# EARTH 471
# Mineral Deposits

## Uranium ore deposits

# Uranium – fun facts!

- Discovered by a German chemist (Klaproth) in 1789 who precipitated a yellow compound by dissolving pitchblende in nitric acid, neutralizing it with a base, heating it with charcoal to produce Uranium oxide
- Names after the planet Uranus
- 1841 a French Chemist (Peligot) produced uranium metal
- Used to colour pottery and glass until it was found to be radioactive in 1896 (Becquerel)
- 1942: Enrico Fermi's research group discover fission

wiki

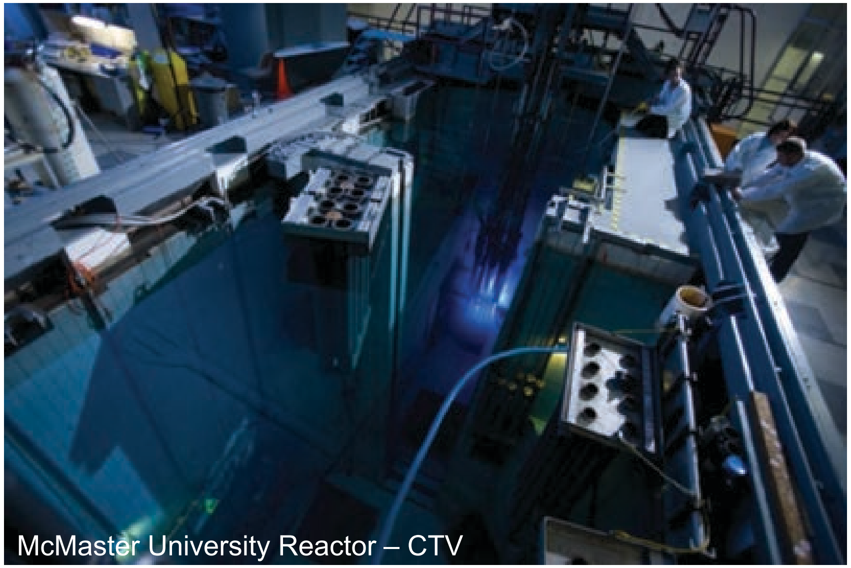
wiki

# Uranium

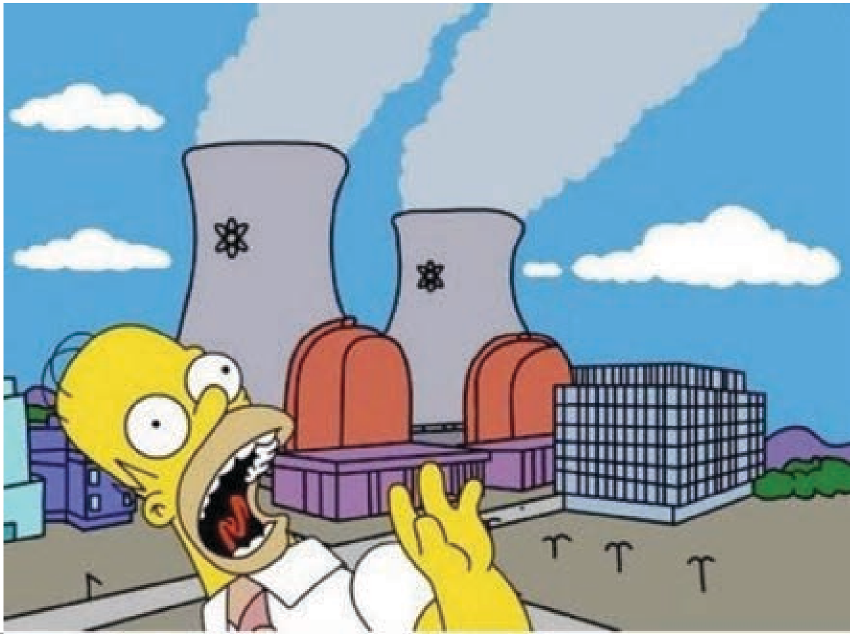
Uses

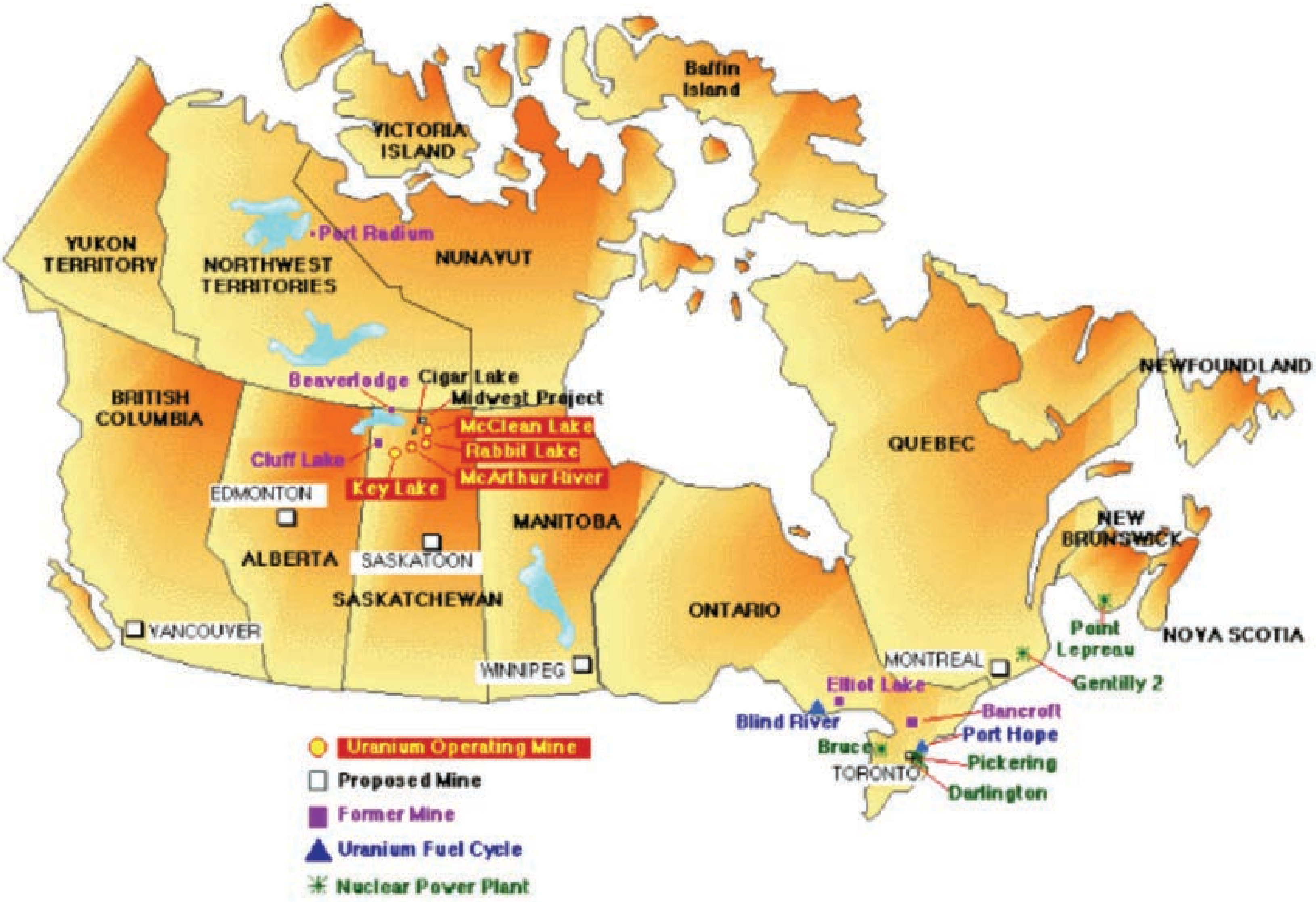
  - Energy
  - Medical isotopes
  - Weaponry

- 17% of world's electricity comes from nuclear power
- 438 nuclear power plants and 270 research reactors worldwide
- We require 155 million pounds of $U_3O_8$ per year



McMaster University Reactor – CTV





http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Canada--Uranium/

# Uranium

- Actinide; Atomic number 92
- $^{238}U$ is most abundant 99.3%
- Half life of $^{238}U$ is 4.46 Ga (~ same age as the Earth
- Occurs as $U^{4+}$ in the magmatic environment (very incompatible)
- Relatively high concentrations in felsic rocks

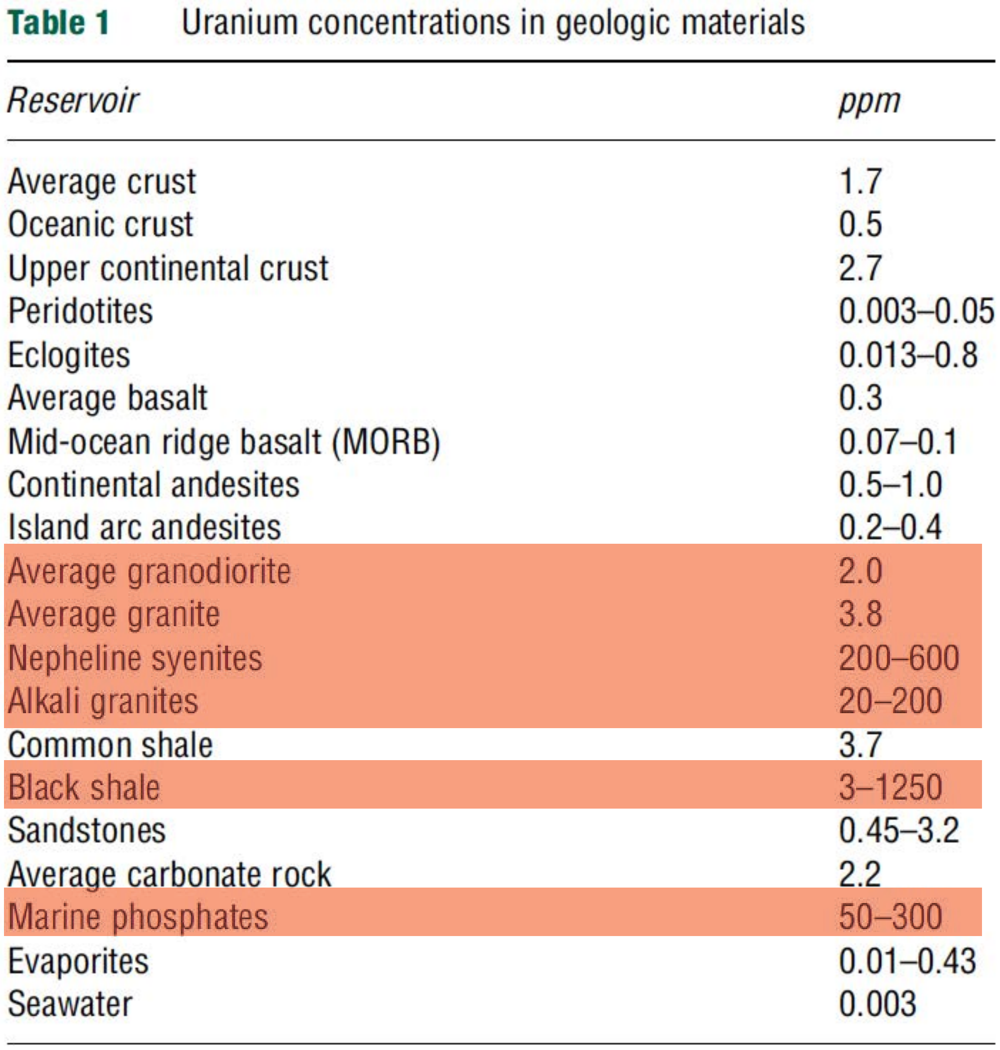


**Table 1** Uranium concentrations in geologic materials

| *Reservoir* | *ppm* |
|---|---|
| Average crust | 1.7 |
| Oceanic crust | 0.5 |
| Upper continental crust | 2.7 |
| Peridotites | 0.003–0.05 |
| Eclogites | 0.013–0.8 |
| Average basalt | 0.3 |
| Mid-ocean ridge basalt (MORB) | 0.07–0.1 |
| Continental andesites | 0.5–1.0 |
| Island arc andesites | 0.2–0.4 |
| Average granodiorite | 2.0 |
| Average granite | 3.8 |
| Nepheline syenites | 200–600 |
| Alkali granites | 20–200 |
| Common shale | 3.7 |
| Black shale | 3–1250 |
| Sandstones | 0.45–3.2 |
| Average carbonate rock | 2.2 |
| Marine phosphates | 50–300 |
| Evaporites | 0.01–0.43 |
| Seawater | 0.003 |

Kyser (2014)

<u>Major minerals:</u>

**<u>Uraninite</u>** ($UO_2$)

Pitchblende (fine-grained uraninite)

# Uranium Economics in Canada

- Canada is the world's second largest producer of Uranium (15% of world production)
- Uranium refined in Blind River Ontario (Cameco)
- Port Hope, ON: only commercial supply of fuel-grade natural uranium dioxide (1/4 worldwide)

https://www.youtube.com/watch?v=xTFFTQ-bCPI

- 85% of Canada's uranium production is exported
- Total production valued at $1 billion
- Exports to USA, Europe and Asia
- CANDU reactors supply 15% of electricity used in Canada
- 19 operating reactors (18 in Ontario)

*Source: NRCAN*

# Uranium Prices

# This is the most complicated U deposits diagram I could find…

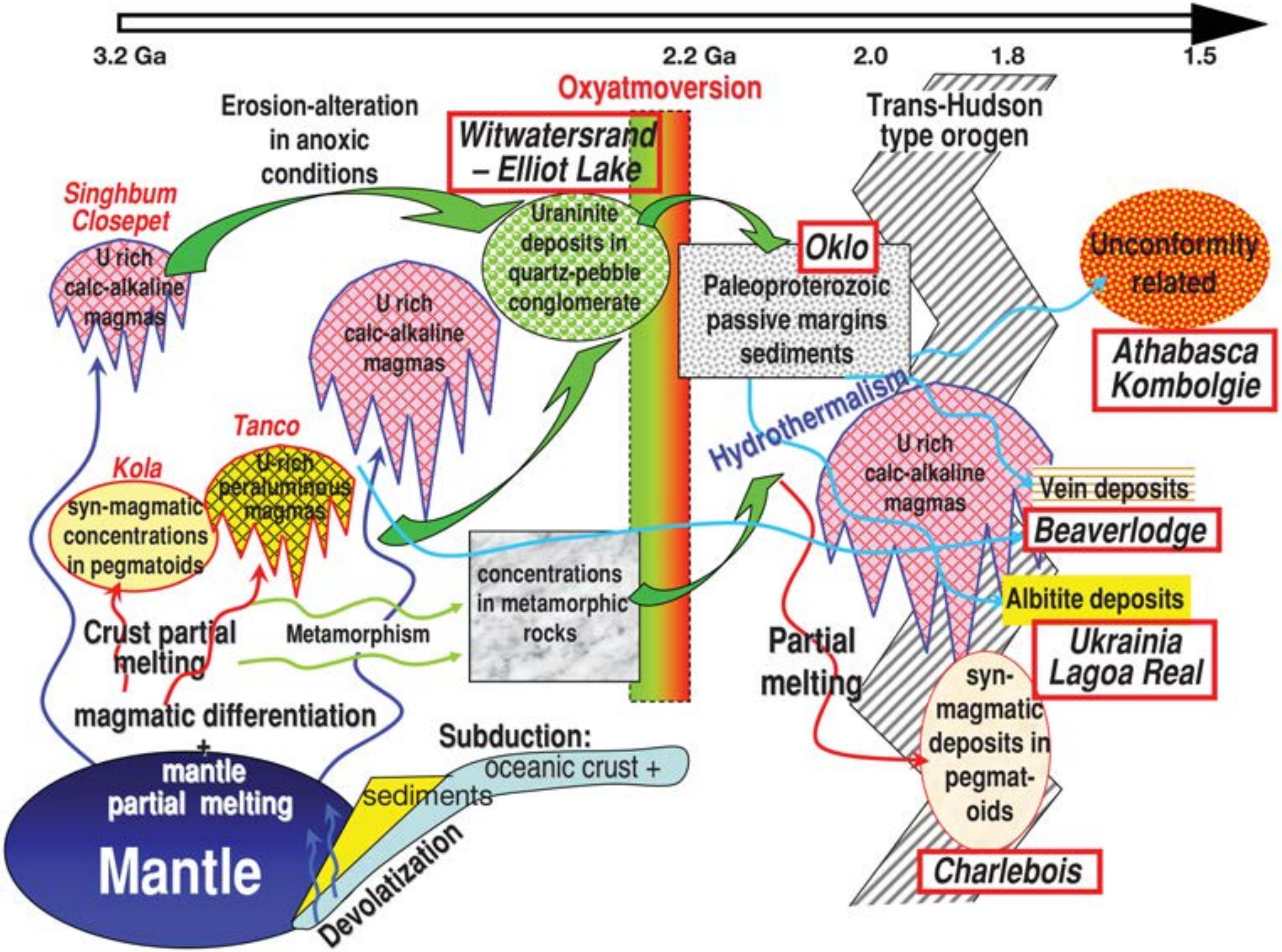
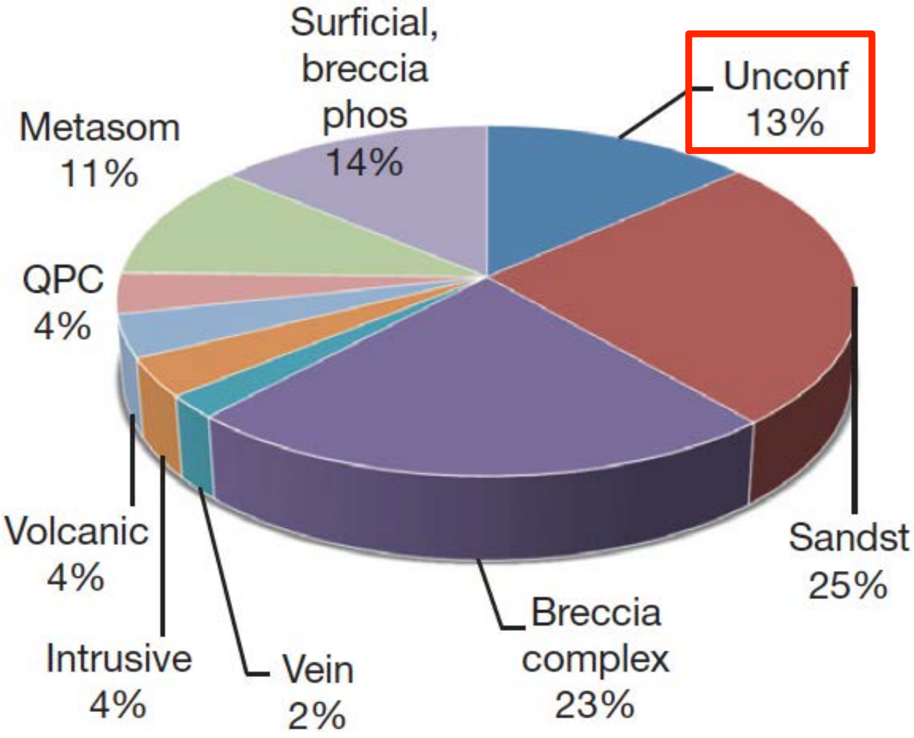


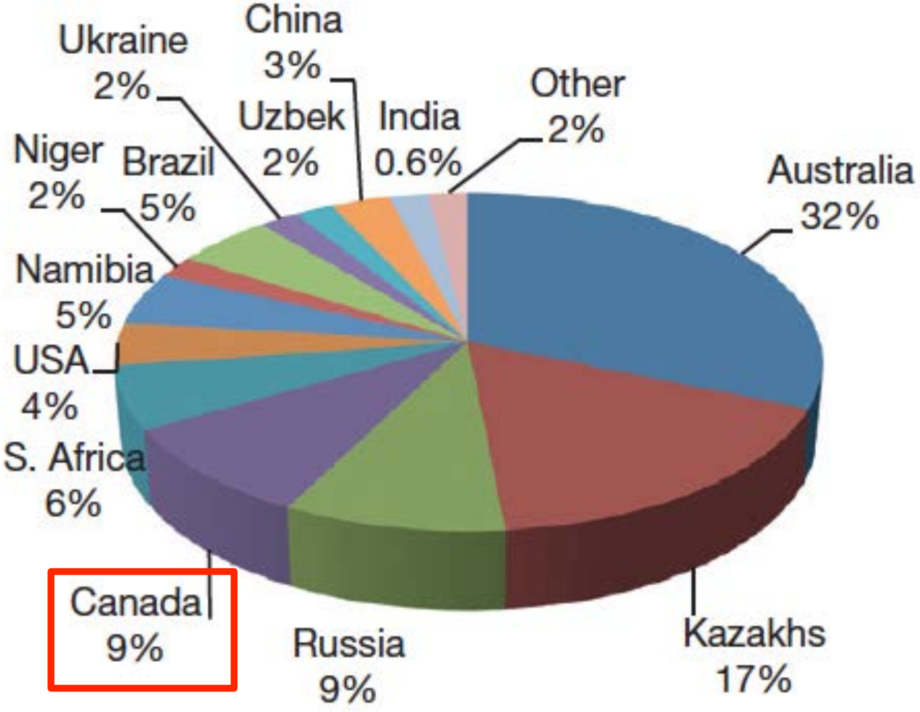
FIG. 2. Evolution of uranium fractionation mechanisms and the genesis of the different uranium deposit types from Mesoarchean to Mesoproterozoic. The fractionation mechanism is in bold, the major occurrences of the different types of ore deposits formed during this period of time are in italics and framed in red.

Cuney (2010, Econ. Geol.)

## Uranium deposit types



## Uranium resources



## UNCONFORMITY-ASSOCIATED URANIUM DEPOSITS OF THE ATHABASCA BASIN, SASKATCHEWAN AND ALBERTA

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### Abstract

This review of the geology, geophysics, and origin of the unconformity-associated uranium deposit type is focused on the Athabasca Basin. Pods, veins, and semimassive replacements of uraninite (var. pitchblende) are located close to unconformities between late Paleo- to Mesoproterozoic conglomeratic sandstone basins and metamorphosed basement rocks. The thin, overall flat-lying, and apparently unmetamorphosed but pervasively altered, mainly fluvial strata include red to pale tan quartzose conglomerate, sandstone, and mudstone. Beneath the basal unconformity, red hematitic and bleached clay-altered regolith grades down through chloritic altered to fresh basement gneiss. The highly metamorphosed interleaved Archean to Paleoproterozoic granitoid and supracrustal basement gneiss includes graphitic metapelitic that preferentially hosts reactivated shear zones and many deposits. A broad variety of deposit shapes, sizes and compositions ranges from monometallic and generally basement-hosted veins to polymetallic lenses located just above or straddling the unconformity, with variable Ni, Co, As, Pb and traces of Au, Pt, Cu, REEs, and Fe.

### Résumé

Cet examen de la géologie, de la géophysique et de l'origine des gîtes d'uranium associés à des discordances est focalisé sur le bassin d'Athabasca. Les minéralisations d'uraninite (variété pechblende) qui prennent la forme de lentilles, de filons ou de corps semi-massifs de remplacement se situent près de la discordance entre des grès conglomératiques de bassin du Paléoprotérozoïque tardif au Mésoprotérozoïque et les roches du socle métamorphisées. La succession sédimentaire de bassin est mince, repose dans l'ensemble à plat, est apparemment non métamorphisée, mais profondément altérée, et se compose principalement d'unités fluviatiles constituées de conglomérats quartzeux, de grès et de mudstones de couleur rouge à chamois pâle. Sous la discordance marquant la base de la succession sédimentaire, un régolite hématitique rouge, décoloré par endroits par une altération argileuse, passe progressivement vers les profondeurs du socle à des gneiss chloritisés puis à des gneiss non altérés. Les roches très métamorphisées du socle, formées d'une intercalation de gneiss granitoïdes et de gneiss supracrustaux de l'Archéen au Paléoprotérozoïque, incluent des métapélites graphitiques qui renferment de manière préférentielle des zones de cisaillement réactivées et un grand nombre de gîtes. Les gîtes sont de formes, de dimensions et de compositions très variées, passant de minéralisations monométalliques, généralement sous forme de filons encaissés dans le socle, à des lentilles polymétalliques présentant des concentrations variables de Ni, Co, As, Pb et des traces de Au, Pt, Cu, de terres rares et de Fe, qui se situent à cheval sur la discordance ou à peu de distance au-dessus.

### Introduction

This synopsis of unconformity-associated uranium (also unconformity-related and -type) deposits emphasizes the Athabasca Basin. The empirical term 'associated' is chosen because some genetic aspects are still under debate and the deposits occupy a wide range of spatial positions and shapes with respect to the unconformity. An expanded version of this paper introduces the final volume for EXTECH IV, Athabasca Uranium Multidisciplinary Study (Jefferson et al., 2007). Citations therefore include the most recent publications of EXTECH IV in addition to classic references.

After a concise definition, the grade, tonnage, and value statistics of unconformity-associated uranium deposits are provided in global and Canadian context. Geological attributes are summarized on continental, district, and deposit scales: favourable expressions of deposits; their size, morphology, and architecture; ore mineralogy and composition; and alteration mineralogy, geochemistry, and zonation. Key exploration criteria are summarized for geology, geochemistry, and geophysics. Genetic and exploration models are reviewed in terms of conventional knowledge and recent advances, with reference to uranium sources, transport and focus of deposition. Conceptual and applied knowledge gaps are evaluated at the district and deposit scales. New lines of research and areas of uranium potential are proposed.

### Definition

Unconformity-associated uranium deposits are pods, veins, and semimassive replacements consisting of mainly uraninite dated mostly 1600 to 1350 Ma, and located close to basal unconformities between Proterozoic redbed basins and metamorphosed basement rocks, especially supracrustal gneiss with graphitic metapelite. Prospective basins in Canada (Figs. 1, 2) are 1 to 3 kilometres thick, relatively flat-lying, unmetamorphosed but pervasively altered, Proterozoic (ca. 1.8 to <1.55 Ga), mainly fluvial conglomeratic sandstone. The basement gneiss is paleoweathered with

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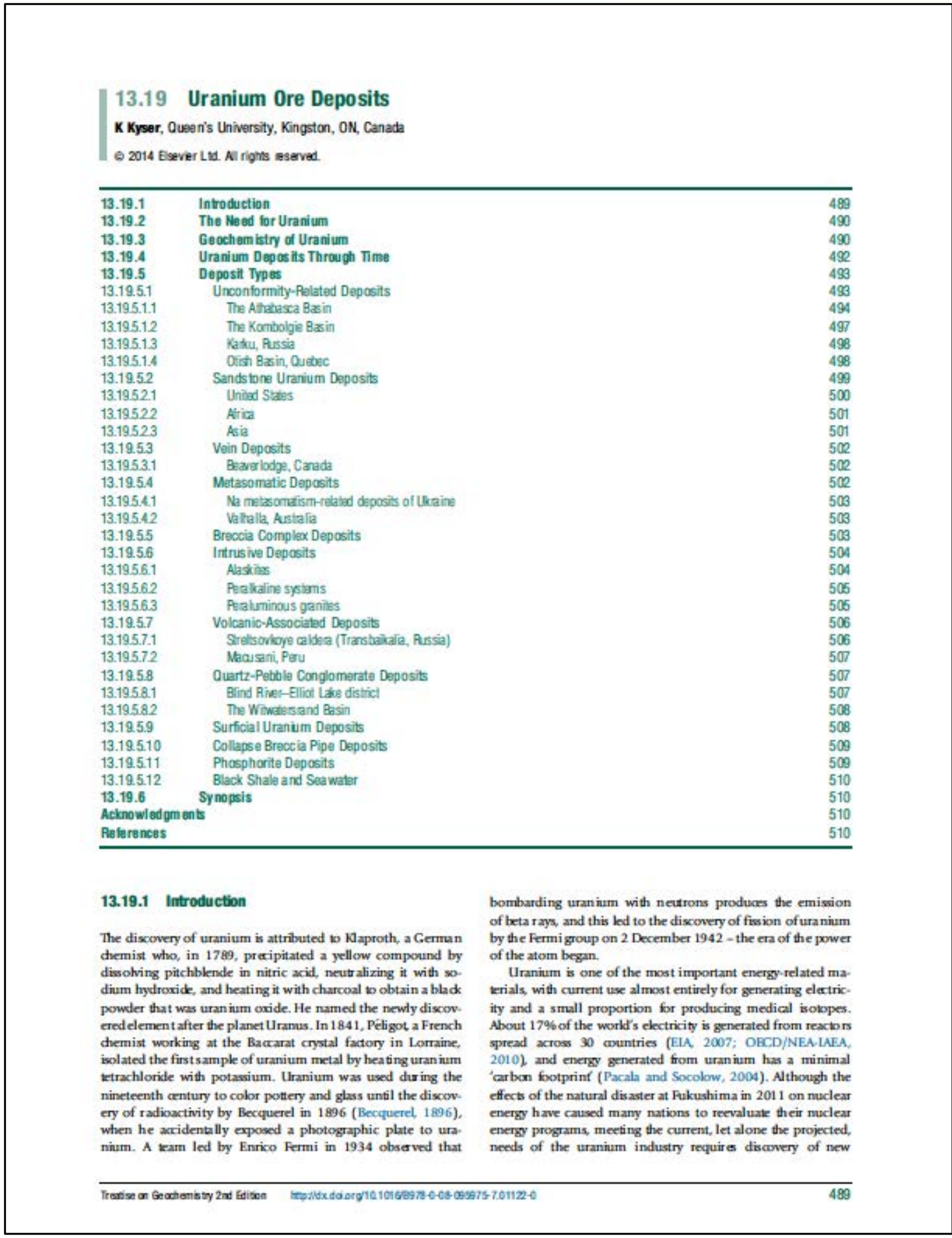
Jefferson, C.W., Thomas, D.J., Gandhi, S.S., Ramaekers, P., Delaney, G., Brisbin, D., Cutts, C., Quirt, D., Portella, P., and Olson, R.A., 2007, Unconformity-associated uranium deposits of the Athabasca Basin, Saskatchewan and Alberta, *in* Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 273-305.



## 13.19 Uranium Ore Deposits

**K Kyser**, Queen's University, Kingston, ON, Canada

### 13.19.1 Introduction

The discovery of uranium is attributed to Klaproth, a German chemist who, in 1789, precipitated a yellow compound by dissolving pitchblende in nitric acid, neutralizing it with sodium hydroxide, and heating it with charcoal to obtain a black powder that was uranium oxide. He named the newly discovered element after the planet Uranus. In 1841, Péligot, a French chemist working at the Baccarat crystal factory in Lorraine, isolated the first sample of uranium metal by heating uranium tetrachloride with potassium. Uranium was used during the nineteenth century to color pottery and glass until the discovery of radioactivity by Becquerel in 1896 (Becquerel, 1896), when he accidentally exposed a photographic plate to uranium. A team led by Enrico Fermi in 1934 observed that bombarding uranium with neutrons produces the emission of beta rays, and this led to the discovery of fission of uranium by the Fermi group on 2 December 1942 – the era of the power of the atom began.

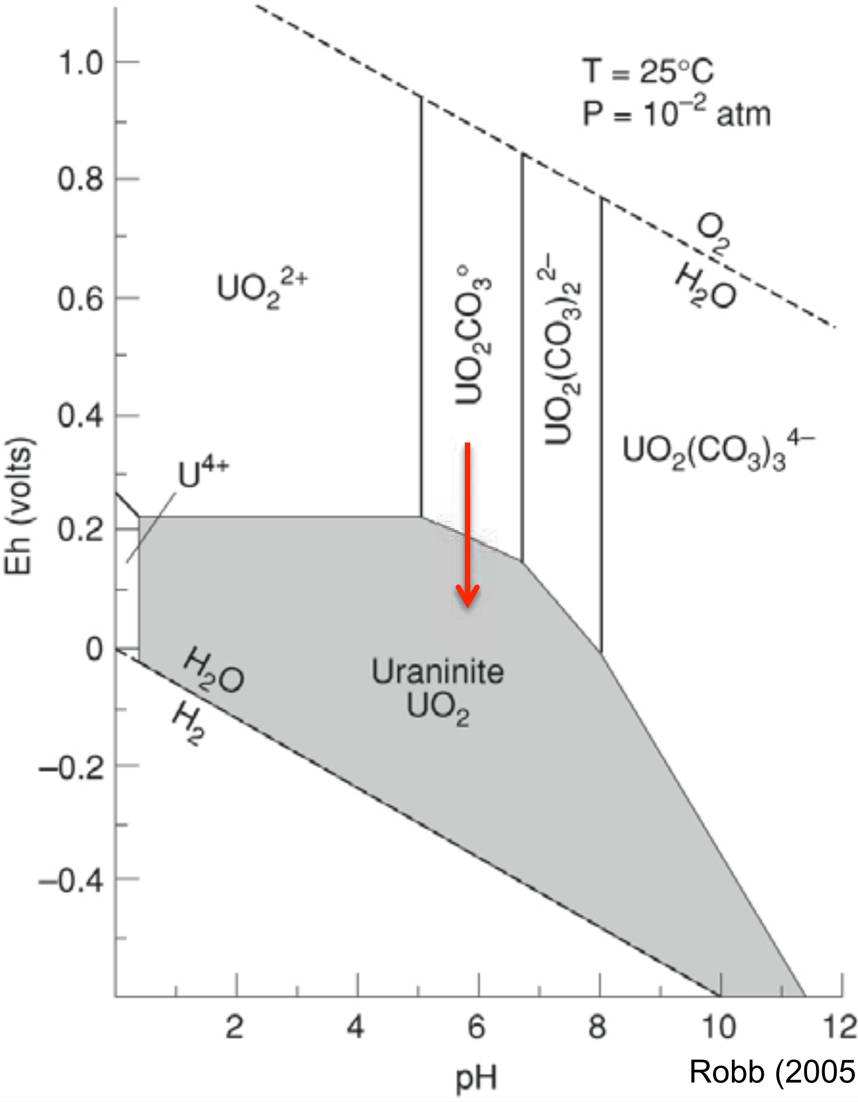
Uranium is one of the most important energy-related materials, with current use almost entirely for generating electricity and a small proportion for producing medical isotopes. About 17% of the world's electricity is generated from reactors spread across 30 countries (EIA, 2007; OECD/NEA-IAEA, 2010), and energy generated from uranium has a minimal 'carbon footprint' (Pacala and Socolow, 2004). Although the effects of the natural disaster at Fukushima in 2011 on nuclear energy have caused many nations to reevaluate their nuclear energy programs, meeting the current, let alone the projected, needs of the uranium industry requires discovery of new

Treatise on Geochemistry 2nd Edition http://dx.doi.org/10.1016/B978-0-08-095975-7.01122-0

# Aqueous geochemistry of uranium

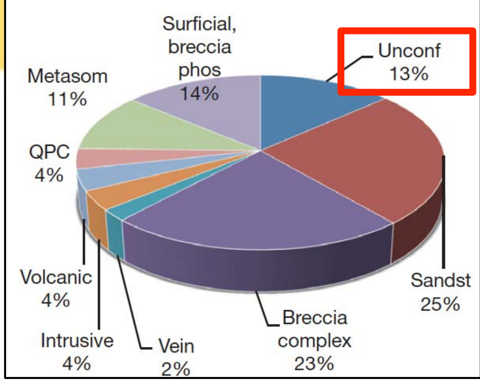
- Uranium is redox sensitive with two main oxidation states: uranyl: $U^{6+}$ (oxidized) and uranous: $U^{4+}$ (reduced)
- Uranium is more soluble in oxidizing, alkaline waters as $UO_2CO_3$ and $UO_2(Cl_2)$ **note $U^{6+}$ oxidation state**
- Soluble in strongly oxidizing waters (e.g. surface waters)
- Mobile during weathering (e.g. oxidizing conditions)

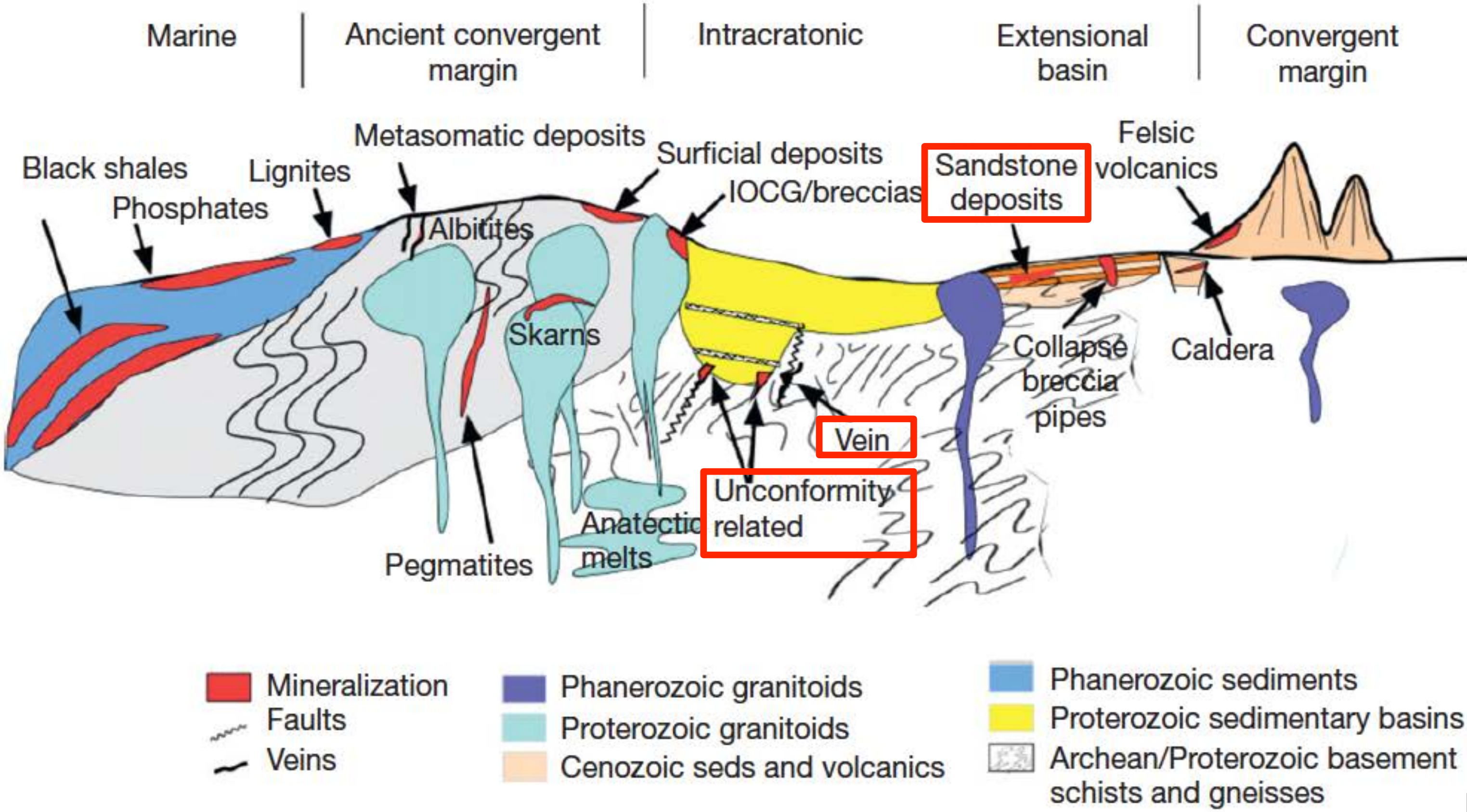
Decrease in $fO_2$ ($U^{6+}$ reduction to $U^{4+}$ by reaction with $Fe^{2+}$)



Robb (2005)

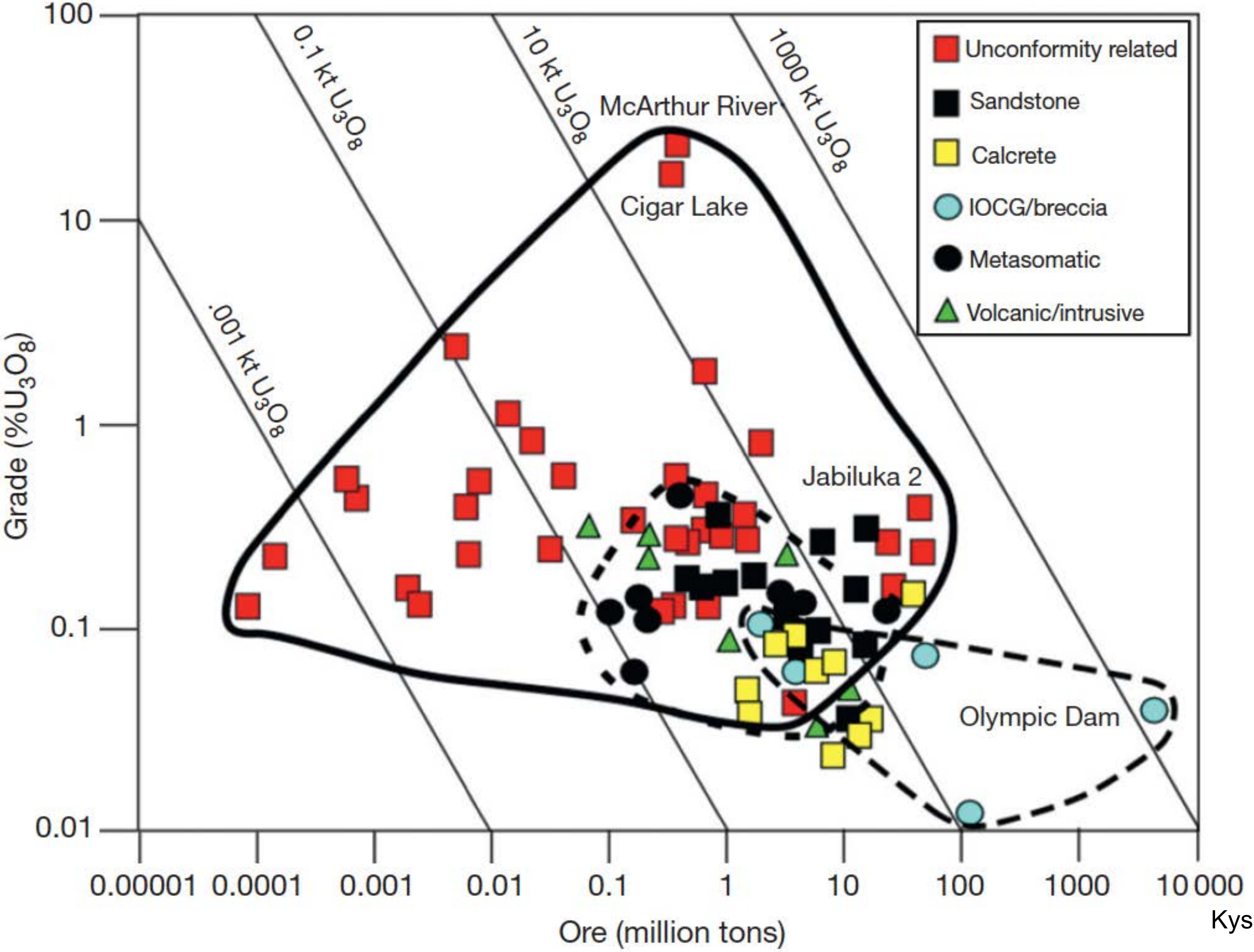
# Uranium deposit types





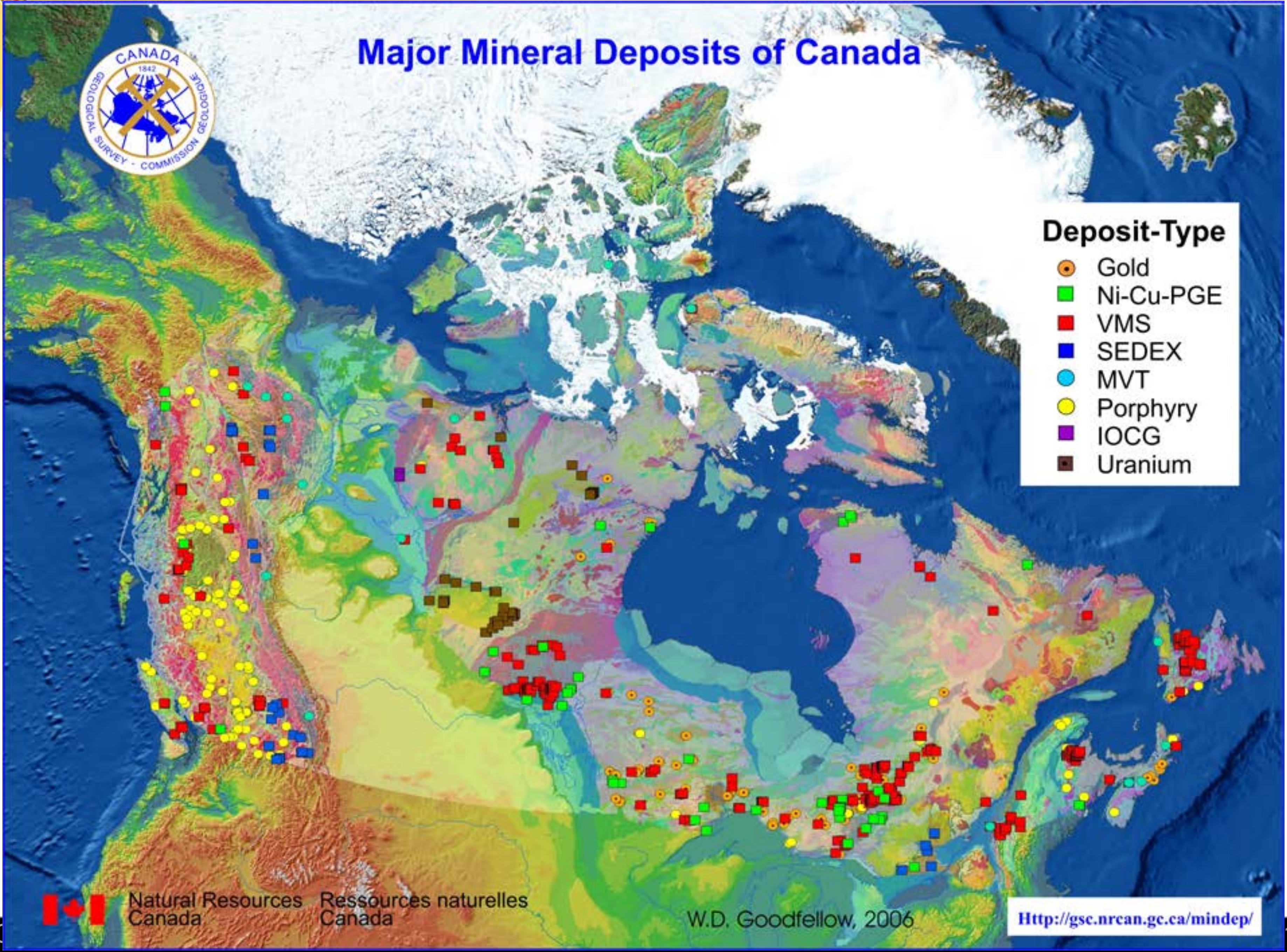
Kyser (2014)

**Figure 3** Schematic representation of the location of various types of uranium deposits. Reproduced from Kyser K and Cuney M (2009) Unconformity-related uranium deposits. In: Cuney M and Kyser K (eds.) *Recent and Not-So-Recent Developments in Uranium Deposits and Implications for Exploration*, *Mineralogical Association of Canada Short Course Series*, vol. 39, pp. 161–220. Quebec: Mineralogical Association of Canada.



Grade ($\%U_3O_8$)
100
10
1
0.1
0.01
Ore (million tons)
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
10 000
.001 kt $U_3O_8$
0.1 kt $U_3O_8$
10 kt $U_3O_8$
1000 kt $U_3O_8$
McArthur River
Cigar Lake
Jabiluka 2
Olympic Dam
🟥 Unconformity related
■ Sandstone
🟨 Calcrete
● IOCG/breccia
● Metasomatic
▲ Volcanic/intrusive

Kyser (2014)



# Major Mineral Deposits of Canada

W.D. Goodfellow, 2006

Http://gsc.nrcan.gc.ca/mindep/

# Important basins for Uranium in Canada

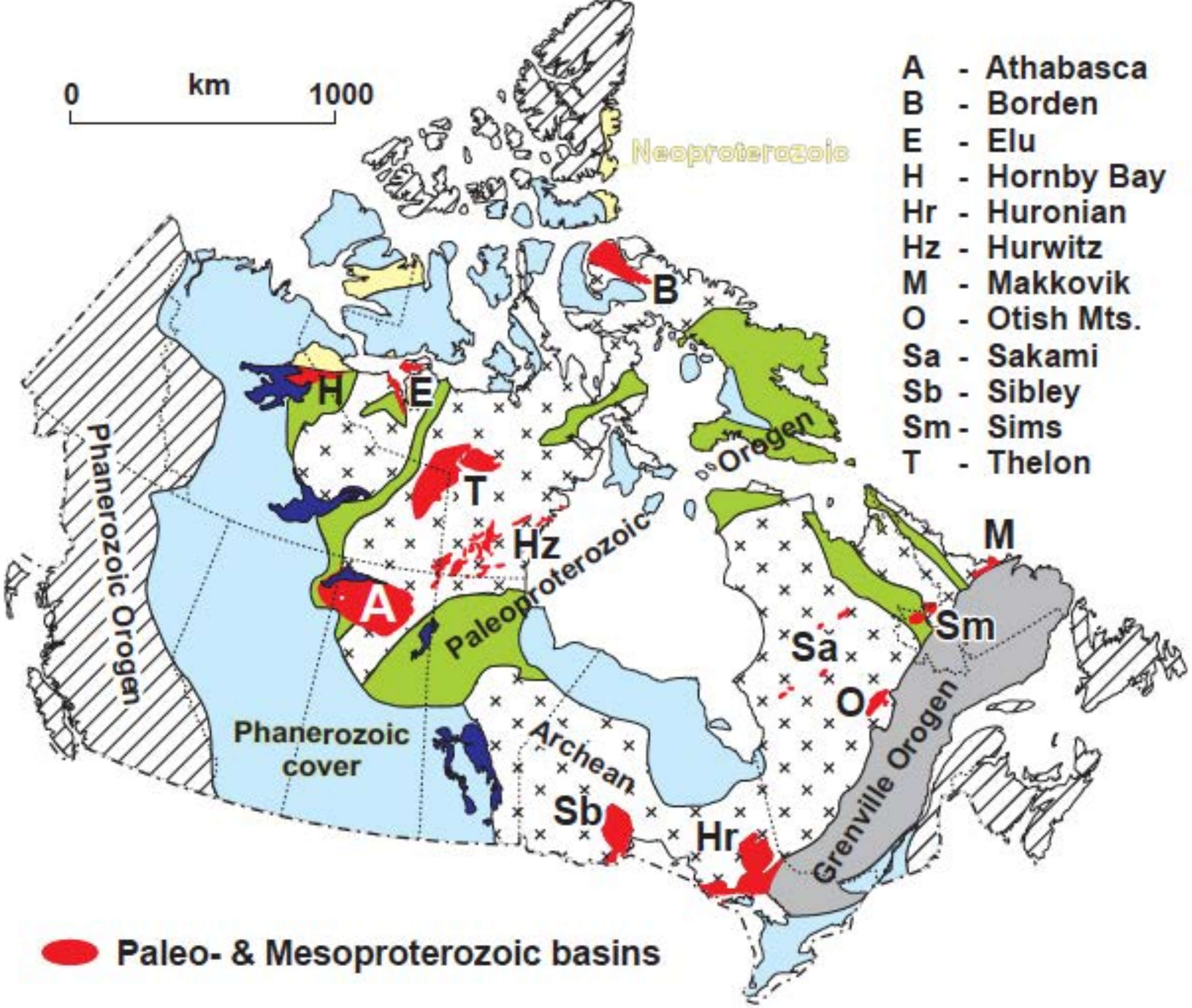
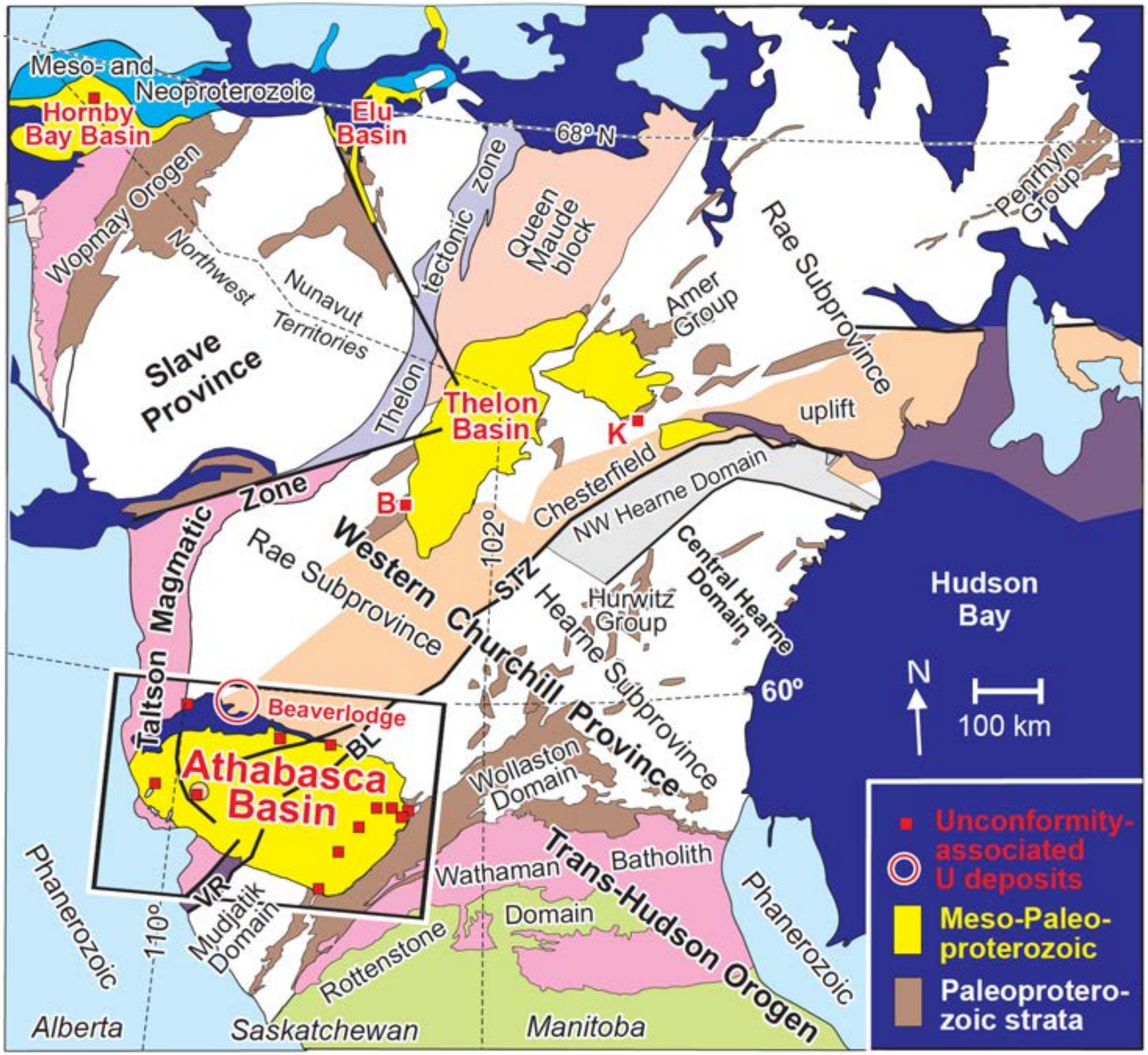


FIGURE 1. Paleo- to Mesoproterozoic basins within the Canadian Shield that contain unconformity-associated uranium deposits (e.g. Athabasca and Thelon) or are considered to have potential for them.

Jefferson et al. (2007)

# Canadian Uranium Deposits



Jefferson et al. (2007)

# Unconformity-related Uranium deposits – general concepts

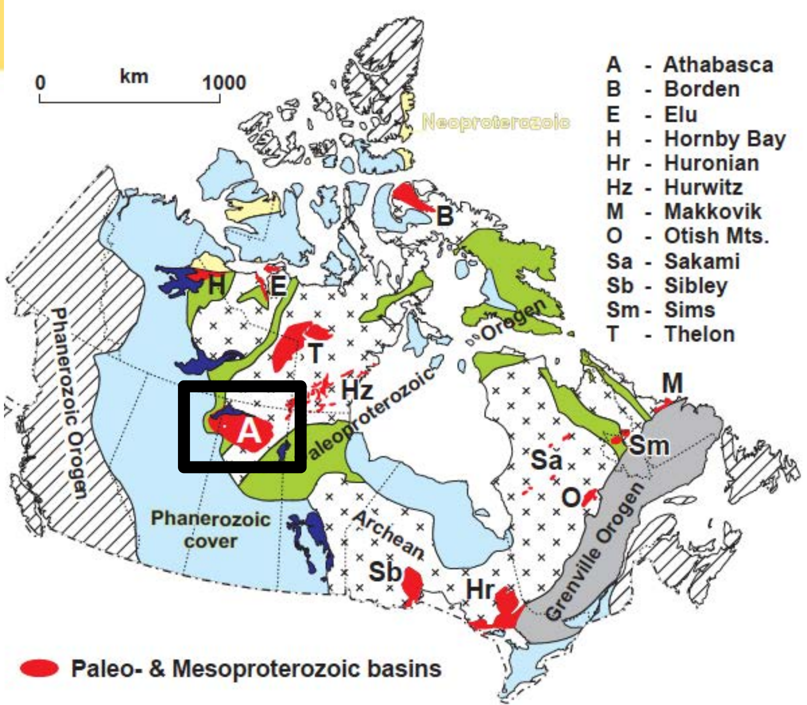
Occur close to major unconformities between Archean–Paleoproterozoic sandstones units in large marginal or intracratonic basins

Deposits occur within the basement or sandstone within a few hundred meters of the unconformity

Formation related to a reduction front near the unconformity between Paleoproterozoic sandstones and underlying metamorphic basement

# Athabasca basin

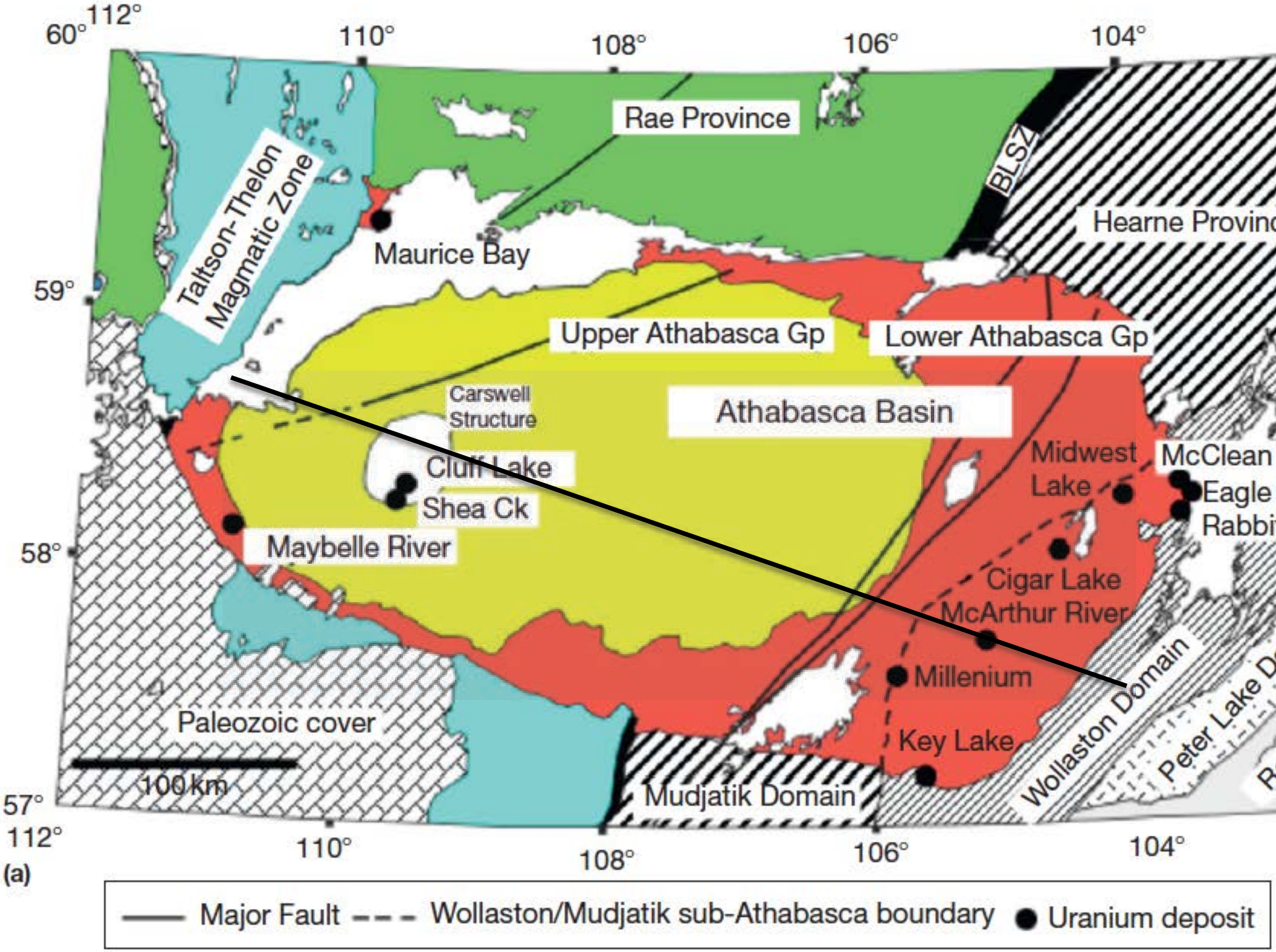
- Largest and highest-grade U deposits worldwide
- Sole source of U from Canada
- Covers more than 85,000 km$^2$
- **96%** of resources underlie a zone near the east margin of the basin
- Most mining is underground



Jefferson et al. (2007)

McArthur River Mine – Cameco

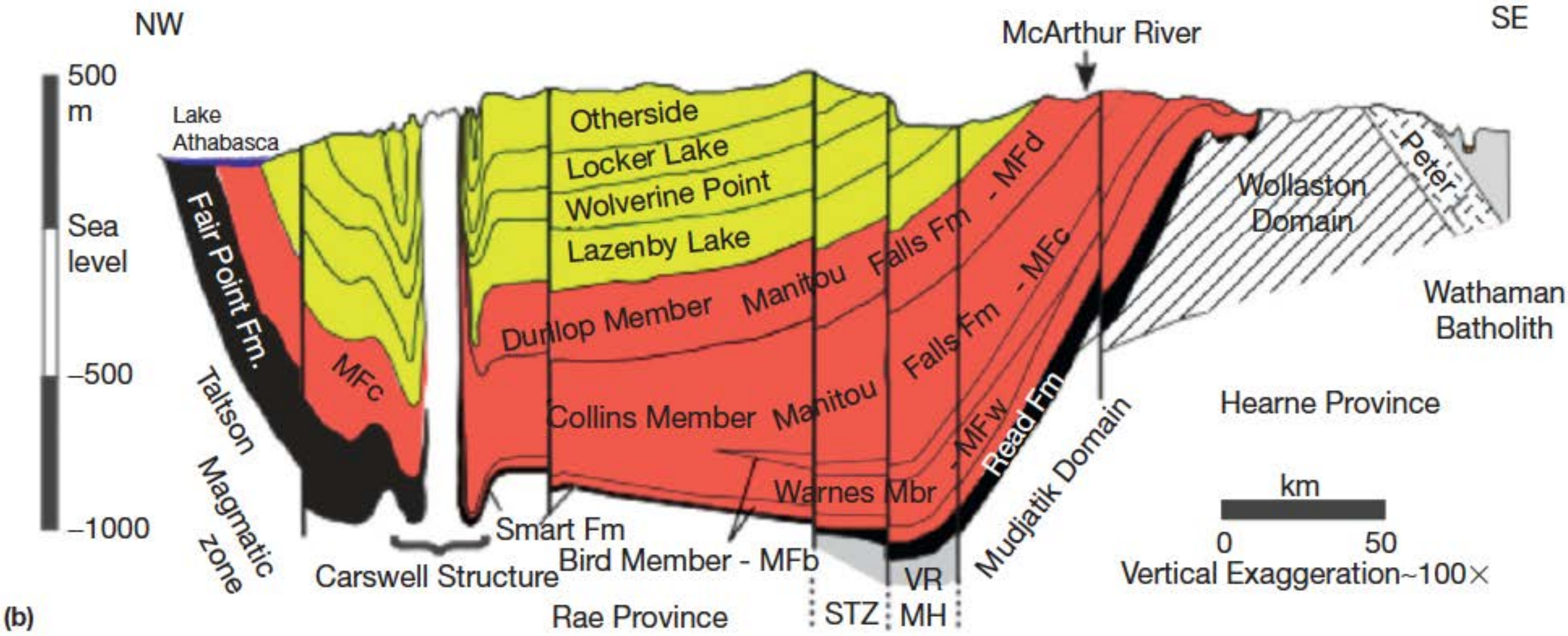
# Athabasca Geology



Kyser (2014)

# Athabasca basin cross section

**note the vertical exaggeration**



Kyser (2014)

# Athabasca ore

## Ore Grade:

- 2% U average grade (5x higher than similar Australian deposits)
- Cigar Lake 875 kT @ 15%
- McArthur River 1,017 kT @ 22.28%

## Ore Minerals:

**Uraninite**: $UO_2$
**Coffinite**: $U(SiO4)_{1-x}(OH)_{4x}$

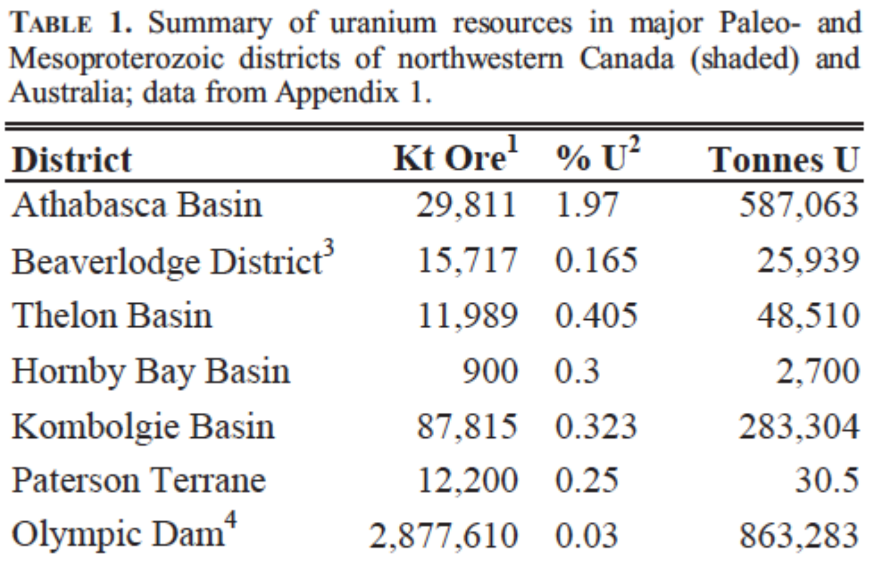


TABLE 1. Summary of uranium resources in major Paleo- and Mesoproterozoic districts of northwestern Canada (shaded) and Australia; data from Appendix 1.

| District | Kt Ore[1] | % U[2] | Tonnes U |
|---|---|---|---|
| Athabasca Basin | 29,811 | 1.97 | 587,063 |
| Beaverlodge District[3] | 15,717 | 0.165 | 25,939 |
| Thelon Basin | 11,989 | 0.405 | 48,510 |
| Hornby Bay Basin | 900 | 0.3 | 2,700 |
| Kombolgie Basin | 87,815 | 0.323 | 283,304 |
| Paterson Terrane | 12,200 | 0.25 | 30.5 |
| Olympic Dam[4] | 2,877,610 | 0.03 | 863,283 |

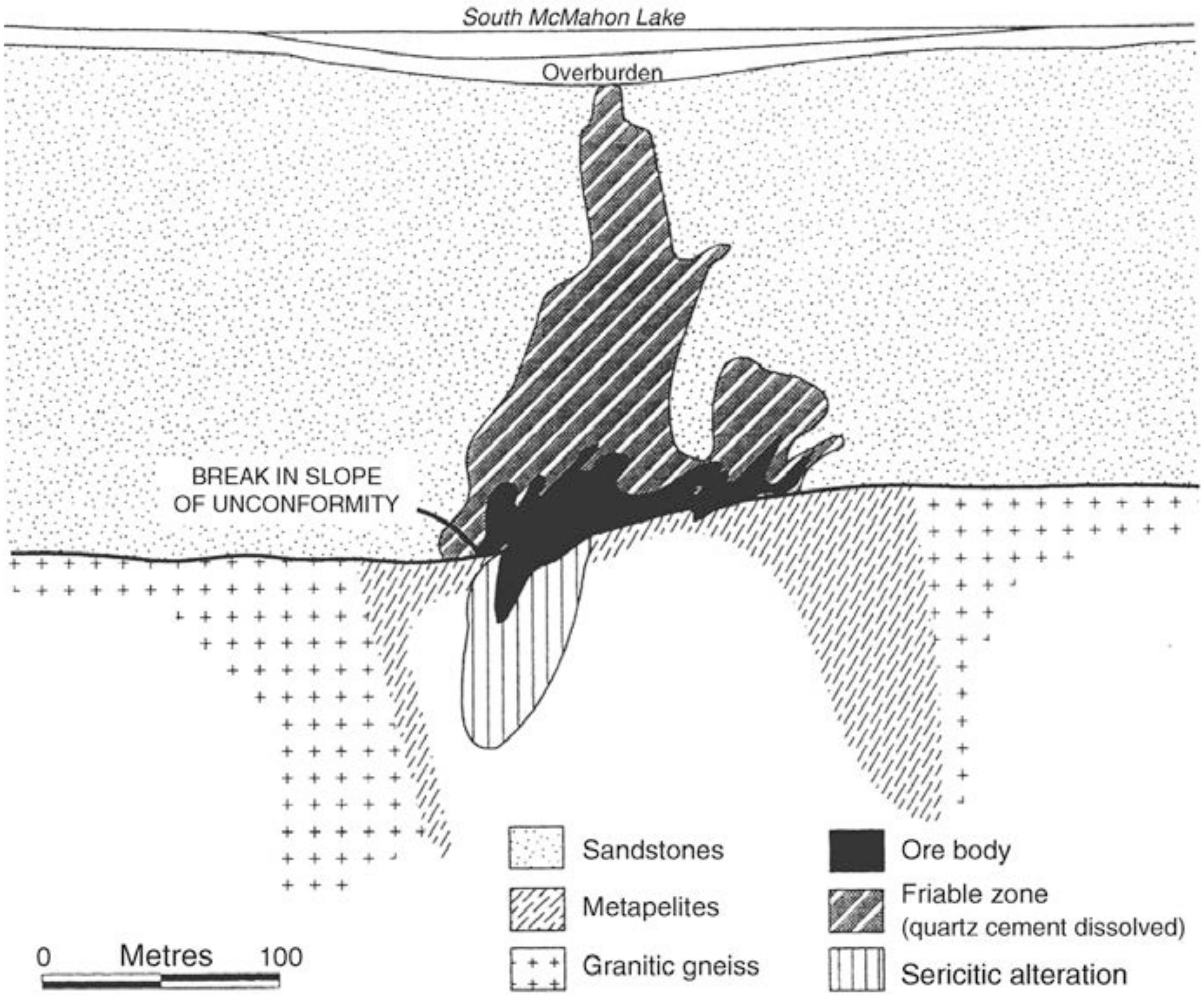
Alexandre et al. (2012) – Centennial deposit

# Geological setting of unconformity uranium

Granitic basement

Unconformity overlain by sandstone

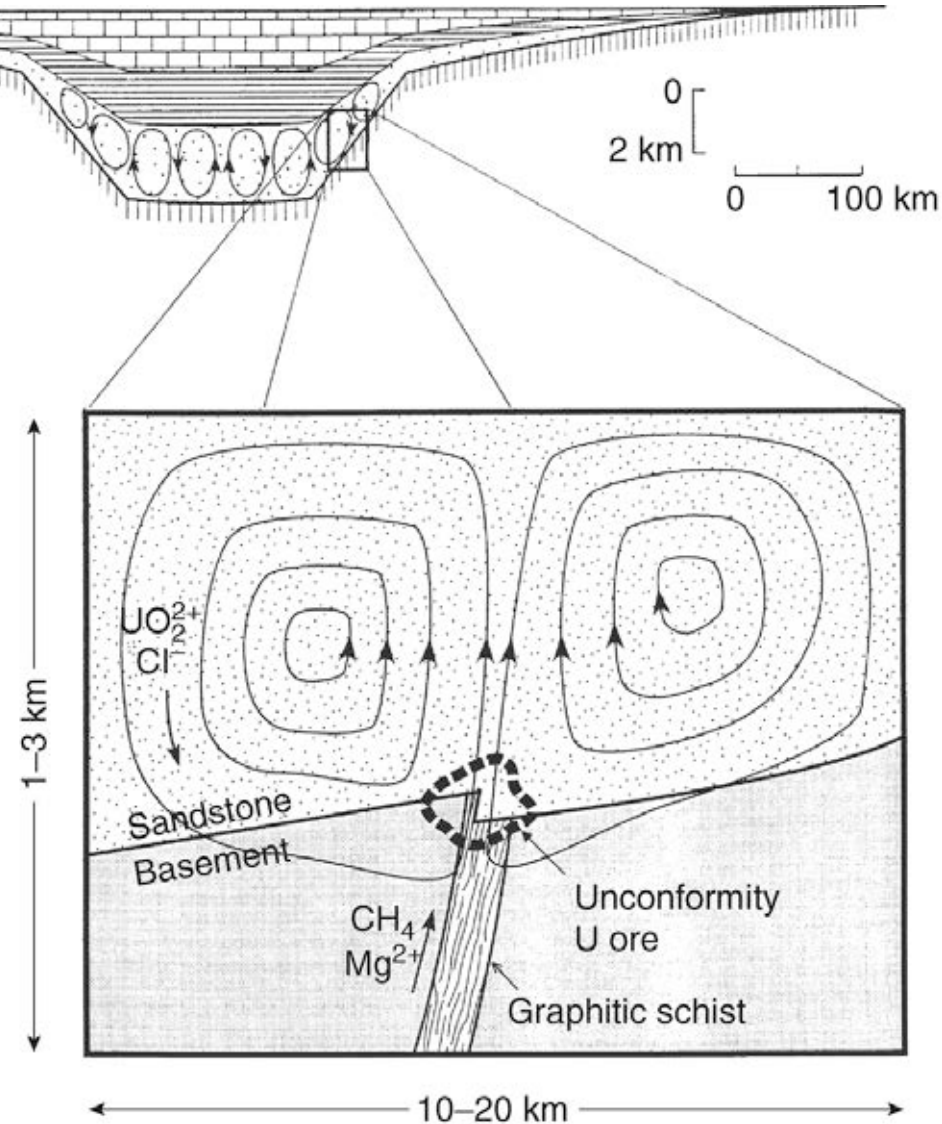
Ore is elongate 10s to 100s of metres across



Ridley (2013)

# Genetic model for unconformity uranium

1. Thick basin develops hydrothermal convection system
2. <u>Oxidized</u> groundwaters leach U from sandstones or underlying basement rocks
3. Interaction of fluids with graphite-rich metasedimentary rocks or basement-derived <u>reducing</u> fluids
4. Deposition of U at reaction front



Ridley (2013)

# Unconformity U summary

- Epigenetic
- High-grade deposits
- Replacement

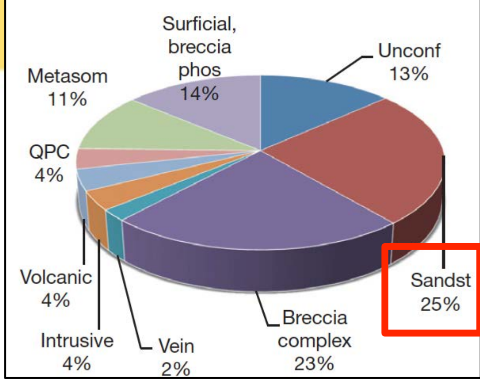
Fluid: oxidized basinal waters

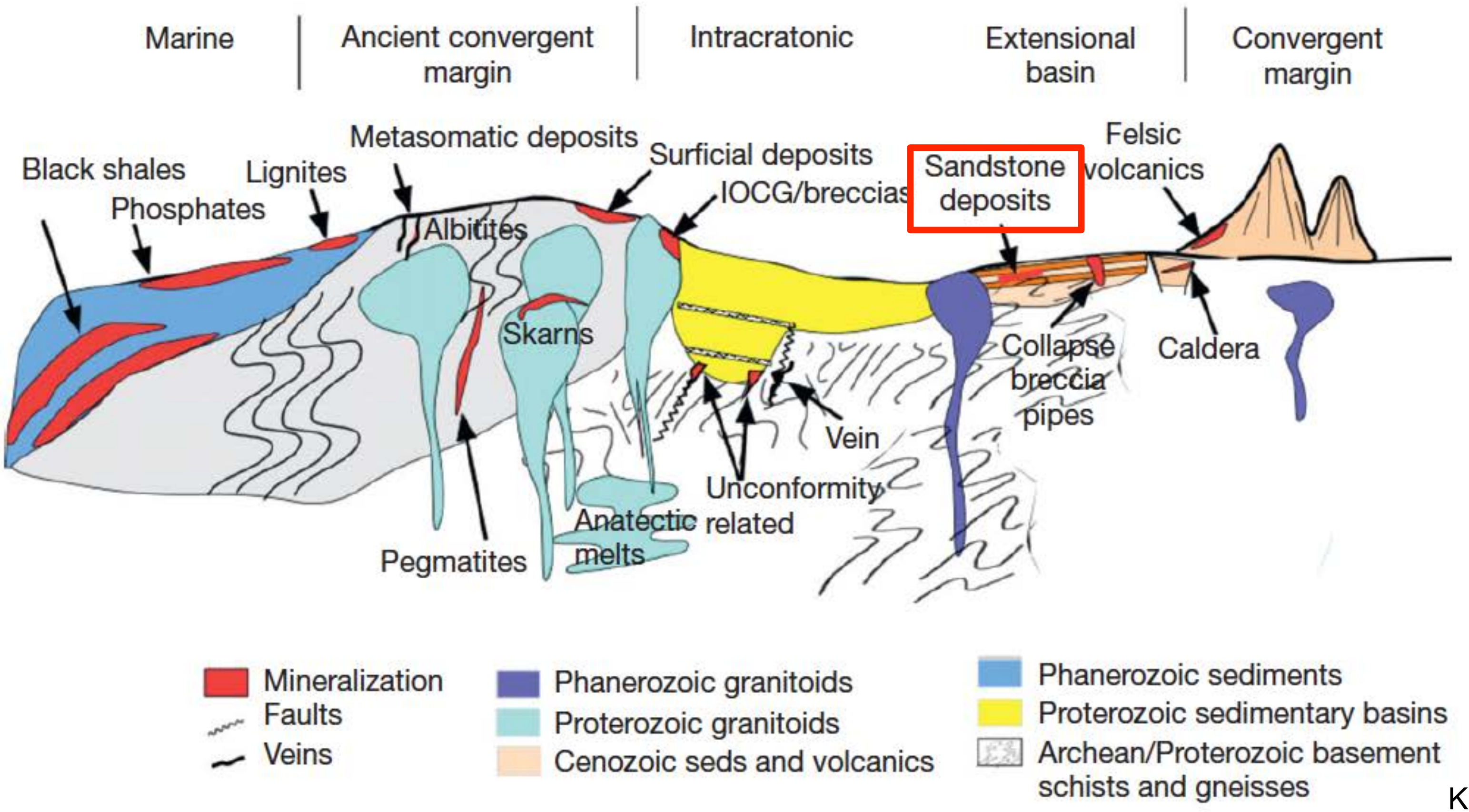
Source of U: S-type granites, pegmatites, metasedimentary terrains (U may have been removed directly from these rocks or via detrital heavy minerals deposited in a sedimentary basin)

Transport: convection in basin, aquifers along the unconformity, brittle faults and local alteration structures

Trap: graphitic metapelitic gneisses (reducing), although some deposits are not associated with graphite

# Sandstone-hosted uranium deposits





Kyser (2014)

**Figure 3** Schematic representation of the location of various types of uranium deposits. Reproduced from Kyser K and Cuney M (2009) Unconformity-related uranium deposits. In: Cuney M and Kyser K (eds.) *Recent and Not-So-Recent Developments in Uranium Deposits and Implications for Exploration, Mineralogical Association of Canada Short Course Series*, vol. 39, pp. 161–220. Quebec: Mineralogical Association of Canada.

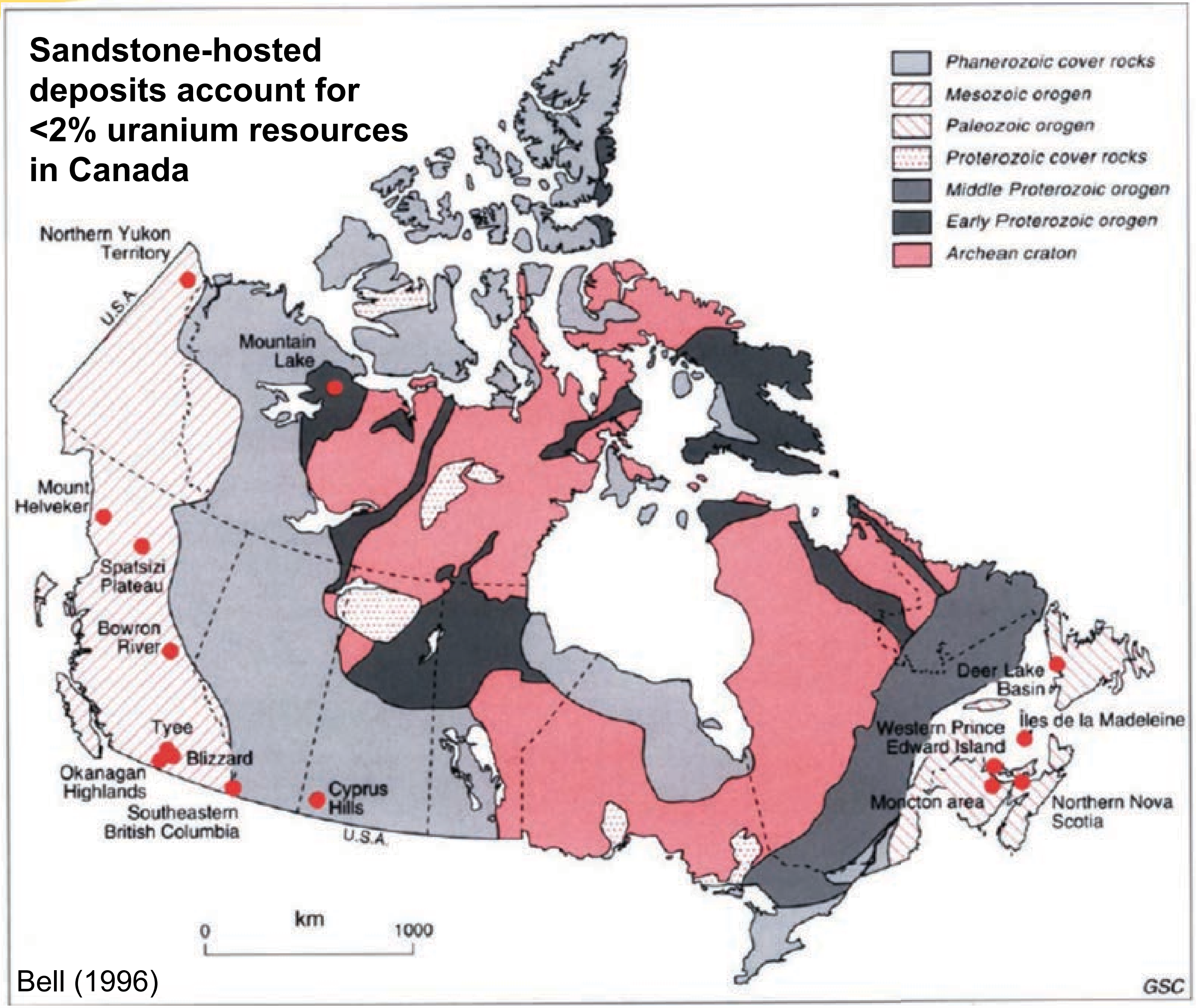
# Sandstone U – general concept

Epigenetic U deposits in fluvial, lacustrine and deltaic sandstones (medium- to coarse-grained).

Sandstones are bounded by impermeable shales/ mudstones.

Migrating oxidized groundwaters deposit U when the basin becomes reducing (e.g. carbonaceous plant material, coal, sulfides, hydrocarbons and mafic volcanic rocks)

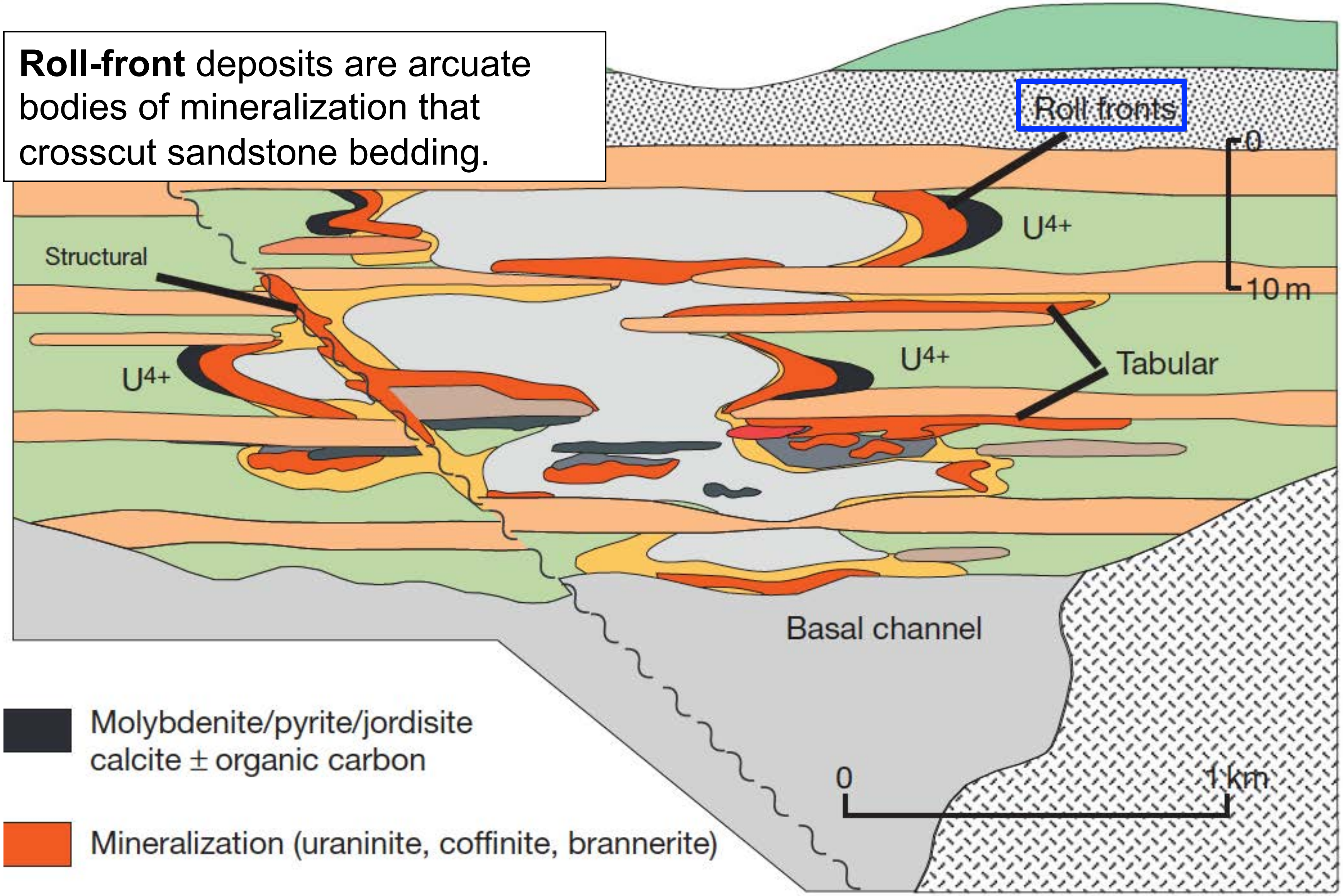
**Sandstone-hosted deposits account for <2% uranium resources in Canada**



Bell (1996)

# Sandstone uranium deposits – 4 types

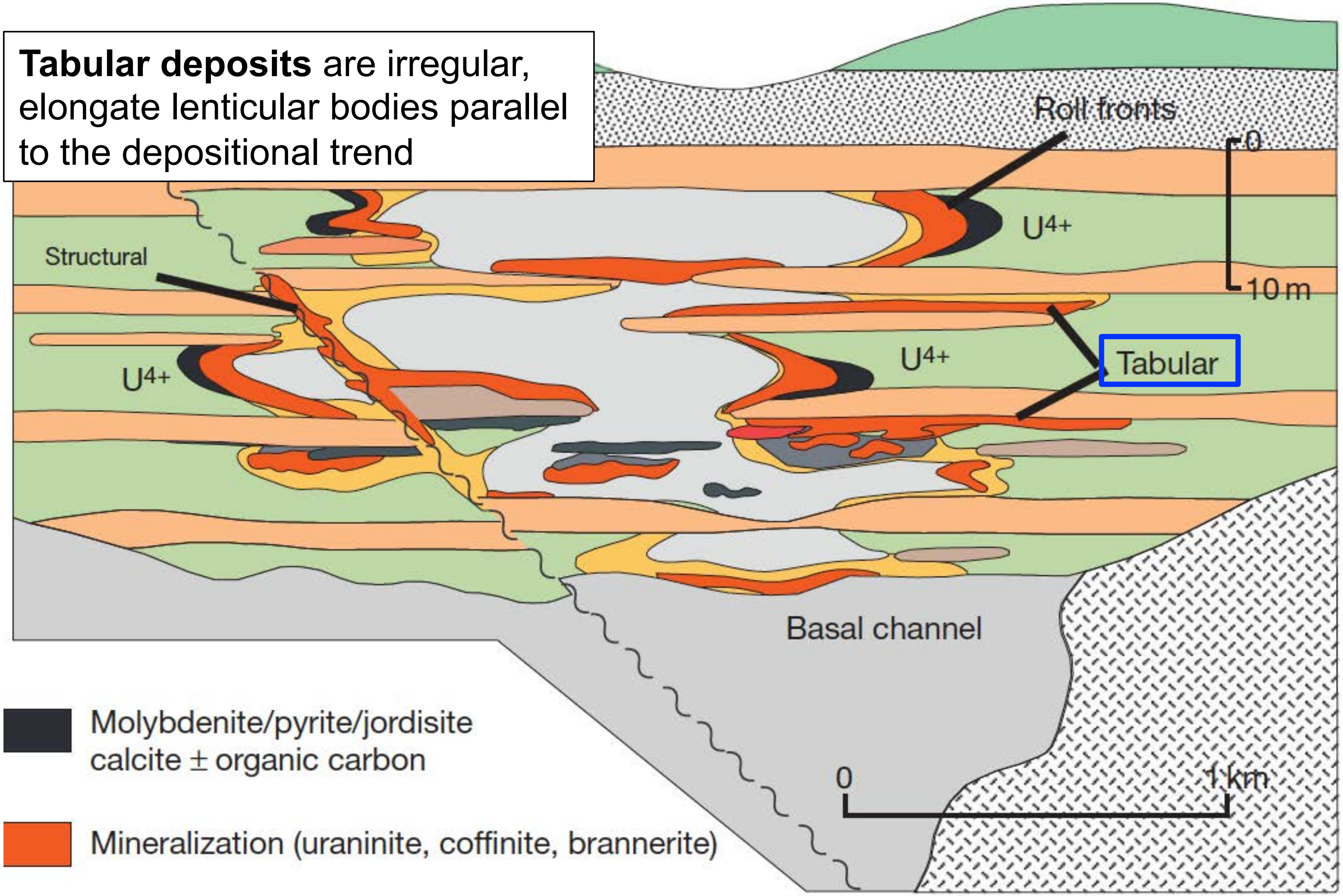
**Roll-front** deposits are arcuate bodies of mineralization that crosscut sandstone bedding.



Kyser (2014)

# Sandstone uranium deposits – 4 types

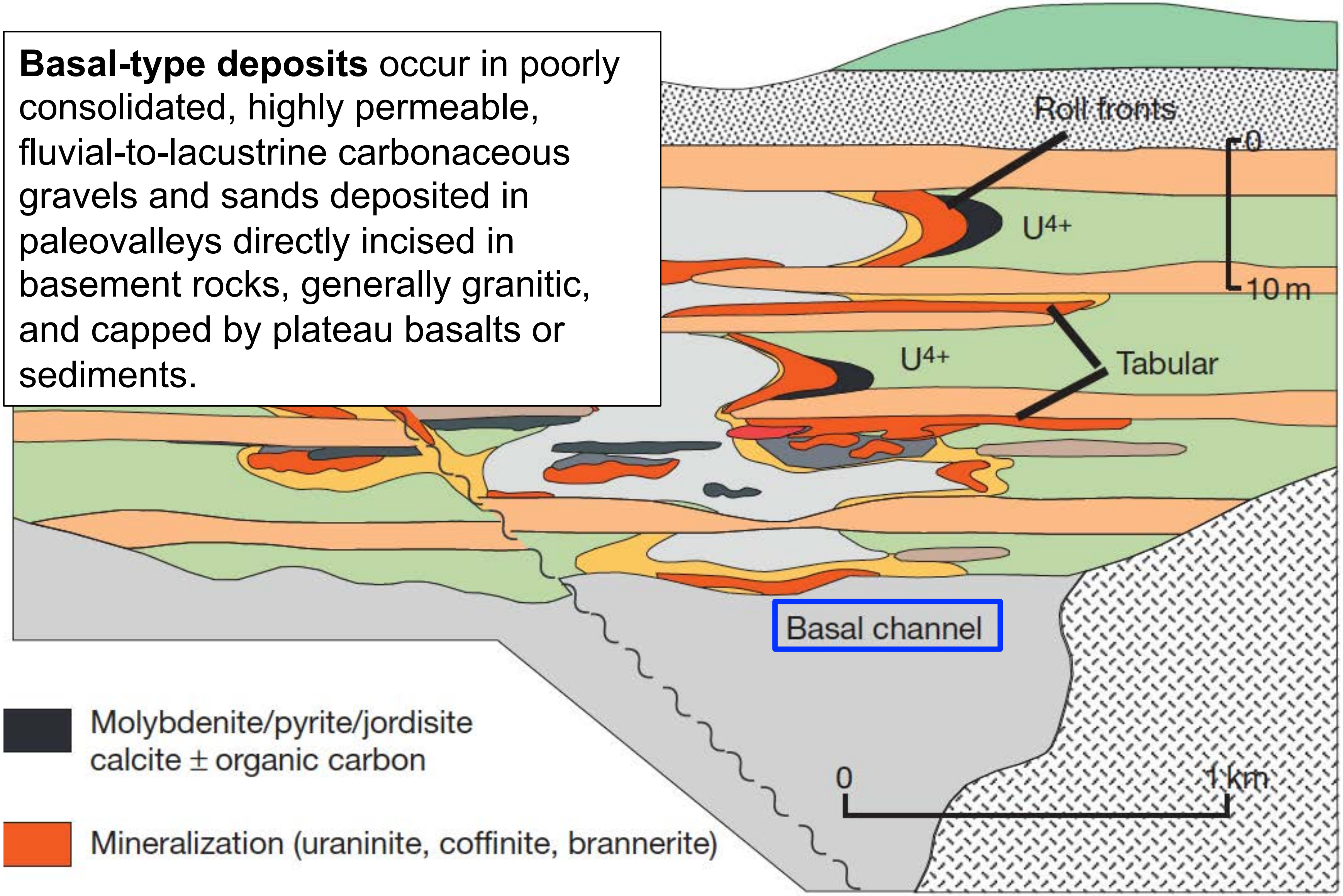
**Tabular deposits** are irregular, elongate lenticular bodies parallel to the depositional trend



Kyser (2014)

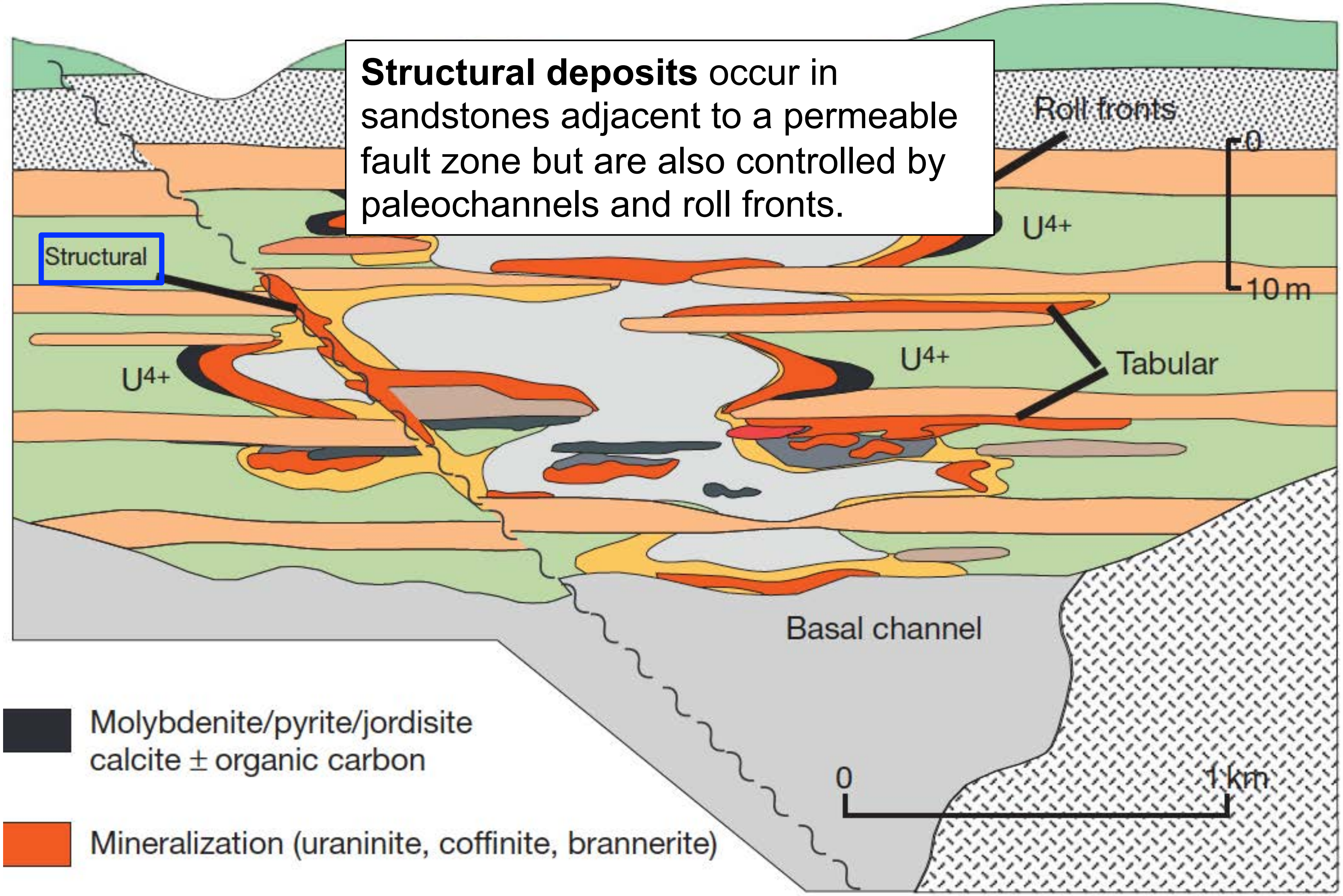
# Sandstone uranium deposits – 4 types

**Basal-type deposits** occur in poorly consolidated, highly permeable, fluvial-to-lacustrine carbonaceous gravels and sands deposited in paleovalleys directly incised in basement rocks, generally granitic, and capped by plateau basalts or sediments.



Kyser (2014)

# Sandstone uranium deposits – 4 types

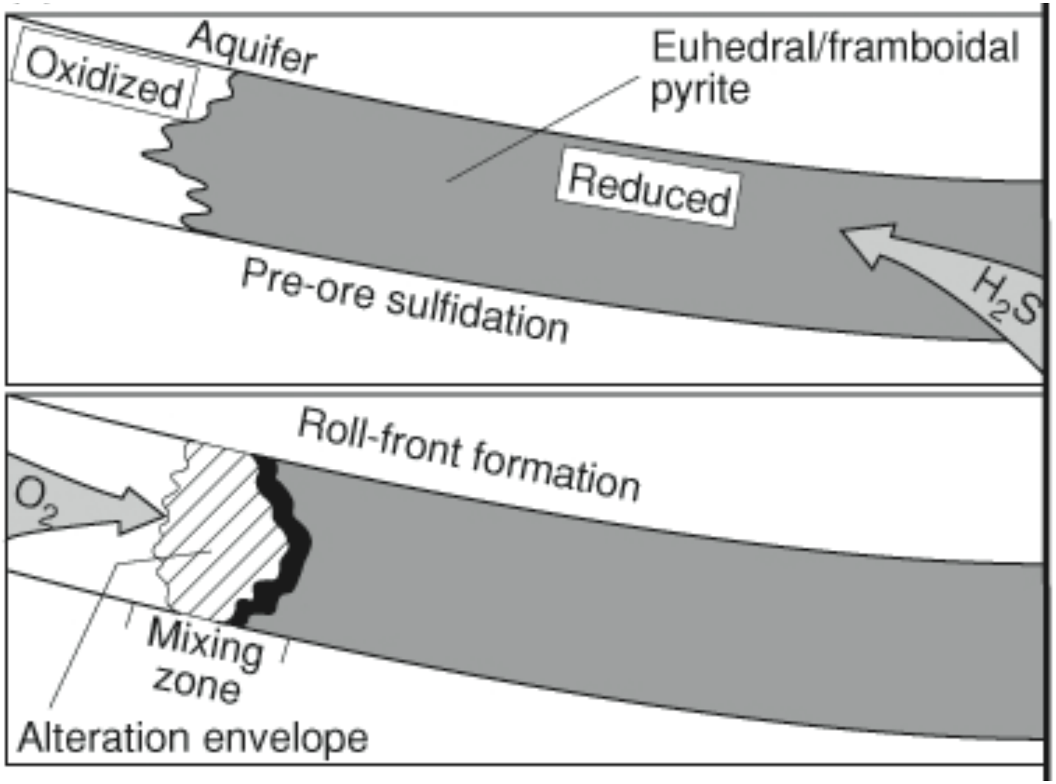


**Structural deposits** occur in sandstones adjacent to a permeable fault zone but are also controlled by paleochannels and roll fronts.

Kyser (2014)

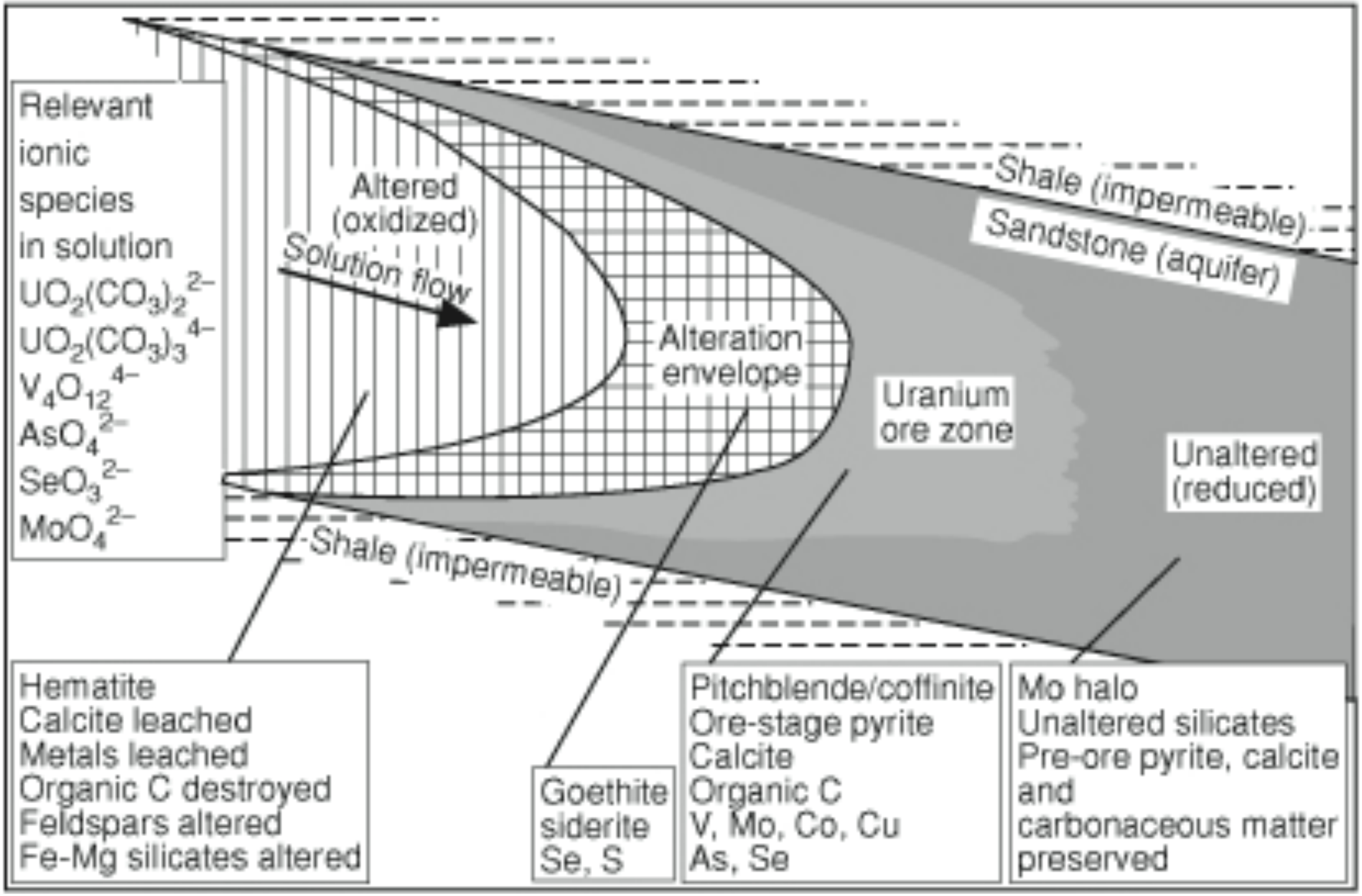
# Roll front uranium genetic model

1) Oxidized meteoric fluids transport uranyl–carbonate complexes in a sandstone aquifer
2) Meteoric fluid encounters reducing conditions (a redox front) and Uranium is precipitated
3) Over time the redox front migrates down dip



Robb (2005)

# Roll front alteration



Relevant ionic species in solution

$UO_2(CO_3)_2^{2-}$

$UO_2(CO_3)_3^{4-}$

$V_4O_{12}^{4-}$

$AsO_4^{2-}$

$SeO_3^{2-}$

$MoO_4^{2-}$

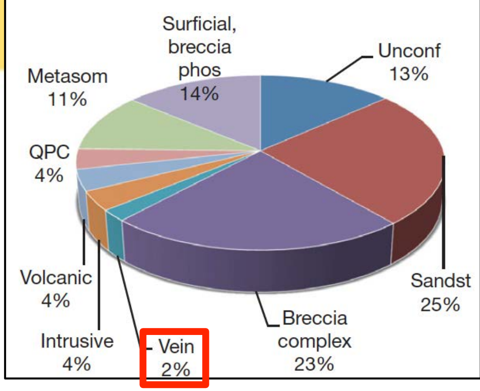
Hematite
Calcite leached
Metals leached
Organic C destroyed
Feldspars altered
Fe-Mg silicates altered

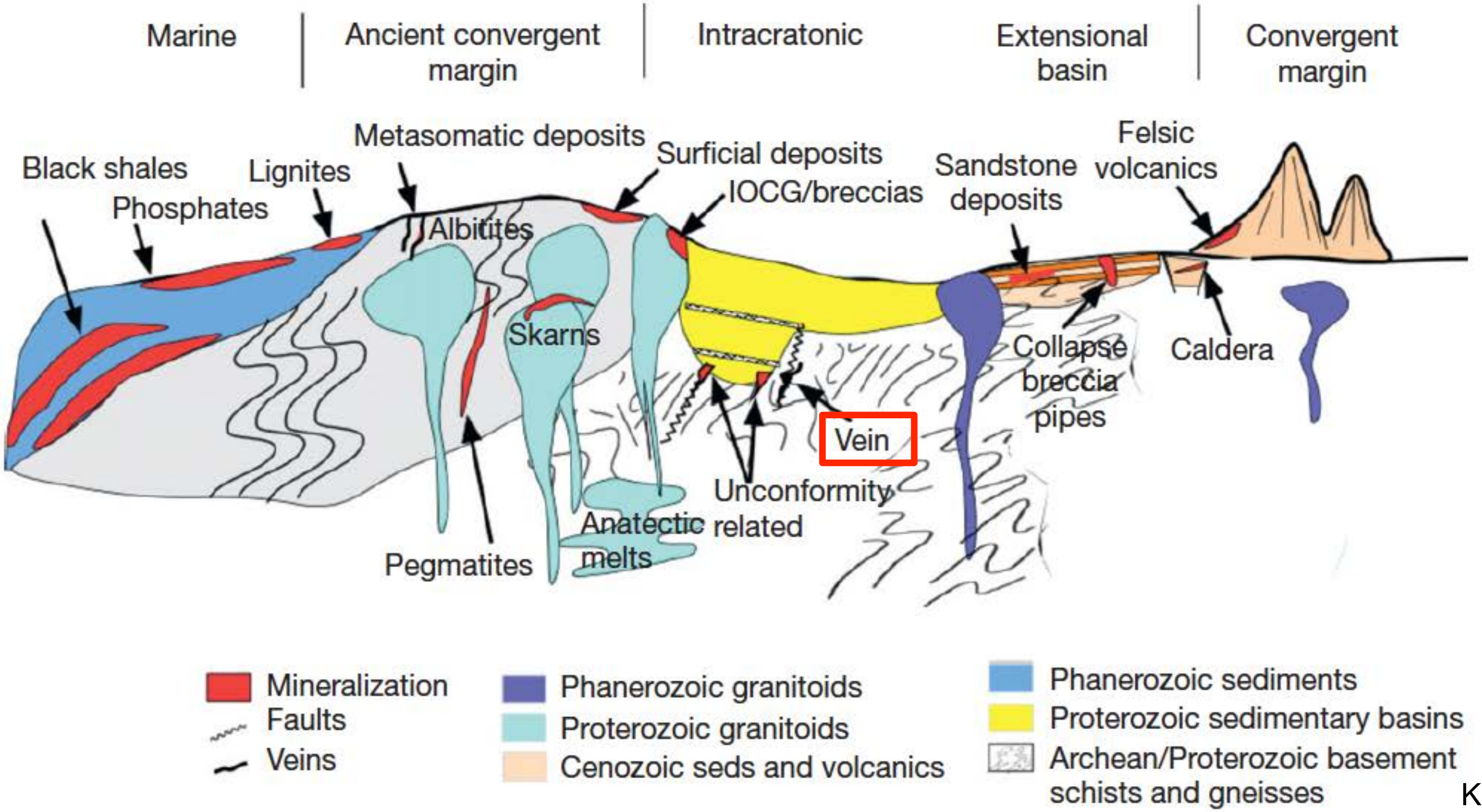
Goethite
siderite
Se, S

Pitchblende/coffinite
Ore-stage pyrite
Calcite
Organic C
V, Mo, Co, Cu
As, Se

Mo halo
Unaltered silicates
Pre-ore pyrite, calcite and carbonaceous matter preserved

# Vein uranium deposits





Kyser (2014)

**Figure 3** Schematic representation of the location of various types of uranium deposits. Reproduced from Kyser K and Cuney M (2009) Unconformity-related uranium deposits. In: Cuney M and Kyser K (eds.) *Recent and Not-So-Recent Developments in Uranium Deposits and Implications for Exploration, Mineralogical Association of Canada Short Course Series*, vol. 39, pp. 161–220. Quebec: Mineralogical Association of Canada.

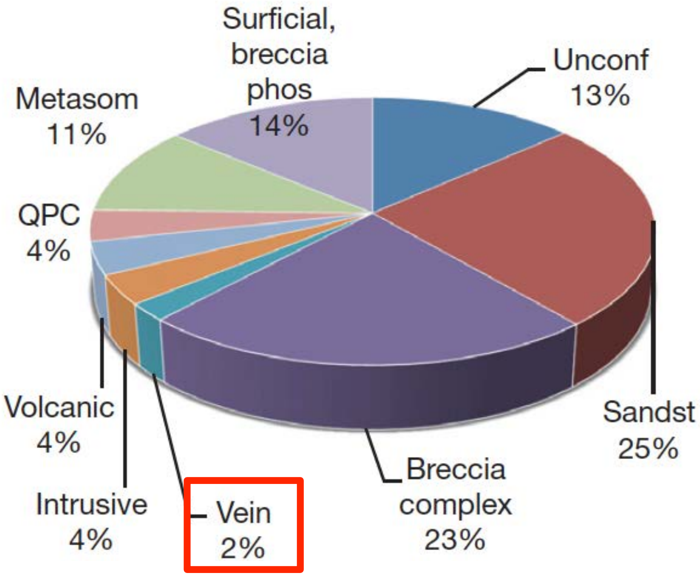
# Vein uranium – fun facts

Occur in metamorphic rocks and do not fit into other categories (e.g. sandstone-hosted, unconformity).

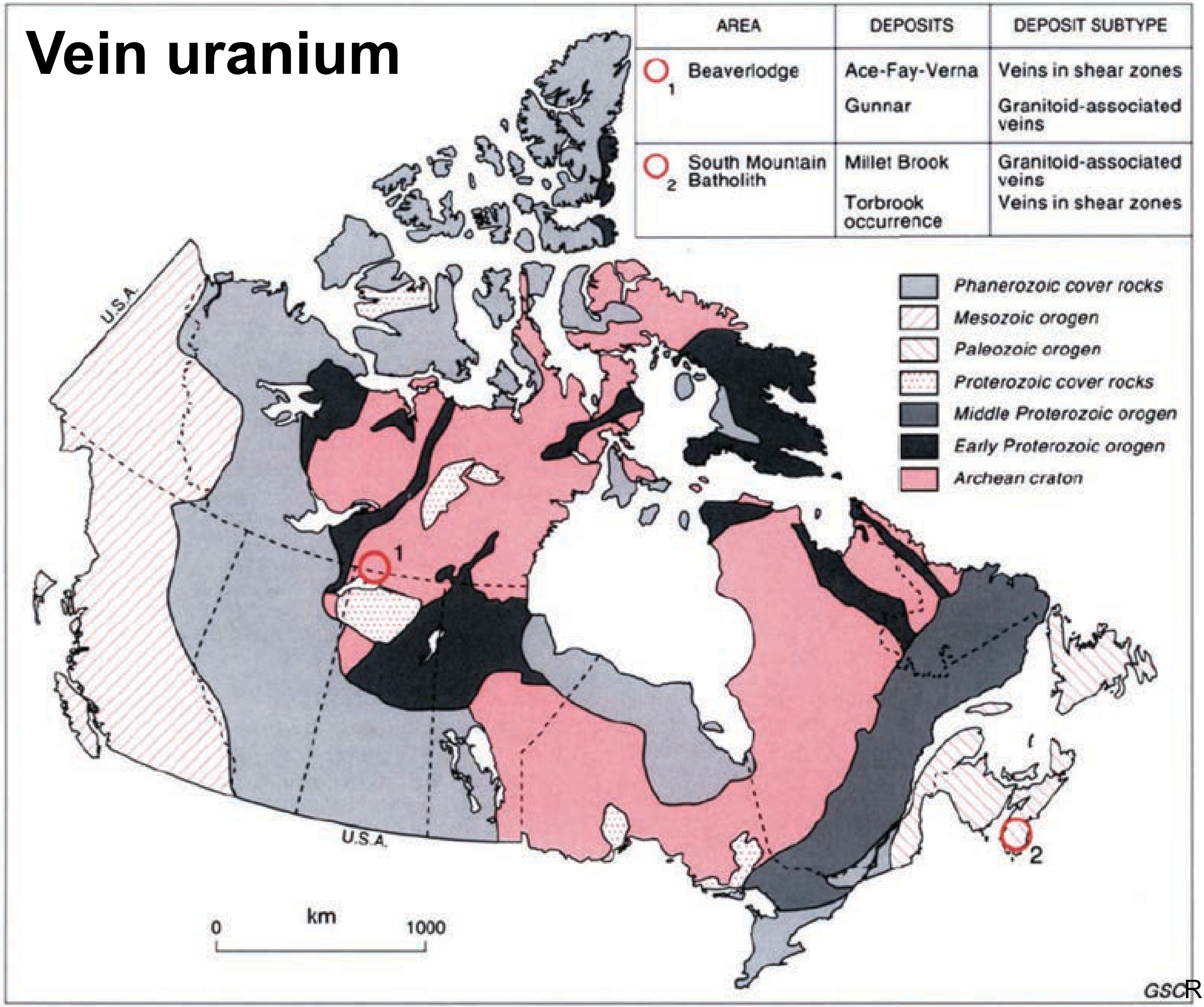
Worldwide: 2% of resources and 10% of total production

All deposits have been mined out:

- Beaverlodge (Canada)
- Jáchymov (Czech Republic)
- Shinkolobwe (DR Congo)



# Vein uranium



| AREA | DEPOSITS | DEPOSIT SUBTYPE |
|---|---|---|
| ○ 1 Beaverlodge | Ace-Fay-Verna | Veins in shear zones |
| | Gunnar | Granitoid-associated veins |
| ○ 2 South Mountain Batholith | Millet Brook | Granitoid-associated veins |
| | Torbrook occurrence | Veins in shear zones |

Ruzicka (1996)

# Beaverlodge

1935: Prospectors who worked at Port Radium mine on Great Bear lake recognized pitchblende on the north shore of Lake Athabasca

1945: 1,000 pitchblende showings documented in the Beaverlodge area

Two cities founded: Eldorado (1949) and Uranium City (1952)

1948–1958: exploration boom

Beaverlodge camp was the biggest U producer in Canada until Elliot Lake (1957)

1950–1982: actively mined

1964: USA cancelled contracts for foreign Uranium – collapse of uranium exploration and mining and decline of communities

Ace–Fay–Verna mine closed in 1982 (produced 16,035 tonnes of U)
Gunnar mine produced 6,982 tonnes of U

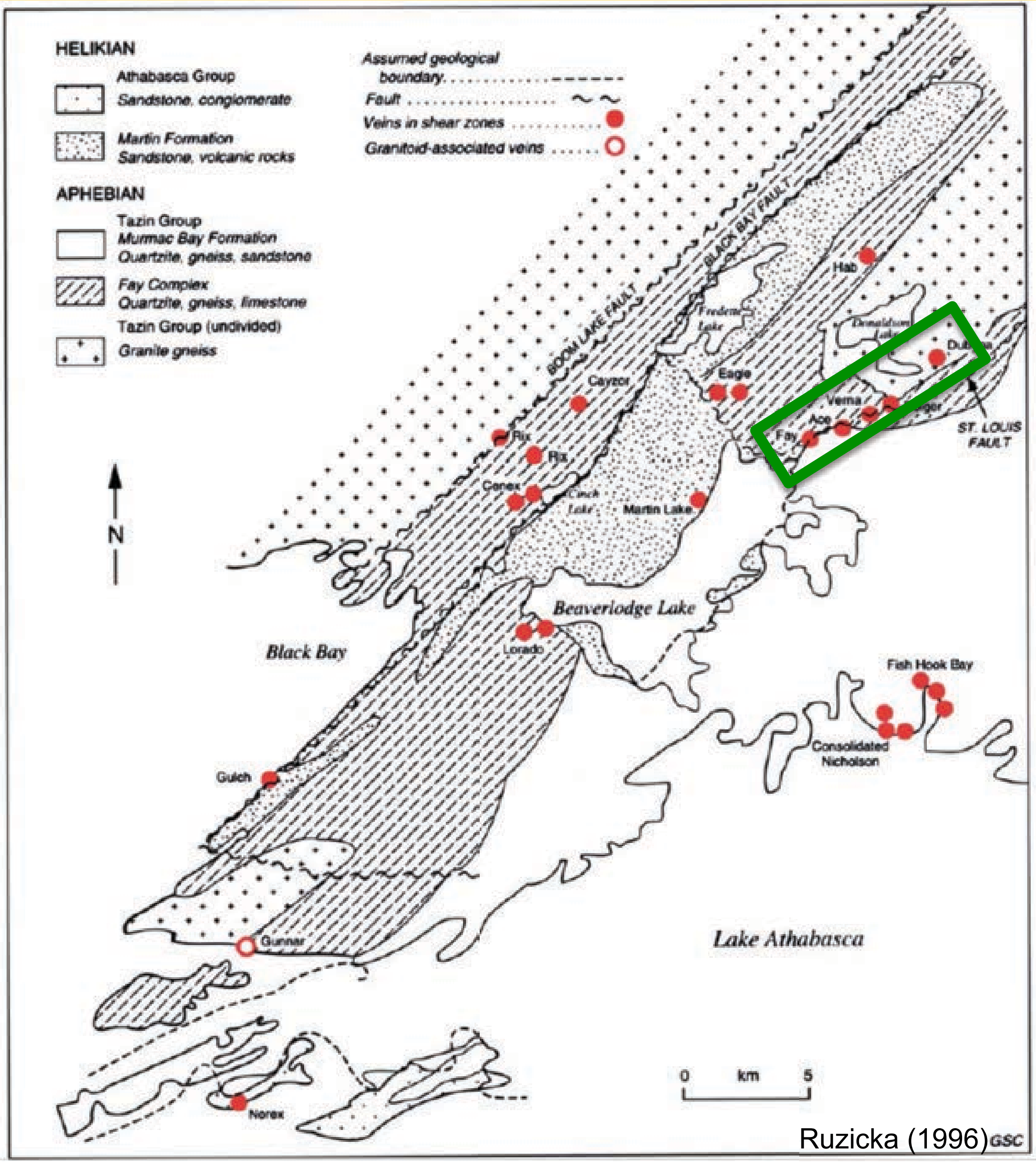
http://harrowsmithalmanac.com/2010/07/17/where-ya-from/

Uranium City: ~5,000 people in the 1960s and ~200 people today

radio-canada

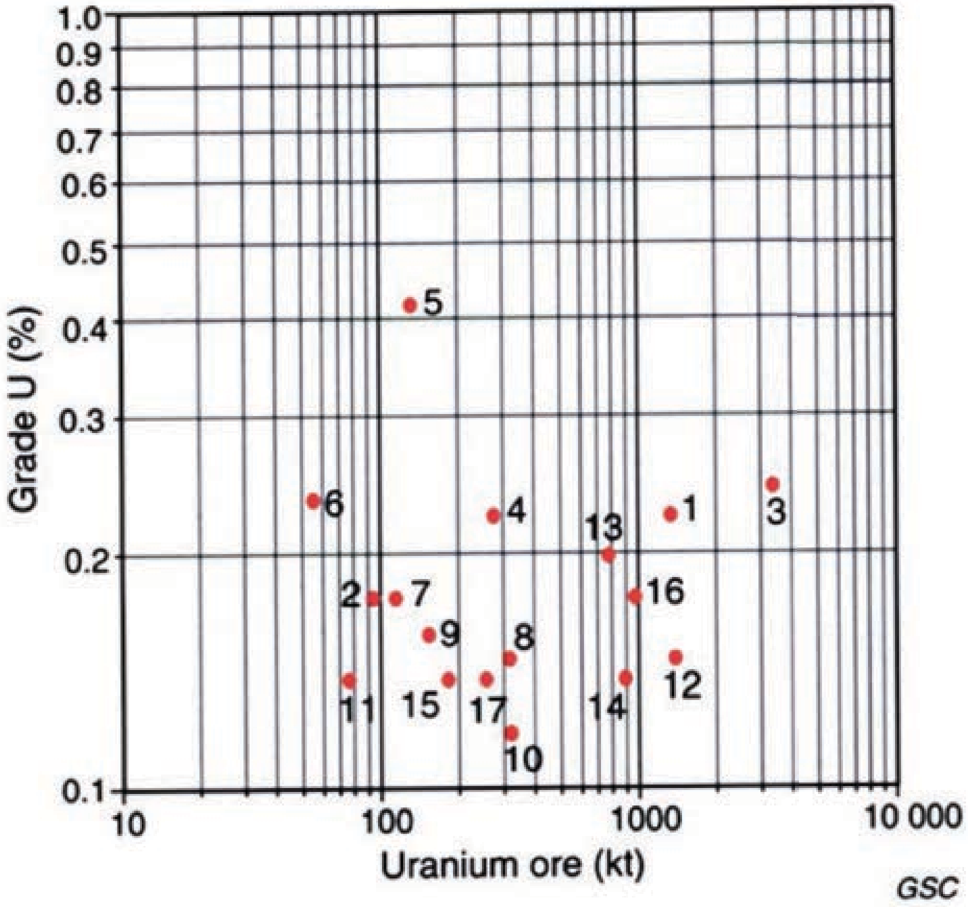
# Beaverlodge geology

- Ore hosted in mylonitized feldspathic quartzite (structural control)
- Epigenetic ore
- Pitchblende is main ore mineral
- Uranium sourced from granitoid plutons (?)
- U remobilized by metamorphic fluids
- Ore occurs as: fillings, stockworks and disseminations

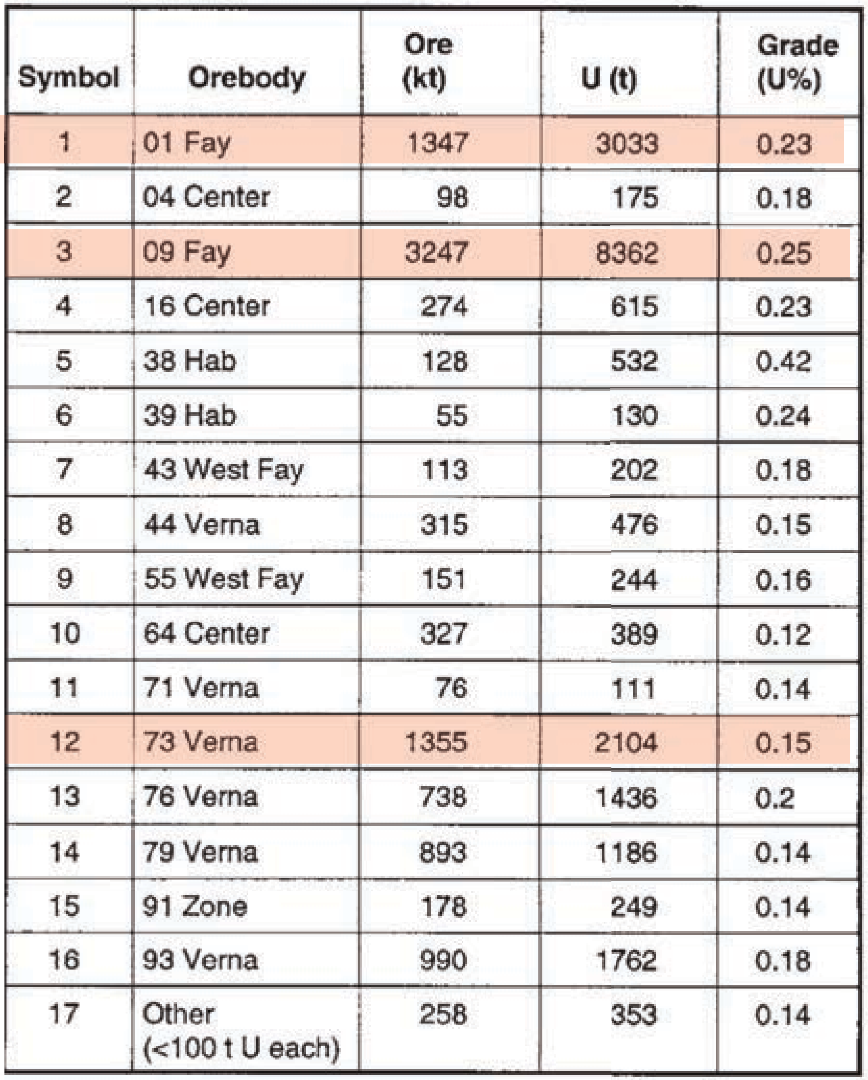


Ruzicka (1996)

# Beaverlodge ore grades



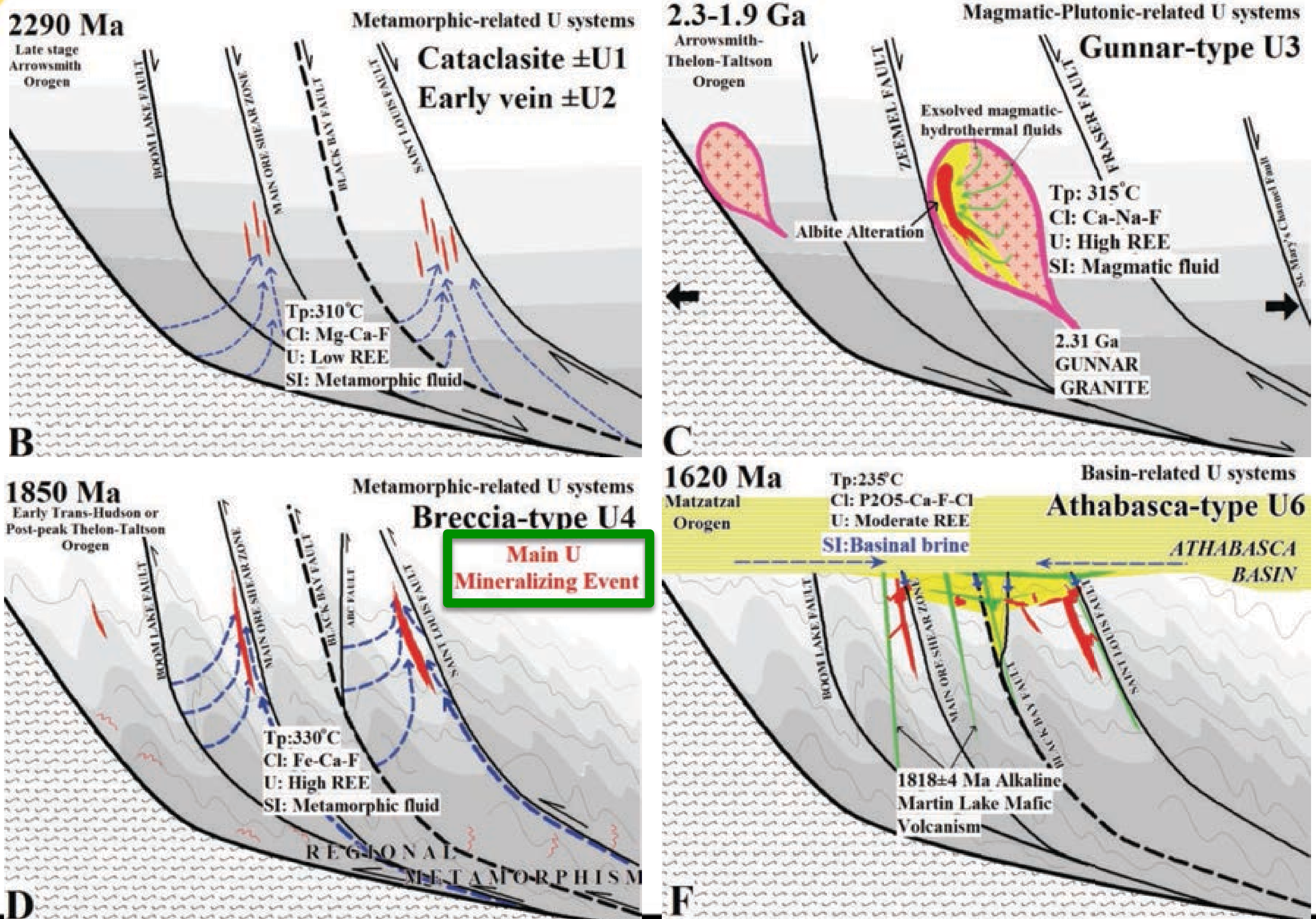
Ruzicka (1996)



| Symbol | Orebody | Ore (kt) | U (t) | Grade (U%) |
|---|---|---|---|---|
| 1 | 01 Fay | 1347 | 3033 | 0.23 |
| 2 | 04 Center | 98 | 175 | 0.18 |
| 3 | 09 Fay | 3247 | 8362 | 0.25 |
| 4 | 16 Center | 274 | 615 | 0.23 |
| 5 | 38 Hab | 128 | 532 | 0.42 |
| 6 | 39 Hab | 55 | 130 | 0.24 |
| 7 | 43 West Fay | 113 | 202 | 0.18 |
| 8 | 44 Verna | 315 | 476 | 0.15 |
| 9 | 55 West Fay | 151 | 244 | 0.16 |
| 10 | 64 Center | 327 | 389 | 0.12 |
| 11 | 71 Verna | 76 | 111 | 0.14 |
| 12 | 73 Verna | 1355 | 2104 | 0.15 |
| 13 | 76 Verna | 738 | 1436 | 0.2 |
| 14 | 79 Verna | 893 | 1186 | 0.14 |
| 15 | 91 Zone | 178 | 249 | 0.14 |
| 16 | 93 Verna | 990 | 1762 | 0.18 |
| 17 | Other (<100 t U each) | 258 | 353 | 0.14 |

# Beaverlodge genetic model

Dieng et al. (2015, Econ. Geol.)



# Fay Mine

http://www.saskmining.ca/media/showGallery/type/photo/sid/10/id/276

http://peel.library.ualberta.ca/postcards/PC012523.html

# **Gunnar Mine** – from K.E. Ashton

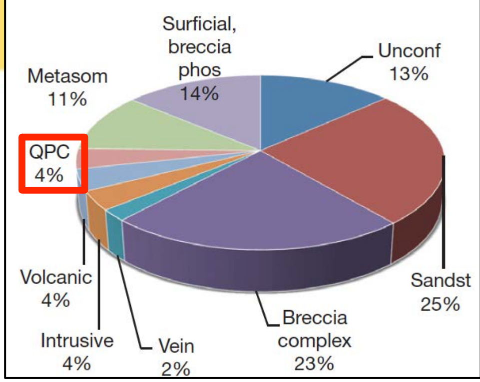
http://www.saskmining.ca/media/showGallery/type/photo/sid/10/id/276

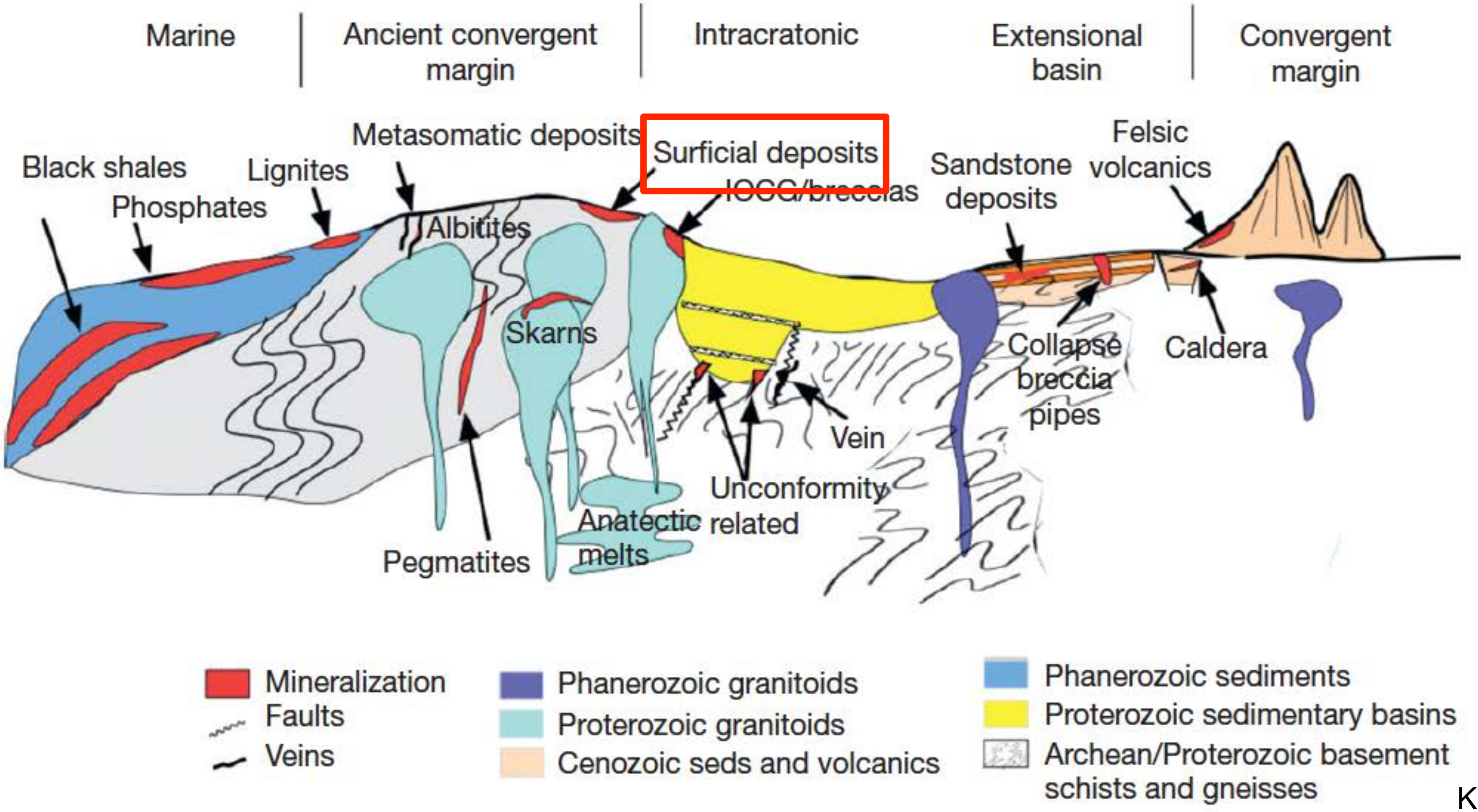
URANIUM CITY HISTORY

past, present, future

*"Helping Keep Uranium City alive on the web"*

# Quartz-pebble conglomerate uranium deposits





Kyser (2014)

**Figure 3** Schematic representation of the location of various types of uranium deposits. Reproduced from Kyser K and Cuney M (2009) Unconformity-related uranium deposits. In: Cuney M and Kyser K (eds.) *Recent and Not-So-Recent Developments in Uranium Deposits and Implications for Exploration*, *Mineralogical Association of Canada Short Course Series*, vol. 39, pp. 161–220. Quebec: Mineralogical Association of Canada.

# Quartz-pebble Conglomerate deposits

Stratiform and stratabound deposits of uraninite and brannerite hosted in pyrite-rich quartz–pebble conglomerates

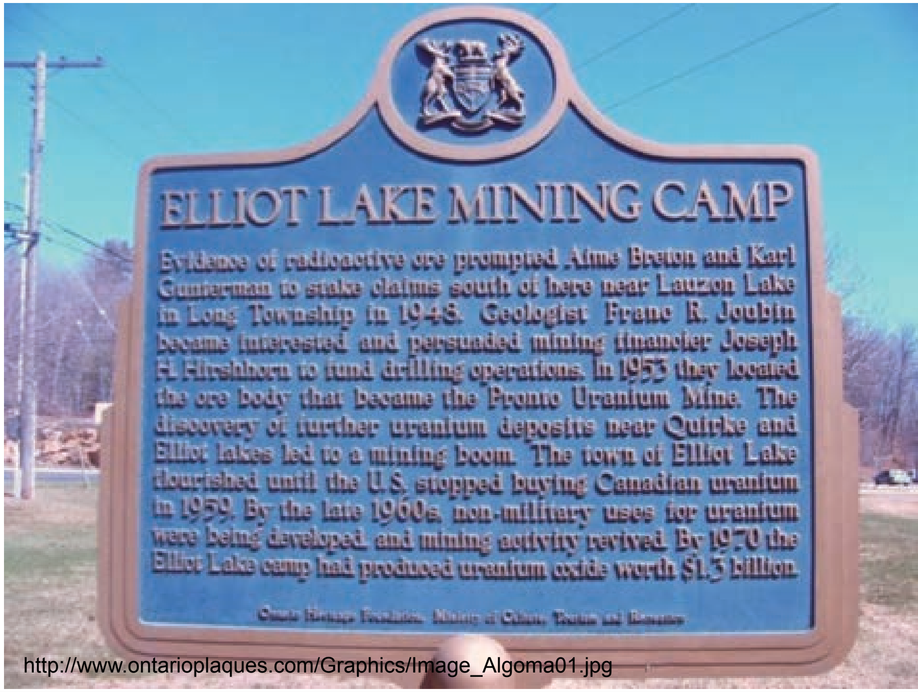
**Two types:**

**(1) Elliot Lake**: Mineralization affected mainly by sedimentary controls

**(2) Witwatersrand type**: ores controlled by local chemical environments (e.g. unconformities, shales, carbonaceous seams)

# Elliot Lake

- 1948: Aime Breton and Karl Gunterman found radioactive conglomerate
- 1953: Exploration and drilling commenced
- City started as a planned community in 1955 for the mining company
- 1950s: population of ~25,000 and was the "Uranium Capital of the World"
- Early 1990s: depleted reserves and low U prices caused the last mines to close (4,000 jobs lost)
- The community has survived and has a current population of ~11,500
- Also a source of HREEs (derived from fluids generated during the uraninite mining process) **was being explored for REE deposits by Pele Mountain Resources



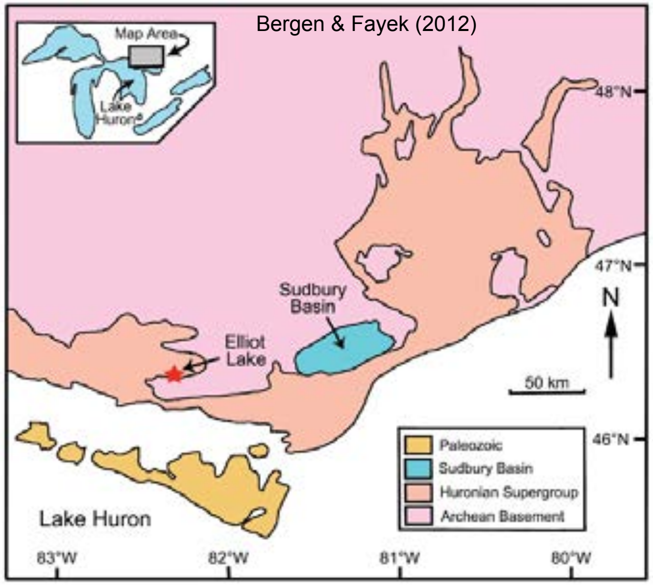
ELLIOT LAKE MINING CAMP

Evidence of radioactive ore prompted Aime Breton and Karl Gunterman to stake claims south of here near Lauzon Lake in Long Township in 1948. Geologist Franc R. Joubin became interested and persuaded mining financier Joseph H. Hirshhorn to fund drilling operations. In 1953 they located the ore body that became the Pronto Uranium Mine. The discovery of further uranium deposits near Quirke and Elliot lakes led to a mining boom. The town of Elliot Lake flourished until the U.S. stopped buying Canadian uranium in 1959. By the late 1960s non-military uses for uranium were being developed and mining activity revived. By 1970 the Elliot Lake camp had produced uranium oxide worth $1.3 billion.

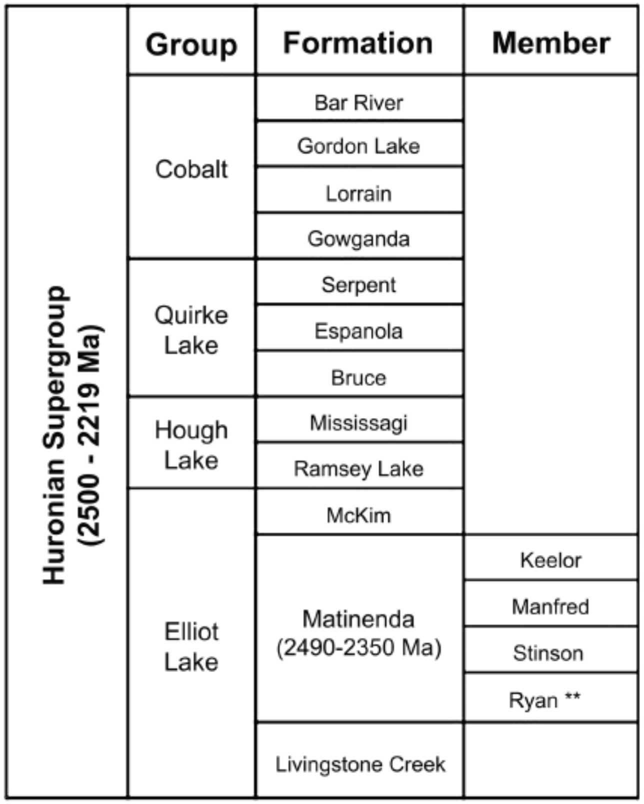
http://www.ontarioplaques.com/Graphics/Image_Algoma01.jpg

# Elliot Lake Geology

- Archean basement (volcanic rocks, sedimentary rocks and granites)
- Paleoproterozoic Huronian Supergroup and post-Huronian intrusive rocks
- Huroninan base (Elliot Lake Group) contains psammites, volcanic rocks and quartz–pebble conglomerates
- Ore minerals: uraninite, brannerite and monazite
- Uraninite grains (up to 0.2 mm, rounded) occur as small clusters of grains between pebbles
- Genesis: placer deposit modified by diagenesis or mild metamorphism
- Uraninite probably sourced from uraniferous Archean granites and pegmatites



Bergen & Fayek (2012)



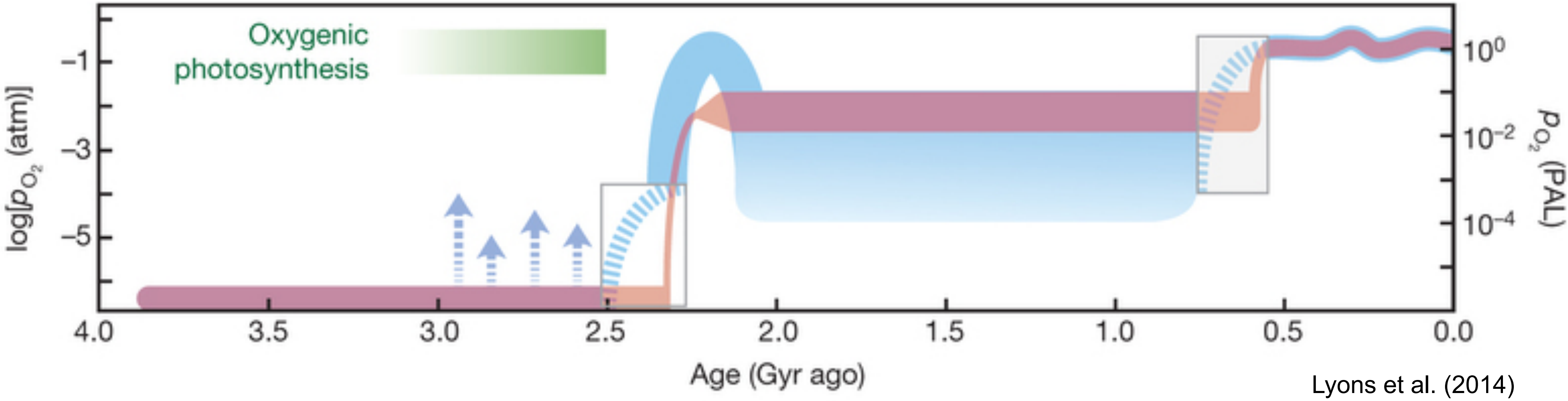
| | Group | Formation | Member |
|---|---|---|---|
| Huronian Supergroup (2500 - 2219 Ma) | Cobalt | Bar River | |
| | | Gordon Lake | |
| | | Lorrain | |
| | | Gowganda | |
| | Quirke Lake | Serpent | |
| | | Espanola | |
| | | Bruce | |
| | Hough Lake | Mississagi | |
| | | Ramsey Lake | |
| | Elliot Lake | McKim | |
| | | Matinenda (2490-2350 Ma) | Keelor |
| | | | Manfred |
| | | | Stinson |
| | | | Ryan ** |
| | | Livingstone Creek | |

# Detrital pyrite and uraninite?

Today this does not occur due to the breakdown of these minerals in oxygenated environments.

However, the Archean atmosphere was different (much less $O_2$).

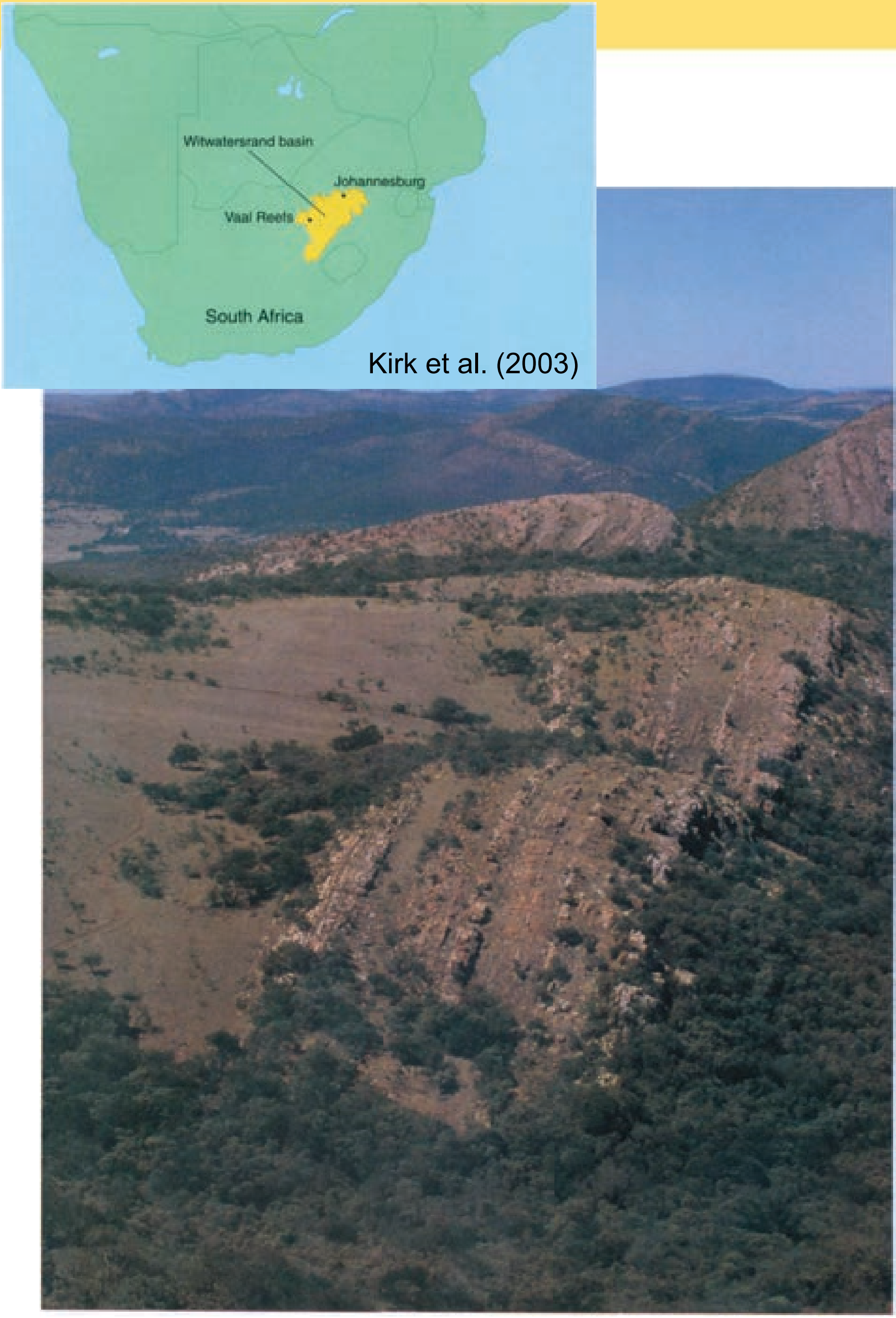
Minter (2006)



Lyons et al. (2014)

# Witwatersrand, South Africa

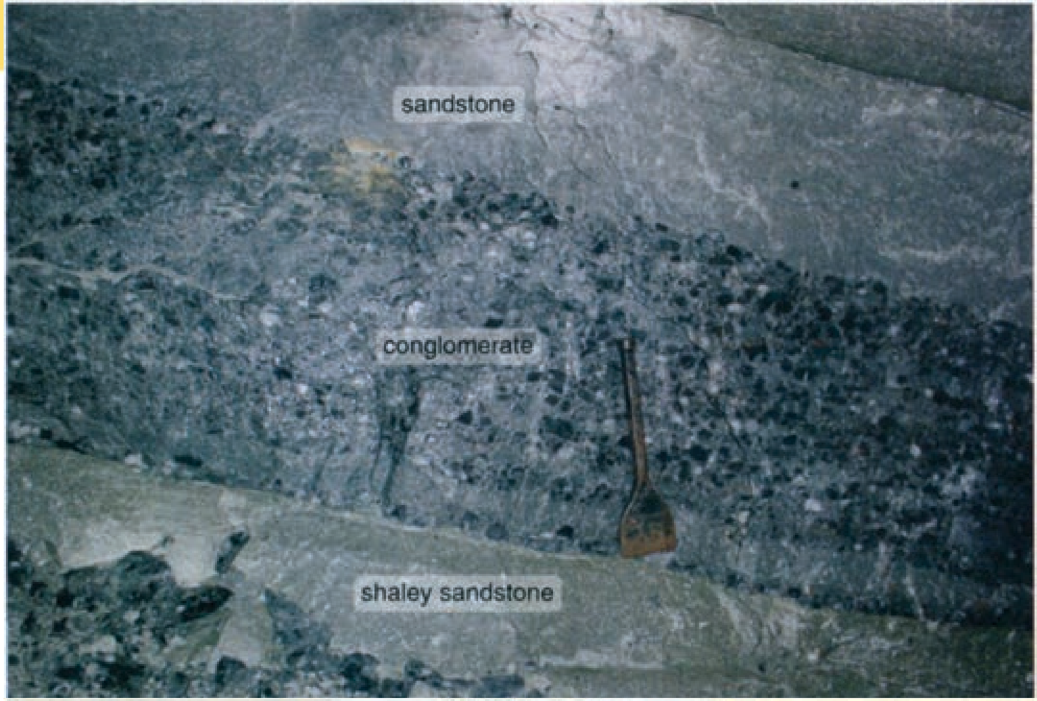
- "Witwatersrand" – White Waters Ridge
- Small scale gold prospecting in the 1850s
- Two prospectors found gold-rich conglomerate on an old farm and sold their claims for a few dollars – today their gold fields are worth billions
- Gold rush in 1886, which led to the establishment of Johannesburg
- >50% of all gold mined in human history comes from here
- 2% of world's U resources

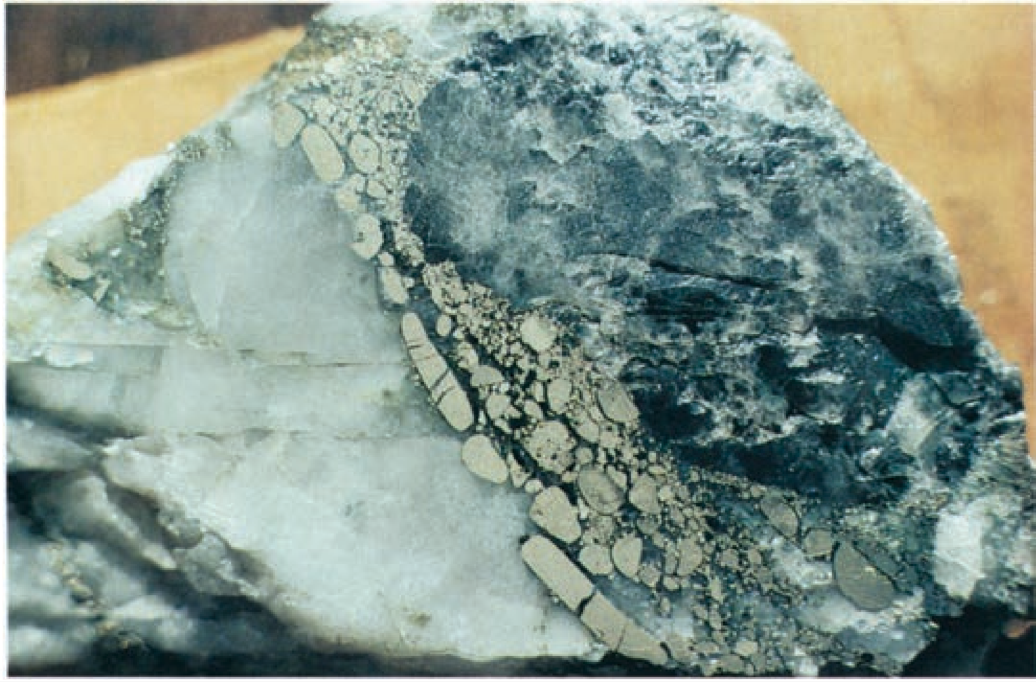


Kirk et al. (2003)

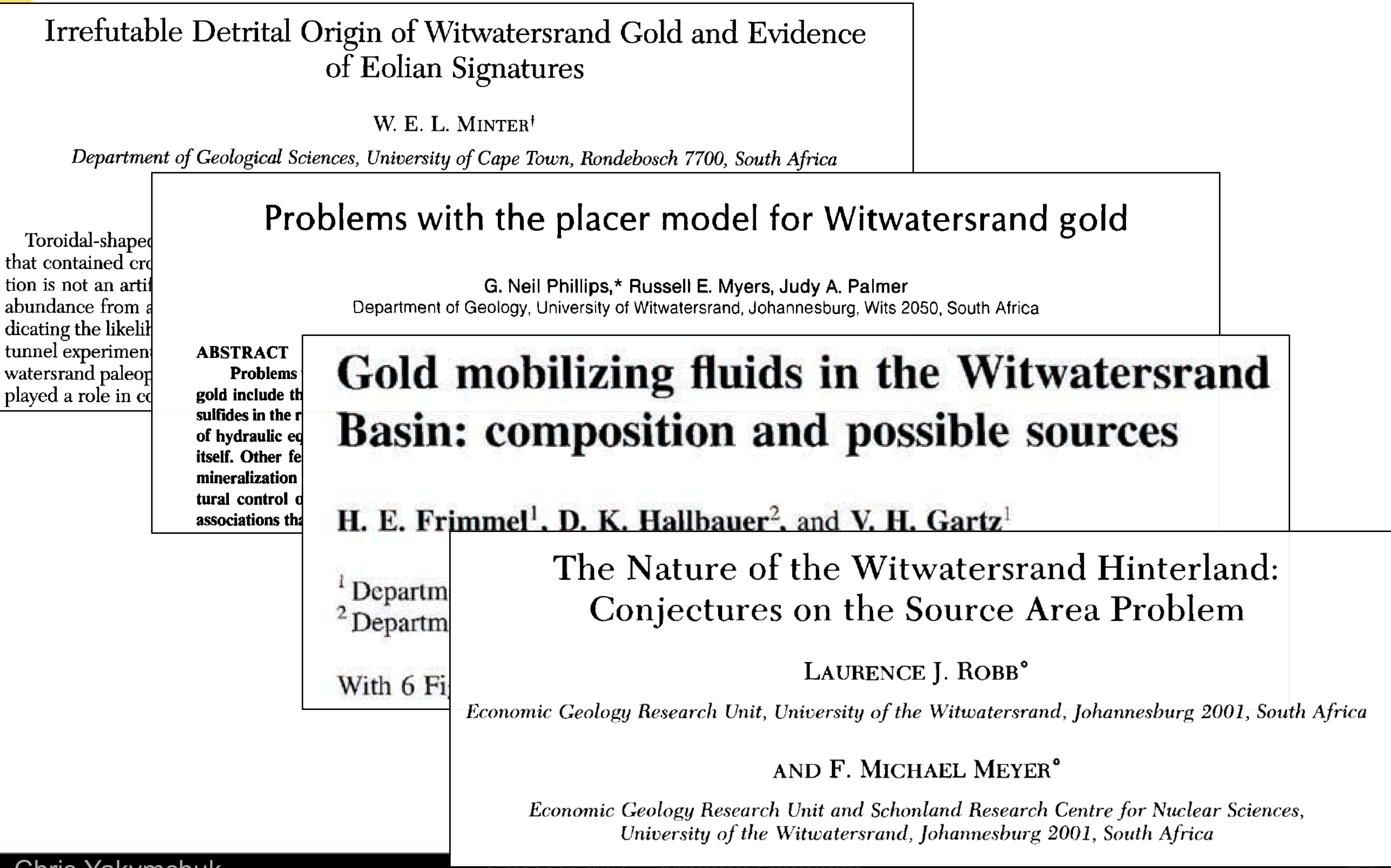
# Witwatersrand Geology

- Late Archean terrestrial sedimentary basin
- 7 km thick sequence of sediments (sandstone, conglomerate, shales)
- Quartz-pebble conglomerates contain pyrite, gold and uraninite
- Uraninite grains have similar age to granites surrounding the basin
- What process caused Au and U mineralization???





# Lots of controversy over Witwatersrand deposits



## Irrefutable Detrital Origin of Witwatersrand Gold and Evidence of Eolian Signatures

W. E. L. MINTER†

*Department of Geological Sciences, University of Cape Town, Rondebosch 7700, South Africa*

Toroidal-shape
that contained cr
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watersrand paleop
played a role in c

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## Problems with the placer model for Witwatersrand gold

G. Neil Phillips,* Russell E. Myers, Judy A. Palmer
Department of Geology, University of Witwatersrand, Johannesburg, Wits 2050, South Africa

**ABSTRACT**

**Problems
gold include th
sulfides in the r
of hydraulic eq
itself. Other fe
mineralization
tural control c
associations th**

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## Gold mobilizing fluids in the Witwatersrand Basin: composition and possible sources

H. E. Frimmel[1], D. K. Hallbauer[2], and V. H. Gartz[1]

[1] Departm
[2] Departm

With 6 Fi

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## The Nature of the Witwatersrand Hinterland: Conjectures on the Source Area Problem

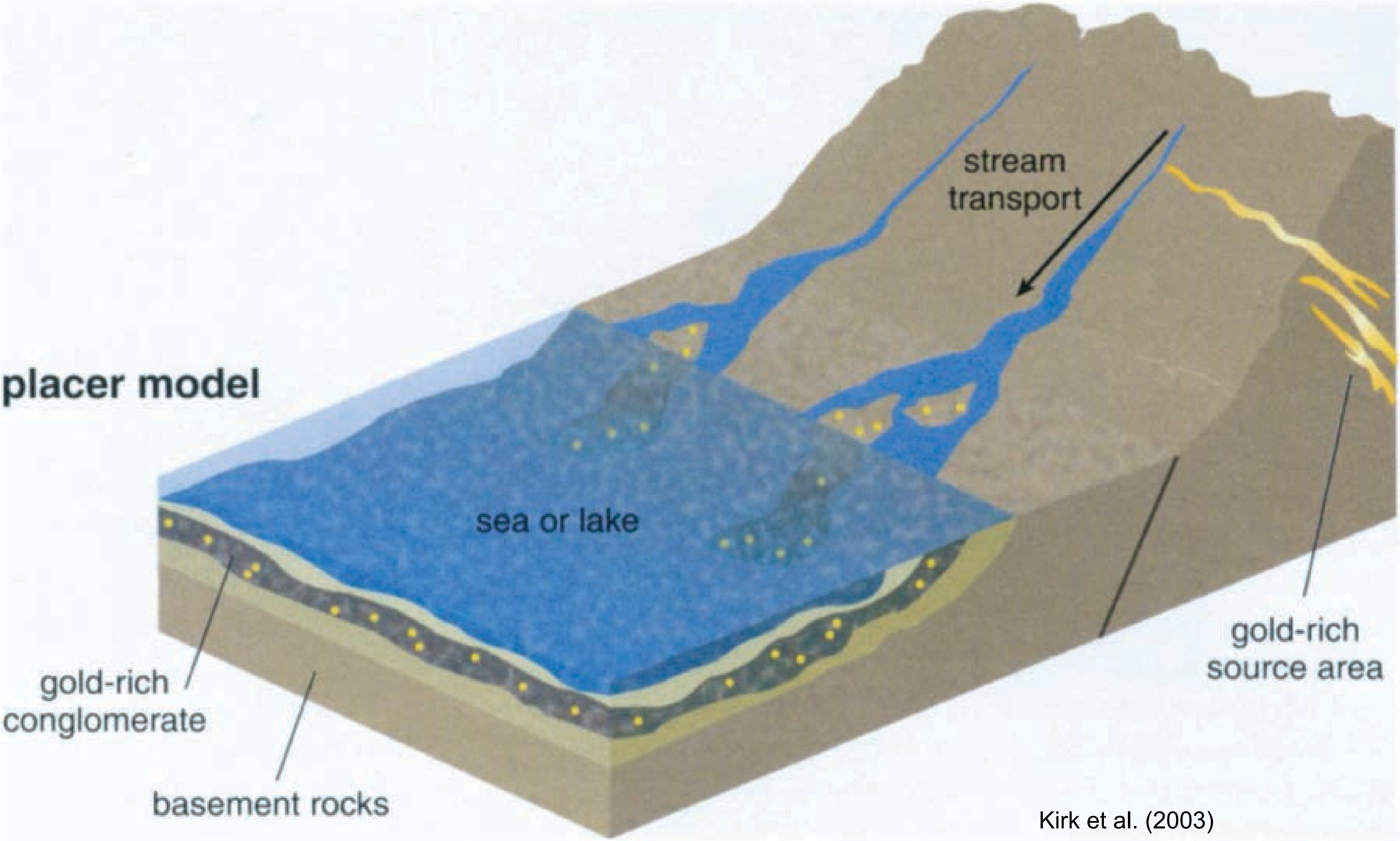
LAURENCE J. ROBB*

*Economic Geology Research Unit, University of the Witwatersrand, Johannesburg 2001, South Africa*

AND F. MICHAEL MEYER*

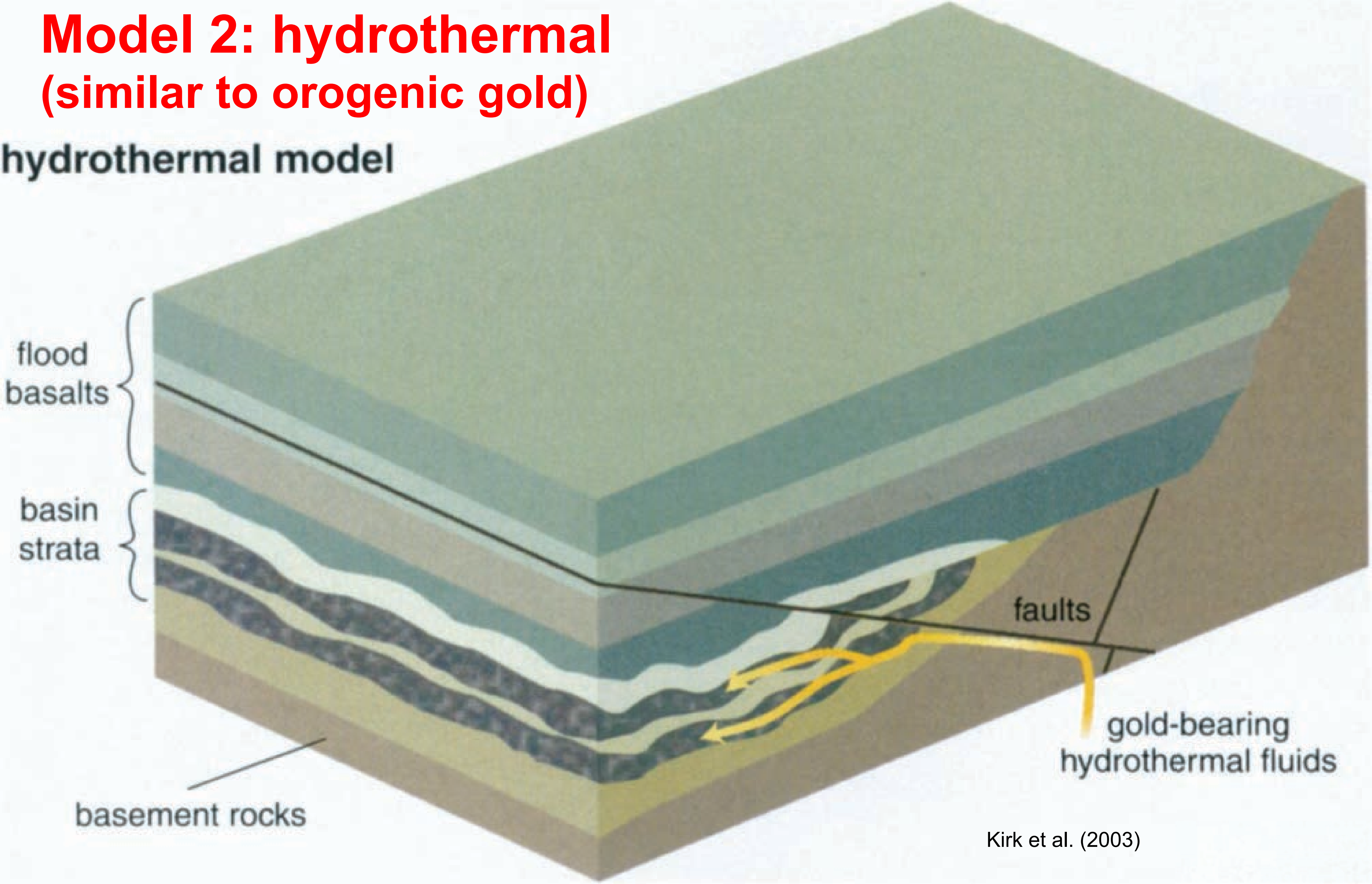
*Economic Geology Research Unit and Schonland Research Centre for Nuclear Sciences, University of the Witwatersrand, Johannesburg 2001, South Africa*

# Model 1: placer



Kirk et al. (2003)

# Model 2: hydrothermal
## (similar to orogenic gold)



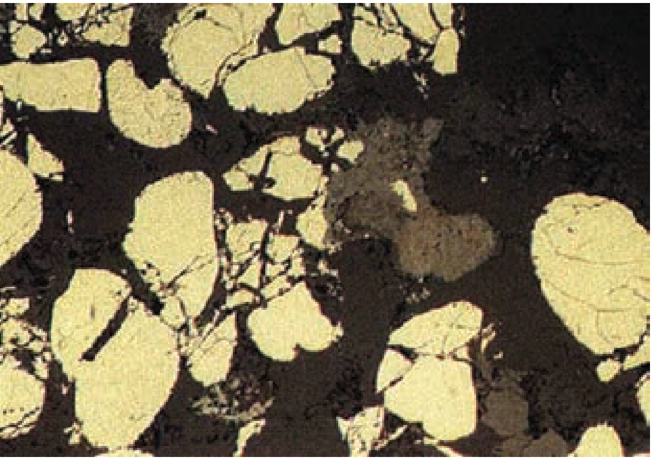
Kirk et al. (2003)

# Witwatersrand ore hypotheses [ M1 = placer, M2 = hydrothermal]

<u>Rounded pyrite and maybe gold (debated)</u>

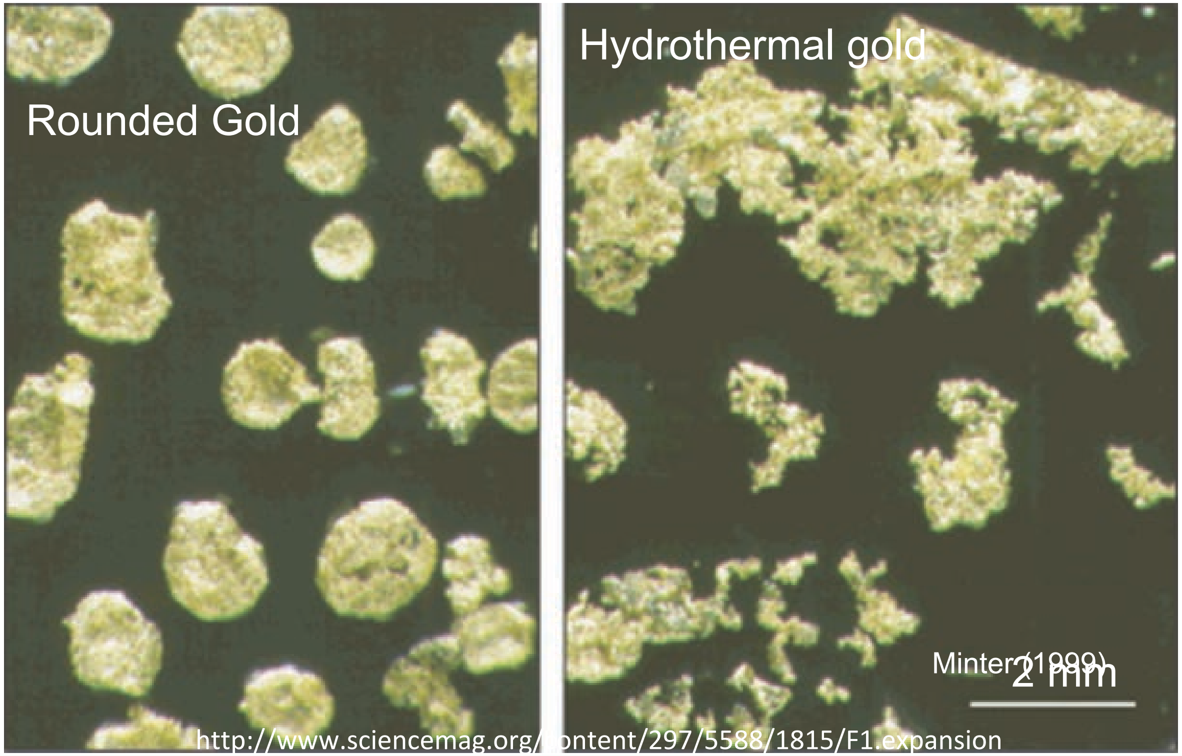
- (M1) Abraded during river transport, or
- (M2) Rounded magnetite reacted with sulfur to produce pyrite

**Rounded pyrite**



http://www.geo.arizona.edu/geo3xx/geo306_mdbarton/classonly/306%20Web%20Materials/306_Lecture041129.htm

Gold from one sample



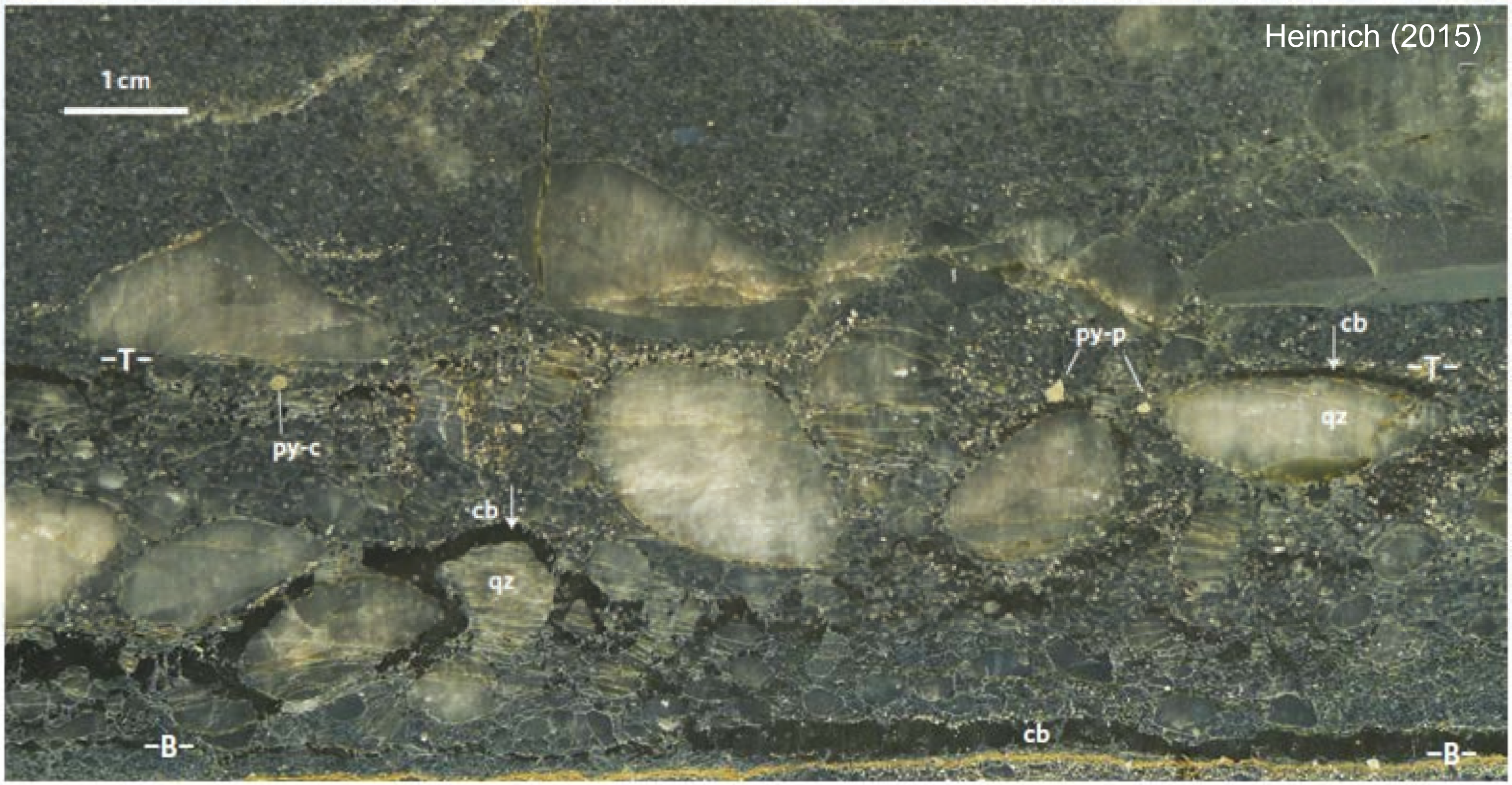
Minter (1999)

http://www.sciencemag.org/ ontent/297/5588/1815/F1.expansion

# Witwatersrand ore hypotheses [ M1 = placer, M2 = hydrothermal]

Gold found almost exclusively in conglomerates

- (M1) High energy fluvial environment, or
- (M2) Permeable horizon for hydrothermal fluids


Heinrich (2015)

# Witwatersrand general consensus:

The preservation of (apparently) detrital pyrite and uraninite suggests placer deposition in an oxygen-poor setting.

Some gold particles show evidence for mechanical transport, but most appear hydrothermal in origin.

Local redistribution of originally placer gold by hydrothermal fluids during metamorphism: known as the "modified placer deposit model".

# Uranium deposit summary

Uranium is redox sensitive: U is soluble in oxidized fluids and relatively insoluble in reducing fluids

Unconformity uranium: oxidized basinal waters interact with relatively reducing rocks (e.g. graphite-bearing) in the basement resulting in U precipitation at the unconformity.

Sandstone uranium: oxidized meteoric waters encounter reducing conditions (e.g. organic matter) resulting in U precipitation – the mineralization zone migrates down dip (e.g. roll-front deposits).

Quartz-Pebble conglomerates: can be a mixture of hydrothermal and sedimentary process (e.g. Witwatersrand).