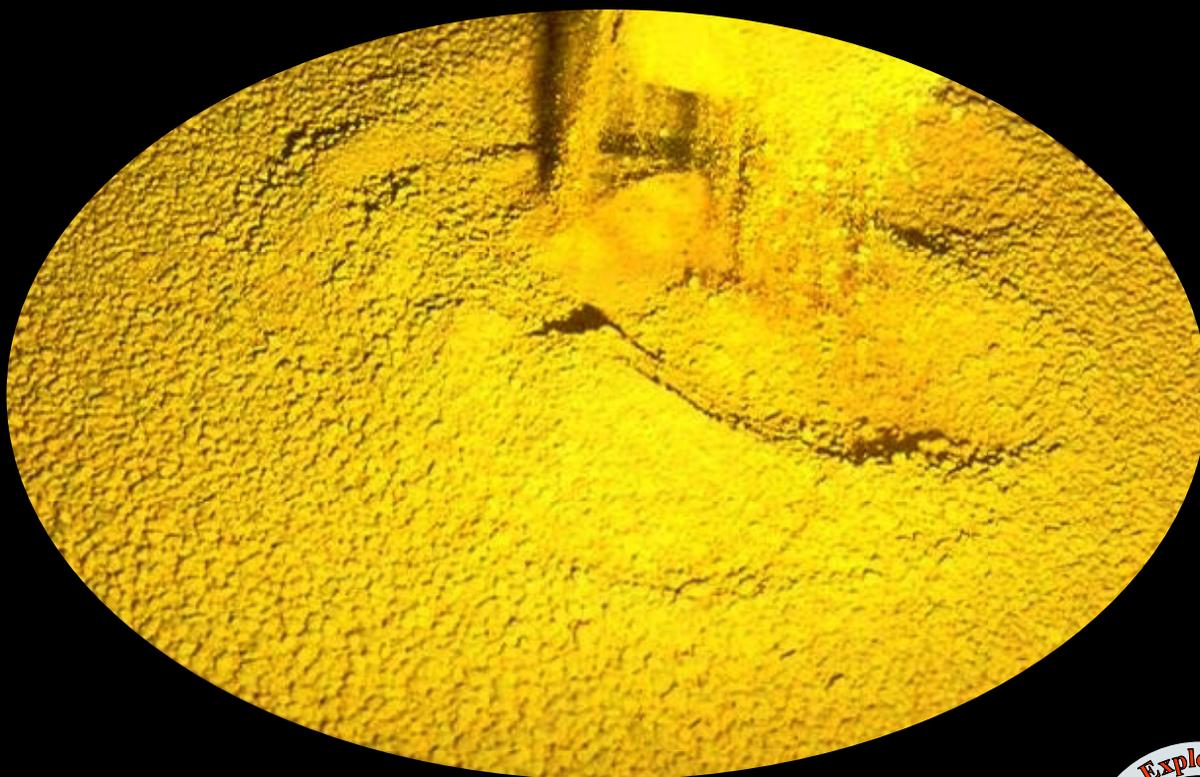


Uranium Exploration in Western Canada

Short Course Notes - MEG - 2006
edited by
Dinu I. Pana



Calgary Mining Forum

Exploring for Uranium in Western Canada

Short Course - MEG - Calgary

April 28th, 2006

- 8:00-8:30 Uranium Supply and Demand
Reg Olson (Alberta Geological Survey/EUB)

- 8:30-9:15 An Overview of Uranium Deposits in Western Canada
Reg Olson (Alberta Geological Survey/EUB)

- 9:15-10:00 Uranium 101-Geochemistry and Uranium Deposit
Metallogenesis
Dave Quirt (COGEMA)

- 10:00-10:15 Coffee break*

- 10:15-11:00 Integrated Exploration for Athabasca Basin
Unconformity-Related Uranium Deposits
Dan Brisbin (CAMECO)

- 11:00-11:30 Basement Geology Relevant to Exploration for
Athabasca Unconformity-Related Uranium Deposits
Dinu Pana (Alberta Geological Survey/EUB)

- 11:30-12:00 Geophysical Exploration Techniques
Doug McConnel (FUGRO)



Uranium Overview

Reg Olson, Tanya Matveeva & Dinu Pana
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Presentation Summary

1. Since 2003 the spot price has increased five-fold to ~\$41US/lb U_3O_8 in April 2006 due to an impending supply shortfall to meet current and expected demand. It is suggested the spot price could continue to rise, perhaps significantly over the next few years.
2. There are two naturally occurring uranium isotopes, U^{238} (99.3%) and U^{235} (0.7%). Both decay through a series of daughter products, including radium and radon, to lead. The decay series isotopes have differing half-lives (from billions of years to seconds), and differing geochemical characteristics; e.g., U^{6+} is highly mobile under oxidizing conditions, whereas radium is not, but is mobile under reducing conditions.
3. It is proposed that all genetic models for epigenetic uranium deposits have five key characteristics: (a) there needs to be a 'fertile' source of uranium; (b) the uranium at the source must be in, or converted to, a readily mobile form (I.e., U^{6+}); (c) there needs to be a transporting fluid with the right chemistry and sufficient volume to move the mobile uranium from the source; (d) there should be a 'conduit' to focus fluid flow (e.g., a porous stratigraphic unit, or a fault zone, etc), and (e) there must be something to cause uranium deposition (e.g., change in Eh, pH or other elements that will cause U^{6+} to either be reduced to U^{4+} or deposit as a U^{6+} mineral).
4. The International Atomic Energy Agency (IAEA) classes uranium deposits into 15 types based on their geological setting; in this presentation, only the 5 most 'important' are discussed, including: (a) unconformity related uranium; (b) sandstone-hosted uranium; (c) quartz pebble conglomerate-hosted uranium; (d) vein-type uranium; and (e) breccia complex uranium deposits.
5. Uranium in the past has been mined by three methods: (a) underground, (b) open pit, and (c) In Situ Leach (ISL). ISL has been used successfully over the past some 25 years in various parts of the world to extract uranium generally from 'lower-grade' deposits that probably would not be economically extractable otherwise. The main uranium 'solvents' in ISL are either an acidic or an alkaline solution.
6. The presentation concludes by noting that, in the authors opinion, uranium is one of the more interesting and challenging metals to explore for. Further, the probability is at least 'fair' to perhaps 'moderate' that either an unconformity related or sandstone hosted uranium deposit will be found within Alberta in the next few years.

Uranium Demand, Supply & Whereto Prices?

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Uranium Demand - Nuclear Power

- Uranium isotopes: U^{238} & U^{235}
- When these isotopes are split (nuclear fission), they emit particles and energy (heat)
- U^{235} is very fissile because it emits 2 or 3 neutrons, which cause other U^{235} atoms to split, resulting in a 'chain reaction'
- But this only occurs if natural U ore is 'enriched' in U^{235} to produce a 'critical mass'
- Nuclear power reactors control fission slowly \rightarrow Heat

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Nuclear Power

Worldwide: ~440+ nuclear plants produce 17% of the world's electric power

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Nuclear Reactors – Renewed Interest for the first time in past 25 years

- Over 60+ new nuclear reactors for electrical power generation could be built within the next 10 to 15 years
- China alone plans to build 30 nuclear reactors over the next 10 years to provide power for their ever-expanding economy
- Gas-powered electrical generation plants are ‘cheap’ to build, but are ‘gas-price’ sensitive with respect to power generation costs
- Nuclear plants are expensive to build, but once built, are not particularly sensitive to uranium fuel costs

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Energy comparison – e.g., McArthur River, Sask. (biggest U mine & deposit in world)



Uranium reserves
460 million lbs

Energy equivalent to



8 billion barrels oil



2 billion tonnes coal

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Some Further Information pertinent to Uranium Demand & Supply

- In the past, over 50% of U production has gone to produce fissile materials (separation of U²³⁵) for atomic weaponry
- This usage, however, has significantly decreased as a result of the fall of the Iron Curtain
- As a result, decommissioning of nuclear weaponry over the past 25 years has fed a large portion of the supply shortfall of uranium for nuclear reactors
- By the early 2000s, however, much of the available decommissioned uranium had been ‘consumed’

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Why Should You, as a Uranium Explorer, Care About the Uranium Price

- Assume the gold price is \$610US/oz, and you have a deposit with an average grade of about 0.3 oz/ton, then the in-ground 'value' of the ore is about \$183/ton
- Assume the copper price is \$2.80US/lb, and you have a porphyry deposit with an average grade of about 0.5% or about 10 lbs/ton, then the in-ground 'value' of the ore is about \$28/ton
- Assume the uranium spot price is \$40.00US/lb, and you have a deposit with an average grade of about 0.3% U³O₈, or about 6 lbs/ton, then the in-ground 'value' of the ore is about \$240/ton
- BUT, what if the U³O₈ price reaches \$400/lb!!!!

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Uranium '101' - Some Fundamentals

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Periodic Table – U is element #92 with an atomic weight of ~238; Th is #90 with an atomic weight of ~232

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A Little History

- Uranium was discovered in 1789 by the German chemist M.H. Klaproth
- Thorium was discovered in 1828 by the Swedish chemist J.J. Berzelius
- Radioactivity was discovered in 1896 by the French physicist Henry Becquerél

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Radioelement Concentrations in Crustal Rocks

Rock Type	U Avg - Max (ppm)	Th Avg - Max (ppm)	K Avg (%)
Crustal Avg	2.7	12	2.1
Laterites	10 - 40	50 - 132	low
Black shale	8 - 250	16 - ?	2.7
Argillaceous Sediments	4 - 13	16 - 47	2.7
Acid Igneous	4.5 - 12	18 - 20	4.0
Intermed. Igneous	2.3 - 7	9 - 20	1-2.5
Limestone	2 - 10	2 - ?	0.3
Mafic Igneous	1 - 3	3 - 10	0.5
Arenaceous Sediments	1 - 2	3 - 6	1.4

After Clark et al., 1966

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Uranium Relative Abundance

An interesting fact: at an average crustal abundance of 2.7 ppm, then in a yard ~16 m x 33 m x 1 m deep with an avg soil SG of ~2.7 g/cm³, there will be about 3,850 g of U, or ~3.85 kg, or ~8.5 lbs of U

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Tetravalent U⁴⁺ & Th⁴⁺ Minerals

Some 72, but generally:

- Usually dark brown-black colour, often metamict (radiation damage), and no fluorescence
- Compositions generally categorized as:
 - **Oxides** – ~34, including **uraninite/pitchblende**, davidite, uranothorite, pyrochlore, betafite, samarskite, brannerite, etc.
 - **Silicates, Phosphates, Carbonates** – ~38, including coffinite, nenadkevite, allanite, xenotime, etc.

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Uraninite/Pitchblende Characteristics

Uraninite (crystalline) or Pitchblende (massive)

- UO₂ (U is in the U⁴⁺ state)
- Habit: **Isometric**, with **Uraninite** habit cubic, octahedral, cubo-octahedral, or **Pitchblende** massive, botryoidal or reniform
- Hardness: **5 - 6**
- Density: **10.95**
- Fracture/tenacity: **brittle, uneven to conchoidal**

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Tetravalent U⁴⁺ - Th⁴⁺ Minerals (2)

Some other common uranium minerals:

- **Brannerite**: a uranium titanate (ideally UTi₂O₆); this is the common mineral at the Elliot Lake quartz-pebble conglomerate deposits
- **Uraniothorite or Thorianite**: a U-rich variety of thorite (ThSiO₄); is most common in siliceous granite and syenites or their pegmatitic facies; main mineral at Madawaska mine, Bancroft, Ont.
- **Coffinite**: ideally USiO₄, but normally U(SiO₄)_{1-x}(OH)_{4x}; has been found in Colorado Plateau ore, and at Elliot Lake, Beaverlodge, Rabbit Lake and Cluff Lake
- **Thucholite**: a radioactive hydrocarbon frequently found in pegmatitic and vein-type deposits (not a true mineral species, but consists of Th-U-C-H-O)

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Hexavalent U⁶⁺ Minerals (1)

Some 128, but generally:

- Compositions categorized as either
 - (a) **uranate series** ($M^+_2U^{6+}_xO_{3x+1}$) which produces minerals that usually are **yellow-orange with an orange-red fluorescence**, and
 - (b) **uranyl series** which contains the relatively stable ($U^{6+}O_2$)²⁺ ion, and produces minerals that are **yellow-green with green-greenish white fluorescence**
- **Uranate series:**
 - **Hydrated Oxides & Hydroxides:** ~16, including becquerelite, schoepite, etc.

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Hexavalent U⁶⁺ Minerals (2)

- **Uranyl Series:**
 - **Phosphates:** ~27, including torbernite, meta-torbernite, autunite, etc.
 - **Molybdates, Vanadates:** ~22, including wulfenite, carnotite, tyuyamunite, etc.
 - **Arsenates:** ~19, including zeunerite, meta-zeunerite, etc.
 - **Sulfates, Selenites, Tellurites:** ~14, including uranopilite, zippeite, etc.
 - **Silicates:** ~16, including soddyite, cuprosklodowskite, uranophane, boltwoodite, etc.
 - **Carbonates:** ~14, including rutherfordine, sharpite, etc.

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Hexavalent U⁶⁺ Minerals (3)

- Commonly referred to as the **Yellow U Oxides** or 'YO'
- However, **NOTE: Normally all Yellow U Oxides are anomalously radioactive**, which distinguishes them from all other red, yellow, green, etc. 'oxides'

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Radioactive Elements

- U^{238} - ~99.3% of all U; decays through 13 daughter products to Pb^{208}
- U^{235} - ~0.7% of all U; decays through 10+ daughter products to Pb^{207}
- U^{234} - results from the decay of U^{238} , but its equilibrium isotopic abundance is only 0.0054%
- Th^{232} - decays through 8+ daughter products to Pb^{208}
- K^{40} - decays to Ar^{40} with half-life of 1.3×10^9 yrs

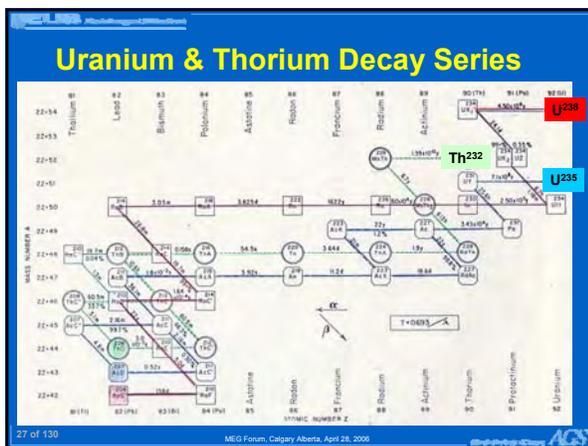
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Radioactive Decay

Uranium (and thorium) decay by emission of:

- **Alpha particle** – positively charged, and consisting of 2 protons & 2 neutrons (it is physically equivalent to a 4He atom)
- **Beta particle** – emission of an electron, typically by decay of a neutron to a proton plus electron; e.g., Pb^{214} (82 protons) decays to Bi^{214} (83 protons)
- **Gamma radiation** – electromagnetic radiation from an atomic nucleus, often accompanying emission of Alpha or Beta particles. Note that scintillometers detect gamma rays \pm Beta particles

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Take NOTE – Sample Packaging & Shipping Standards have changed since the 1970s!

Shipping Nuclear Substances

A Training Guide to the Safe Consignment of Radioactive Materials

Jan Semenov, *B.Sc., EMF*
Susan Reschny, *B.Sc.*

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For example, some of the changes for surface shipping of radioactive samples includes:

For example, for 'Land' Shipment of Samples:

- For 'Excepted Materials': (a) radiation must be less than 5 microsieverts/hour (sievert is a 'Dose Equivalent'), (b) they can be shipped without 'Transportation of Dangerous Goods Documentation (TDG)', (c) they do require a Uranium Natural number (UN2910), and (d) the package must bear the marking "Radioactive" on an internal surface that is visible when opened.
- In contrast, for 'Low Specific Activity (LSA) Radioactive Material (e.g., most low to moderate radioactivity rock samples and core), (a) radiation limits on the external surface must be <0.1 millisieverts/hr, (b) the package must be accompanied by proper TDG documentation, (c) the package must meet IP1 (for rocks) design standards, (d) there must be appropriate external labeling with the appropriate UN# (UN2912), etc. **NOTE: The responsibility for the above rests entirely with the shipper, and not with the receiving lab or destination.**
- In short, Shipping Nuclear Substances Training should be mandatory for all field staff doing uranium exploration.

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'Uranium 101' – In summary

- Two U isotopes (U^{238} , U^{235}) decay through a series of daughter products (including Radium & Radon) to Lead
- Half-lives in the decay series range from: billions of years (e.g., 4.5×10^9 yrs - U^{238}), to hundreds of years (e.g., 1,622 yrs - Ra^{226}) to days, minutes & seconds (e.g., 3.8 days - Rn^{222})
- U^{6+} is very mobile in oxidizing conditions; U^{4+} is immobile in reducing conditions (in contrast, for Radium the reverse is true)
- U content ranges from ~1 to 10+ ppm in the Earth's continental crust; U is more common than arsenic, molybdenum and tungsten, and much more common than mercury, silver and gold

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Some Key 'Principles'
in order to form
an economic Uranium Deposit

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A Few Key Principles or Criteria for Uranium Deposit Genesis*

- Note that although these 'Principles' deal with Uranium Deposit Genesis, they are NOT meant to be taken as an overall 'model' for Uranium Deposit formation
- Instead, they are meant as 'general principles' that should be considered with respect to the mineralization models proposed for various types of uranium deposits

*Apply to perhaps all 'Epigenetic' or 'Diagenetic' uranium deposits, but exclude the clearly 'syndimentary' uranium deposits

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Some Key Principles for the Formation of Uranium Deposits (1)

1. There needs to be an 'adequate' uranium source (i.e., preferably a 'fertile' source of U such as acidic igneous rocks, black shales, fresh or preferably altered granitoid or 'acidic' metamorphic basement, or other such sources with elevated U contents)

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An Example – To Form the McArthur River Deposit (~460 million lbs U³O⁸, or ~390 million lbs U, or ~177.3 million kg U)

To form this deposit would require:

- If the source had an average content of 3 ppm and a SG of 3, and 50% of the source U (i.e., 1.5 ppm) is leached, then the volume of rock needed as a source to form McArthur River would be ~39.4 km³,
- OR a cube of rock about 3.4 km on each edge,
- OR a faulted zone about 0.8 km wide by 1.2 km deep by ~41 km long,
could be a source for all the uranium in the McArthur River deposit

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Some Key Principles for the Formation of Uranium Deposits (2)

1. There needs to be an 'adequate' uranium source
2. The uranium needs to be in a 'mobile' form (i.e., typically in the U⁶⁺ state), or is readily convertible to such form

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Some Key Principles for the Formation of Uranium Deposits (3)

1. There needs to be an 'adequate' uranium source
2. The uranium needs to be in 'mobile' form (U⁶⁺)
3. There needs to be a fluid that can transport the mobile U⁶⁺ (e.g., magmatic hydrothermal, other hydrothermal, expelled connate, groundwater, etc.), with both the right chemistry and in sufficient volume

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Some Key Principles for the Formation of Uranium Deposits (4)

1. There needs to be an 'adequate' uranium source
2. The uranium needs to be in 'mobile' form (U^{6+})
3. There needs to be a fluid to transport the mobile U^{6+}
4. Typically, there needs to be a 'conduit' to focus fluid flow (e.g., a porous unit, a fault, fault intersections or other such zones of focused permeability)

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Some Key Principles for the Formation of Uranium Deposits (5)

1. There needs to be an 'adequate' uranium source
2. The uranium needs to be in 'mobile' form (U^{6+})
3. There needs to be a fluid to transport the mobile U^{6+}
4. There needs to be a 'conduit' to focus fluid flow
5. There needs to be a cause of uranium deposition (e.g., a change in Eh, pH or a reductant to cause U^{6+} to be 'reduced' [gain electrons] to U^{4+} and precipitate, or to cause the U^{6+} in solution to precipitate as a U^{6+} mineral)

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In Summary - Key Principles for the Formation of Uranium Deposits (6)

1. There needs to be an 'adequate' uranium source
2. The uranium needs to be in the 'mobile' U^{6+} form
3. There needs to be a fluid to transport the mobile U^{6+}
4. There needs to be a 'conduit' to focus fluid flow
5. There needs to be a cause of uranium deposition

To form an 'Epigenetic' uranium deposit (i.e., formed later than its host rocks)

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Principal Uranium Deposit Types

GUIDEBOOK TO ACCOMPANY IAEA MAP
WORLD DISTRIBUTION OF URANIUM DEPOSITS

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Principal Uranium Deposit Types

- There are various classifications of Uranium Deposit Types, but the one presented here is from the International Atomic Energy Agency (IAEA) of June, 2003
- The IAEA classification assigns the Uranium Deposits according to their geological setting (15 types), and ranks them according to their current and former economic importance as Uranium sources

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Principal Deposit Types listed by relative importance (1)

1. Unconformity-related
2. Sandstone-hosted
3. Quartz-pebble conglomerate
4. Vein-type deposits
5. Breccia complex
6. Intrusive-related (e.g., Rossing in Namibia)
7. Phosphorite deposits (e.g., in Florida)
8. Collapse breccia pipes (Orphan Mine in USA)
9. Volcanic deposits (e.g., Michellin in Quebec)

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Principal Deposit Types listed by relative importance (2)

10. Surficial deposits (Yeelirrie in West Aust.)
11. Metasomatic deposits (Johann Beetz in Que.?)
12. Metamorphic deposits (Bancroft in Ontario)
13. Lignite (Nebraska, SW Sask. & SE Alberta)
14. Black shale deposits (Alum shale in Sweden)
15. Other

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Principal Uranium Deposit Types (a 'variation')

Deposit type	Initial Resource (tU)
Unconformity	~2,800,000
Sandstone	~500,000
Quartz-pebble conglomerate	~800,000
Vein	~1,500,000
Hematitic Breccia Complex	~400,000
Volcanic	~200,000
Intrusive	~600,000
Metasomatic	~1,700,000
Other	~1,800,000

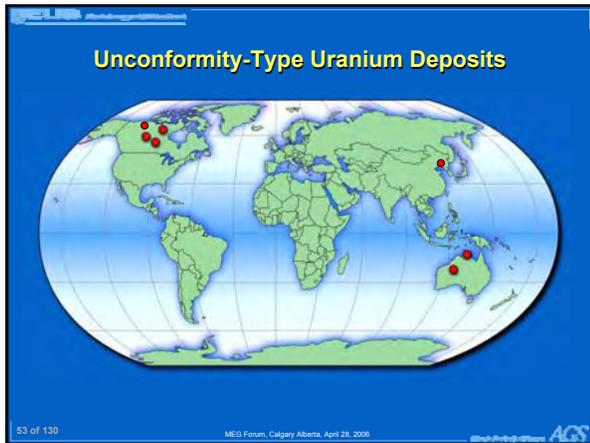
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Principal Uranium Deposit Types (discussed today)

1. Unconformity-related
2. Sandstone-hosted
3. Quartz-pebble conglomerate
4. Vein-type deposits
5. Breccia complex

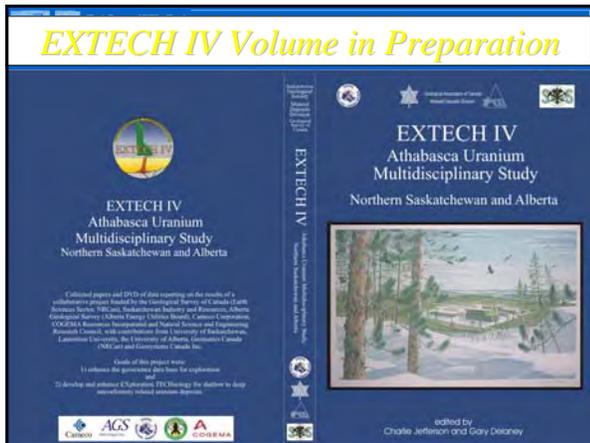
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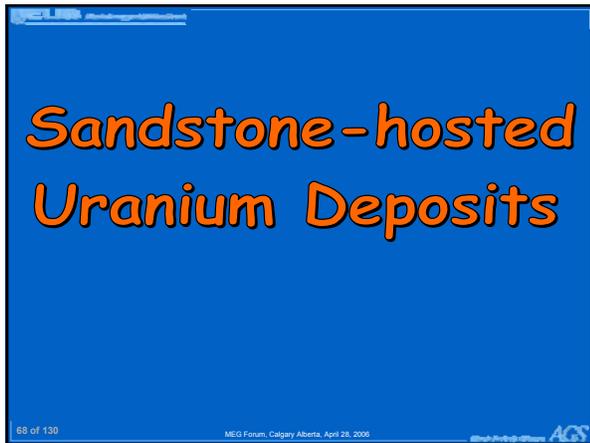
Unconformity-type Uranium Deposits

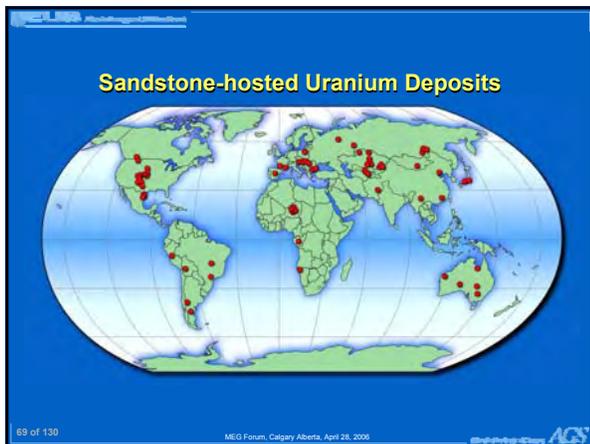


Unconformity Related U deposits

Tectonic setting:	Interiors of large cratons, at the base of clastic sedimentary strata resting on peneplaned, typically saprolitic, tectonometamorphic complexes
Age:	Lower-Middle Proterozoic, rare Phanerozoic
Host Rocks:	Below the unconformity in basement rocks, at the unconformity in the 'altered' (saprolitic?) zone, or above the unconformity in quartzitic, typically red bed, sandstones
Structure:	-Ancient lineaments and mylonite zones in basement -Repeatedly reactivated reverse structures in the basement, with extensions into the overlying sandstone
Alteration:	-Paleoweathering of basement -Post sandstone illitization, chloritization, carbonatization, tourmalinization, silicification & de-silicification, sulphidization, destruction of graphite, corrosion of quartz
Minerals:	Pitchblende/uraninite; various Ni, Co, U, etc. minerals



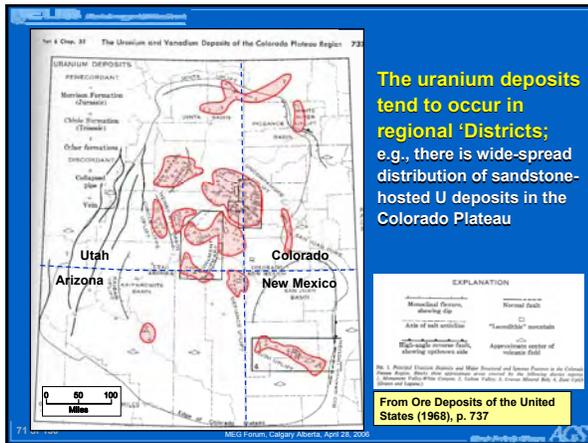


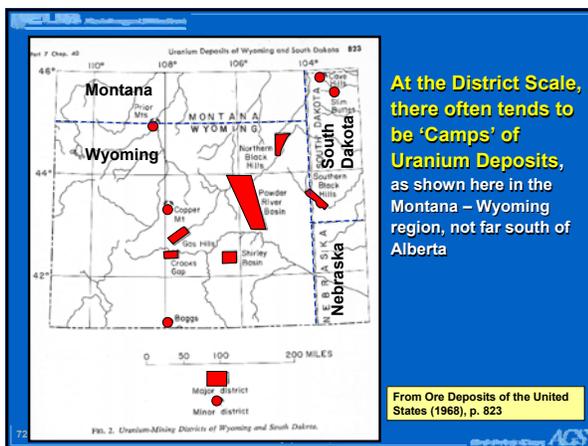


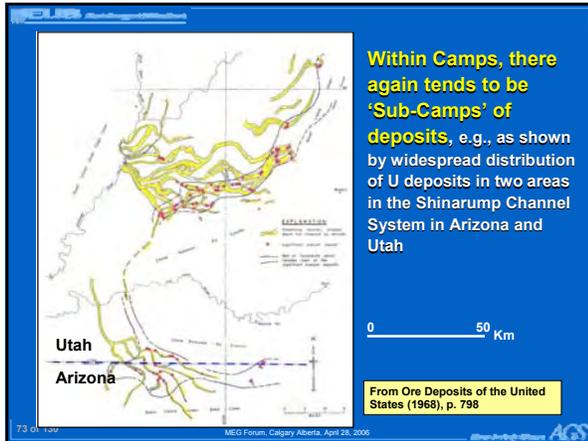
Sandstone hosted U deposits

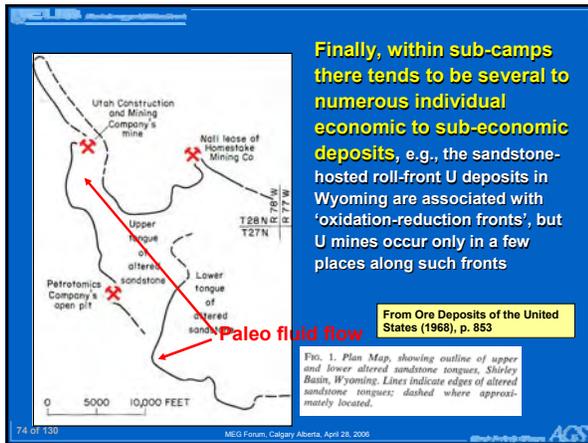
Tectonic setting:	Stable platform or foreland-interior basin, shelf margin; adjacent major uplifts provide favorable topographic conditions
Age:	Generally mid-Paleozoic and younger, minor Precambrian
Host Rocks:	Reduced fluvial and lacustrine sediments, continental or marginal marine environment
Structure:	Low-angle permeable sandstones interbedded with less permeable horizons
Alteration:	Reduction alteration contact between 'fresh' and 'mineralized' sandstone is reflected by colour change from grey-green (reduced) to reddish - light yellow-brown (oxidized)
Minerals:	Pitchblende, coffinite, various YO's and vanadium minerals

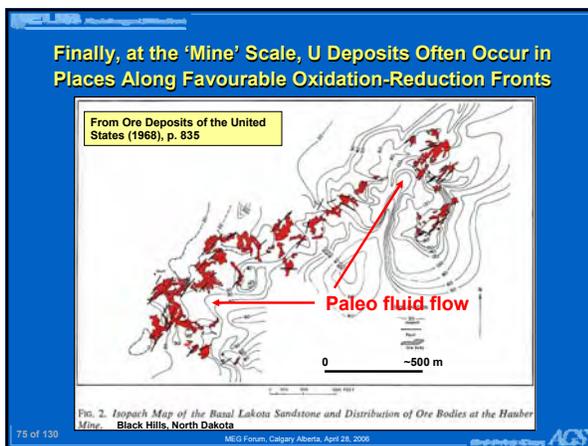
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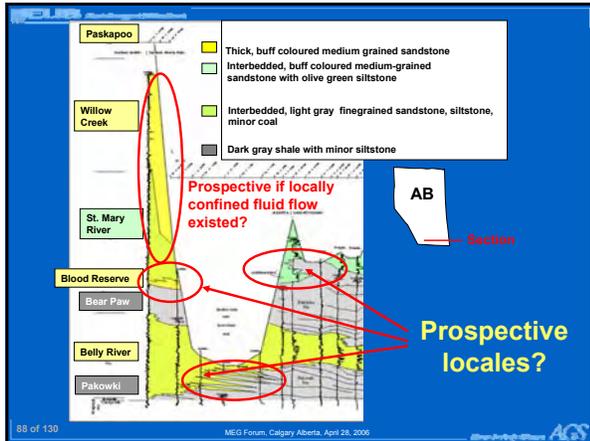


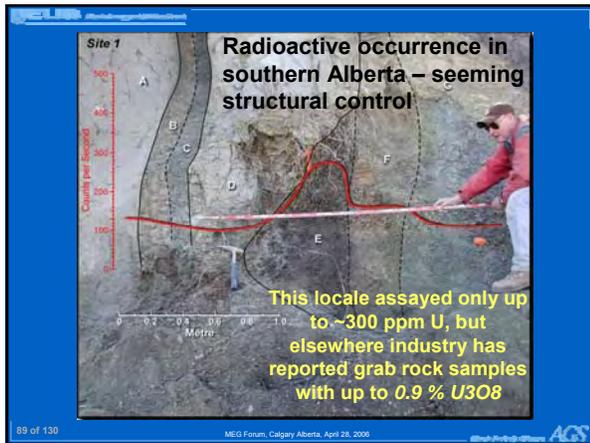




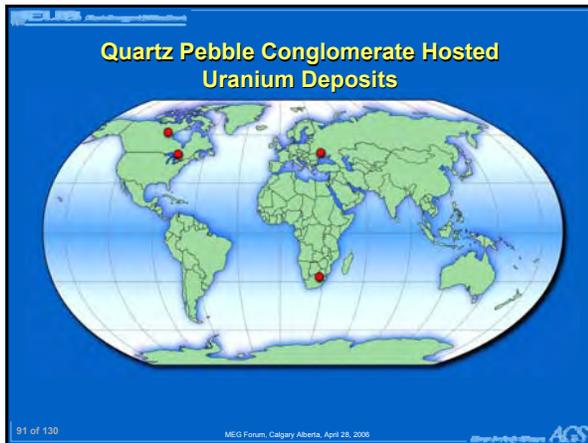








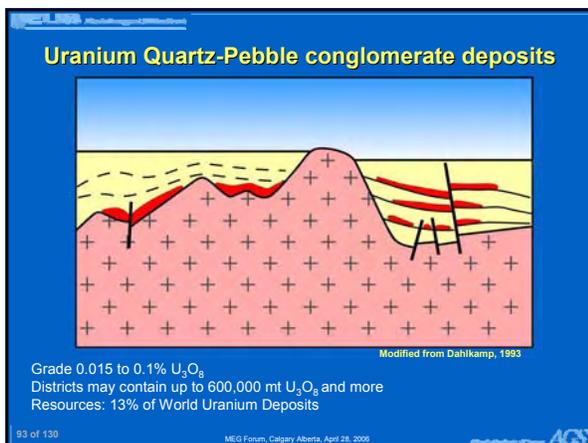
**Quartz Pebble
Conglomerate Hosted**

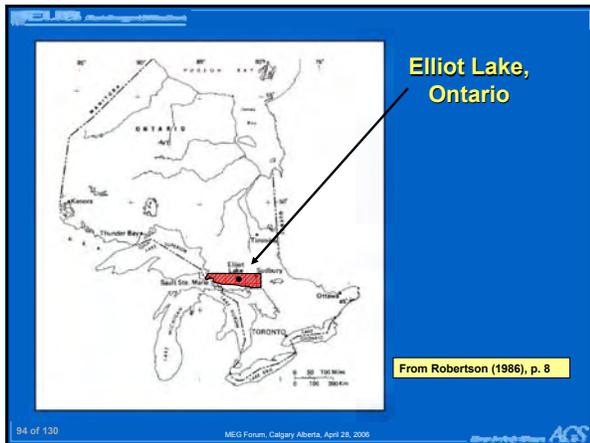


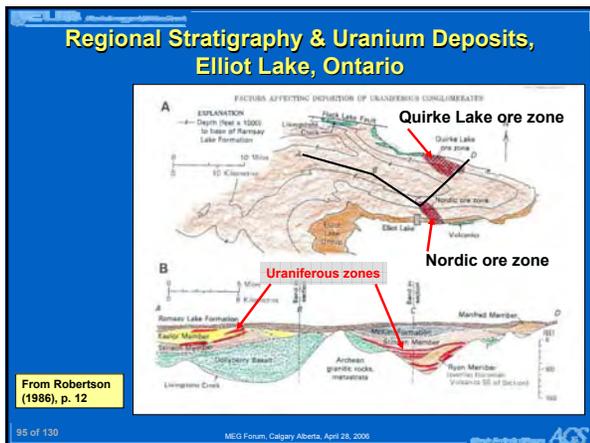
Quartz-Pebble Conglomerate U Deposits

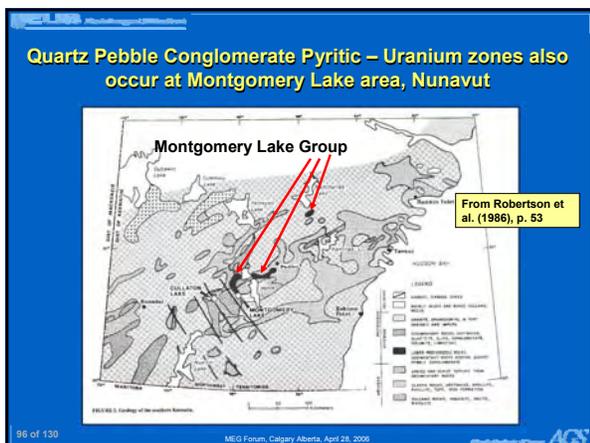
Tectonic setting:	Basins flanked by Archean granites and greenstone belts. Slow subsidence of Archean craton. Later moderate uplift and erosion to remove Phanerozoic strata and retain Early Proterozoic rocks.
Age:	Lower Proterozoic – prior to oxy-atmosphere?
Host Rocks:	Oligomictic quartz-pebble conglomerates composed of well-rounded, well-sorted pebbles often with a highly pyritiferous siliceous matrix
Structure:	Very thick onlapping sedimentary deposits in elongate epicontinental basins or half-grabens. Middle and basal reaches of alluvial fans deposited on steeper side of basins.
Alteration:	Deep physical weathering and erosion of Archean paleosurface, sericitization of plagioclase
Minerals:	Detrital uraninite, brannerite, coffinite, thucholite, gold

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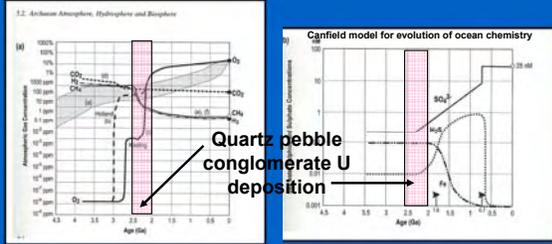






But, What If the Oxy-Atmversion Model is Wrong?

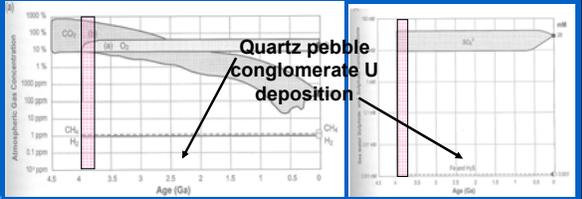
Cloud-Walker-Holland-Kasting Model in which Oxy-Atmversion occurs ca ~2.3 to 2.0 Ga, with the quartz-pebble uraninite-pyrite paleoplacers deposited ca >2.2 Ga



From Ohmoto (2004) MEG Forum, Calgary Alberta, April 28, 2006

Versus the Dimroth-Ohmoto Oxy-Atmversion Model
In this model oxy-atmversion occurred ca 4.0 Ga, shortly after the formation of the oceans and continents.

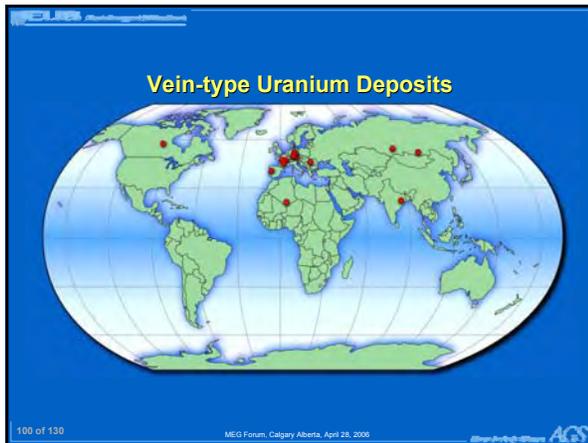
If this model is correct, then perhaps another genetic model must be sought for the inferred paleoplacer Quartz Pebble Conglomerate U deposits, AND
If so, then this opens up the prospectivity for this type of U deposit to occur in rocks of other, even younger, ages?



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Vein Type Uranium Deposits

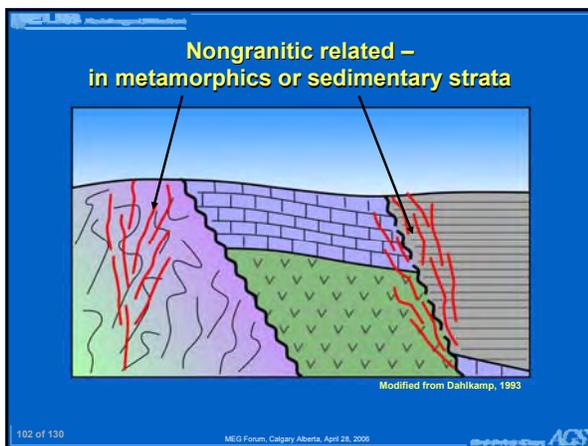
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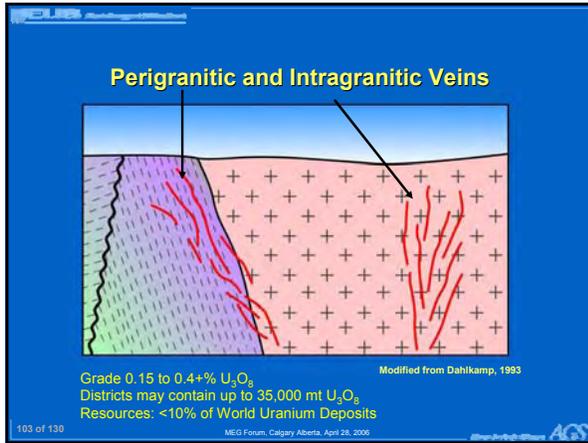


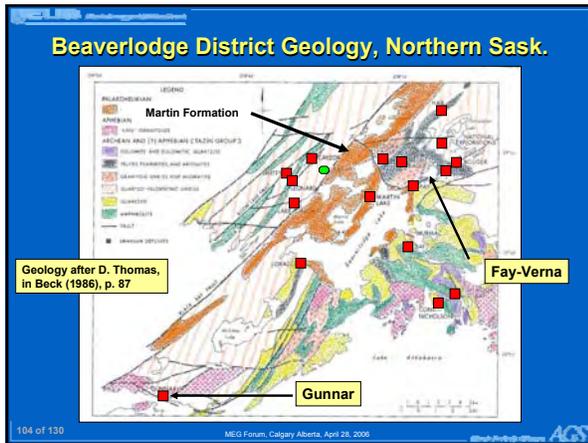
Vein-Type Deposits

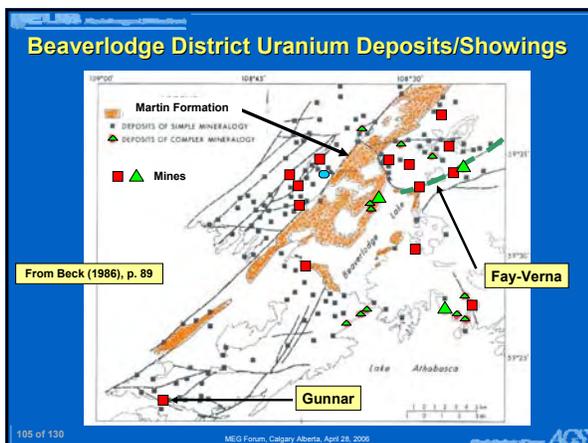
Tectonic setting:	Postorogenic continental environments, commonly associated with calcalkaline felsic plutonic and volcanic rocks; also may be an 'unconformity' connection?
Age:	Proterozoic to Tertiary. None are older than approximately 2.2 Ga
Host Rocks:	Granite, metamorphic rocks, sediments
Structure:	Tabular or prismatic ore bodies in dilatant zones in major fault systems and shear zones
Alteration:	Chloritization, hematitization, feldspathization
Minerals:	Pitchblende, uraninite, coffinite

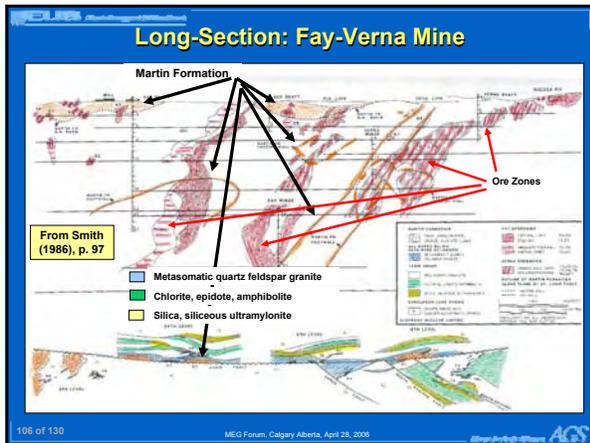
101 of 130 MEG Forum, Calgary Alberta, April 28, 2006

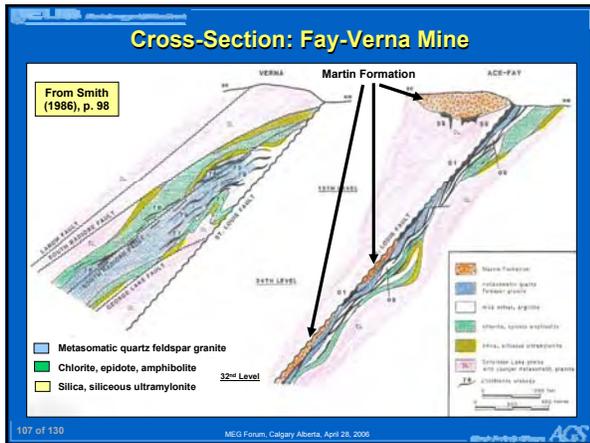






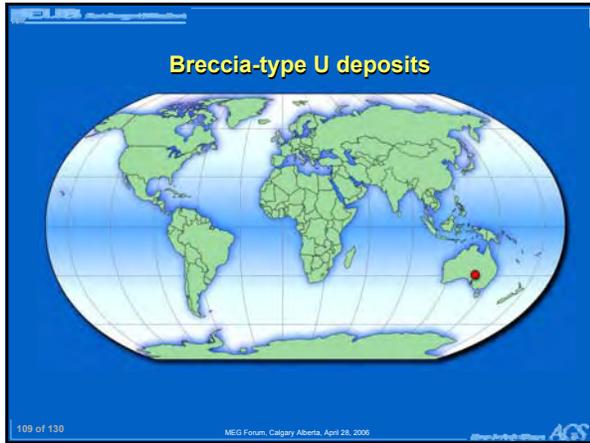






Breccia Type Uranium Deposits

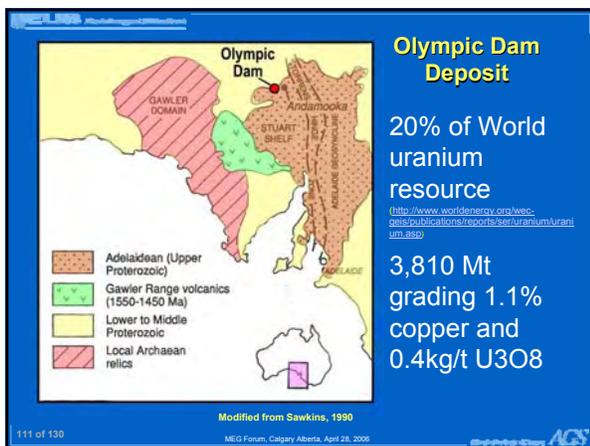
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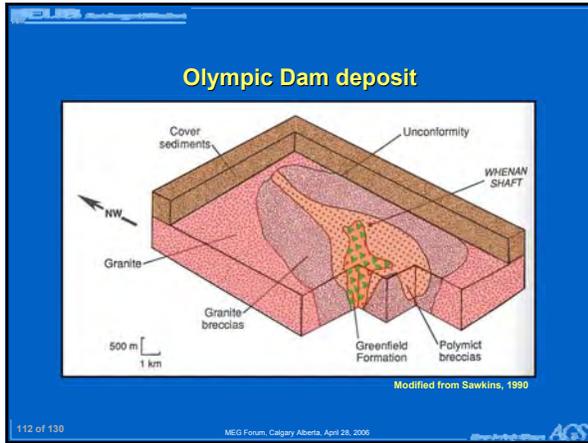


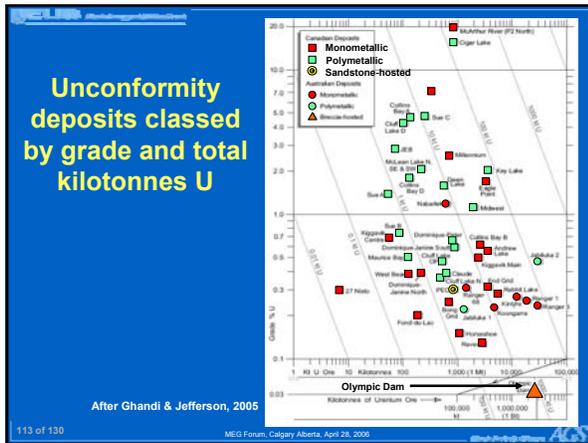
Breccia Complex

Tectonic setting:	Extensional tectonic zones within stable cratons
Age:	Early-Mid Proterozoic
Host Rocks:	Hematite-rich granite breccia complex in red K-feldspar granites
Structure:	High- to low-angle splay offs of major crustal-scale faults
Alteration:	Hematite, chlorite, sericite, quartz, carbonates Sodic at deeper levels, potassic at shallower depths
Minerals:	Pitchblende, coffinite

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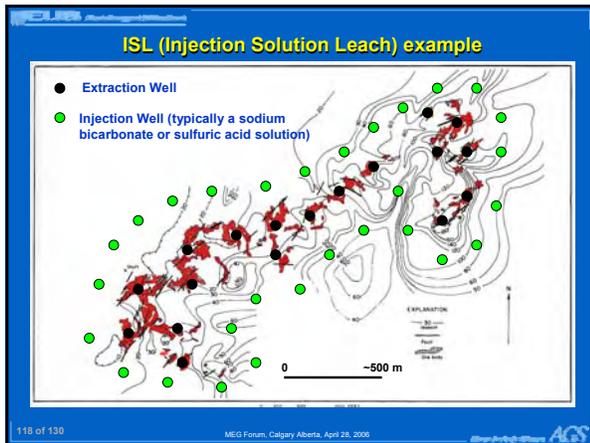


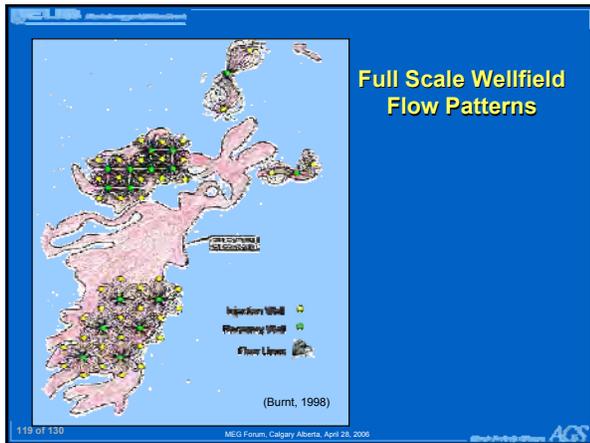


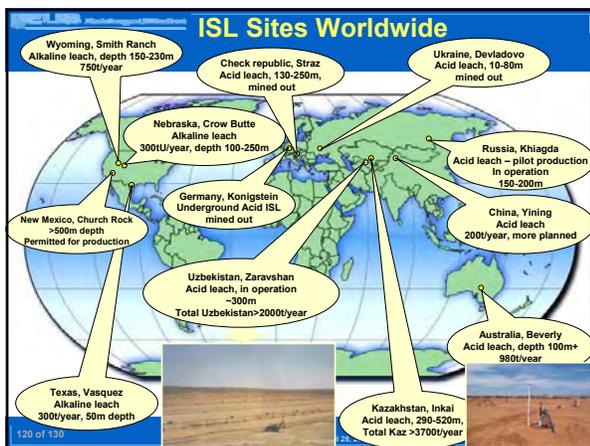


Uranium Mining & Extraction Methods, including ISL

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Conclusions & Final Thoughts



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Uranium is one of the most interesting metals to explore for!

Complexities include:

- Isotopic decay series
- Daughter products have diverse geochemical and geophysical signatures
- Diverse U deposit types



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Some Concerns & Issues

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Can 'Green Power' provide sufficient future power for the world's ever expanding population, economic activity and rising standard of living?

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However, I suggest 'Green Power' is NOT alone going to provide the expected future Megawatts of World Electrical Power Demand

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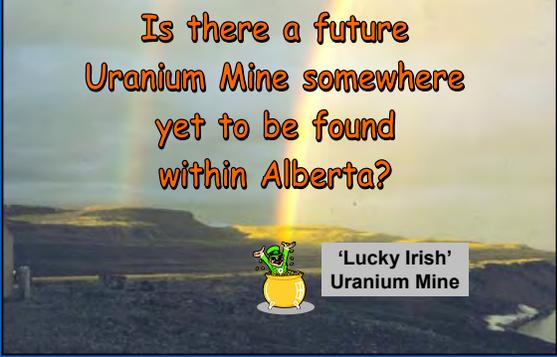
Directions - Which way to the future?

- Alberta has many Energy Options – i.e., Oil, Gas, Coal, Oil Sands, Nuclear Power?
- The primary current downside to nuclear power is the long-term secure storage of spend highly radioactive, reactor fuel
- Re-processing in future, may both provide added reactor fuel, and reduce the storage issue?



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Is there a future Uranium Mine somewhere yet to be found within Alberta?



**'Lucky Irish'
Uranium Mine**

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Uranium 101: Geochemistry and Uranium Deposit Metallogenesis

David Quirt

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An introduction to the basic chemistry and the aqueous geochemistry of uranium will be given. This information is essential as it forms the background to the presentation on the metallogenesis of uranium, in particular the metallogenesis of the unconformity-type uranium deposits. Also to be presented as a foundation to the metallogenesis of the unconformity-type uranium deposits is the geology of the sub-Athabasca basement, the paleoweathering profile, and the Athabasca Group sediments.

For the uranium metallogenesis, the diagenetic-hydrothermal basement-sandstone interaction model for unconformity-type uranium deposits will be introduced and discussed. This model relates uranium mineralization to Athabasca Group diagenetic processes and attributes the spatial association of deposits with the sub-Athabasca unconformity to movement and interaction of diagenetic brines with basement-equilibrated fluids. It attributes the origin of the deposits to fluid interactions between oxidized Athabasca basinal brines and variably reduced basement fluids (fluid-fluid interaction) and/or reduced basement lithologies (fluid-rock interaction) in an intimate coupling of diagenesis, basin evolution, and ore formation, and particularly to periods of active tectonics.

To illustrate the geological and metallogenetic ideas, Alberta examples of sub-Athabasca basement, paleoweathering, and Athabasca Group sediments will be presented. As well, the only example of unconformity-type uranium mineralization in Alberta (Maybelle) will be used to illustrate the uranium metallogenesis.



Uranium 101: Geochemistry and Uranium Deposit Metallogenesis

Dave Quirt
AREVA Resources Canada Inc.

Calgary Mining Forum April, 2006





Introduction and location

Uranium (geo)chemistry
basic chemistry and aqueous geochemistry

Athabasca geology
basement and sandstone

Unconformity-type uranium deposits
metallogenesis, fluids, sandstone mineralization, and basement mineralization

Summary





Uranium:

- discovered in 1789 by Martin Klaproth, a German chemist, in the mineral called pitchblende; also present in large amounts in accessory minerals such as thorite, zircon, fluorite, and monazite
- named after the recently-discovered planet Uranus
- the density of U (19.05) is 19 times greater than water, 1.7 times as dense as Pb (11.34), and nearly as dense as Au (19.30)
- found to be radioactive by French physicist Henri Becquerel in 1896
- occurs in most rocks in concentrations of 2 to 4 parts per million and is as common in the earth's crust as tin, tungsten, and molybdenum
- occurs in seawater and could be recovered from the oceans if prices rose significantly
- seldom sufficiently concentrated to be economically recoverable: a U orebody
- radioactive decay provides the main source of heat inside the earth, causing mantle convection and continental drift



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Summary

Periodic Table

Group 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Period 1 2 3 4 5 6 7

1 H 2 He

2 Li Be B C N O F Ne

3 Na Mg Al Si P S Cl Ar

4 K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr

5 Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe

6 Cs Ba * La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

7 Fr Ra ** Ac Th Pa U Pu Am Cm Bk Cf Es Fm Md No Lr

Uranium (U) is highlighted in red in the periodic table.

- Uranium, chemical symbol is U, is in the actinide series, which corresponds to the filling of the 5f electron orbital subshell
- the six valence electrons of uranium are $5f^6d^17s^2$
- the actinides have large atomic radii and so often have high coordination numbers.

Lanthanides 57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu

Actinides 89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr

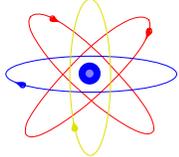
- atomic number (# of protons found in the nucleus of the atom) is 92
- melting point is 1132°C
- the uranium isotope U-235 is used as nuclear fuel and in nuclear weapons

Atomic properties

Crystal structure	orthorhombic
Oxidation states	4+, 6+ (weakly basic oxide)
Electronegativity	1.38 (Pauling scale)
Ionization energies	1st: 597.6 kJ/mol 2nd: 1420.0 kJ/mol
Atomic radius	1.75 Å
Van der Waals radius	1.86 Å
Covalent radius	1.42 Å
Melting point	1132°C
Density	19.07 g/cm ³
Atomic volume	12.59 cm ³ /mol

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- U has a large size and a high charge (+4 or +6), preventing it from entering crystal lattices of the major rock forming minerals, although they may contain U in lattice defects or adsorbed along crystal inhomogeneities and grain margins.
- It occurs in large amounts in accessory minerals such as thorite, zircon, monazite, and fluorite, and it typically is found as pitchblende (a form of uraninite): UO_2 .



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- U^{+4} is enriched in late-stage igneous differentiates - usually with K-orthosilicates and quartz, the last phases to solidify. So U contents are typically high in pegmatoids and leucosomes derived from partial melting → rock types common in high-grade metasedimentary assemblages (eg. Wollaston Domain). For example, U in accessory allanite in highly-evolved grey granites and K-spar porphyritic granites.



- U is typically low in high-grade metamorphic rocks, because it has moved out and upwards with any anatexic melts.

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Mafics and ultramafics	<1 ppm
Felsics (granites, pegmatoids)	10 – 100 ppm
Shales	3.5 ppm
Orthoquartzites (clean sst)	0.45 ppm
Monazite	500 – 20,000 ppm
Xenotime	300 – 35,000 ppm
Zircon	100 – 6,000 ppm

Out of 548 hydrothermal U occurrences in the USA, 83% occurred in or next to pre-Tertiary granites with > 5ppm U

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- U occurs in slightly differing forms called 'isotopes'. These isotopes differ from each other in the number of neutrons found in the nucleus. 'Natural' uranium as found in the earth's crust is a mixture of two main isotopes: uranium-238 (U-238 or ^{238}U): 99.3%, and U-235 (^{235}U): 0.7%

U-238: 92 protons, 146 neutrons
extra neutrons - heavier

U-235: 92 protons, 143 neutrons
lighter and more active

- U-235 is important because under certain conditions it can readily be split (said to be 'fissile'), which yields a lot of energy: thus the use of the expression 'nuclear fission'

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The Uranium atom

NUCLEUS
NEUTRONS (143 or 146) PROTONS (92)
ELECTRON (92 of these)

- on a scale based on increasing mass of their nuclei, uranium (U) is the heaviest of all the naturally-occurring elements
- the nucleus of the U-235 atom comprises 92 protons and 143 neutrons ($\Sigma = 235$)
- when the nucleus of a U-235 atom captures a neutron it splits in two (fissions), releasing some energy (heat) and two or three additional neutrons

- if enough of these expelled neutrons cause the nuclei of other U-235 atoms to split, releasing further neutrons, a fission 'chain reaction' of many millions of atomic splits can be achieved, producing a large amount of energy (heat) from a relatively small amount of uranium
- this process of 'burning' uranium in a nuclear reactor produces the heat used to make steam to produce electricity

CLINK!

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Radioactive Decay

- all radioactive isotopes decay, but both U-235 and U-238 decay very slowly (ie. low radioactivity)
- their half-lives are similar to the age of the earth (~4500 million years)
- radioactive decay generates ~0.1 watts/tonne energy - enough to warm the earth's core
- three decay mechanisms:
 - Alpha particle (^4He nucleus) emission - very low penetration depth
 - Beta particle (electron) emission - low penetration depth
 - Gamma radiation (high energy photon) - high penetration depth

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Units of Radioactivity and Decay Law

Becquerel (Bq) = 1 decay/sec
Curie (Ci) = 3.7×10^{10} Bq

Radioactive decay obeys first-order kinetics:

$$N = N_0 e^{-kt}$$

The **half-life** of a quantity of a radioactive substance is the time required for half of it to decay:

$$t_{1/2} = -\ln(0.5)/k \text{ or } \ln(2)/k$$

where k is a positive constant (the decay constant)

Alpha decay (α) is a form of radioactive decay in which an atomic nucleus ejects an alpha particle and transforms into a nucleus with mass number 4 less and atomic number 2 less. For example:

$${}_{92}^{238}\text{U} \rightarrow {}_{90}^{234}\text{Th} + {}_2^4\text{He}^{2+},$$

although this is usually written as:

$${}^{238}\text{U} \rightarrow {}^{234}\text{Th} + \alpha.$$

An alpha particle is a helium nucleus and both mass number and atomic number are conserved. Alpha decay can essentially be thought of as nuclear fission where the parent nucleus splits into two daughter nuclei.

Spontaneous fission (SF) is a form of radioactive decay characteristic of very heavy isotopes like the trans-actinide elements, such as rutherfordium.

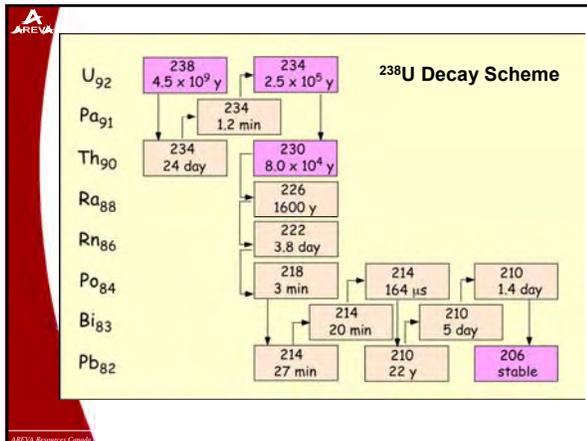
For uranium and thorium, the spontaneous fission mode of decay does occur and it follows the same process as nuclear fission, only it is not self-sustaining and does not generate the neutron flux necessary to "go critical" and continue such fissions. But spontaneous fissions release neutrons as all fissions do.

The spontaneous fission of uranium-238 leaves trails of damage in uranium-containing minerals as the fission fragments recoil through the crystal structure. These trails, or **fission tracks**, provide the basis for the fission track radiometric dating technique.

Spontaneous fission rates:
 U-235: 0.2 - 0.3 fissions/s-kg
 U-238: 7 fissions/s-kg

Notable isotopes

isotope	natural abundance	half-life	decay method	decay energy (MeV)	decay product
²³² U	synthetic	68.9 y	α & SF	5.414	²²⁸ Th
²³³ U	synthetic	159,200 y	SF & α	4.909	²²⁹ Th
²³⁴ U	0.006%	245,500 y	SF & α	4.859	²³⁰ Th
²³⁵ U	0.72%	7.038×10 ⁸ y	SF & α	4.679	²³¹ Th
²³⁶ U	synthetic	2.342×10 ⁷ y	SF & α	4.572	²³² Th
²³⁸ U	99.275%	4.468×10 ⁹ y	SF & α	4.270	²³⁴ Th



Oxidation state

The **oxidation state** is a measure of the degree of oxidation of an atom in a chemical compound and is the *hypothetical* charge that an atom would have if all bonds to atoms of different elements were 100% ionic. Oxidation states are associated with a sign (positive or negative) unless zero (metals).

An increase in oxidation state of an atom is called oxidation; a decrease in oxidation state is called reduction. Such reactions involve the transfer of electrons with a net gain in electrons being a reduction and a net loss of electrons being an oxidation.

The algebraic sum of oxidation states of all atoms in a neutral molecule must be zero, while in ions the algebraic sum of the oxidation states of the constituent atoms must be equal to the charge on the ion.

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The two common ionic/oxidation states of uranium found in nature are +4 and +6.

- 'Uranous' is the chemical term for the reduced uranium anion (U^{4+}) with +4 valence/oxidation state. Uranous compounds are relatively unstable as they tend to revert to the oxidised form on exposure to air (eg. uranium dioxide [UO_2]). Uranous minerals are relatively subdued in colour, typically brown or black, and occur in reducing environments (uraninite and pitchblende [UO_2], and coffinite [$U(SiO_4)$]).
- 'Uranyl' is the term for the oxidised uranium anion (U^{6+}) with +6 valence/oxidation state. Solid uranyl compounds are often colored red, yellow, orange, or green (autunite [$Ca(UO_2)_2(PO_4)_2 \cdot 8H_2O$] and uranophane [$Ca(UO_2)_2(SiO_3)(OH)_2 \cdot 5H_2O$]).
- The U^{6+} uranyl ion is the most common species encountered in the aqueous chemistry of uranium. The solvated U^{4+} ion is normally not present in water.

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Summary

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- uranium is a lithophile element with a high affinity to oxygen
- in most subsurface conditions, uranium occurs as U^{4+} , while U^{6+} is stable only under near-surface oxidizing conditions

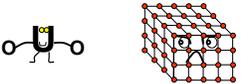
the uranyl complex ($= UO_2^{2+}$) develops in an aqueous solution

$$U^{4+} + 2H_2O \rightleftharpoons (U^{6+}O_2)^{2+} + 4H^+ + 2e^-$$

(solid) (dissolved)

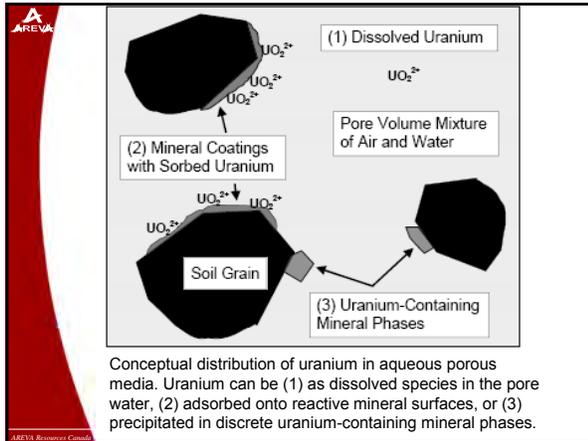
↓

this complex has a linear dumbbell-shaped structure that is difficult to fit into other crystal structures

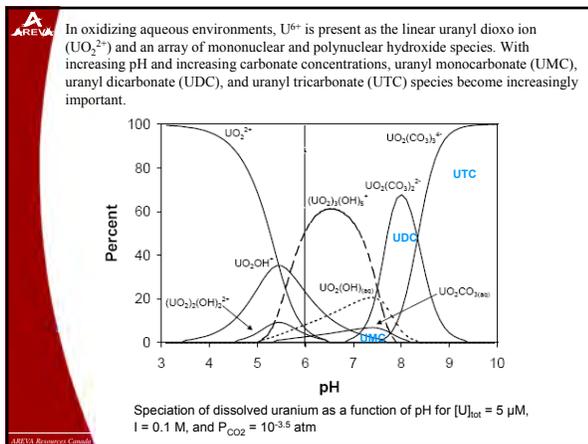


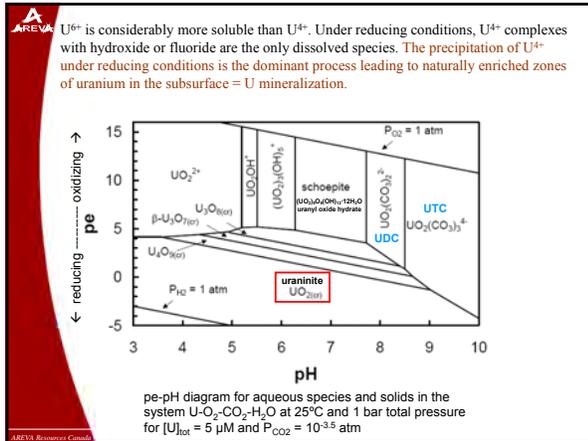
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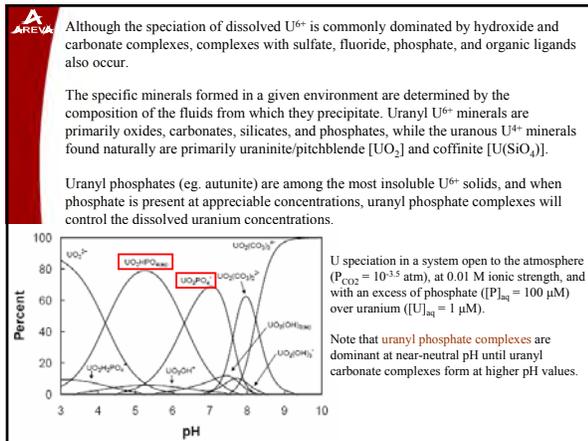
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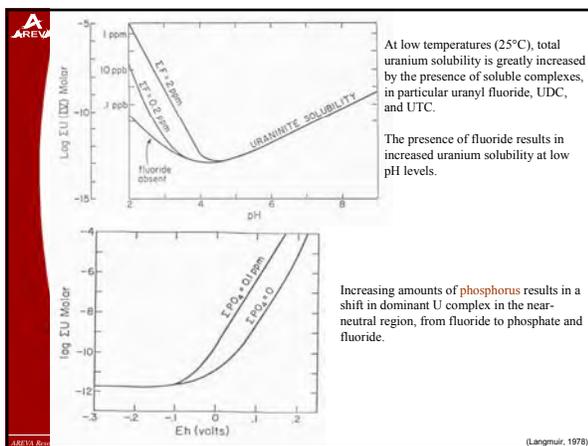


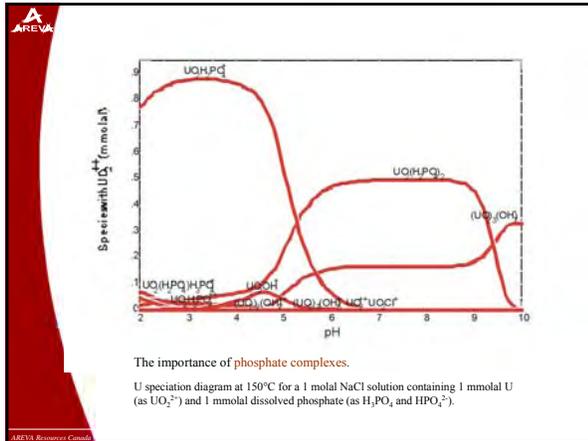
- In aqueous solution, uranium can exist in oxidation states of +3, +4, +5, and +6, but under most environmental conditions only the +4 and +6 states are stable.
 - U in the +6 oxidation state is relatively soluble and can be detected in almost any natural water. Seawater is the largest reservoir of dissolved uranium and contains uranium at a highly uniform value of 3.3 ppb ($\mu\text{g/L}$). The concentration of uranium in groundwater is usually in the range 0.1 to 50 ppb. The weathering of uranium-bearing rocks and minerals is the primary source of dissolved uranium in groundwaters.
 - Uranium solubility in aqueous systems is predominantly controlled by three factors:
 1. oxidation-reduction potential (Eh), pE (-log of the activity of the electron), etc.
 2. pH (-log of the activity of hydrogen ion)
 3. dissolved anions (carbonate, phosphate, fluoride, hydroxyl)
- (only in dilute solutions is the activity coefficient unity: activity = concentration)

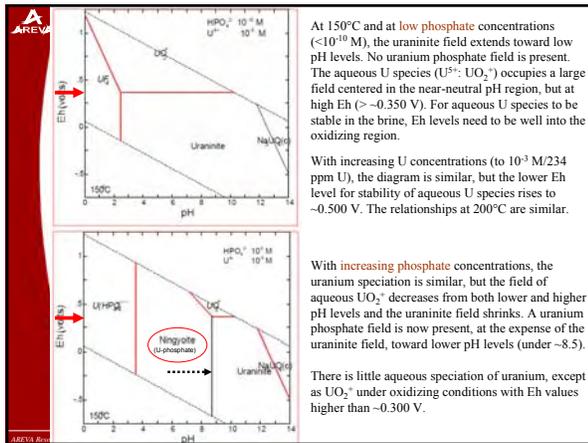


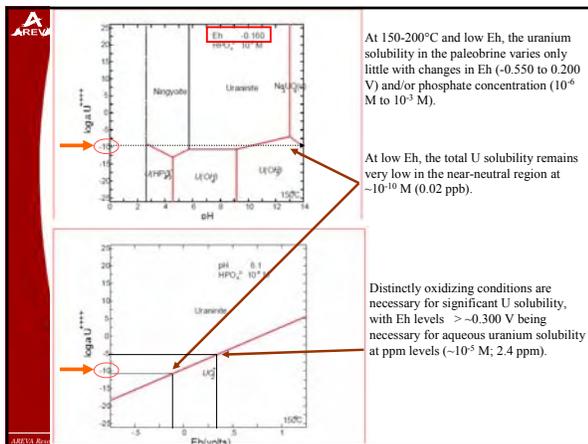


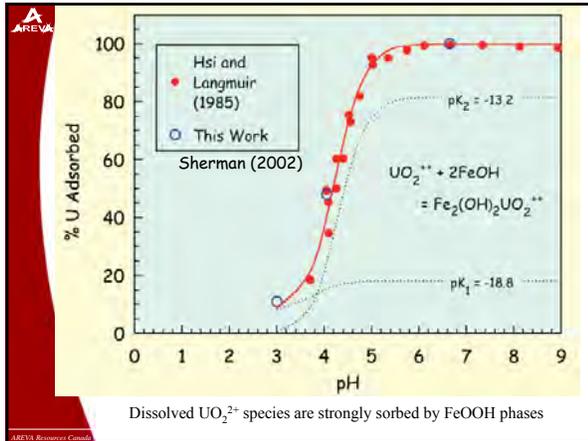












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metallogenesis, fluids, sandstone mineralization, and basement mineralization

Summary

Basement Geology

(Retrograde) metamorphic assemblages

- paragneiss: pelitic to psammitic gneisses to calc-silicate gneisses to metaquartzite
Quartz, feldspar (plagioclase/K-feldspar), biotite, cordierite, sillimanite, garnet, tourmaline, pyrite, and graphite; accessory zircon, apatite, monazite, ilmenite, chalcopyrite, sphalerite; retrograde Fe-Mg chlorite, muscovite, sericite/saussurite, titanite, rutile
- orthogneiss: tonalite to granodiorite to granite to leucogranite
Plagioclase, K-feldspar, quartz and biotite; lesser amphibole, magnetite, apatite; wide variety of minor accessory minerals (zircon, monazite, pyrite, ilmenite, titanite, allanite ...); retrograde chlorite, sericite/saussurite, hematite, and locally epidote, muscovite, carbonates, and monazite

Example: Wollaston Group; Wollaston Domain

- Wollaston Group metasediments: pelitic to calc-pelitic to psammopelitic to psammitic to metaquartzite ...
- Graphitic pelitic gneiss: structurally, mineralogically, chemically important to metallogenetic model
- Mega-strike-slip orogenic belt (Domain)
- Wollaston-Mudjatik Domain Boundary: close spatial association with mineralization

Overprints:

- Paleoweathering
Hematite, kaolinite, illite, and aluminous sudoitic chlorite at the expense of the metamorphic minerals
- Diagenetic-hydrothermal alteration
Typically reducing (lack of hematite), magnesian and potassic (chloritization/illitization); graphite destruction; tourmalinization locally important

The Paleoweathering profile

- Originally clay-rich kaolinite + goethite; now well-recrystallized kaolinite + hematite grading down to +/- illite +/- sudoite +/- hematite
→ an aquitard
- Variable thickness of colour and mineralogical zoning depending on basement lithology and fracturing
- Re-equilibrated during prograde diagenesis
- Basin-wide redox boundary at bottom of red-green zone, not at unconformity
- Locally diagenetic-hydrothermally altered: illitization, chloritization, bleaching

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- Only minor depletions of trace elements are typically found in paleoweathered zones beneath the white zone
- Paleoweathered material is clay-altered such that plagioclase is not present (sodium-depletion: <0.10% Na₂O and the S content is low (<0.10% S), due to oxidation of original sulphide (pyrite)
- Magnesium content increases with depth, due to the increasing abundance of chlorite - sudoite or, in the green zone, Fe-Mg chlorite
- The depth-related colour zones (white, red, red-green, and green) are a result of iron oxidation/reduction. At least initial reddening of green zone paleoweathered material is solely a function of iron addition (as hematite) to the rock
- Red-zone material gives stable isotope data consistent with re-equilibration under peak diagenetic conditions
- Clay mineralogy also displays a well defined zonation with depth, parallel to the colour zonation

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Unconformity

- Major lithological separator
- Major fluid separator
- Intersection of unconformity with sub-Athabasca structures important for localization of mineralization processes
- Not ultimate peneplane: significant relief, some pre-Athabasca, some post-Athabasca; important consideration in modelling Athabasca fluid flow

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Introduction and location

Uranium (geo)chemistry
basic chemistry and aqueous geochemistry

Athabasca geology
basement and sandstone

Unconformity-type uranium deposits
metallogenesis, fluids, sandstone mineralization, and basement mineralization

Summary

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Athabasca Group

- Three major fining-upward clastic to marine/lacustrine successions (FP, MF → WP, LL → DG/CW)
- Eastern Athabasca contains Manitou Falls orthoquartzitic sandstone with minor basal conglomerates
- Western Athabasca contains Fair Point clay-rich, coarse-grained, orthoquartzitic sandstone
- Cut by Mackenzie Swarm diabase sills/dikes
- Composed of dominant detrital quartz with minor matrix clay +/- hematite and crandallite-group phosphate, trace detrital zircon, tourmaline, and Fe-Ti oxides
- Original matrix clay assemblage was kaolinite-dominant

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Detrital and diagenetic minerals

- The dominant detrital mineral phase is quartz; minor detrital phases are kaolinitic clay with traces of hematite and anatase/rutile (after Fe-Ti oxides), mica, zircon, and tourmaline
- The dominant neofomed or recrystallized diagenetic mineral phases are the clay minerals (kaolinite and dickite, illite, and sudoite chlorite) and hematite
- Current background matrix clay assemblage is prograde-diagenetic: dickite (± relict kaolinite) with lesser 1Mc illite
- Trace accessory minerals include authigenic crandallite-group phosphate (goyazitic) and dravitic overgrowths on detrital tourmaline. Locally present are siderite, pyrite, and apatite

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Diagenesis

- Nearly all of the current matrix minerals are alterations of detrital precursors or are authigenic
- The primary mineralogical features related to prograde burial diagenetic and retrograde diagenetic alteration of the Athabasca sandstone are:
 - (1) precipitation of Q1 quartz overgrowths,
 - (2) iron (re)mobilization (hematization and 'bleaching'),
 - (3) clay mineral transformations and conversions (kaolinite → dickite; kaolin → 1Mc illite) and neofomations (sudoite just above the u/c; retrograde kaolinite)
- Onset of 'peak' diagenesis was likely between 1650-1550 Ma
- Other authigenic minerals include crandallite-group phosphate (goyazite) and anatase

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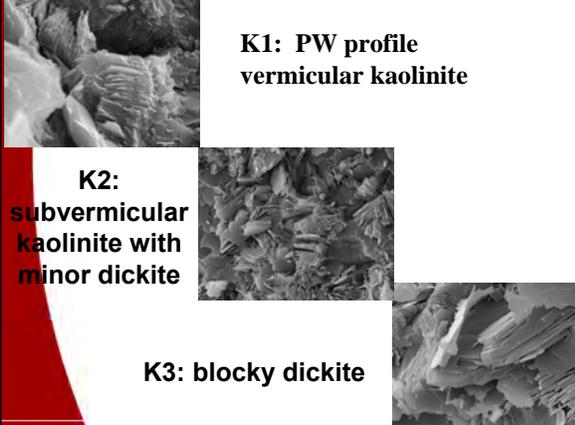
Diagenetic mineral reactions

$\text{SiO}_{2(aq)} \rightarrow \text{Quartz}$ (quartz overgrowths)

$2\text{Goethite} \rightarrow \text{Hematite} + \text{H}_2\text{O}$ (specular hematite)

$1.14\text{Kaolinite} + 1.23\text{Quartz} + 0.81\text{K}^+ + 0.11\text{Mg}^{2+} + 0.08\text{Fe}^{2+} \rightarrow \text{Illite} + 1.19\text{H}^+ + 0.68\text{H}_2\text{O}$ (illitization)

(note that the reaction for illitization of kaolin(ite) consumes silica)



**K1: PW profile
vermicular kaolinite**

**K2:
subvermicular
kaolinite with
minor dickite**

K3: blocky dickite

Introduction and location

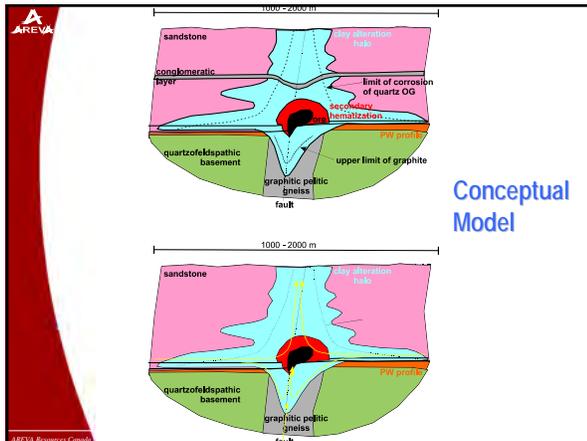
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- The diagenetic-hydrothermal model relates uranium mineralization to Athabasca Group diagenetic processes and attributes the spatial association of deposits with the sub-Athabasca unconformity to movement and interaction of diagenetic brines with basement-equilibrated fluids.
 - The model attributes the origin of the deposits to fluid interaction between oxidized Athabasca basinal brines and variably reduced basement fluids (basement-sandstone interaction) in an intimate coupling of diagenesis, basin evolution, and ore formation, particularly to periods of active tectonics.
 - Geological relationships suggest that diagenetic-hydrothermal systems of basement-sandstone interaction developed in many structurally-controlled locations along traces of graphitic basement rocks subcropping at the unconformity. Significant ore precipitated only where local hydrodynamic conditions were conducive to the formation of a stationary redox front.



- AREVA Resources Canada
- Basement lithology and structure played a major role in the formation and location of the uranium deposits:
 - (1) the location of brittle faulting (brecciation/gouge) tends to be focused at/near contacts of lithologies of greater competency with rocks of lesser competency (rheology contrasts),
 - (2) the formation/preservation of reduced fluids is favoured by the presence of graphitic, Fe²⁺-bearing lithologies,
 - (3) ore constituent-enriched (U, S, As, base metals) basement lithologies may have provided sources for some ore constituents to either reduced or oxidized basement fluids,
 - (4) some lithologies weathered less than others, resulting in a distinct paleotopography which influenced the direction(s) of basal Athabasca aquifer flow along the unconformity.

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- The source of ore metals in the unconformity-type deposits is still a contentious issue. Although chemical contributions by both sandstone and basement form a fundamental aspect of the diagenetic-hydrothermal concept of basement-sandstone interaction, the basement and sandstone played significantly different roles as suppliers of ore constituents.
- Available evidence suggests that the constituents of the Athabasca unconformity-type uranium deposits were derived from **both** sandstone and basement sources. The relative proportions of constituent input are unknown at this time, especially for U. Some constituents were most likely basement-derived (K, Mg, Fe²⁺, B, As, S, base metals, HREE) and some were most likely sandstone-derived (LREE, Sr, Ti, V).

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Sandstone: alteration

- Diagenetic-hydrothermal alteration involves clay mineral conversion/neoformation (illite and/or chlorite), bleaching and desilicification (hematite, quartz removal), and local neoformation of tourmaline, siderite, and pyrite.
- Cigar Lake alteration is bleached, desilicified, illitized (2M₁ and 1Mt (3T)) with lesser chloritization (sudoite) and local minor pyrite and/or siderite. The ore zone is highly desilicified with zircon alteration, has an inner hematite-free region and an outer hematite cap, and contains Fe-chlorite and Fe-Mg chlorite with sudoite and much lesser illite, trace apatite and Fe- and V- bearing clays. Remobilized mineralization ("perched" zones) is associated with kaolinite and hematite/goethite.
- McArthur River fracture-associated alteration is superimposed on early Q2 pervasive silicification and is illitized and chloritized, and locally tourmalinized; late(?) kaolinitization.

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Sandstone

- Diagenetic-hydrothermal alteration
 - $2\text{Mg}^{2+} + 3.5\text{kaolinite} + 3\text{B(OH)}^+ \rightarrow \text{dravite} + \text{SiO}_2(\text{aq}) + 5\text{H}_2\text{O} + 2.75\text{O}_2(\text{aq})$ (tourmalinization)
 - quartz $\rightarrow \text{SiO}_2(\text{aq})$ (desilicification)
 - hematite $+ 6\text{H}^+ + 2\text{e}^- \rightarrow 3\text{H}_2\text{O} + 2\text{Fe}^{2+}$ (bleaching)
 - $1.14\text{kaolinite} + 1.23\text{quartz} + 0.81\text{K}^+ + 0.11\text{Mg}^{2+} + 0.08\text{Fe}^{2+} \rightarrow \text{illite} + 1.19\text{H}^+ + 0.68\text{H}_2\text{O}$ (illitization)
 - kaolinite + quartz + 7H₂O + 5Mg²⁺ → clinocllore + 10H⁺ (chloritization)
 - illite + 8.62H₂O + 5.57Mg²⁺ → 1.14clinocllore + 0.10quartz + 10.16H⁺ + 0.81K⁺ + 0.08Fe²⁺ (chloritization)

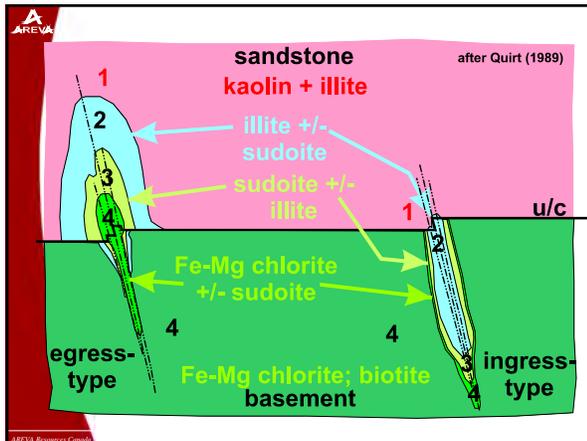
Note that the reactions for illitization and chloritization of kaolin(ite) consume silica. Depending on the chlorite mineral chemistry used (ie. sudoite versus clinocllore), chloritization of illite may also consume silica.

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Ore Parageneses

Simplistically, the U deposits can be subdivided into:

1. those formed dominantly through **fluid – fluid** interactions:
sandstone ore
- and
2. those formed dominantly through **fluid – rock** interactions:
basement ore



Host-rock alteration

- The pattern of alteration mineral zonation of 'ingress-type' deposits is the same as for 'egress-type' deposits, but in a reversed setting. In both settings, the broad zonation patterns are:
 - (1) basement-related Fe-Mg trioctahedral chlorite (± sudoite)
 - (2) sudoite ± 1Mt illite
 - (3) 1Mt illite ± sudoite (± kaolin)
 - (4) background sandstone kaolin + 1Mc illite
- In the 'egress-type' deposits, alteration zones (1), (2), and (3) extend into the sandstone, while in the 'ingress-type' deposits, alteration zones (3) and (2) extend into the basement fault system.

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Transport mechanisms for metals in fluids

- Most recent literature sources agree that highly saline, oxidized, moderately high-temperature brines are suitable for much elemental transport.
- Oxidized groundwater is the most likely fluid medium for transport of redox-sensitive elements like As, Cu, Ni, Se, V, and Mo which are soluble (along with uranium as U^{6+}) as oxyanions.
- These elements tend to precipitate as insoluble minerals, approximately along with uranium (as a U^{4+} mineral: pitchblende/uraninite), for example in the reduced waters present around roll-front or other sedimentary uranium deposits.
- Transport of U and base metals (Cu, Ni, As, etc.) has similarly been attributed to hydroxide, chloride, fluoride, phosphate, and carbonate complexes in oxidized brines.

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Fluid – fluid interactions

- near-massive, high-grade core at the unconformity, surrounded by lower-grade, more dispersed, fracture-controlled mineralization in sandstone (and sometimes basement)
- ore - near-massive pitchblende/uraninite and Ni-Co-arsenides
 - often forming dendritic and nodular aggregates in a laminated or structureless clay matrix (illite and sudoite)
- pitchblende/uraninite - at least three distinct generations
- paragenetic succession parallels a spatial zonation with early, high-grade, arsenide-rich ore at the unconformity being surrounded by later, lower-grade, sulphide-dominated ore in sandstone as As and Ni activities decreased

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- diagenetic-hydrothermal systems of basement-sandstone interaction developed in many structurally-controlled locations along traces of graphitic basement rocks subcropping at the unconformity
- fluid interaction between (mixing of) oxidized Athabasca basinal brines and variably reduced basement fluids occurred during diagenesis and basin evolution (diagenetic-hydrothermal basement-sandstone interaction)
- significant ore precipitated only where local hydrodynamic conditions were suitable for formation of a stationary redox front where the dominant mineralization feature was co-precipitation of pitchblende/uraninite with hematite, likely resulting from coupled oxidation-reduction reactions \rightarrow the Fe-U redox couple:

$$2Fe^{2+} + U^{6+} + 4H_2O + 0.5O_2(aq) \rightarrow \text{hematite} + \text{uraninite} + 8H^+$$

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- dominant mineralization-related components are uraninite/pitchblende and hematite with widely varying amounts of arsenide and sulfarsenide minerals (skutterudite, rammelsbergite, lollingite, niccolite, maucherite, gersdorffite, cobaltite) and minor sulphides (pyrite, chalcopyrite, sphalerite, galena, molybdenite)
- many other minerals are present in trace to minor quantities, including phosphates (xenotime, apatite, and complex Ca-Sr-Al-Th-LREE phosphate) and coffinite

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Fluid – rock interactions

- the strongly dominant basement mineralization-related components are pitchblende/uraninite and hematite
- the Fe-U redox couple as a uranium mineralization process also is important in fluid-rock interactions:
 - biotite, chlorite, pyrite, and amphibole,(etc.) are:
 - relatively ferrous iron-rich
 - commonly-found wall-rock minerals
 - providers of ferrous iron for hydrothermal reaction purposes
 - in the presence of ferrous iron in the wall-rock adjacent to ore fluid pathways, coupled oxidation-reduction reactions can occur, resulting in the overall Fe-U redox couple forming uraninite/pitchblende and hematite:

$$2\text{Fe}^{2+} + \text{U}^{6+} + 4\text{H}_2\text{O} + 0.5\text{O}_2(\text{aq}) \rightarrow \text{hematite} + \text{uraninite} + 8\text{H}^+$$

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Sandstone and Basement

- Mineralization reactions

The dominant mineralization feature is co-precipitation of pitchblende/uraninite with hematite

$$2\text{Fe}^{2+} + \text{U}^{6+} + 4\text{H}_2\text{O} + 0.5\text{O}_2(\text{aq}) \rightarrow \text{hematite} + \text{uraninite} + 8\text{H}^+$$

Arsenides/Sulfarsenides

$$0.5\text{Co}^{3+} + 0.5\text{Ni}^{2+} + 3\text{As}(\text{OH})_3 \rightarrow \text{skutterudite} + 3(\text{OH})^-$$

$$\text{Ni}^{2+} + 2\text{HAsO}_4^{2-} \rightarrow \text{rammelsbergite} + \text{H}_2\text{O} + 1.5\text{O}_2(\text{aq})$$

$$\text{Ni}^{2+} + \text{Fe}^{2+} + \text{HAsS}_2 \rightarrow \text{niccolite} + \text{pyrite} + \text{H}^+$$

$$2\text{Ni}^{2+} + \text{Fe}^{2+} + 2\text{HAsS}_2 \rightarrow 2\text{gersdorffite} + \text{pyrite} + 2\text{H}^+$$

$$0.7\text{Co}^{2+} + 0.3\text{Ni}^{2+} + \text{HAsS}_2 \rightarrow \text{cobaltite} + \text{HS}^-$$

Sulphides

$$\text{Fe}^{2+} + 2\text{HS}^- + 0.5\text{O}_2(\text{aq}) \rightarrow \text{pyrite} + \text{H}_2\text{O}$$

$$\text{Fe}^{2+} + \text{Cu}^{2+} + 2\text{HS}^- \rightarrow \text{chalcopyrite} + 2\text{H}^+$$

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Mineral precipitation

- For precipitation of U, Fe oxides, Ni-Co arsenides, Cu-Fe sulphides) one or more processes of mineral formation must occur: (a) boiling, (b) cooling, (c) dilution, and (d) reduction.
 - Boiling of a hydrothermal fluid typically results from a change in confining pressure from lithostatic to hydrostatic. This process tends to enrich the fluid in metals and complexing ligands which can result in supersaturation conditions and subsequent mineral precipitations.
 - Cooling of a hydrothermal fluid changes the solubility of the complexes held in the fluid. For example, a decline in temperature is sufficient to precipitate quartz and to destabilize some carbonate and hydroxyl complexes.
 - Dilution, like cooling, can augment precipitation through destabilization of soluble complexes.

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Mineral precipitation - reduction

- Reduction of components in a hydrothermal fluid results from an encounter with reducing agents, for example carbonaceous, sulphidic, or ferrous materials in the wall-rock, or mixing with a more reduced second fluid. The reduced species of a number of elements (eg. U, Cu, Ni, Co, As) are relatively insoluble relative to the equivalent oxidized species, so reduction can be a major contributor to ore deposition. Colloform and dendritic textures of early pitchblende and Ni-arsenide minerals from many of the deposit types examined in this report suggest that supersaturation and rapid crystal growth occurred.
- The environments of formation of many of the minerals under consideration appear to be controlled by the electron potential (Eh). While acid-base, substitution, and redox reactions may all take place, the mineral precipitation processes can be mostly attributable to redox-controlled reactions. In the redox-controlled precipitation process, the amounts of mineral precipitated are related to initial aqueous metal ion concentration and to the duration of the mineralizing event.

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Mineral precipitation – Cu reduction

- Cu minerals are commonly present in Ingress-type deposits, intimately associated with pitchblende**
- formation of native copper can occur through reduction of ionic copper by ferrous iron (Fe-Cu redox couple):

$$\text{Cu}^{2+} + 2\text{Fe}^{+2} \rightarrow \text{Cu}^0 \text{ (native copper)} + 2\text{Fe}^{+3}$$
- Cu sulphide minerals like chalcopyrite can form through:
 - replacement (substitution) of iron by copper in pyrite:

$$2\text{FeS}_2 \text{ (pyrite)} + \text{Cu}^{2+} \rightarrow \text{CuFeS}_2 \text{ (chalcopyrite)} + \text{Fe}^{+2}$$
 - precipitation from solution:

$$\text{Cu}^{2+} + \text{Fe}^{+2} + 2\text{HS}^- \rightarrow \text{CuFeS}_2 \text{ (chalcopyrite)} + 2\text{H}^+$$
- higher-Cu sulphide minerals (eg. bornite, covellite, chalcocite) form through replacement (substitution) of Fe by Cu in lower-Cu sulphides (eg. chalcopyrite, pyrite) and by redox reactions:

$$\text{CuFeS}_2 \text{ (chalcopyrite)} + \text{Cu}^{2+} \rightarrow 2\text{CuS} \text{ (covellite)} + \text{Fe}^{+2}$$
- minor amounts of Ni arsenide occur later in the paragenesis

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Fe-U-Cu-Au redox relationship

- The Fe-U redox couple as a uranium mineralization process. Biotite, chlorite, pyrite, and amphibole, etc., are relatively ferrous iron-rich and are commonly-found wall-rock minerals, and can provide ferrous iron for hydrothermal reaction purposes. In the presence of ferrous iron in the wall-rock adjacent to ore fluid pathways, a pair of coupled oxidation-reduction reactions can occur, resulting in the overall reaction forming uraninite/pitchblende and hematite:

$$2\text{Fe}^{2+} + \text{U}^{6+} + 4\text{H}_2\text{O} + 0.5\text{O}_2(\text{aq}) \rightarrow \text{hematite} + \text{uraninite} + 8\text{H}^+$$
- In a manner analogous to the Fe-U redox couple, formation of native copper and gold through reduction of ionic copper/gold by ferrous iron (Fe-Cu and Fe-Au redox couples) can also occur:

$$\text{Cu}^{2+} + 2\text{Fe}^{+2} \rightarrow \text{Cu}^0 (\text{native copper}) + 2\text{Fe}^{+3}$$
- Native copper and gold is only commonly present in a few of the deposits (eg. Eagle Point), but copper sulphide minerals are ubiquitous. Chalcopyrite can form through replacement (substitution) of iron by copper in pyrite:

$$2\text{FeS}_2 (\text{pyrite}) + \text{Cu}^{2+} \rightarrow \text{CuFeS}_2 (\text{chalcopyrite}) + \text{Fe}^{2+}$$
 although it can also precipitate directly from solution:

$$\text{Cu}^{2+} + \text{Fe}^{+2} + 2\text{HS}^- \rightarrow \text{CuFeS}_2 (\text{chalcopyrite}) + 2\text{H}^+$$

More Fe-U-Cu redox

- The base metal mineralization in the unconformity-type U deposits have a mineral progression and copper enrichment zonation that follows Schurmann's electromotive series.
- This electromotive series is a list of metals whose order indicates the relative tendency of the metals to be oxidized, or to give up electrons. The electromotive series begins with the metal most easily oxidized, i.e., the metal with the greatest electron-donating tendency, and ends with the metal least easily oxidized.
- Formation of higher-copper sulphide minerals (eg. bornite, covellite, chalcocite) can proceed through replacement (substitution) of iron by copper in lower-copper sulphides (eg. chalcopyrite, pyrite) and by redox reactions:

$$\text{CuFeS}_2 (\text{chalcopyrite}) + \text{Cu}^{2+} \rightarrow 2\text{CuS} (\text{covellite}) + \text{Fe}^{2+}$$

$$\text{CuFeS}_2 (\text{chalcopyrite}) + \text{Cu}^{2+} + 4\text{H}_2\text{O} \rightarrow \text{Cu}_2\text{S} (\text{chalcocite}) + \text{Fe}^{2+} + \text{SO}_4^{2-} + 8\text{H}^+ + 6\text{e}^-$$

$$\text{CuS} (\text{covellite}) + \text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}_2\text{S} (\text{chalcocite})$$

Sulphidation state

- The sulphidation state of a geochemical system describes the relative values of the chemical potential of sulfur implied by the sulfide mineral assemblages. Typically, the sulphidation state in base-metal veins will increase as unbuffered hydrothermal solutions evolve from high to low temperatures.
- The defining features of high-sulphidation ore deposits include the presence of 'high sulphidation-state' hypogene pyrite-rich sulphide assemblages containing, for example, enargite [Cu_3AsS_4], bornite [Cu_5FeS_4], digenite [Cu_9S_8], chalcopyrite [CuFeS_2], chalcocite [Cu_2S], and covellite [CuS] (eg. Sillitoe, 2000), commonly present as partial replacements of pyrite.

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- The presence of arsenides and sulpharsenides in an ore mineral assemblage indicates that the assemblage is characterized by a 'low sulphidation-state' during deposition. For example, deposition of niccolite [NiAs], rammelsbergite [(Ni,Co)As₂], loellingite [(Fe,Ni)As₂], gersdorffite [NiAsS], arsenopyrite [FeAsS].
- The concept of increasing sulphidation state with evolution of the hydrothermal fluids from higher to relatively lower temperatures may explain the arsenide through sulpharsenide to sulphide mineral parageneses.

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1. the oxidizing basinal fluid

A fluid composition was calculated for the Athabasca Group paleobrine using data from earlier workers, from sea water, and from somewhat analogous brines, such as from the Red Sea.

species	molality	species	molality
Na ⁺	3.98	Cl ⁻	4.91
K ⁺	0.36	Br ⁻	0.04
Ca ²⁺	0.22	F ⁻	0.0003
Mg ²⁺	0.11	SO ₄ ²⁻	0.01
Fe ²⁺	0.0001	HPO ₄ ²⁻	0.001
		HCO ₃ ⁻	0.002

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2. the reduced basement fluid

An estimate of the chemical conditions of 'typical' egress-type ore formation can be made from the observed mineral assemblages, alteration features, and thermodynamic data, as summarized in the log f_{O_2} -pH diagram.

At the point of discharge from the basement, the composition of the emerging basement fluid was approximately at **point A**, as basement host rock alteration is characterized by **illitization, chloritization, graphite destruction, and hydrocarbon formation.**

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Fluid equilibria: clay mineralogy

Temperature change has relatively little effect on the location of the mineral stability fields.

But change in K^+ activity has a more dramatic effect.

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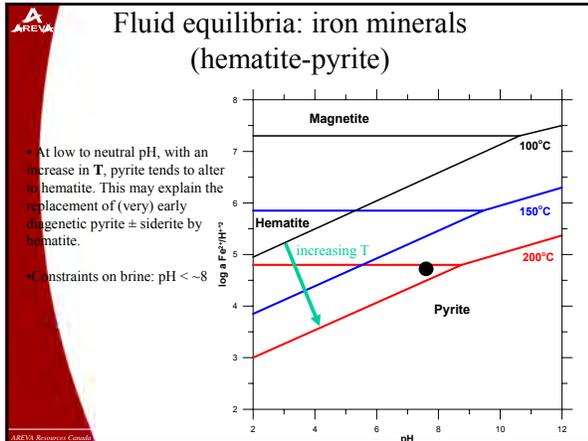
Formation of illite is favored by increasing activity of K^+ .

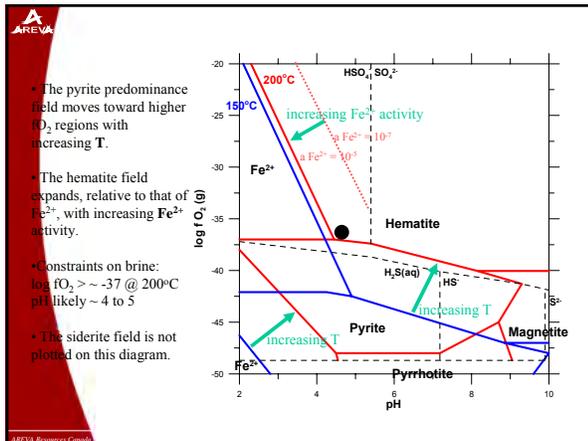
Formation of chlorite is favored by increasing activity of Mg^{2+} or increasing T, or both.

Constraints on brine:
 $\log a K^+/H^+ \sim 2.2$
 $\log a Mg^{2+}/H^+ < \sim 7$
 increasing Mg^{2+}

K + I stable @ 150°C
but
I + C stable @ 200°C

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Geochemical Reactions

- Conditions of alterations:
 - Paleoweathering - 25C, 1 Bar
 - Early diagenesis - 100-150C, 10-200 Bar
 - Peak diagenesis - 200C, 1 KBar
 - Host-rock alteration - 200C, 1 KBar
 - Mineralization - 200C, 1 KBar
 - Retrograde diagenesis - 50C, 500 Bar



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Sandstone host-rock alteration

Host-rock alteration associated with egress-type unconformity-type uranium deposits in the Athabasca Basin affects the overlying sandstones, basement rocks, and the paleoweathering profile:

- (1) clay mineral alteration (illitization, chloritization, kaolinitization)
- (2) loss of rock coherence (quartz dissolution); formation by volume loss of a clay mineral 'cap'
- (3) formation of a shell of secondary hematitization around high-grade ore at the unconformity
- (4) bleaching/hematitization phenomena
- (5) local development of a zone of olive-green chloritic alteration spatially associated with the shell of secondary hematitization
- (6) local tourmalinization and carbonatization





- Diagenetic-hydrothermal alteration: clay mineral conversion/ neof ormation (illite and/or chlorite), bleaching and desilicification (hematite, quartz removal), and local neof ormation of tourmaline, siderite, and pyrite
- Cigar Lake alteration is bleached, desilicified, illitized (2M₁ and 1M₁) with lesser chloritization (sudoite) and local minor pyrite and/or siderite. The ore zone is highly desilicified with zircon alteration, has an inner hematite-free region and an outer hematite cap, and contains Fe-chlorite and Fe-Mg chlorite with sudoite and much lesser illite, trace apatite and Fe- and V-bearing clays. Remobilized mineralization ('perched' zones) is associated with kaolinite and hematite/goethite
- McArthur River fracture-associated alteration is superimposed on early Q2 pervasive silicification and is illitized and chloritized, and locally tourmalinized; late(?) kaolinitization



Silicification

- Pervasive silicification (Q2) and fracture silicification (Q3)
- Pervasive silicification: 'silica flooding'; where quartz precipitation has overgrown and/or replaced much, if not all, of the earlier clay mineral matrix as at McArthur where Q2 silicification is likely related to underlying basement lithologies and fluid movements out of fault structures
- Fracture-related silicification: euhedral quartz crystals forming within brittle fractures, locally present in fracture/breccia zones in the sandstone, but most commonly found in the (distal) alteration halo around unconformity-type uranium deposits such as at Cigar Lake
- Silicification - both Q2 and Q3 - is interpreted as being a consequence of relatively nearby quartz dissolution elsewhere in the sandstone column or in the basement

Clay signatures of egress-type deposits

- There are two main variations of clay signatures around deposits:
 - pre-mineralization silicification (McArthur River)
 - syn-mineralization clay alteration and desilicification (Cigar Lake) (also McArthur River)

McArthur River

Cigar Lake

modified after Thomas et al (1998)

after Derome and Cuney (2000)

silicification

- abundant overgrowths
- very little clay matrix

desilicification

- corroded quartz grains; no overgrowths
- abundant clay matrix – significant residual enrichment and neof ormation

Tourmalinization

- Weak diagenetic tourmalinization of the sandstone matrix by neoformation of dravite (Mg-Al tourmaline) is often observed in Athabasca Group sandstone as wispy tufts of radiating needles originating from surface defects on detrital quartz grains and as oriented overgrowths on detrital tourmaline grains
- Strongly dravitized sandstone matrix, due to basement-sandstone diagenetic-hydrothermal interaction, contains abundant, randomly oriented, acicular dravite needles, fans, and rosettes which can comprise nearly all of the matrix
- Coincident brecciation, Q3 silicification, and dravitization suggest a correlation with tectonism (brecciation/faulting, fracturing)

Mineralization

- 'Egress'-type ore bodies consist of a near-massive, high-grade core at the unconformity, surrounded by lower-grade, more dispersed, fracture-controlled mineralization in sandstone and generally minor amounts in the basement
- The ore consists of near-massive pitchblende/uraninite and Ni-Co-arsenides, often forming dendritic and nodular aggregates in a laminated/structureless clay matrix of illite and di,triocahedral chlorite (sudoite)
- Pitchblende/uraninite is generally present in at least three distinct generations and the As and Ni activities decreased throughout the paragenetic succession
- The paragenetic succession is parallel to a crude spatial zonation with early, high-grade, arsenide-rich ore at the unconformity is surrounded by later, lower-grade, sulphide-dominated ore in the sandstone

Key Lake

- uraninite (pitchblende, sooty pitchblende/coffinite)
- di-arsenides (rammelsbergite)
- mono-arsenides (niccolite, maucherite)
- sulpharsenides (gersdorffite)
- sulphides (millerite, pyrite, galena)

- decreasing As activity and increasing Co and S activities with time (and with local reversals with decrease in S activity)

All egress-type mineralizations show similar parageneses

→ repetitive and pulsatory mineral phases reflecting distinctive conditions of element transport and deposition

Introduction and location

Uranium (geo)chemistry
basic chemistry and aqueous geochemistry

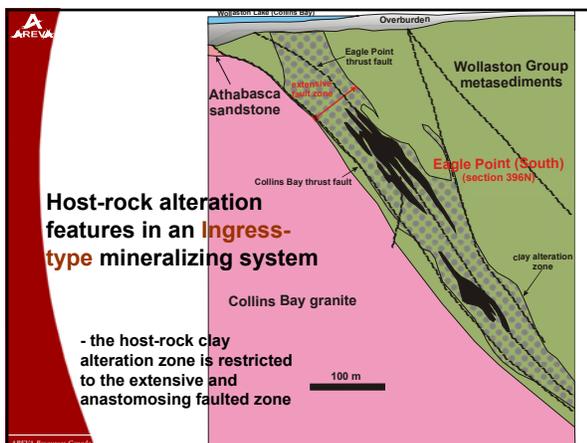
Athabasca geology
basement and sandstone

Unconformity-type uranium deposits
metallogenesis, fluids, sandstone mineralization, and basement mineralization

Summary

Host-rock alteration

- In the sub-Athabasca basement, host-rock alteration is demonstrated by extensive clay mineral alteration (chloritization, illitization) of original retrograde metamorphic and/or paleoweathering-related minerals, conversion of clay mineral species, and 'bleaching' by destruction of hematite and ferromagnesian minerals
- Destruction of basement graphite and formation of solid hydrocarbon beads ('buttons') in altered basement rocks has been recognized in most deposits in the basin



Introduction and location

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basement and sandstone

Unconformity-type uranium deposits
metallogenesis, fluids, sandstone mineralization, and basement mineralization

Summary

- in most subsurface conditions, uranium occurs as U^{+4} , while U^{+6} is stable only under near-surface oxidizing conditions
- uranium solubility in aqueous systems is predominantly controlled by three factors:
 - oxidation-reduction potential (Eh), pE (-log of the activity of the electron), etc.
 - pH (-log of the activity of hydrogen ion)
 - dissolved anions (carbonate, phosphate, fluoride, chloride, hydroxyl)
- the precipitation of U^{+4} under reducing conditions is the dominant process leading to naturally enriched zones of uranium in the subsurface = U mineralization
- although the speciation of dissolved U^{+6} is commonly dominated by hydroxide and carbonate complexes, complexes with sulfate, fluoride, phosphate, and organic ligands also occur

- when phosphate is present at appreciable concentrations, uranyl phosphate complexes will control the dissolved uranium concentrations
- the total solubility of uranium in the near-neutral range in the 150 to 200°C range in low salinity fluids under reducing conditions is very low ($\sim 10^{-9.5}$ M; < 0.1 ppb U)
- distinctly oxidizing conditions are necessary for significant U solubility, with Eh levels $> \sim 0.300$ V being necessary for aqueous uranium solubility at ppm levels ($\sim 10^{-5}$ M; 2.4 ppm)
- Dissolved UO_2^{2+} species are strongly sorbed by FeOOH phases

 **Basement geology**

- one high-temperature alteration:
 - retrograde metamorphism
- three low-temperature alterations:
 - paleoweathering
 - Athabasca diagenesis
 - host-rock alteration/mineralization

AREVA Resources Canada

 **clay alteration**

- 'fresh' retrograde metamorphic pelitic gneiss typically contains Fe(-Mg) trioctahedral chlorite and chlorite is present in the lower portions of the paleoweathering profile, but increasingly paleoweathered equivalents (green to red-green zones) contain increasingly more magnesian trioctahedral chlorite
- red-green zone PW material contains increasing amounts of Al-Mg sudoite with increasing depth; around the red-green zone - green zone boundary a distinct change in chlorite structural type occurs where Al-Mg di, trioctahedral chlorite (sudoite) gives way to green zone trioctahedral chlorite (Mg-Fe, Mg types); PW-related green zone material is overprinted by red zone-related hematite
- typical diagenetic sandstone illite is the platy 1Mc polytype and the chlorite, where present, is sudoite (Al-Mg di, trioctahedral chlorite)

AREVA Resources Canada

 **clay alteration**

- host-rock clay mineral alteration around basement egress zones is desilicification with illite + sudoite which **crosscuts the earlier hematitic kaolinitic paleoweathering profile** with greenish alteration overprinting earlier hematite; the hydrothermal alteration illite is the 'hairy' 1Mt polytype
- the alteration assemblage in and around high-grade uranium mineralization is typically sudoite ± illite; the entire paleoweathering profile has been chloritized to sudoite, as has the overlying basal sandstone
- McArthur-type silicification appears to be prior to mineralization
- kaolinite may be part of the alteration halos or may be retrograde diagenetic
- ingress-type halos are tight to the basement mineralization, but are also illitic and chloritic; this mineralization is only locally reflected by illitization in the sandstone

AREVA Resources Canada

AREVA

Mineralization

- dominant mineralization-related components are uraninite/pitchblende and hematite formed through redox reactions during fluid-fluid interaction of an oxidized basinal brine and a relatively reduced basement fluid or fluid-rock interaction of the basinal brine with ferrous iron-bearing basement rock
- saline, relatively oxidized fluids containing phosphate appear to be most suitable for transport of Ni, Co, As, Cu, V, and U.
- in egress-type deposits, widely varying amounts of arsenide and sulfarsenide minerals (skutterudite, rammelsbergite, lollingite, niccolite, maucherite, gersdorffite, cobaltite) are present, as are minor sulphides (pyrite, chalcocopyrite, sphalerite, galena, molybdenite)
- many other minerals are present in trace to minor quantities, including phosphates (xenotime, apatite, and complex Ca-Sr-Al-Th-LREE phosphate) and coffinite
- in ingress-type deposits, the mineralization is relatively simple with dominant uraninite/pitchblende and only trace to minor amounts of Cu&Fe sulphides and Ni-arsenide/sulfarsenide minerals

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AREVA

- The unconformity-type deposit arsenide/sulpharsenide/sulphide mineral parageneses indicate that decreasing As and Ni activities and increasing Co, Fe, and S activities occurred as the mineralization events progressed. The As activity decreased with time with a concurrent increase in S activity and, also concurrently, the Ni activity decreased while the Co and Fe activities increased.
- Initial precipitation of uranium oxide as colloform and botryoidal grains in the Athabasca unconformity-type uranium deposits suggests that formation of this first mineral phase occurred under near-equilibrium conditions.
- The succeeding arsenide, sulpharsenide, and sulphide mineral assemblages display ubiquitous disequilibrium features in these deposits with mineral resorption and replacement textures being typical.
- The occurrences of pyrite, chalcocopyrite, and native copper show relatively few replacement features, suggesting that chalcocopyrite did not form through replacement of pyrite and that native copper likely formed through the Fe-Cu redox couple.

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- Oxidation-reduction and acid-base processes appear to be the most important in ore mineral formation in the Athabasca unconformity-type uranium deposits. The pitchblende-hematite-native copper associations fit with pure oxidation-reduction processes, while the arsenide and sulphide mineral assemblages may have formed through a combination of oxidation-reduction and acid-base reactions.
- The progression from arsenide to sulphide mineral assemblages is typical and it is consistent with the concept of increase in sulphidation state of the hydrothermal fluids with evolution of the fluids from higher temperature to somewhat lower temperature.

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Integrated Exploration for Athabasca Basin Unconformity-Related Uranium Deposits

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Integrated Exploration for Athabasca Basin Uranium

Dan Brisbin
Senior Economic Geologist
Cameco Corporation

2006 Calgary MEG Uranium Short Course

OUTLINE

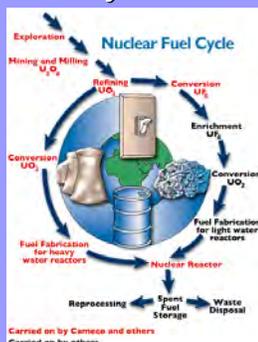
- Uranium supply-demand drivers for uranium price increase
- Integrated Athabasca Basin uranium exploration model
- Model application at different scales
 - Regional scale
 - District scale
 - Property scale
- McArthur River and Eagle Point case studies



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Nuclear Fuel Cycle



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Uranium Demand



- 440 reactors operating worldwide require 176 million pounds U_3O_8 per year
- 1,000 MWe reactor needs 500,000 pounds of natural uranium per year
- Demand increasing (new builds, license extensions, improved utilization)



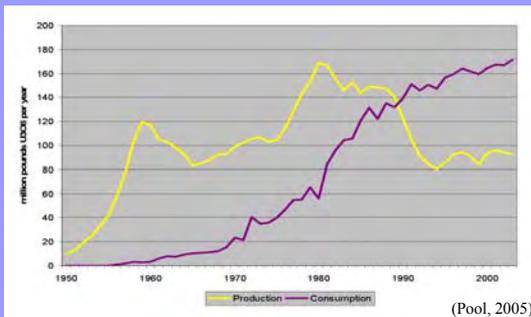
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Uranium Fuel Supply Sources

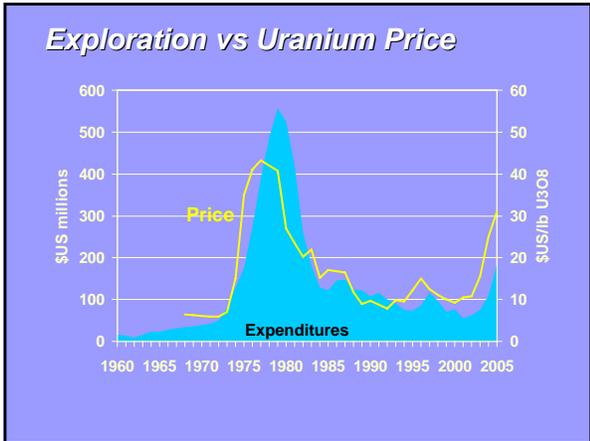
- Primary (mining)
 - Conventional (Athabasca Basin)
 - In situ leach (Western United States)
 - By-product (Olympic Dam)
- Secondary
 - Inventories (producer, government, utility)
 - Downblending weapons grade uranium (HEU)
 - Reprocessing enrichment tails
 - Recycling spent fuel plutonium as MOX fuel

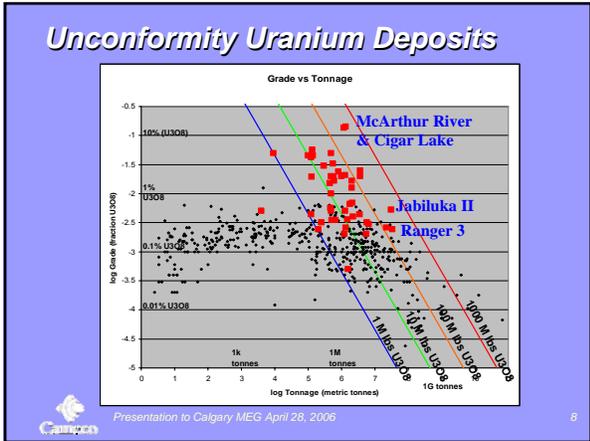
Uranium Production vs Consumption

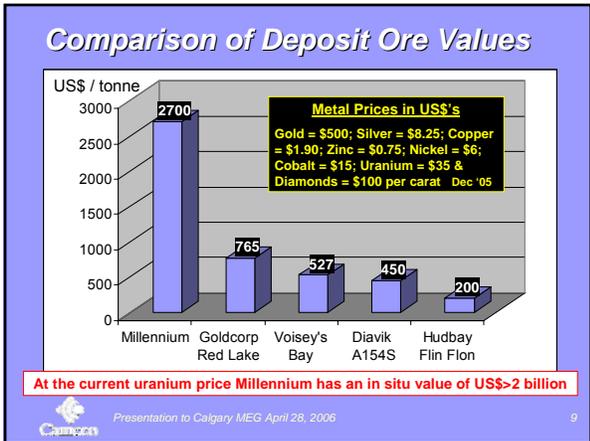


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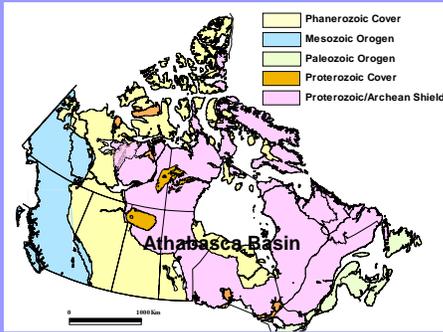
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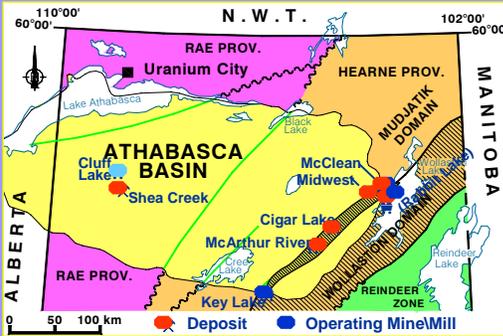


Athabasca Basin Location



1000 km
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Athabasca Basin Uranium Deposits

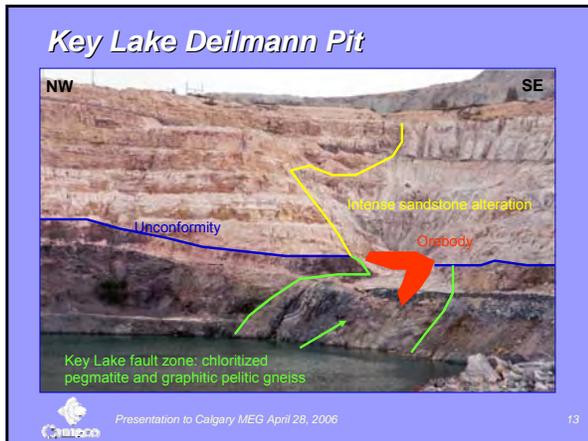


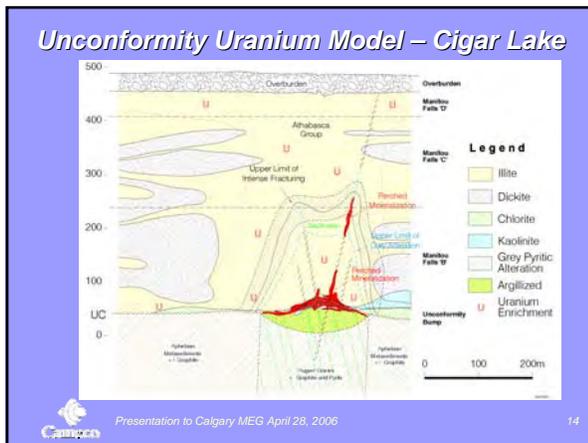
110°00' 60°00' N.W.T. 102°00' 60°00'
50 100 km
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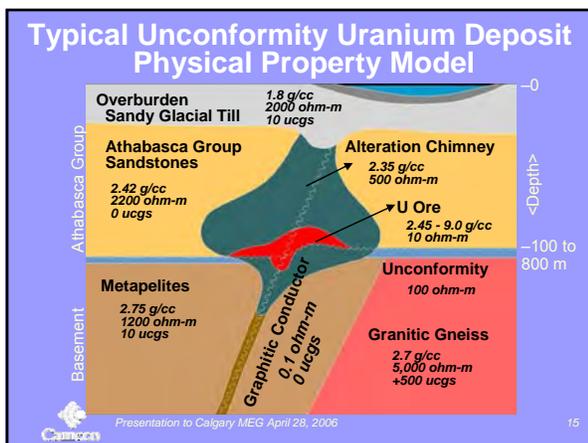
Unconformity Type Uranium - Definition

- Unconformity-type uranium deposits are high grade uranium concentrations located at the unconformity between relatively undeformed quartz rich sandstone basins and the underlying metamorphic basement rocks.

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Alteration Paragenesis

- Relationship of alteration identified to uranium?
- Three alteration stages in Athabasca Basin
 - Early diagenesis: silica overgrowths, hematite, phosphate minerals, 150-170oC
 - Peak diagenesis; dickite/kaolinite, illite, dravite, chlorite, hematite, uranium, sulphides, arsenides, 180-240oC, saline, oxidizing basinal brines & reducing basement fluids
 - Post-ore/meteoric events: kaolinite, dravite, pyrite, carbonate, uranium (remob?), <50oC, low salinity

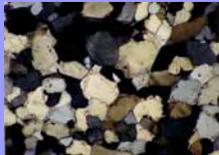


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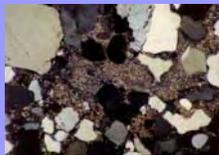
16

Alteration Paragenesis

Early Diagenesis/Silicification



Argillization/Desilicification



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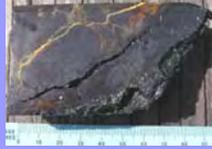
17

Alteration Paragenesis

Draviteization



Brecciated Massive Pitchblende



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Alteration Mapping

- Visual and petrographic
- Normative mineralogy
- X-Ray diffraction (XRD)
- Short wave infrared reflectance spectroscopy
 - PIMA and ASD for boulders, outcrop, drill core
 - Hyperspectral airborne
- Spectral gamma K
 - Portable, borehole and airborne tools



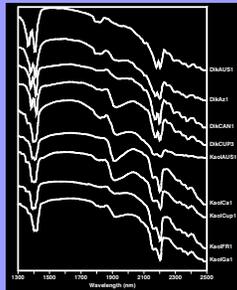
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Alteration Mapping



PIMA SWIR Spectrometer



Kaolinite/Dickite Reference Spectra



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Geochemistry and Radiometrics

- Total extraction versus partial extraction
- Pathfinder suite versus multi-element ICP-MS
- U, Pb, Cu, Ni, Co, As, V, B
- Composite versus spot sampling
- Radiometric surveys
 - Total counts (scintillometer) versus K, Th, U (spectrometer)
 - Geiger-Mueller tubes and shielded scintillometers for ore grades (eU)



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REGIONAL EXPLORATION

- Identification of prospective districts or belts within a permissive basin:
 - Belts of pelitic gneisses (magnetic lows)
 - Regional graphitic faults (electromagnetic conductors)
 - Lithotectonic boundaries (magnetic and conductor patterns)
 - Anomalous lake sediment geochemistry
 - Anomalous sandstone boulder clay mineralogy and geochemistry
 - Hyperspectral and airborne radiometric surveys



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Regional Exploration Techniques

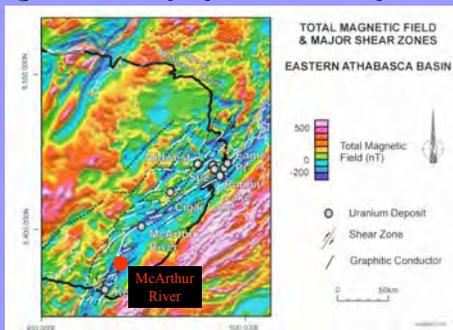
- Lithology and structure:
 - Airborne magnetics, radiometrics
 - Compilation
- Mineralization
 - Airborne radiometrics
 - Lake sediment sampling
 - Compilation



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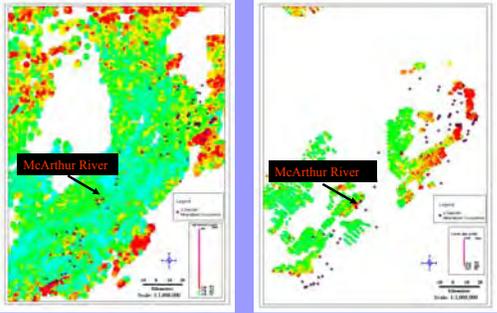
Regional Geophysical Surveys



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Regional Geochemical Surveys

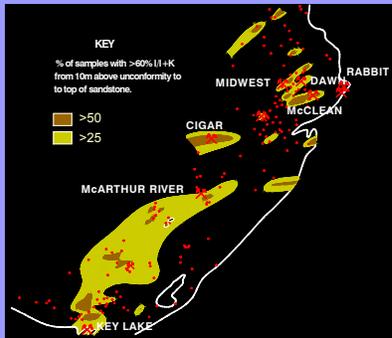


Lake Sediment Uranium Boulder Uranium (partial)


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Regional Illite Distributions



(from Earle & Sopuck, 1989)


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DISTRICT EXPLORATION

- Identification of prospective corridors:
 - Regional faults, lithotectonic boundaries, high strain zones from magnetic and conductor maps.
 - Anomalous alteration, radioactivity and geochemistry in boulders and sandstone drill core.
 - Anomalous lake sediment geochemistry.
 - Post-sandstone faults and paleotopography from unconformity elevation map.
 - Areas of enhanced conductivity from EM inversions.
 - Hyperspectral and airborne radiometric surveys


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District Exploration Techniques

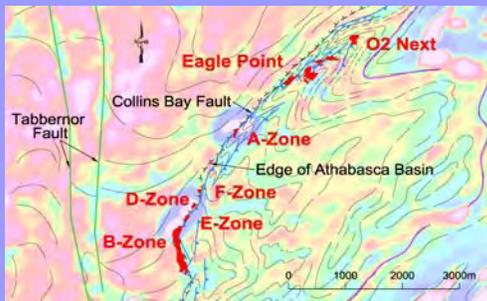
- Lithology and structure:
 - Airborne magnetics, EM, gravity, radiometrics
 - 2D seismic
 - Compilation
- Mineralization
 - Airborne radiometrics
 - Lake sediment/water sampling
 - Boulder radioactivity, chemistry, alteration
 - Till geochemistry
 - Compilation



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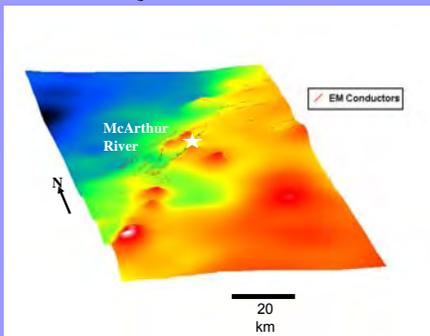
Geology Interpreted From Vertical Gradient Magnetic Field and Conductors



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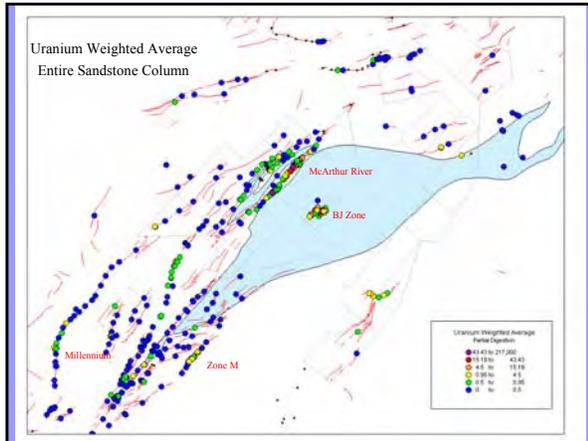
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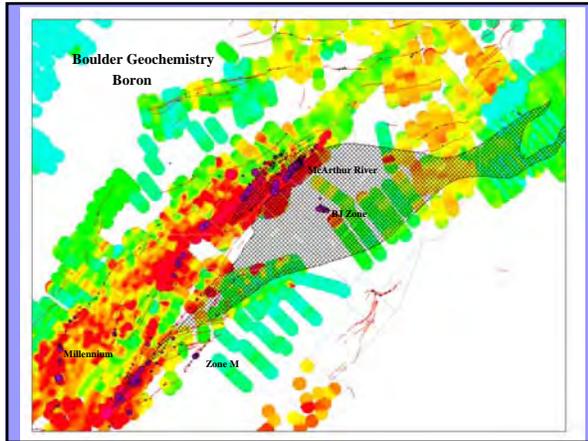
Unconformity Elevation Model

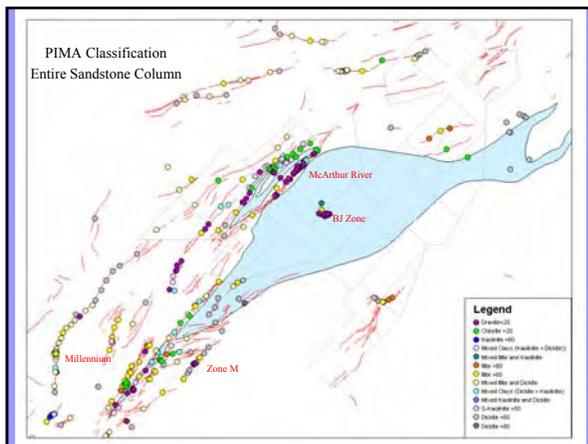


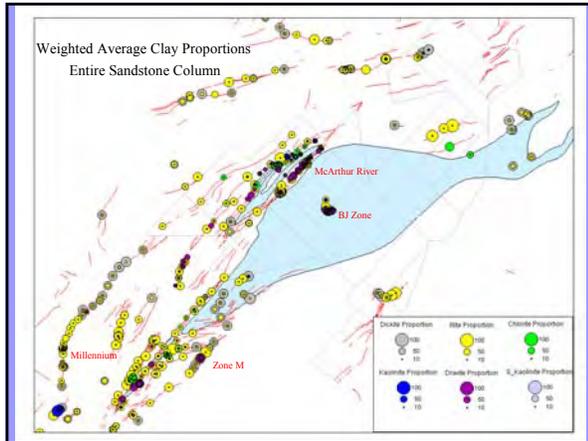
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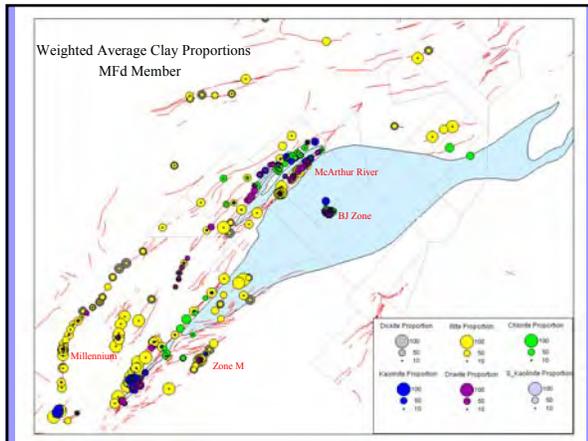
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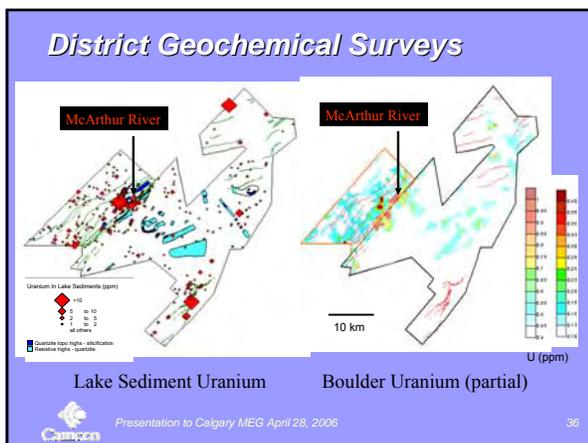












PROPERTY EXPLORATION

- Identification of drill targets within prospective "camps":
 - Application of deposit model.
 - Structural targets from magnetic and conductor maps.
 - Areas of enhanced basement conductivity from EM inversions.
 - Resistivity lows in sandstone (elevated porosity)
 - Anomalous alteration, radioactivity and geochemistry in boulders and sandstone drill core.



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Property Exploration Techniques

- Lithology and structure:
 - High resolution airborne magnetics, EM, gravity
 - Ground magnetics, EM, gravity, resistivity, seismic
 - Geological mapping and prospecting (locally)
 - Drilling
 - Geology (+/- oriented structure)
 - Core and borehole radiometrics
 - Lithogeochemistry and mineral spectra
 - Borehole geophysics (e.g. resistivity)
 - Compilation



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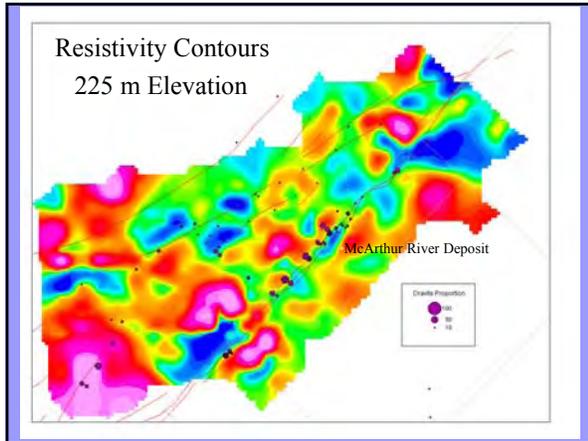
Property Exploration Techniques

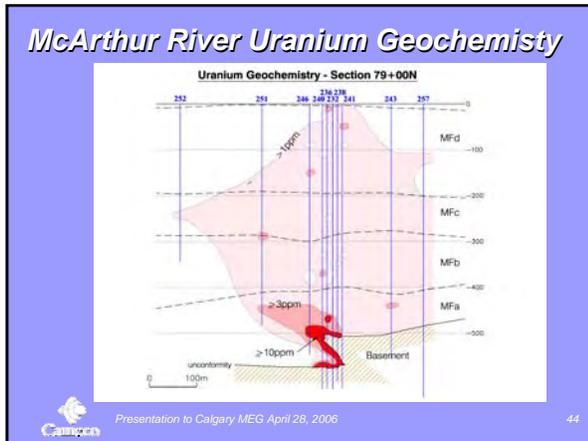
- Alteration and Mineralization
 - High resolution airborne EM, gravity
 - Ground EM, gravity, resistivity
 - Geological mapping and prospecting (locally)
 - Drilling
 - Boulder radioactivity, chemistry, alteration
 - Till geochemistry
 - Compilation

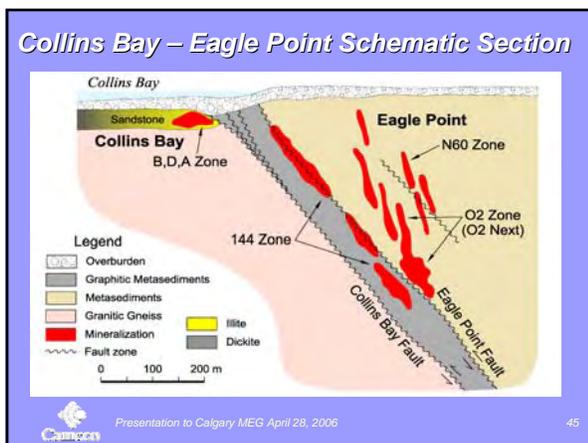


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Exploration Hints Derived from a Two-Stage Tectogenetic Model for the Athabasca Unconformity-Related Uranium Deposits

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Any metallogenetic model incorporates descriptive features common to a sufficiently large number of deposits and their explanation in terms of geological processes. The metallogenetic model proposed here for the uranium deposits in the Athabasca Basin and adjacent areas of the Shield is based on the following common features:

- uranium occurrences and deposits are structurally controlled at all scales; uranium ore exists as fracture fillings or disseminations in wall rock and is found either within shear/fault zone, at the interface between shear zone and Athabasca clastic rocks or within the fractured Athabasca clastic rocks;
- strained rocks including or underlying uranium deposits show variable degrees of metasomatism and retrogression to greenschist and subgreenschist facies rocks, while the overlying Athabasca clastics are overprinted by a plume-like epithermal alteration halo elongated along the trend of the underlying shear zone;
- the mineralization is variably polymetallic with mineral assemblages typical for polyphase hydrothermal discharge;
- the richest deposits, both in terms of grade and reserve, exist in areas blanketed by the Athabasca clastic strata, or areas that were once covered by these strata; the ore grade in many Athabasca unconformity-related uranium deposits is two order of magnitude higher than in other types of uranium deposits.

Existing data on the Athabasca unconformity-related uranium deposits are here integrated in a two-stage uranium enrichment metallogenetic model consistent with geological and hydrogeological processes associated with crustal scale shear zones (e.g., Newton, 1990; Cox et al., 2001; Sibson, 1977; 2001; Oliver et al., 2001):

Stage I: mobilization of large ion lithophile elements (LIL: U, Th, K, Rb and REE) from the lower crust by mantle-derived volatiles streaming along transcrustal shear zones and formation of uranium fertile protoliths at intermediate crustal levels;

Stage II: tectonic reworking of fertile protoliths and formation of uranium deposits through long-lasting fault zone-related hydrothermal activity under a low permeability stratigraphic cap.

In stage I, mantle-derived volatiles streamed along transcrustal shear zones would mobilize LIL from the lower crust and form uranium enriched protoliths at higher crustal levels. Protracted deformation and syntectonic exhumation of these shear zones has involved the evolution of shear zones through intermediate and shallow structural levels. In the process, strain was heterogeneously partitioned, migrated and concentrated in narrower steeply dipping greenschist mylonite and cataclasite belts to create effective and gradually more focused fluid pathways. During the passage of the shear zone through the

brittle-ductile structural level, the nature of fluids involved in the metallogenic process shifted from dominantly mantle-derived CO₂ and H₂O in the lower and middle crust to dominantly aqueous of surficial origin, in the shallow brittle crust. Surficial water convection within subvertical fault aquifers is the main agent for uranium extraction, transport and deposition; the development of a low-permeability cap (the regolith and the Athabasca strata) triggered overpressuring of the basement hydrodynamic cells, accompanied by multiple rupturing-mineral sealing cycles over hundreds of million years, which maximized fluid/rock interaction. The development and persistence of the seal atop basement fault zones is the prerequisite for the development of high-grade/tonnage deposits.

The model integrates previous apparently mutually exclusive genetic models (“magmatic-hydrothermal”; “metamorphic hydrothermal”, “supergene” and “diagenetic hydrothermal”), explains their major shortcomings, reconciles existing temperature, pressure and time data, and also recognizes the critical metallogenic significance of the development of a Proterozoic clastic basin.

Primary uranium enrichment processes in transcrustal shear zones

Megashears in the basement of the Athabasca Basin

The present erosional level of the Shield and the sub-Athabasca unconformity provides a horizontal section through:

- 1) dry continental deep crust formed in the major Late Archean period of crustal growth, granulite formation and stabilization. Granulite facies parageneses are exposed either as extensive areas of dome and basin structures in the Mudjatik domain of the Hearne terrane and portions of the Rae terrane or as smaller tracts in younger tectonic belts (e.g., Taltson basement complex, Wollaston belt);
- 2) wide linear zones of Paleoproterozoic tectonomagmatic recycling; these include the ca. 2.0-1.93 Ga southern segment of the Taltson-Thelon orogen and the ca. 1.86-1.80 Ga Wallaston belt of the Trans-Hudson orogen. These linear zones are dominated by amphibolite facies metamorphic conditions and contain smaller, variably retrogressed tracts of granulite facies rocks.
- 3) infrastructures of transcurrent megashears marked by linear zones of granulite to amphibolite facies mylonites overprinted by anastomosing belts of low-grade mylonite to cataclazite.

Transcrustal fault/shear zones are vertical tabular features flaring out with increasing depth to reach 25 km widths in the lower crust (e.g., Hanmer, 1988) and show an elusive transition through strain and hydration gradients to more or less intact adjacent crust. From west to east the most prominent exhumed infrastructures of Early Proterozoic megashears are: the Charles Lake braided shear zone (~5-10 km wide) and the concealed Maybelle shear zone in the Taltson magmatic zone, the Tazin River shear zone (~25 km wide) near the eastern margin of the Taltson magmatic zone, north of Lake Athabasca, the Beaverlodge shear zone (~18 km wide) overprinting the Rae terrane, the Virgin River-Black Lake shear zone and the Wollaston Lake shear zone bounding the Archean Mudjatik crust to the west and east, respectively. Their length of hundreds of kilometres, great original width (>10 km), conspicuous strike-parallel mineral stretching under granulite to lower amphibolite metamorphic conditions indicate transcurrency accommodated over broad continental areas of the Canadian shield. Each of these zones is overprinted by braided systems of subparallel greenschist and subgreenschist facies mylonite belts tens to hundreds of metres wide. Concealed by the Athabasca Group, segments of low-grade mylonite belts overprinting amphibolite grade mylonite gneisses have been identified at each Athabasca unconformity-related uranium deposit. This association indicates that the megashears continued to accommodate regional stress during crustal erosion and uplift: the greenschist facies mylonites record the passage of

these ancient zones of weakness through the brittle-ductile transition zone, while associated hematite/limonite cemented breccia, cataclasites and gauge record strain localization at near surface conditions.

Therefore, classical districts of uranium mineralization (e.g., Beaverlodge, Wollaston) are found within these continental-scale linear tectonic trends accompanied by variable degrees of retrogression and metasomatic phenomena.

Fluids in the lower crust

Hydration and metasomatism of the lower crust is commonly related to advection of large quantities of mantle-derived fluids along transcrustal tectonic discontinuities (e.g., Beach, 1976; Ferry, 1984; Lapin and Ploshko, 1988; Morel, 1988; Lottermoser, 1988, Newton, 1990; Kennedy et al., 1997). Mantle degassing and upwards streaming of volatiles through deep-seated shear zones was originally inferred based on metamorphic, metasomatic and igneous petrological and field data. In the last decade, the advection of mantle-derived volatiles to the Earth's surface has been well documented (Giggenbach, 1992; Kennedy, 1997; Siegel et al., 2004, Newell, 2005; Crossey et al., 2006). Carbonates-, amphibole- and phlogopite-bearing mantle constitutes an immense reservoir of metasomatizing volatiles CO₂ and H₂O (e.g., Menzies et al., 1985; Newton, 1990). At depth of about 180 km, depending on their mineral proportions, bulk-rock water content in the eclogites may range from 3070 to 300 ppm H₂O by weight (870 ppm H₂O in omphacite, 130 ppm H₂O in garnet and 740 ppm H₂O in rutile) (Katayama et al., 2006). Rising partially molten volatile-bearing mantle diapirs under different conditions of fast or slow ascent could release fluids of various ratios of CO₂/H₂O (e.g., Newton, 1990). Experimental melting curves for the upper mantle and crustal rocks suggest that fluids released from magmas crystallizing at the mantle solidus below pressures of 20 kb are CO₂-dominated and become increasingly H₂O-rich at higher pressures. At shallow depths in a strongly-rising diapir a partially melted mantle might approach closely to the surface, generating alkali-basalt or tholeiitic magmas; freezing outside the mantle carbonate stability field would occur with the release of dominantly CO₂-rich fluids, and CO₂ would stream upward into the crust. Melts freezing at higher pressure would release large amounts of both H₂O and CO₂, but both volatiles could be variably screened out en route to the surface by mantle hydration and carbonation reactions if they move slowly through the volatile-poor mantle; however, they might penetrate the crust if they streamed rapidly upward through volatile-saturated mantle (Newton, 1986; 1990).

Mantle-derived fluids would cause metasomatism or melting as they entered the crust, especially with advective heat transport. However, major metasomatism and temperature increase occur only at fluid/rock ratios of about one or higher (Ferry, 1984; Kreulen, 1988) therefore, these phenomena will be restricted to transcrustal/lithospheric scale shear zones with enhanced permeability. Hot CO₂-H₂O fluids have a strong metasomatic effect, and might trigger various kinds of shear zone metasomatism including regional carbonatization, fenitization, granitization/migmatization, large-ion lithophile (LIL) elements leaching, as well as diverse magmatism. Mid-crustal levels are enriched in radioactive elements and thus become zones of high heat production as an intrinsic part of crustal evolution (e.g., Condie et al., 1982; Wightman 1983; Janardhan et al., 1982; Friend, 1985; Allen et al., 1986; Gopalakrishna et al., 1986). CO₂ can either percolate the shear zone upwards or get captured in metamorphic reactions (e.g., carbonates, graphite) or mineral structures (e.g., cordierite may contain up to 2.4 wt% CO₂ and some CO; Khomenko and Langer, 2005).

The Early Proterozoic Charles Lakes, Tazin Lake, Beaverlodge and portions of the Wollaston belts include amphibolite facies mylonite gneisses that record creep processes characterized by quasi-steady state permeabilities higher than those of the surrounding, less rapidly deforming Archean granitoid-granulite crust. Carbonate impregnated quartzo-feldspatic gneisses, synkinematic carbonate and quartz segregations, impure quartzite and feldspatic quartzite, all very common in the Proterozoic megashears of

the Beaverlodge and Wollaston districts, record intense CO₂- and/or SiO₂-rich fluid migration during steady-state ductile deformation below the brittle-ductile transition zone. Similar rocks described from uranium mining and drilling operations in these uraniferous districts contribute to a three dimensional perspective on the extensive shearing, retrogression and metasomatic processes within the megashears (e.g., lithological description at Rabitt Lake by Hoeve and Sibbald, 1978 and at Key Lake by Dahlkamp, 1978).

Conspicuous hydration, carbonatization, silicification associated with the development of the gneissic foliation along the Beaverlodge and Key Lake-Collins Bay megashears, as well as their intrusion by multiple generations of gabbro-basalt-dolerite and granitic pegmatite dykes, testify for hot-fluid advection along wide linear zones of strain during and after the Taltson and Trans-Hudson tectonism. Thus, LIL elements, notably U, Th, K, Rb, and REE, have migrated from the lower crust either in partial melts or in mineralized CO₂-H₂O vapour flux. Both modes of uranium enrichment of the middle crust levels are known in the area of the Athabasca Group. Thus, uraninite-bearing granite pegmatites as well as uraninite-rich leucogranites and pegmatites are known in the Beaverlodge (e.g., Beck, 1985) and Wollaston (e.g., Madore and Annesley, 2000) districts, respectively, and synkinematic calcalkaline plutonic rocks of late Taltson age near Shea Creek, in the west central part of the Athabasca Basin, are enriched in K, Th, U and REE (e.g., Brouand et al., 2003). Similarly, the retrogressive amphibolite facies rocks of the Wollaston belt are relatively enriched in uranium as uraninite (Dahlkamp, 1978). Unlike uraniferous granitic pegmatites that intrude metasomatized high-grade metamorphic rocks in other regions (e.g., Bancroft area, Ontario; Griffith, 1985), the pegmatites in the area of the Athabasca Basin are not ore grade. Instead, the mineralization in the entire Athabasca area is vein type, commonly associated with carbonate metasomatism, which indicates that carbon-rich aqueous fluids were the primary agent for uranium transport to mid-crustal levels. Noteworthy, the vast majority of uranium occurrences and deposits have been found within greenschist/subgreenschist facies fault rocks (Tremblay, 1978; Rabitt Lake, Hoeve and Sibbald, 1978; Key Lake, Dahlkamp, 1978). This suggests that uranium transport and concentration by fluids is critically related to the passage of the shear zone above the brittle-ductile transition zone where the narrowing of the strain belts allows for focussed fluid flow and higher water/rock ratios.

The presence of a basement zone of strain concentration/retrogression/metasomatism is the prerequisite for the development of the Athabasca unconformity-related uranium deposits and constitutes the first order, regional and easily recognizable metallogenetic indicator for uranium exploration. Implicitly, Archean high-grade terranes characterized by anhydrous granulite/charnockite and tonalite paragenesis, and no metasomatism are uranium depleted and have little or no potential for uranium deposits.

Secondary Uranium enrichment by fault zone-related hydrothermal activity

The fault zone aquifer

Basement rocks at all uranium deposits in the area of the Athabasca Basin include greenschist to subgreenschist facies mylonitic fabrics. The onset of greenschist facies metamorphic conditions within exhuming continental shear zones corresponds to the fundamental change in shearing processes from quasi-plastic to frictional, over the depth interval corresponding to the 450°C and 300°C isotherms (cessation of flow through dislocation creep in feldspar and quartz, respectively). The transition from continuous aseismic shearing recorded by wide amphibolite facies mylonitic gneisses to the mixture of discontinuous and continuous shearing processes in the frictional seismogenetic upper crust has major metallogenetic implications: fluid redistribution and related hydrothermal processes are either directly driven or strongly modulated by stress and permeability cycling tied to the earthquake stress cycle of fault zones (e.g., Muir-Wood and King 1993; Barton et al., 1995). Potentially large, cyclic changes in fault permeability cause episodic fluid flow that may induce mineral precipitation at specific structural sites

through dramatic reduction in fluid pressure and/or fluid mixing (Cox, 1999; Sibson, 2001). The association of mylonitic fabrics interlaced with pseudotachilites and fine-grained, compact gouges marking fault slip domains with multiple generations of hydrothermal fault-veins (quartz and/or carbonate) and mineralization pulses recognized in all uranium deposits in the area of the Athabasca Basin provide spectacular evidence of episodic slip and fracturing with creation of permeability and interseismic sealing by mineral precipitation during ongoing deformation and active hydrothermal activity.

A critical issue in previous debates on the genetic models for the Athabasca-type uranium deposits was the source of the mineralizing fluids: essentially ascending juvenile or metamorphic (dehydration reactions at depth) for the magmatic- and the metamorphic-hydrothermal model, respectively, and descending meteoric water or groundwater for the weathering and diagenetic hydrothermal model, respectively. Although all deposit features are typical for hydrothermal systems, the lack of any significant sin- or post-Athabasca tectonomagmatic event in the region led to dismissal of both endogen hypotheses and encouraged the development of the “diagenetic-hydrothermal hypothesis” (e.g., Hoeve and Sibbald, 1978). In contrast to the 1970s, the fault zone concepts evolved greatly starting with Sibson’s (1977) seminal paper, and the overwhelming involvement of surficial water sources in deep penetrating hydrothermal cells in the upper crust is now well documented. Therefore, previous limitations of the role of faults to only provide access for diagenetic fluids to graphite metapelites and advection to the Athabasca unconformity with the mobile reductant required by uranium precipitation from basinal fluids are no longer justified. The depth of gravitationally driven fluid penetration are typically up to several kilometres, but vigorous circulation of surficial waters down to midcrustal levels has been documented for various fossil hydrothermal systems (e.g., Taylor, 1990; Foster and Smith, 1990). In stable continental areas, most of the heat flow could be generated within the ~35 km thick crust with very low heat flux from the mantle. Surface heat flow data modeling predicts downward-decreasing exponential distribution of radiogenic heat production although significant departures could be induced by large variations in uranium and thorium concentration in the crust (Brady et al., 2005).

While fresh and undeformed granite has indeed low-porosity (typically in the order of 1%), the fractured granite reaches porosities of up to 8% allowing for focused fluid flow along the fault zone (e.g., Caine and Foster, 1999; Onishi and Shimizu, 2005). However, permeability is not determined by porosity alone, but by combined effects of crack density, crack width and connectivity of fracture networks. Permeabilities in fractured crystalline rocks can be more than 1 darcy ($k = 10^{-12} \text{ m}^2$) and even partly overlap the range of gravel permeabilities (e.g. Foster and Smith, 1990, Nesbitt, 1990). Thus, fault rock permeabilities are considerably more effective than those of common sandstone and orders of magnitude greater than the Athabasca orthoquartzite.

The regolith profile under the Athabasca Basin, with deep red-green pockets towards basement shears, the intense hematitization of variously strained rocks along fault/shear zones accompanied by long linear, brick-red “mud gauge”, high oxygen fugacities (hematite field) and carbonate $\delta^{18}\text{O}$ values (6‰ to 19‰, SMOW) in the alteration zones associated with uranium mineralization testify for oxidized fluids of surficial origin focussed along steeply dipping fault zones in both the Beaverlodge and Wallaston belts (e.g., Beck, 1985; Wallis et al., 1985). Thus, ore fluids were in most part surficial waters that infiltrated the gneiss-granitoid floor of the Athabasca Basin and in particular the shear/fault zones and were involved in metal extraction and transport from basement to the top of the shear zone and into the overlying clastic strata.

Fault-controlled fluid pressure cycles

Faulting occurs to relieve accumulated shear stress on faults. Periods of steady linear accumulation of shear stress and elastic strain during interseismic periods (decades to thousands of years) are punctuated by rapid stress drops during rupturing (seconds) and aftershock relaxation (month to years) (Sibson,

2001). The sawtooth pattern of accumulation and release of shear stress on the seismogenic structures leads to cycling of both shear and mean stress (affecting fluid content) throughout the surrounding rock mass, with significant fluid redistribution during the aftershock phase following large earthquakes. In the immediate postrupture phase, faults are highly permeable structures; the drop in pressure accompanying the rupture promotes fluid discharge and mineral precipitation along the transiently permeable rupture zone or zones which causes local reversion towards a hydrostatic fluid pressure gradient. As soon as porosity drops below the percolation threshold, fluid flow will shut off and the fault may become an aquitard until a later slip event (e.g., Sibson, 2001; Cox et al., 2001). Thus, progressive interseismic hydrothermal self-sealing of fluid conduits allows fluid overpressures to rebuilt at depth.

Important precipitation mechanisms linked to intermittent seismic slip include the suction-pump mechanism arising from rapid slip transfer across dilational fault jogs and bends, and various forms of fault-valve action where ruptures transect boundaries to overpressured portions of the crust. Valving action, involving the postfailure discharge of fluids through fault-fracture systems, occurs wherever ruptures breach impermeable barriers bounding overpressured portions of the crust. These barriers (low-permeability stratigraphic horizons, tabular zones of hydrothermal cementation or gouge or clay-rich fault seals) can be subhorizontal (Rice, 1992; Byerlee, 1993) but may also involve steep sealing faults bounding fluid pressure compartments (Hunt, 1990; Powley, 1990). Seals may even exist at different structural levels within a fault zone separating overpressured compartments with local fluid redistribution occurring at the time of earthquakes (Byerlee, 1993).

The apparent paradox of uranium association to minor displacement fault

Although the Athabasca unconformity-related uranium deposits are spatially and genetically related to spectacular basement mylonites, cataclasites and polyphase hydrothermal veining, the nearby Athabasca unconformity and the overlying Athabasca strata do not record any major, regional-scale tectonism. While in principle, the intensity of the hydrothermal activity along a fault zone is related to fault activity (i.e., strain and displacement), at the high-grade/high tonnage Athabasca uranium deposits there is no direct correlation between the intensity of the hydrothermal processes and displacement along the nearby fault zone. Instead, the mineralization appears to be synkinematic with the post-Athabasca low-displacement hosting faults and most isotope dates obtained so far are younger than the Athabasca Group. The only logical explanation, may as well be the key to understanding the unique metallogenetic system that led to the exceptionally rich Athabasca type uranium deposits: they are spectacular examples of fluid-driven faulting and extreme valving action resulting from a) mineral sealing typical to any hydrothermal system, added by b) the deposition and diagenetic alteration of the Athabasca Group clastic strata in the discharge areas of fault zone hydrodynamic cells.

Mineral sealing of fractures can be rapid relative to the lifetimes of hydrothermal systems, and sustained fluid flow occurs only in active structures where permeability is repeatedly renewed (Cox, 2001). In sub-Athabasca fault zones the permeability was spasmodically renewed for about one and a half billion years without significant displacement. A Re-Os age of 1906 ± 7 Ma on pyrite (Creaser, personal communication) from a mafic mylonite of the uraniumiferous Maybelle River shear zone in Alberta, indicates that the hydrothermal/metallogenetic processes may have started soon after the major Taltson tectonism (ca. 1.95-1.92 Ga). In the Beaverlodge district, initial pitchblende mineralization occurred at 1780 ± 20 Ma (Koeppel, 1968), well before the deposition of the Athabasca Group and uranium concentration in soil at the Bolger pit shows that the Verna ore system near the St Louis fault has been active until pre-glacial times (Smith, 1985).

Fracture growth can occur in response to stress differences (through changes to σ_1 and/or σ_3) and to changes in fluid pressure. An increase in pore fluid pressure (P_f) would reduce the effective normal stress (σ_n) according to the relationship:

$$\sigma_{n(\text{effective})} = \sigma_n - P_f$$

and implicitly the shear strength (τ) in a rock of certain cohesive strength (C) according to the Coulomb shear failure criterion:

$$\tau = C + \mu\sigma_{n(\text{effective})} \quad (\mu - \text{coefficient of friction})$$

In hydrothermal regimes, the influx of fluids even under constant stress differences ($\sigma_1 - \sigma_3$), can induce brittle failure: for low normal stress differences ($\sigma_1 - \sigma_3$), increasing fluid pressure results in extensional failure, whilst at high normal stress differences ($\sigma_1 - \sigma_3$), increasing fluid pressure would induce shear failure (Cox, 2001). Such purely fluid-driven failure without changing the absolute stress state may explain the association of uranium ore in the area of the Athabasca Basin with small displacement faults of no regional consequence. The pre-Athabasca steeply dipping belts of greenschist/subgreenschist fault rocks constituted a tectonically weak and porous medium allowing infiltration of connate, diagenetic and meteoric waters in these subvertical aquifers, which could have driven the spontaneous growth of fractures even without significant changes in the stress regime. The orientation and magnitude of these faults was controlled by the orientation of the principal stresses, magnitude of the stress differences and geometry of pre-existing mechanical anisotropies in the rock mass.

A clay-rich saprolite layer may have been a low-permeability barrier leading to the development of near surface overpressured (supra-hydrostatic) compartments within fault zones even before the deposition of the Athabasca Group. However, following the deposition of the lower Athabasca strata, an effective lid to the advecting hydrothermal fluids developed in time through compaction and diagenesis of the clastic sediments, as well as through further low temperature alteration of the granite-gneiss floor to “regolith” by diagenetic fluids in the Athabasca Basin. The less permeable layer on top of fault zone hydrodynamic cells allowed for prolonged interaction between hot hydrothermal fluids and basement rocks. Hydrothermal plumes infiltrating the Athabasca strata led to the building up of an even less-permeable silicification and/or argillization carapace atop fault zones. Consequently, repeated pulses of fluid discharge would transfer metals into the zone of fluid-driven shear failure and self-organizing network of hydrofracture veining, which extends hundreds of metres below the carapace (e.g., McArthur River deposit). Fracturing of the low permeability carapace would provide cross-stratal conduits for occasional outbursts of mineralizing fluid. Ore-sealed fractures and disseminated ore within this altered sandstone carapace make up major sandstone hosted deposits (e.g., Rabbit Lake and Cigar Lake deposits).

The model explains why intense late faulting recognized in uranium mining operation within the Athabasca Basin has not been noticed outside the erosional edge of the basin. In the stable regions hosting intracratonic basins, ancient fault/shear zones do not need to be tectonically reactivated, instead their segments covered by Proterozoic sequences set up the peculiar locus of self promoting and self organizing fluid-driven faults with minor displacement.

Fluid inclusion studies indicate that temperatures and pressures of mineralizing fluids decreased from approx. 220°-160°C and 1-1.25 kbar to approx. 160°-140°C and 0.6 kbar; (Pagel et al., 1980; Kyser et al., 2000; Cuney et al., 2003), consistent with hydrothermal alteration within the shallow subgreenschist facies segment of fault/zones that were gradually uplifted from 7 to 4 kilometres depth (~35°C/km geothermal gradient). Various stages of the mineralization process during this long lasting erosion and uplift are recorded by fluid inclusion temperatures of 195°C in gangue minerals at McClean (Wallis et al., 1985) and of 185-160°C in ore at Rabbit Lake (Pagel et al., 1980). Fluid inclusion studies at Rabbit Lake and Carswell deposits suggest that the mineralization phase is, at least occasionally, related to a basement-derived, low salinity, CH₄-bearing fluid commonly mixed with NaCl brines (Derome et al., 2003). Overgrowths on detrital quartz in alteration halos are NaCl-rich, suggesting a genetic relationship between the mineralization and the development of the alteration halo. Incongruent dissolution of monazite in the basement with U-P-LREE leaching corroborated with Ca, REE, U, Al, P enrichment of

zircon in the alteration halos above shear zones (Hecht and Cuney, 2000, 2003; Cuney et al., 2003) are strong evidence relating uranium mineralization to basement-derived hydrothermal plumes. The identification of secondary Ca-enriched fluid inclusions in pervasively silicified zones and drusy quartz, close to the mineralized zones (Derome et al., 2002, 2003) is consistent with the alteration of plagioclase to albite during long-lasting interaction of mineralizing brines with rocks within the shear zone channelways. Thus, the “syenite” at the Gunnar deposit (Evoy, 1985) and the “plagio-clasite” at the Rabbit Lake deposit (Hoeve and Sibbald, 1978) are different stages of intense metasomatism “albitization”.

The hydrated greenschist-grade mineral assemblages within the fault zone is dominated by chlorite, albite and sericite derived from the K-feldspar and biotite-dominated granitoid-gneiss wall-rock. The significant loss of K and SiO₂ within the basement shear zones can be directly correlated with the K and silica zones of the linear uranium mineralization alteration halos that crosscut the overlying Athabasca sandstone. Oxygen isotope data for illite at the McClean deposits define fields that overlap the juvenile fluids field and their hydrogen isotopes indicate that illite from the alteration halo could not have formed in equilibrium with formation waters (Wallis et al., 1985). Ascending fluids along fault conduits were K-rich with the acidity controlled by the kaolinite-illite buffer to a pH of about 4.5 at 200°C (Cuney et al. 2003). Ca as well as Mg and Fe from dissolving plagioclase and mafic minerals, respectively appear to have contributed to the carbonitization processes responsible for spectacular development of carbonate veins and masses (e.g., Gunnar mine, Evoy, 1985; Rabbit Lake; Hoeve and Sibbald, 1978; Ruzicka, 1985). Stable isotope data provide scattered hints to the involvement of juvenile origin fluids in the metasomatic processes accompanying uranium mineralization. Thus, $\delta^{13}\text{C}$ (PDB) values in carbonates ranging from -13‰ to -1.7‰ in the McClean deposits of the Wallaston district and from 0‰ to -16.5‰ in the Beaverlodge district (Sessano et al., 1972; Tortosa and Langford, 1985) depart markedly from typical organic carbon values (average organic $\delta^{13}\text{C}$ of -25‰). Similarly, $\delta^{13}\text{C}$ values from graphite ranging from -25‰ to -19.5‰ in the McClean deposits (Wallis et al., 1985) and from -25‰ to -14‰ in the Maybelle River occurrence (Pană et al., 2006) indicate fractionation and/or mixing with carbon from juvenile sources (average mantle $\delta^{13}\text{C}$ of -5 ‰).

The tectogenetic model discussed here emphasizes the metallogenetic efficiency of fault zone mechanisms that induce abrupt localized reduction in fluid pressure at specific structural sites, triggering phase separation and hydrothermal precipitation throughout the postseismic period of readjustment (aftershock phase). However, renewal of fault-fracture permeability may have also led to episodic mixing of fluids derived from different sources. For example, each fault-valve discharge may have promoted precipitation through the mixing of originally deep, hot, overpressured fluids of juvenile origin (previous section) with colder fluids in hydrostatic regime above the brittle-ductile transition. Further up, near-surface discharge of chemically evolved metal-bearing fluids advecting along fault aquifers would necessarily mix with oxidizing barren fluids infiltrating from the Athabasca strata.

Basin development

In the tectogenetic model favoured here, the development of a Proterozoic basin remains a key factor in uranium mineralization. First, the development of an intracontinental basin records either minor tectonism (Athabasca type sag basins) or more intense tectonism (Thelon-type pull-apart basins) that may have respectively, reactivated or initiated zones of strain concentration/high permeability in the basement. Second, basin development provides the source of water for the subvertical hydrodynamic cells formed within highly permeable basement fault/shear zones. Finally, by far the most important role of the Athabasca Basin development was the deposition of the clastic strata to cap the fault zone hydrodynamic cells. Hydrothermal plumes infiltrating the Athabasca strata led to the building up of a less-permeable silicified and/or argillized sandstone carapace atop fault zones and thus allowed for prolonged interaction between hot/boiling hydrothermal fluids and basement rocks. Although similar fault zone metallogenetic systems have been active elsewhere on the Canadian Shield, giant uranium deposits with exceptional

grades formed only where Middle Proterozoic strata capped the boiling fluids within the fault zone “pressure cooker”.

From an exploration point of view, it is critical to understand the tectonic stress regime and mode of faulting, the geometry of fault irregularities, the level in the crust and the fluid pressure state at the time of mineralization in order to identify the specific conditions that promote focused large-flux flow at specific sites along a fault zone. Dilatant fault bends, stepover regions, or jogs that link approximately planar segments of faults and shear zones around fault termination zones, fault splays, wing cracks, or brecciated regions and areas of competence contrast are the highest permeability sites that localized fluid flow and ore deposition (Cox et al., 2001).

Structural analysis holds great promise for identifying likely mineralization sites around complex fault traces through the recognition of areas of enhanced failure potential. Thus:

- 1) low-displacement faults with a high degree of complexity are much more favourable as mineralizing sites than fault segments with large displacement and increased smoothing (Wesnousky, 1988);
- 2) dilational jogs (stopovers) and bands that may act as suction pumps are extremely attractive uranium exploration targets; in contrast, contractional stopovers tend to be water depleted and hold limited metallogenetic potential (Harris, 1998).
- 3) simple dilational jogs usually develop approximately perpendicular to fault slip vectors, acting as pipe structures of locally enhanced permeability within fault zones; the internal structure of large dilational jogs is generally a fault-fracture mesh comprising various combinations of subsidiary faults, sheeted arrays of extension veins and multiply recemented wall-rock breccias developed by hydraulic implosion.
- 4) regardless the stress regime, all stress-controlled components of structural permeability such as dilational jogs and fault-fracture intersections lie parallel to the σ_2 axis; as well, development of conjugate fault sets inevitably leads to strong σ_2 directional permeability. Strong directional permeability along σ_2 implies that the three dimensional geometry of dilational structure is paramount to exploration:

- in normal and reverse faulting regimes, extensional and contractional jogs have subhorizontal plunges. Dip-slip fault systems may induce significant postfailure strike-parallel redistribution of fluids, with lateral movement of fluids away from a failed normal fault segment but inwards towards a failed reverse fault segment. Dilational jogs in dip-slip systems tend to enhance along-strike permeability; thus upward flow of buoyant hydrothermal plumes may be significantly deflected by gently raking jogs. A possible example of this case may be the Southeast Pod in the McClean deposit, which starts 17 m below the unconformity at the east end and rises up to 35 m above the unconformity at its west end, over a length of approximately 300 m (Wallis et al., 1985).

- in strike slip systems, dilational jogs result in strong localized enhancement of vertical permeability/connectivity; en echelon strike slip fault segments are linked through structural irregularities that may extend through the full depth of the seismogenic zone (e.g., Reasenber and Ellsworth, 1982). Larger dilational jogs may serve to localize magmatic intrusions, which may set up powerful hydrothermal systems. A spectacular example is along the Fay fault zone in the Beaverlodge district, where many steeply plunging ore shoots are found along faults linked to the ring-shape andesite intrusions in the Martin Group (Tremblay, 1972).

Conclusions

The exploration strategy for Athabasca unconformity-associated uranium deposits is based on a series of empirical criteria derived from observations at regional and local scale and their coherent interpretation. The vein type Athabasca deposits have similar characteristics to the classical Great Bear and Beaverlodge vein uranium deposits. The later may represent the exhumed roots of similar metallogenetic systems once capped by the Hornby Bay-Dismal Lakes and Martin groups, respectively. Thus, shear/fault zone-

controlled convection through fertile granitoid basement must be integral to the genesis of unconformity-associated uranium deposits in the Athabasca Basin. Late Paleoproterozoic anatectic granitoid plutons and pegmatites are rich in U-Th hosted by minerals such as monazite, zircon, titanite, and uraninite. The development of thermal convection cells in fault zone subvertical aquifers involved inflow of externally derived fluids balanced by upflow of mineralized fluids. High-grade/large-tonnage uranium deposits are found only in the Athabasca Basin, where Proterozoic strata have provided an efficient seal to the basement hydrodynamic cells.

The two stage metallogenetic model discussed here provides the following metallogenetic indicators to exploration for Athabasca unconformity-associated uranium deposits:

- Ancient graphite-bearing greenschist and subgreenschist facies fault/shear zones that could have provided high porosity and occasionally permeability for hydrodynamic cells in the fertile granitoidic basement; the graphitic layers with low shear strength would favour brittle faulting and a reducing geochemical environment.
- Fault-controlled hydrothermal cells commonly develop at dilational stopovers (jogs) and bents along faults and have a cyclical activity; multiple generations of quartz and/or carbonate veining within brittle and brittle-ductile mylonites are the most favourable exploration sites for uranium and other metals.
- Proterozoic clastic strata capping such fault/shear zones trigger overpressuring of the fault-controlled hydrothermal system and leading to the development of a peculiar locus of fluid-driven faulting/mineral precipitation cycles; also, clastic strata are excellent collectors for U-bearing fluids migrating up the steep high-permeability channels within the fault/shear zone. If the shear zone has been fertile, then the clastic cap must have recorded it. If such a collecting cap is not present, graphitic fault/shear zones can still host U ore if the erosion did not proceed too deep into the ancient hydrothermal system.
- If the sedimentary cap is still present, mineral zonation (kaolinite-illite-dravite) in alteration halos vector towards the center of an ore-forming hydrothermal plume. If the regolith is still present, red-green deep-penetrating alteration pockets overprinting strained basement rocks may be a good pathfinder for zones of enhanced permeability.

Therefore, the highest potential for new discoveries should be considered the under-explored areas overlain by the Athabasca Group. In general, intensive exploration has been carried out only in the easternmost part of the Athabasca Basin. However, in fact the entire basal unconformity surface is prospective where it intersects belts of graphite-bearing greenschist mylonites and cataclasites.

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Basement Control on the Athabasca-Type Uranium Deposits

Dinu Pana
Alberta Geological Survey

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Why Basement

COMMON FEATURES

- U occurrences & deposits are structurally controlled at all scales
U ore exists as fracture fillings or disseminations in wall rock and is found either within shear/fault zone, at the interface between shear zone and Athabasca clastic rocks or within the fractured Athabasca clastic rocks
- U mineralization is variably polymetallic with mineral assemblages typical for polyphase hydrothermal discharge
- Shearing, metasomatism and retrogression to greenschist and -greenschist facies rocks in basement, correspond to a plume-like epithermal alteration halo in overlying Athabasca clastics
- Richest deposits, both in terms of grade and reserve, exist in areas blanketed by the Athabasca clastic strata, or areas that were once covered by these strata; the ore grade in many Athabasca unconformity-related uranium deposits is two orders of magnitude higher than in other types of uranium deposits

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Outline

- Tools
- The Big Picture
- Main Lithotectonic Assemblages
 - Taltson
 - Tazin-Beaverlodge
 - Tantato
 - Western Granulite
 - Virgin River
 - Mudjatik
 - Wollaston
- Communalities
- Athabasca Uranium Deposits – Fault zone hydrodynamic cells

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Basement Studies - Tools

- Petrography & Geochemistry – rock description (field+TS)
- Petrology – genetic processes
 - metamorphic transformations
 - kinematic indicators
 - isotope geology – tracers, geochron
 - mineral chemistry – PTt path
- Geophysics – map extent of geological features
 - aeromagnetic and gravity maps

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Field data

In basement terranes we are mapping:

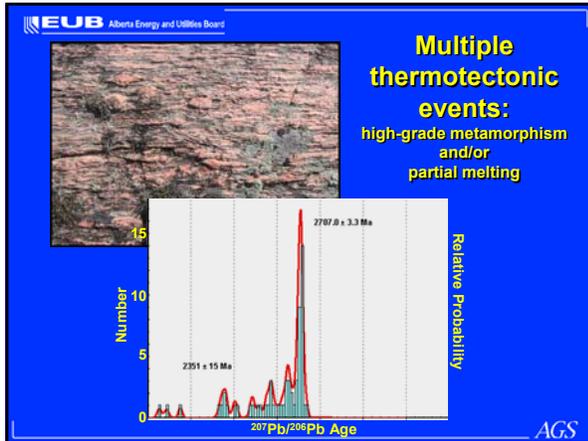
- strain gradients and
- metamorphic reactions

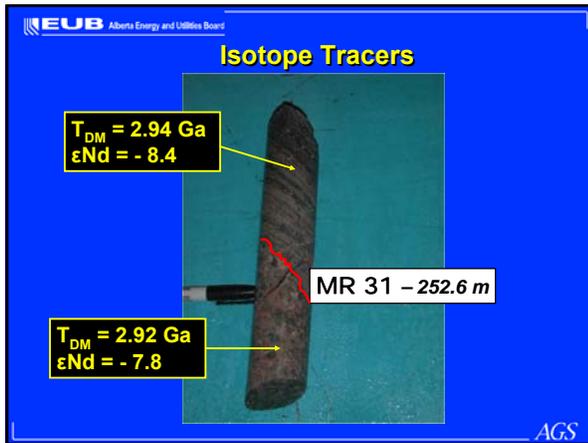
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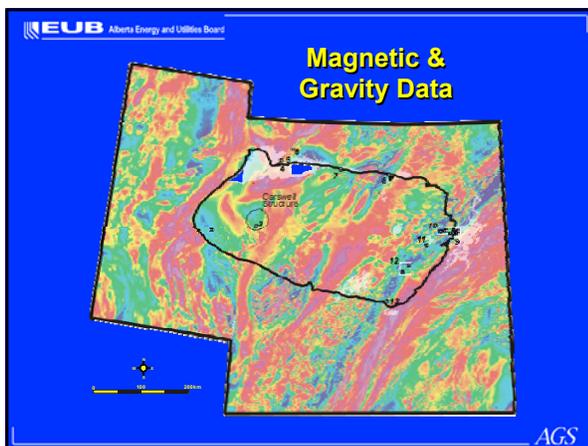
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Microscopy data

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Trans-Hudson orogen

"The Cree Lake Zone (Hearne Province) ... in northern Saskatchewan" is part of the "upper plate western hinterland of the Paleoproterozoic Trans-Hudson Orogen"

Bickford, Collerson and Lewry (1994)

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"...designations, such as Wollaston Lake Fold Belt, are avoided because of possibly misleading genetic and temporal connotations."

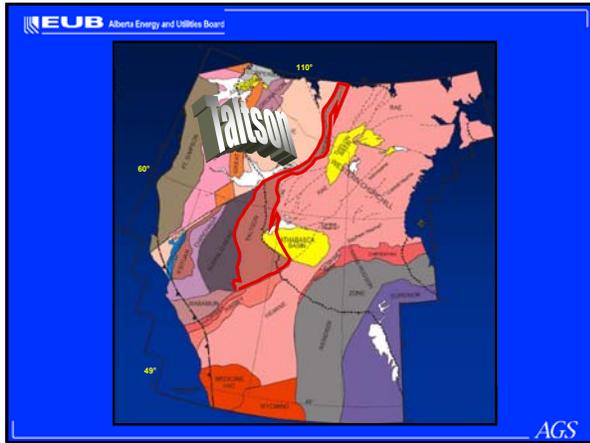
Lewry and Sibbald (1980)

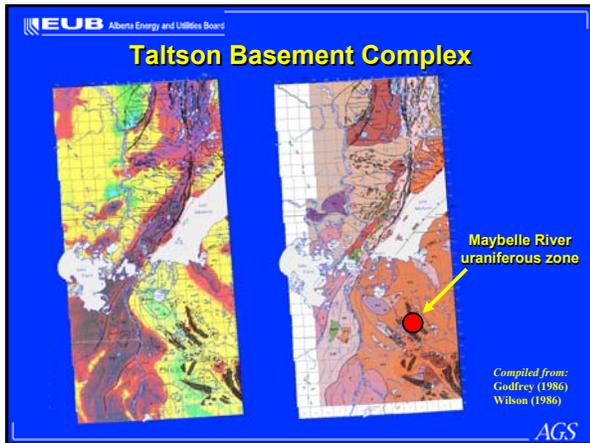
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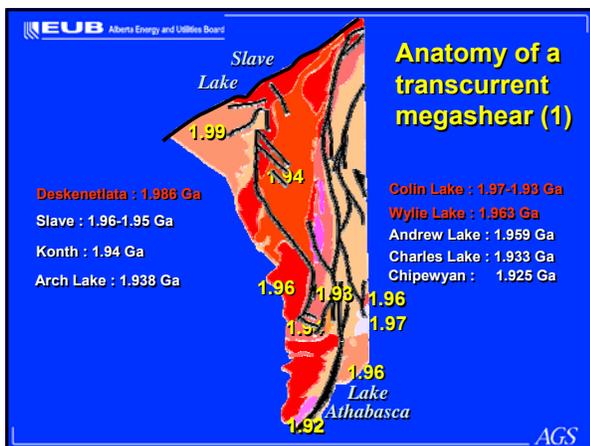
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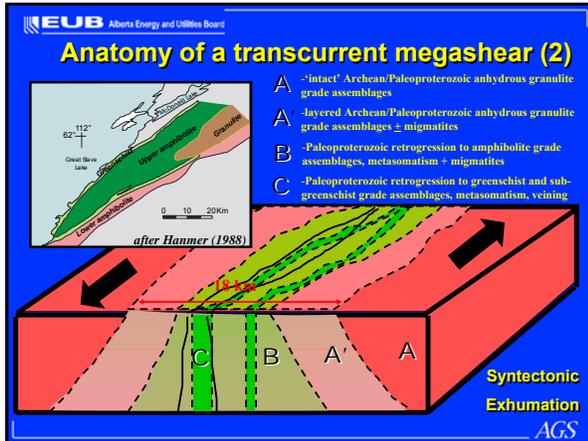
From data to model

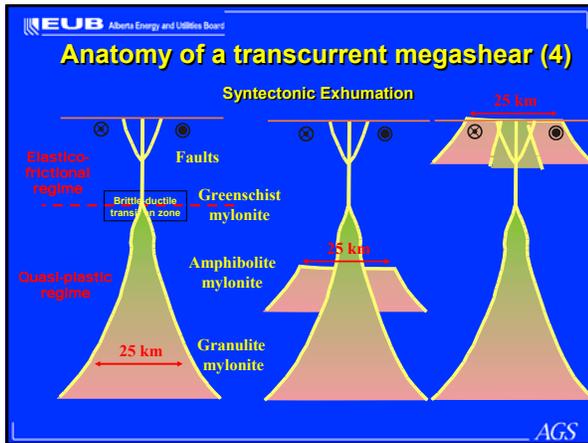
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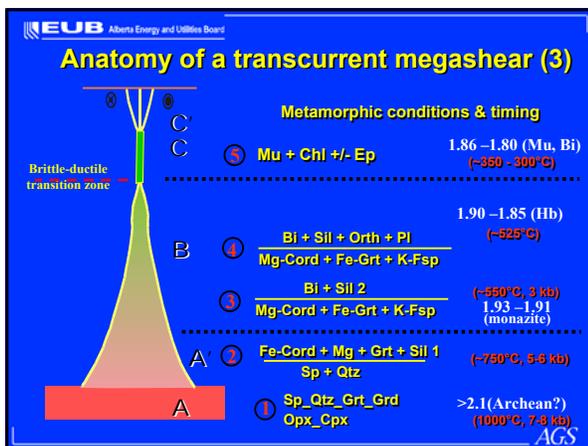


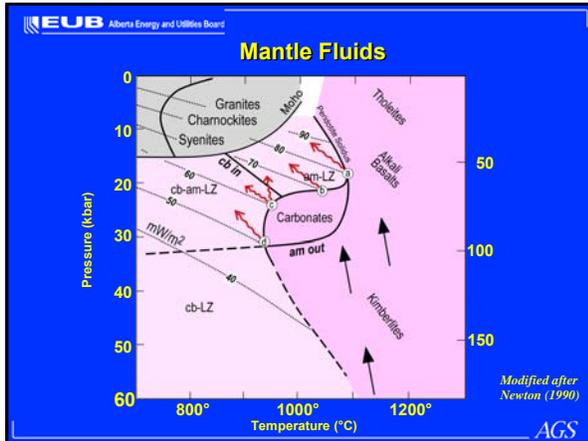


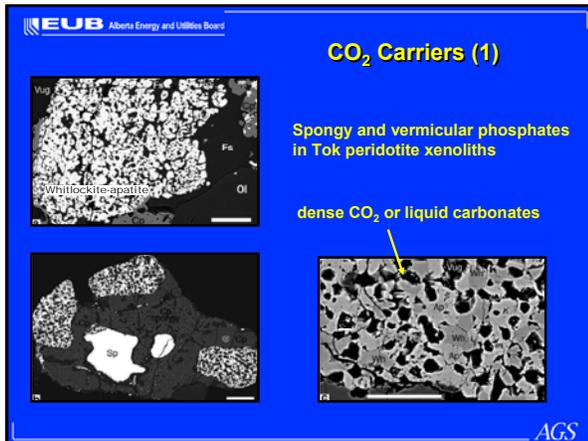


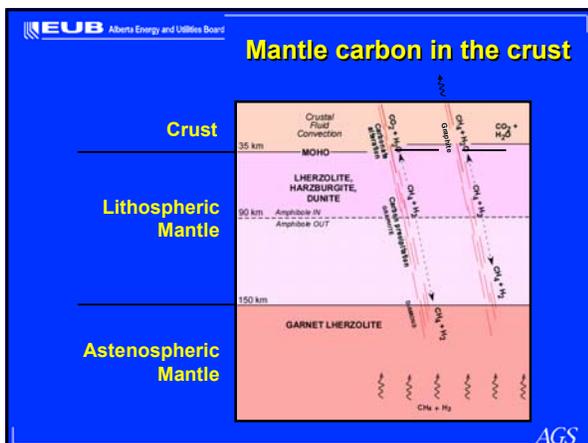


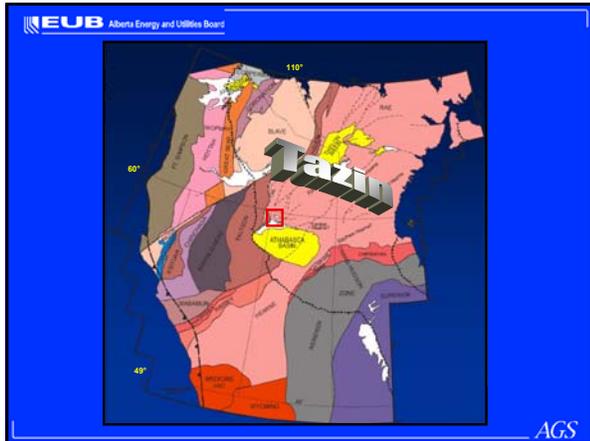


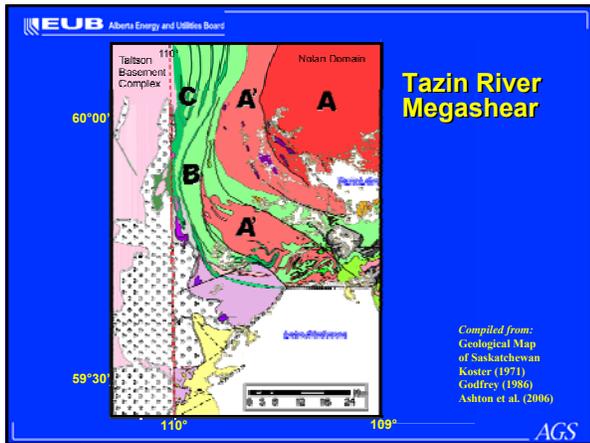


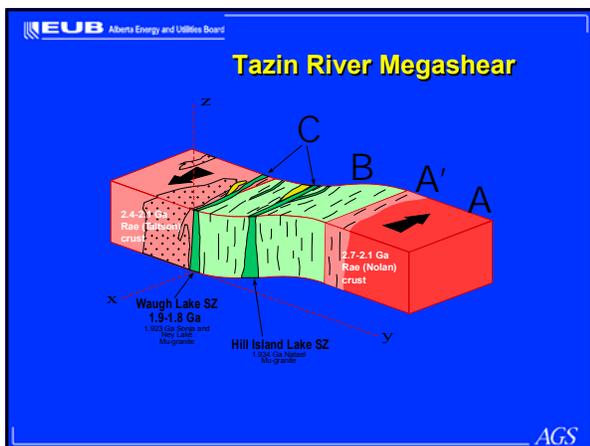


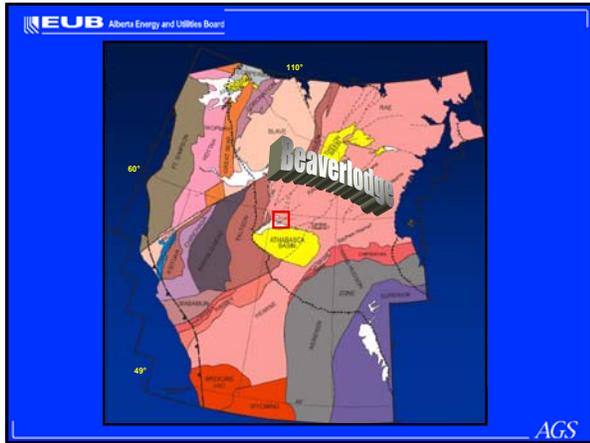


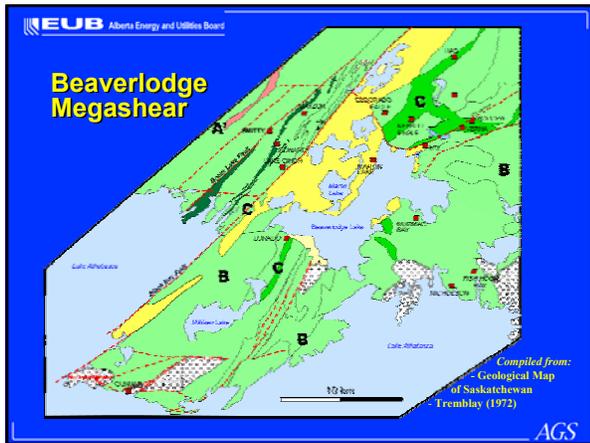


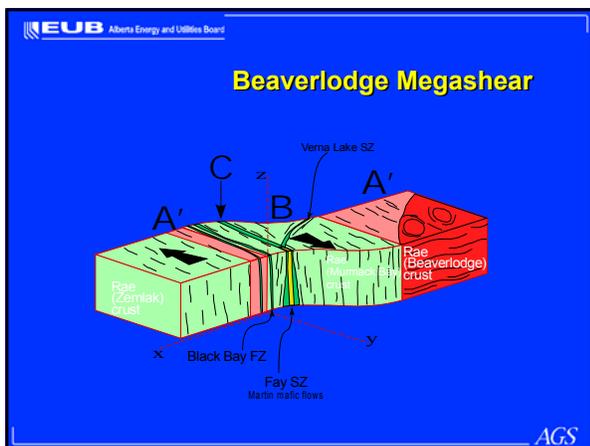


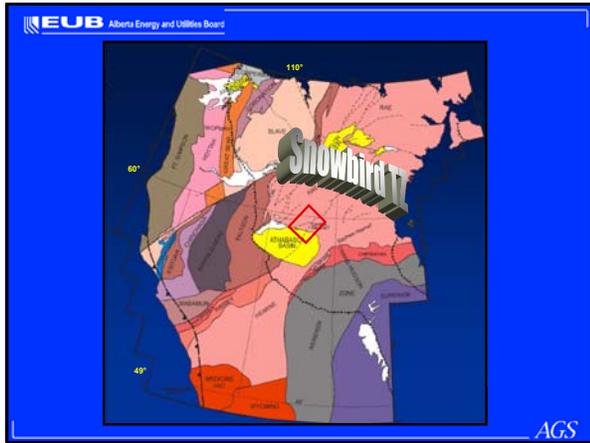


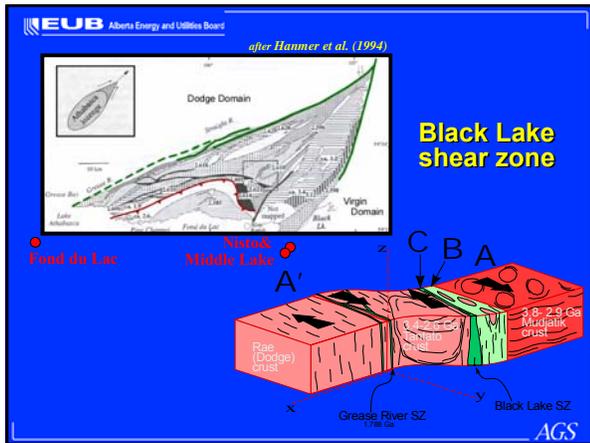


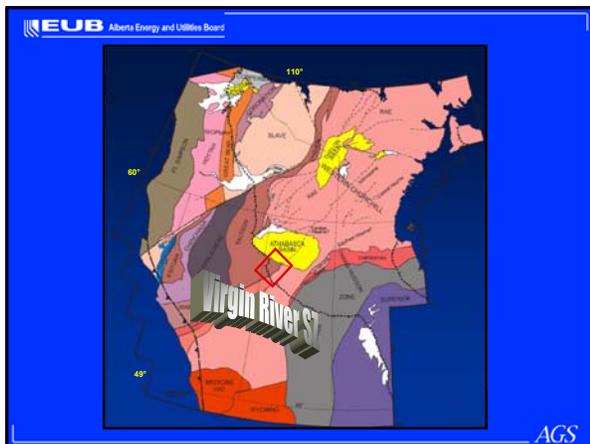


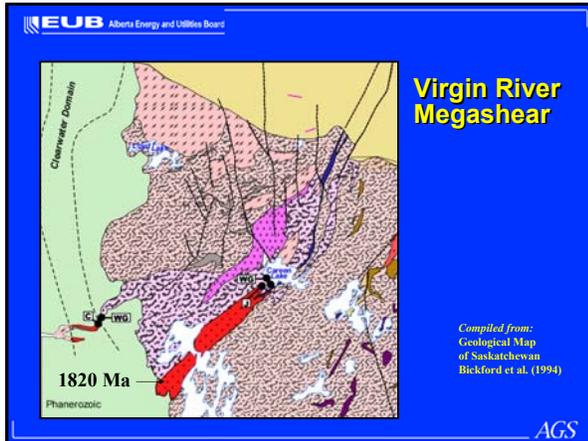


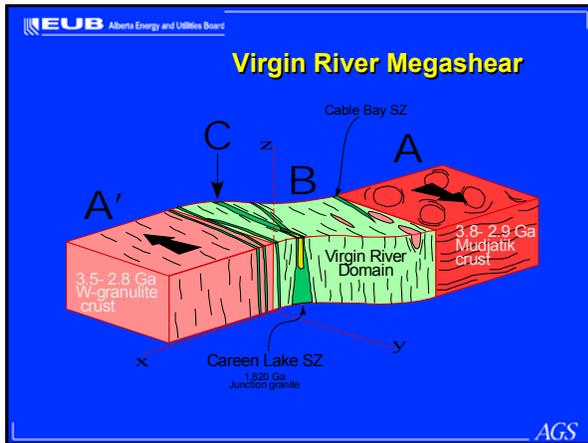


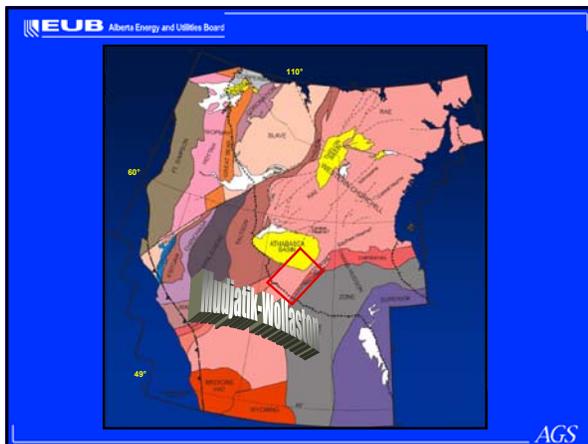




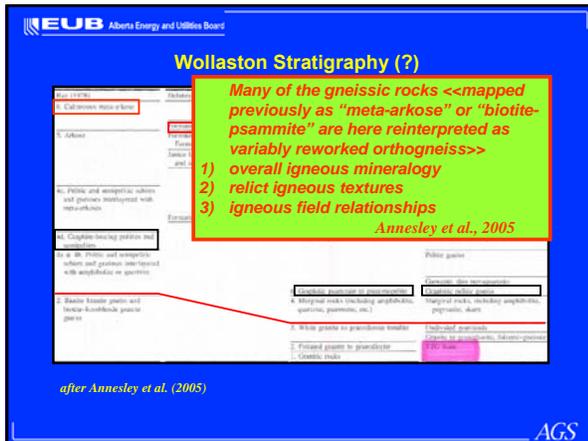


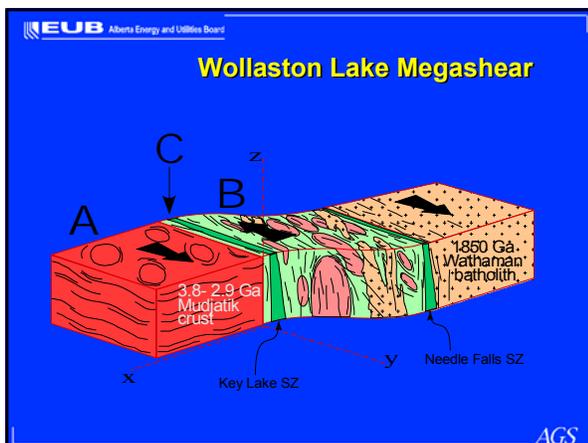


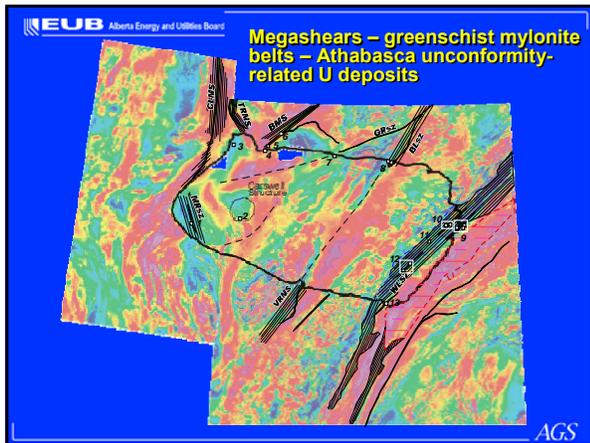


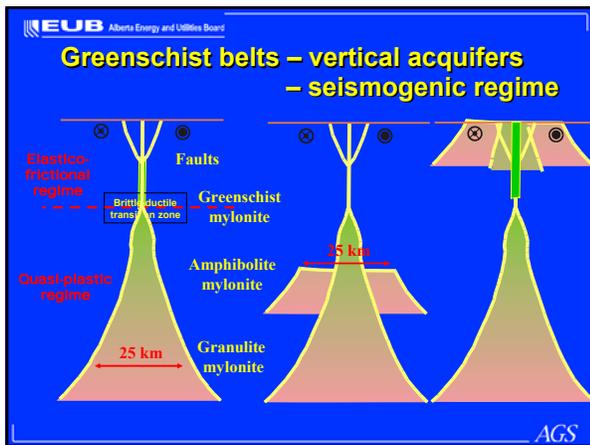


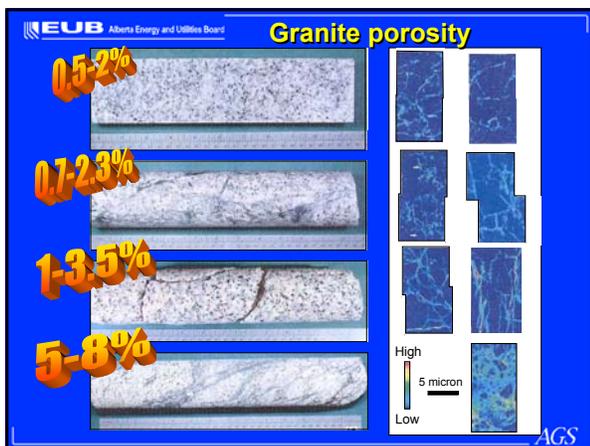


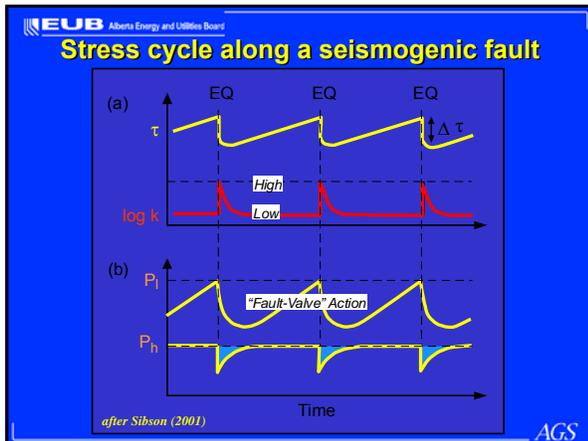


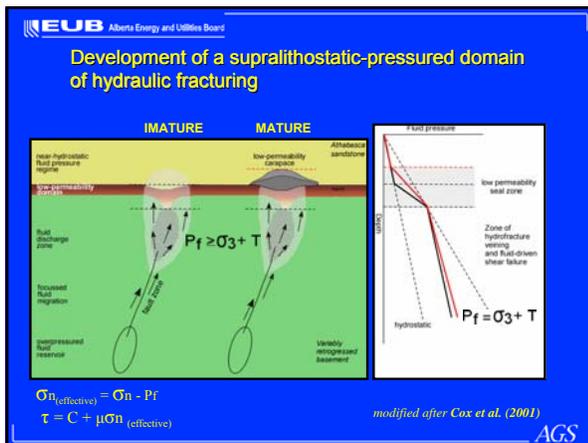












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Exploration Hints

- Graphite-bearing greenschist and subgreenschist facies fault/shear zones (C) may have provided high porosity and occasionally permeability for hydrodynamic cells in the fertile granitoidic basement (B);
- Fault-controlled hydrothermal cells commonly develop at dilational stopovers (jogs) and bents along faults;
- Athabasca clastic strata capping fault/shear zones
 - trigger overpressuring of the fault-controlled hydrothermal system and
 - are excellent collectors for U-bearing fluids migrating up the fault/shear zone;
- If the collecting cap is not present, graphitic fault/shear zones can still host U ore if the erosion did not proceed too deep into the ancient hydrothermal system

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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.

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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.

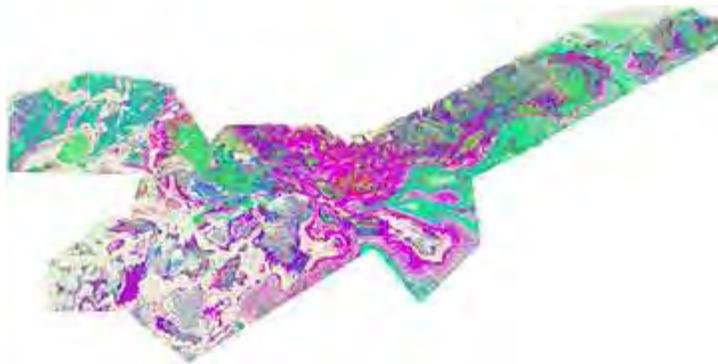
The Exploranium GR-820 is a self-stabilising, multi-channel (256 or 512) spectrometer that can be configured with up to 67.2 litres of sodium-iodide detector volume. It includes an upward-looking detector spectrometer which may be configured with up to 12.6 litres of detector volume. The GR-820 is a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

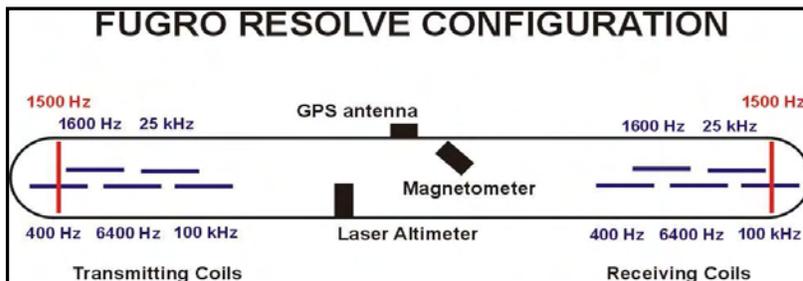
Frequency domain helicopter EM (HEM) systems (right, below) are inherently different than fixed wing time domain (FTEM) systems (above) or Helicopter time domain EM (HTEM) systems (left). The differences have less to do with the domain than with the coil array. The Laplace transform can yield frequency 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.



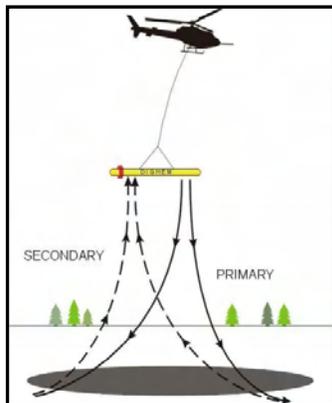
Most EM surveys include a magnetometer in addition to an electromagnetic system. The compact symmetric transmitter-receiver system geometry in helicopter time domain and frequency domain systems produces simpler anomaly shapes in profile and plan, which are independent of flight direction. Helicopter 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.

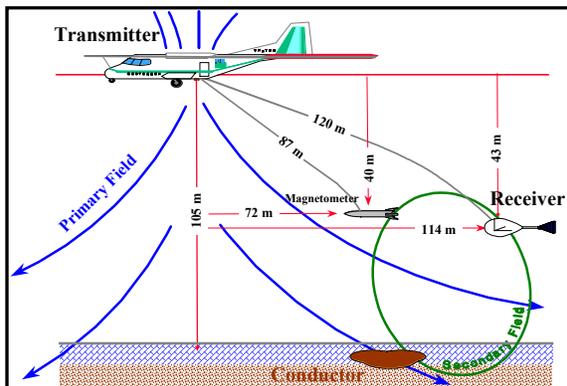


Frequency Domain System Description

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 to 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 more limited.

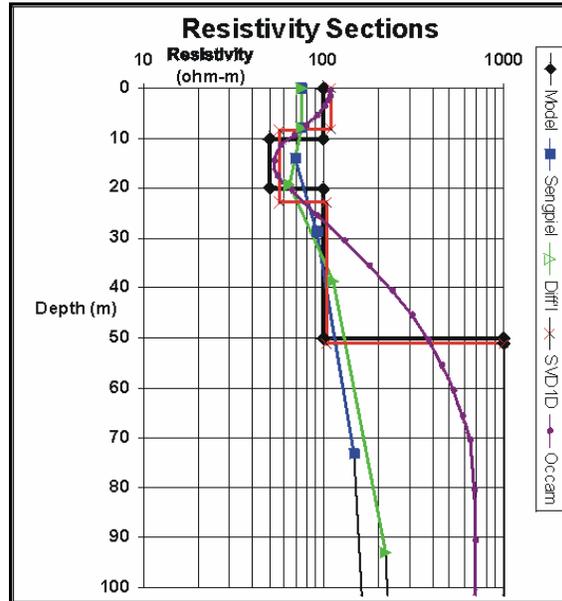
Resistivity Depth Sections and Inversions

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.

Airborne Gravity Systems

Single vertical sensor airborne gravity system¹

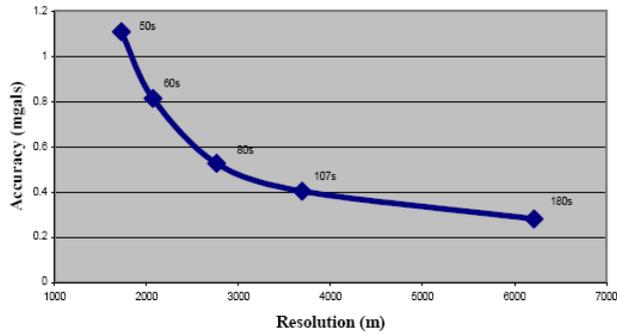
The INS DGPS single vertical sensor airborne gravity system is the most common technology for commercial gravity survey. Recent case studies comparing airborne and ground gravity data (the GT-1A) demonstrated an error < 0.5 mgals for halfwavelength of 4 km after 1st order tie-line levelling. This compares favorably with most regional ground gravity datasets with equivalent ground gravity station spacing.

INTRODUCTION

The challenge presented by airborne gravity is being able to accurately discriminate between the aircraft accelerations (may be as large as 100 000 mgals) and accelerations due to variations in geology (10's of mgals). Although commercial surveys have been carried out from the late 1970s, the advent of Differential GPS provided the cost-effective means of mapping the aircraft velocity, key for vertical aircraft accelerations, Eötvös and Coriolis effects. As GPS technology advanced the accuracy/resolution of airborne gravity systems improved. By 2001, sub-mgal accuracies for ~ 6 km resolution were reported using modified LaCoste and Romberg single sensor marine gravimeters. Despite this progress, commercial application of single sensor airborne gravity was limited primarily to basin mapping for the petroleum market where it was focused in transition zones and rugged topography where access made ground or marine gravity unfeasible. The limited application was partly due to relatively high survey cost and low production rates.

A typical airborne gravity system (such as the GT-1A) is a single vertical sensor, INS DGPS scalar gravimeter with a Schuler-tuned three-axis platform. The gravity sensor is a custom-designed accelerometer mounted inside a gyro-stabilized unit. Inputs from fiber optic gyro, inclinometers, angle sensors and dual frequency GPS are used to drive servo motors, which maintain the sensor in a vertical position. This virtually eliminates the effects of horizontal accelerations in the measured signal. The entire assembly is mounted on a rotation table, maintaining the sensor orientation at the same heading. Gravity data are sampled at ~18 Hz, sub-sampled to 2 Hz and integrated with dual frequency DGPS data to remove effects of vertical aircraft acceleration and Eötvös effect. Final gravity is reduced using a non-stationary adaptive Kalman filter using: raw gravity; aircraft vertical velocity (DGPS phase information); and platform misalignment errors. Filter length is user-defined according to resolution requirements. Gabell *et al.* (2004) provide a detailed description of the system.

¹ From: *New Fugro airborne gravity system – Survey test over the Vredeford structure (South Africa)* L. AMEGLIO, Fugro Airborne Surveys (Central Region) - 22 Packard Street, Woodmead - P.O. Box 47, Sunninghill, 2157 -Gauteng, Republic of South Africa



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

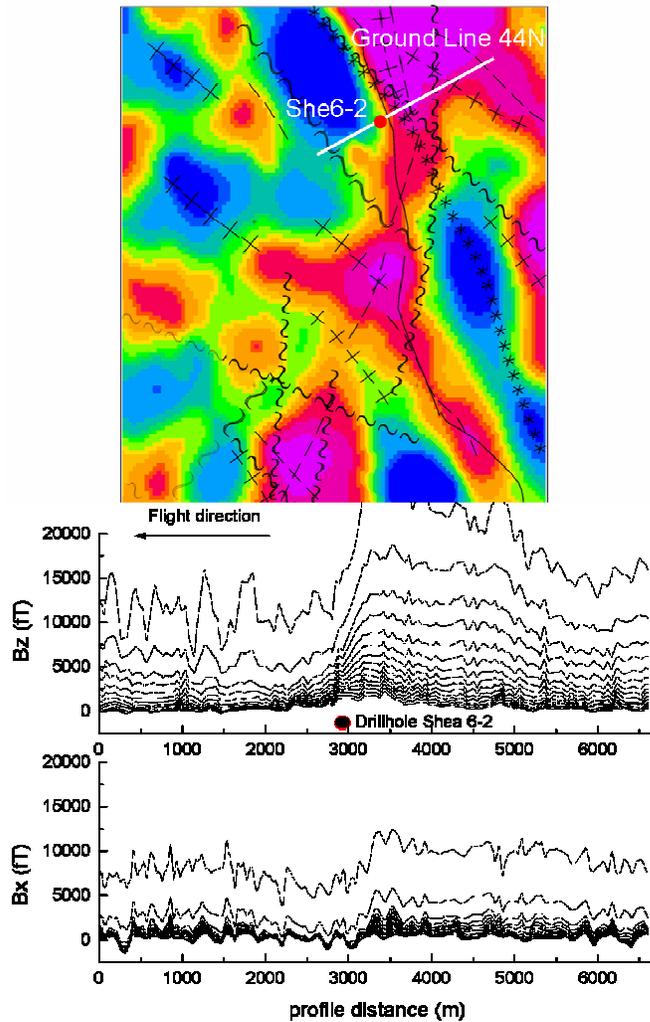
Uranium

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.

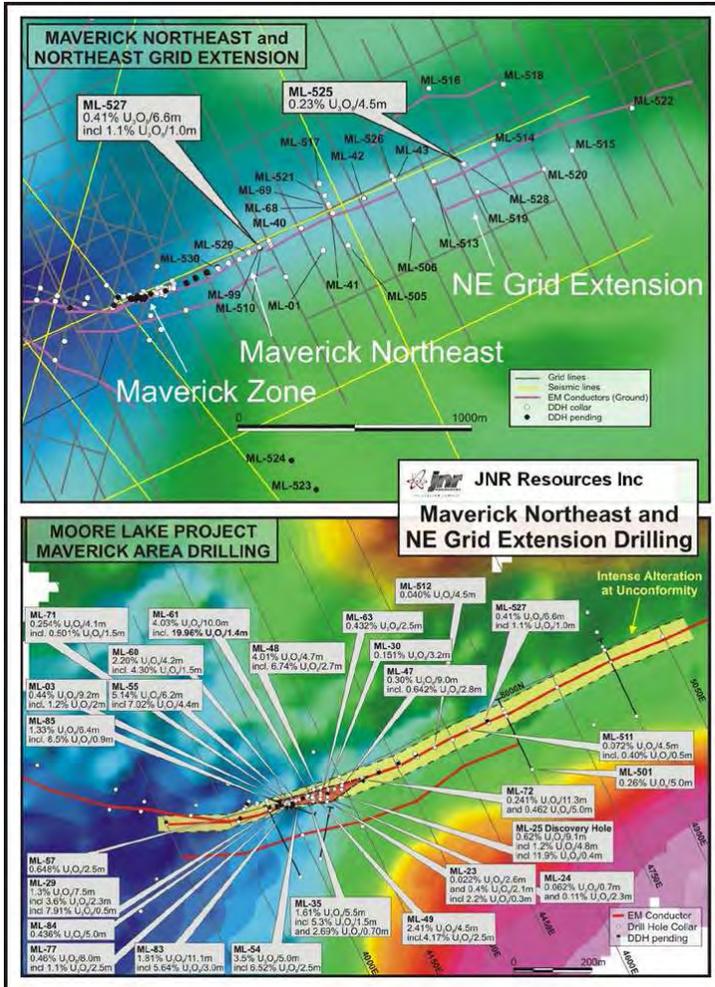
A large regional Gravity low is thought to be associated with the Olympic Dam deposit in Australia and similar lows in other areas of favourable geology have been the target of further exploration.



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.

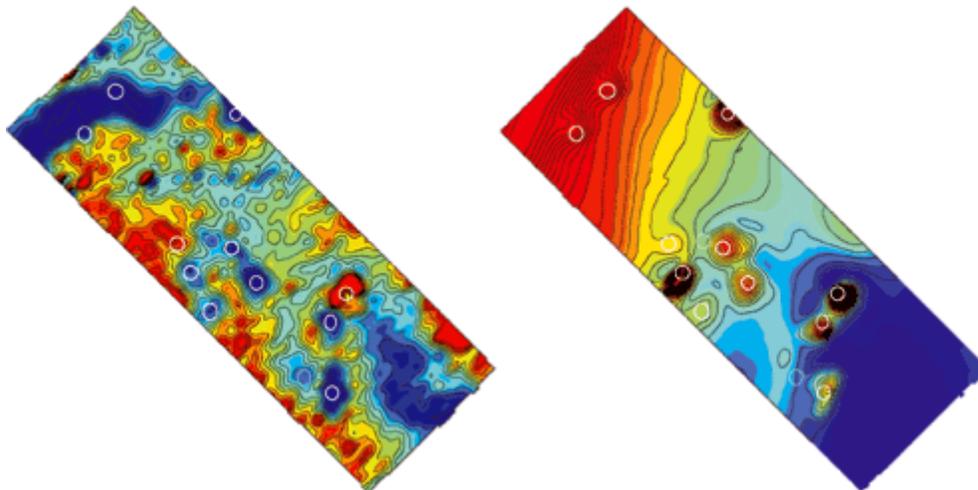
In the JNR example above, the red and purple NE trending lines are EM conductor axis. The conductive alteration at the unconformity, which is associated with concentrated uranium mineralization, is caused by graphite associated with altered pelites and or clay mineralisation.

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.

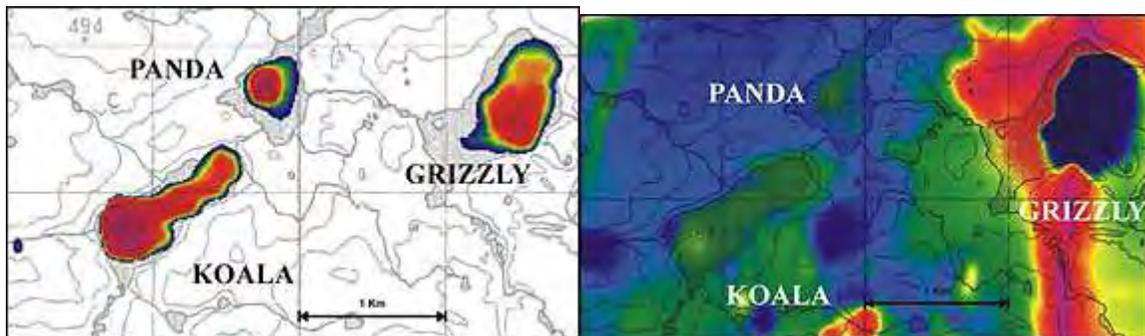
A combined AEM/Magnetic survey was flown over a 12 km by 4 km area in 1996. The area contained 11 kimberlite bodies defined by magnetics (see Total Field Magnetic Intensity Map) and confirmed by drilling. The time-domain EM survey utilised both a 30 Hz and 90 Hz waveform frequency: the former with a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

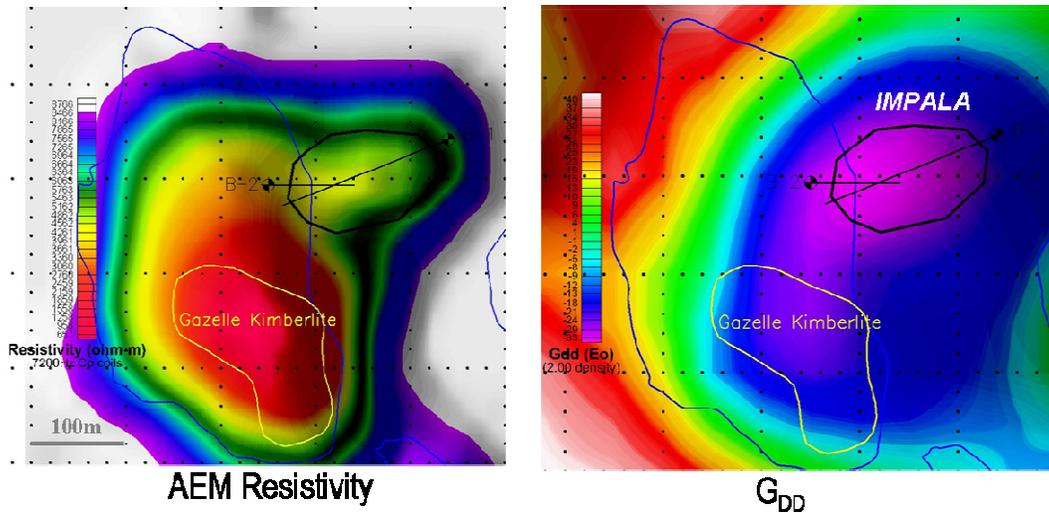
Jellicoe, B.C., Robertshaw, P., Williamson, P. and Murphy, J.D., 1998, Summary of Exploration Activities and Results for the Fort à la Corne Diamond Project, Saskatchewan, in Summary of Investigations, 1998, Saskatchewan Geological Survey.



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..



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.

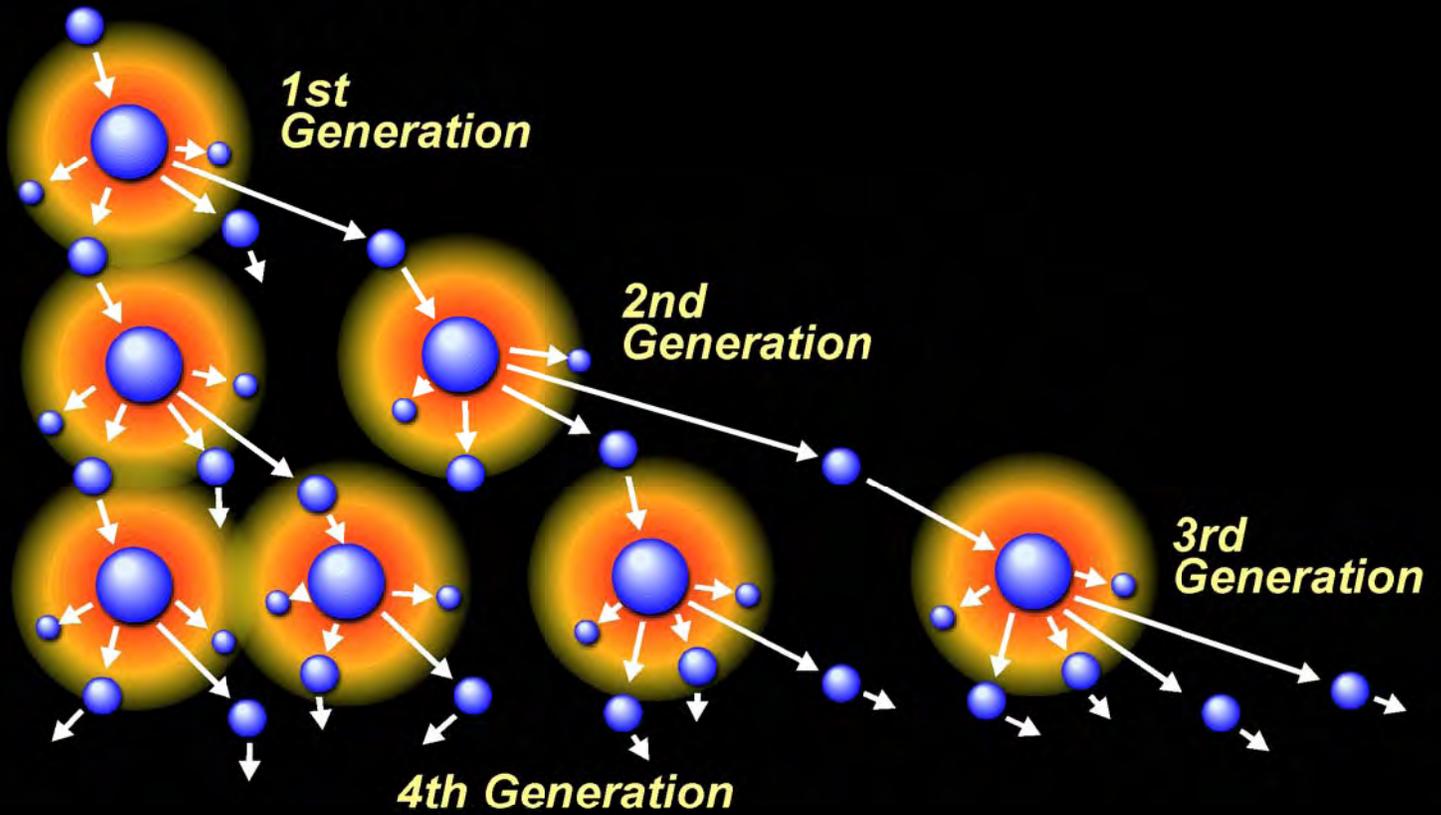
The Falcon airborne gravity gradiometer survey at Ekati was flown in the summer of 2000 at 100 m line spacing and 80 m ground clearance.

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.

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Fission Chain Reaction



- Fission fragment
eg. Ke, Cs, Rb, Ba, Xe or Sr
- Neutron
- Uranium-235 atom