the transmitter loop. In the time domain, the induction processes are usually realised as secondary field transients, or decays, during the primary off-time. The primary field transitions are usually repetitive and themselves comprise a periodic frequency transmission. It is important to note that the decay of a secondary field is actually as a result of the complex reactance of a conductive region to the primary field transition. The primary field is prevented by a “back EMF” from changing in unison with the current in the transmitter source, resulting in a modified field transition - this is seen as a decay when the receiving sensor is an inductor; that is, a device which reacts to the rate of change of the field applied to it.

The base frequency and placement of the off-time and on-time recording windows are user selectable. This allows for some adjustment of the system to the conductivity of the geological environment and required depth resolution. In ideal conditions, in highly resistive ground such as the Athabasca basin, conductors can be detected at up too 1000m (MEGATEM FTEM system). Depth resolution is limited to 200 to 300 metres in areas with more conductive bedrock in the western Canadian sedimentary basin.

Data Collection

The survey aircraft flies traverse lines at a spacing ranging from 50m for some detailed HEM applications up to 250m for fixed wing or helicopter regional mapping applications. However regional or reconnaissance surveys have been done with 400m, 1 kilometre or greater line separation. Airborne EM systems have base level and real time phase and gain checks (frequency domain only) done periodically during survey flying.

Verification and preliminary products are completed in the field in 24 to 48 hours after flying for each day’s data.

Data processing

A variety of digital filtering and processing techniques are used to significantly reduce ambient noise. Final processing and interpretation may take 4 to 12 weeks from collection of data for depending on the size and complexity of the work and interpretation.

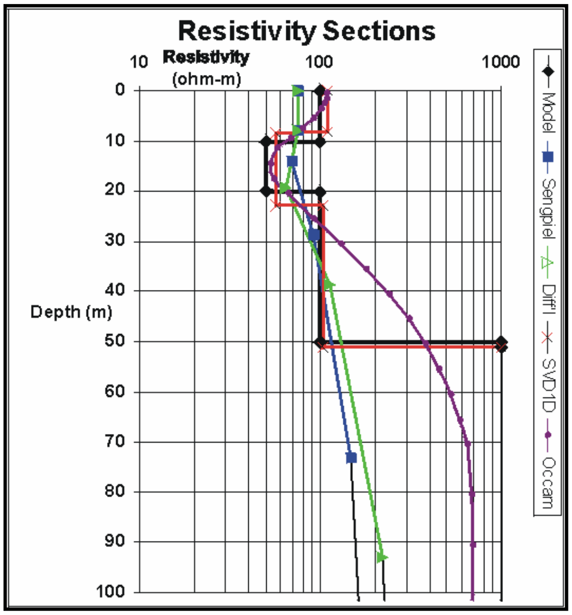
The airborne EM data handling procedures are fairly automated. They yield profile records, the EM anomaly map, contour and image maps of resistivity in plan and section, and the EM data can be inverted or transformed to produce an earth model.

For the frequency domain EM system, resistivities may be mapped over a huge dynamic range, from less than 0.02 ohm-m to in excess of 20,000 ohm-m and areas as small as 0.2 hectares may be resolved. The time domain EM systems have spatial resolution and dynamic range that is s more limited.

Resistivity Depth Sections and Inversions

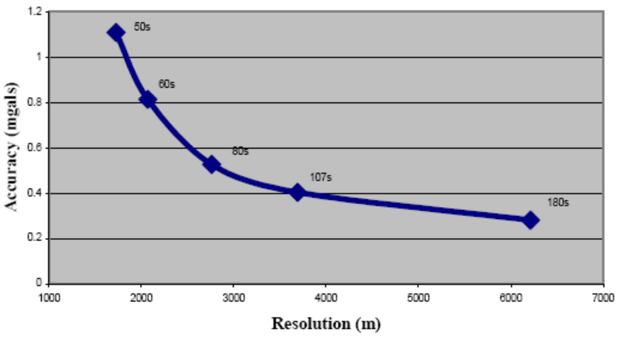
Resistivity sections, conductivity depth images (CDI) and inversions are methods of defining the earth’s resistivity distribution with depth. Resistivity sections where the apparent resistivity for each frequency (for frequency domain surveys) is plotted at a depth related to the skin depth at each frequency are a robust way of producing a smooth approximation of the earth’s layering from HEM data. The CDI section is a transform of the time domain decay information.

Inversions are generated by computing the layered earth resistivity model that would best match the measured EM data. From the starting model, an EM response that would be measured over that model is calculated. The model is repeatedly varied for each of the forward model parameters in turn to try and minimise the error between the modelled data and the input data.



Inversions define the resistivity distribution in the earth (hence the geo-electrical properties of the earth which can be used to define geology) more accurately than resistivity maps or sections. Because of this, they are preferable as a product where defining layering is important. However, they are more complicated to produce than calculated apparent resistivity maps and depth sections, and therefore less robust. The figure at right shows a comparison of the actual resistivity changes with depth of an earth model (black) with: the apparent resistivity section (blue), differential resistivity transform (green), smooth inversion (purple) and simple layered earth inversion (red).

Prepared by Fugro Airborne Surveys with material from:
Jaggar, Sue; Smith, Richard; Wolfgram, Peter; Geological Applications of Airborne Electromagnetic Methods, Time Domain Course Notes, September 3, 1996.
Fraser, D.C.; Geological Applications of Airborne Electromagnetic Methods, Frequency Domain Course Notes, September 3, 1996.



Resolution-Accuracy (69 m/s speed) of the new GT-1A INS DGPS single sensor gravity system for a range of Kalman filter length used in gravity data reduction.

Airborne Gravity Gradiometer Systems

Gravity gradiometer systems with multiple tensors developed by Lockheed Martin represent a significant improvement in resolution over single vertical sensor gravity systems. These systems have been used successfully for kimberlite mapping. Currently these gravity systems are mounted in single engine aircraft which have suitable flying and vibration characteristics.

Commercial Gravity gradiometers are complex and proprietary systems but in general consist of two or more gravimeters mounted together such that all sensors are subject to the same movement of the aircraft. Subtraction of the measurements removes noise from aircraft movement leaving a gradient measurement. This gradient measurement must be further corrected for terrain.

There is a great deal of useful information on the gravity method available on the internet. One place to start is:
http://www.gravmag.com/listserv.html

Examples

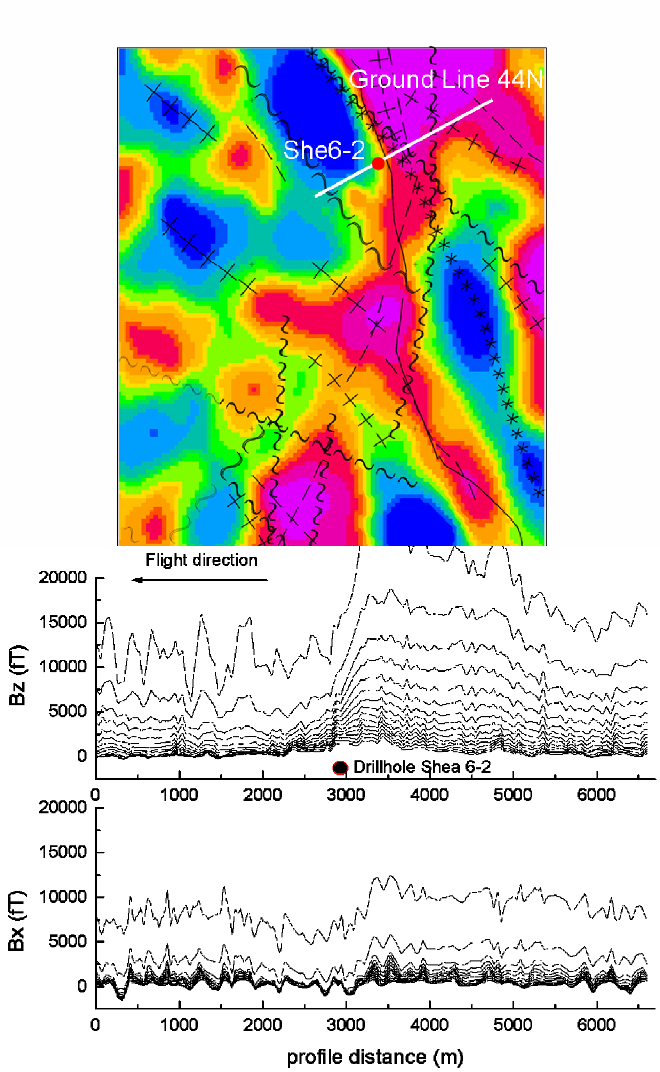
Uranium

Unlike gold and diamond exploration, uranium can be detected directly with geophysical methods. Airborne Gamma-ray Spectrometer (AGRS) measurements can identify anomalous uranium concentrations near surface directly detecting the uranium by its radioactive decay. This is an appropriate method for structurally controlled and iron oxide copper gold (IOCG) type deposits that may be associated with uranium.

EM surveys are commonly used to detect the conductive graphitic sediments normally associated with unconformity associated deposits such as those that occur in the Athabasca Basin in northern Saskatchewan and Alberta. "Roll front" deposits have been located by mapping the resistivity contrasts caused by the paleochannels in which they are hosted.

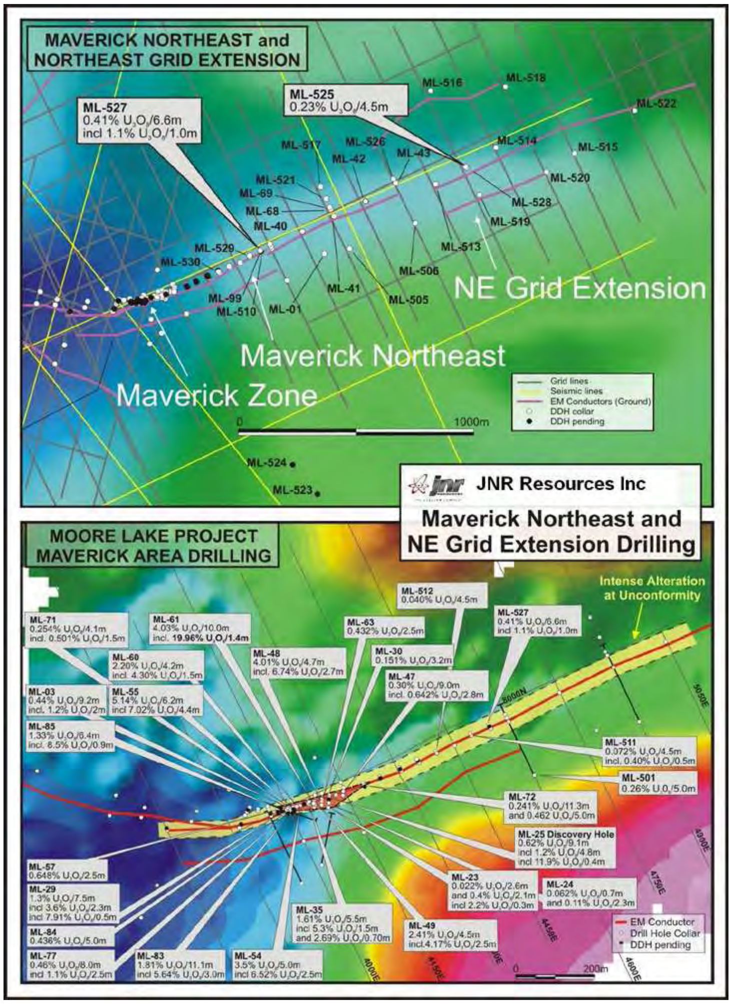
Magnetic surveys which can be done separately or almost always accompanying airborne EM or airborne Gamma-ray Spectrometry are used to map structures which may have controlled mineralizing fluids and provide other geological and structural information.

A large regional Gravity low is thought to be associated with the Olympic Dam deposit in Australia and similar lows in other areas of favourable geology have been the target of further exploration.



Above; 1990 Time domain EM survey with discovery drill location, below; recent time domain EM survey showing drill location.
From: Koch and Dalidowicz (1996), MinExpo '96 Symposium, Sask. Geological Soc., Data courtesy of Cogema Resources Ltd.

In the Cogema example above the original airborne EM survey identified a fault structure of interest. A ground EM follow up survey indicated a deep anomaly that was drilled to discover the Shea deposit. A subsequent regional airborne EM survey with a more powerful modern tool (Megatem) also showed the structure of interest (profile data). The deposit is associated with graphite and clay altered rock within a fault structure at an unconformity.



Above; Detail maps from JNR Resources website showing drill locations and inferred uranium mineralization.

With permission from: JNR Resources website; http://www.jnrresources.com/s/Moore_Lake.asp This website has a great deal of very informative information about Athabasca uranium exploration as well as JNR's results and corporate information.

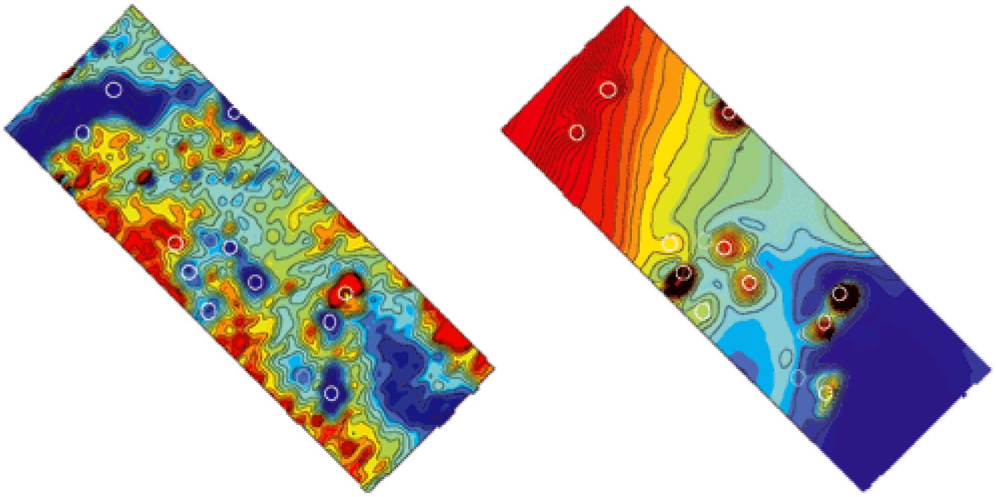
In the JNR example above, the red and purple NE trending lines are EM conductor axis. The conductive alteration at the unconformity, which is associated with concentrated uranium mineralization, is caused by graphite associated with altered pelites and or clay mineralisation.

Kimberlites

Like gold, diamonds cannot be detected directly with geophysics, however the geophysical signature of the kimberlite in which they occur may present a clear contrast with the surrounding rocks. Electromagnetic surveys are generally quite reliable, and when the kimberlites are hosted in crystalline igneous rocks, the pipes appear as conductive targets. In sedimentary rocks they are likely to be more resistive than their host rock. In non-glaciated terrain, the deep weathered cap of the kimberlite pipe may be quite conductive compared to the host.

Kimberlite has a higher proportion of magnetite than most rocks into which it intrudes, so kimberlite pipes often create magnetic anomalies. However, due to the rapid rate of intrusion and cooling, there is often strong remanent magnetisation that can oppose the induced magnetic field. Thus a kimberlite pipe can have a positive anomaly, a negative anomaly, or virtually no anomaly at all.

Ground based gravity is preferable for locating anomalies due to kimberlite pipes in a variety of environments due to the relatively low density of the crater and pyroclastic facies of the kimberlite. Airborne gravity does not have the necessary spatial resolution, however airborne gravity gradiometer systems have produced useful results for diamond exploration.



Left; 30 Hz/4 ms Apparent Conductivity Z-Axis Data, right; Total Field Magnetic Intensity.
Airborne data presented with permission of Fort à la Corne Joint Venture (Kensington Resources, Monopros Limited, Cameco Corporation), and Fugro Airborne Surveys.

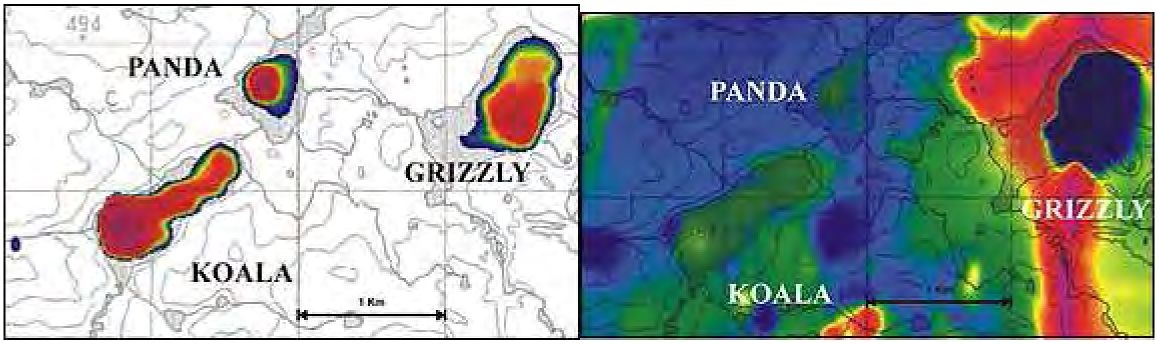
A combined AEM/Magnetic survey was flown over a 12 km by 4 km area in 1996. The area contained 11 kimberlite bodies defined by magnetics (see Total Field Magnetic Intensity Map) and confirmed by drilling. The time-domain EM survey utilised both a 30 Hz and 90 Hz waveform frequency: the former with a 4 ms pulse width; the latter with 2 ms.

The AEM data outlined 10 of the 11 kimberlites as high-resistivity anomalies and one as a low-resistivity anomaly. This one low-resistivity anomaly is also one of the strongest magnetic features, supporting other studies that showed a strong correlation between lower kimberlite resistivity and higher magnetic response.

Overall the resistivity background of the survey area is quite active with drill-proven glacial overburden depths of up to 130 metres. The data effectively sees through this cover which could mask the kimberlite signatures.

Reference

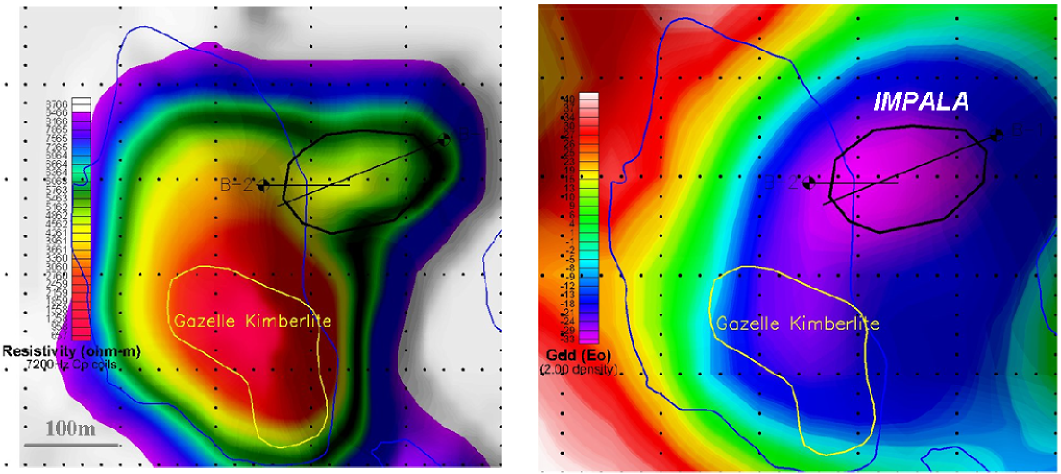
Jellicoe, B.C., Robertshaw, P., Williamson, P. and Murphy, J.D., 1998, Summary of Exploration Activities and Results for the Fort à la Corne Diamond Project, Saskatchewan, in Summary of Investigations, 1998, Saskatchewan Geological Survey.



Left; Apparent resistivity map, right; 7200 Hz Total Magnetic Field Data courtesy of BHP Diamonds Inc. and Dia Met Minerals Ltd.

The apparent resistivity map, calculated from 7200Hz coplanar data of the helicopter frequency domain (Dighem) survey, clearly shows the economic pipes in this data block as low resistivity anomalies. The Koala and Panda pipes give clear anomalies, and are underneath lakes.

Kimberlite often has more magnetite than typical Slave rocks, so it is common for kimberlite pipes to cause magnetic anomalies. But this is not always so. Some pipes have inverted (low) magnetic anomalies, due to remanent (permanent) magnetisation which is opposite to the earth's magnetic field. Two non-economic pipes, the Grizzly and Leslie, both have strong magnetic anomalies, but notice that the Grizzly anomaly is negative (low). The Koala pipe has a very weak anomaly, which could be easily overlooked in many conditions..



AEM Resistivity

G_{DD}

Impala pipe returned microdiamond counts as follows but is deemed uneconomic

Drillhole	Dip	Interval	kg	Stones (<0.5mm)	Stones (>0.5mm)	Total Ct
01-05	-50°	35.7 - 103.1 m	72.8	31	20	0.128
01-05	-50°	103.1 - 170.9 m	92.7	34	27	0.059
01-05	-50°	170.9 - 240.0 m	112.4	46	25	0.195

Left; Apparent resistivity map, right; Gravity Gdd map
Case example provided by BHP Billiton and used with their permission.

The Falcon airborne gravity gradiometer survey at Ekati was flown in the summer of 2000 at 100 m line spacing and 80 m ground clearance.

The Gazelle pipe had been discovered by AEM prior to the Falcon survey but the small extension of the resistivity anomaly in the north-east had not been considered significant. However, the Falcon vertical gravity gradient data show this as the main gravity anomaly. Drilling hit a new kimberlite (the Impala pipe) with significant micro-diamond counts but the Impala pipe proved to be sub-economic.

The Alberta Energy and Utilities Board is the publisher of *Diamond Exploration in Western Canada* short course notes, released at the MEG Forum, April 28, 2006. The presentations and abstracts submitted to Dinu Pană, Alberta Geological Survey, were edited for style and format, but not content, and were converted to PDF.