IAEA-UNECE Interregional workshop on uranium, coal and oil & gas classification: Towards a better understanding of energetic basins and application of UNFC-2009

Project Number & Title: INT2/019

Developing Technology and Management of Sustainable Uranium Extraction

Ulaan Baatar, Mongolia
August 16-19th, 2016

Organizer
The International Atomic Energy Agency (IAEA)
in collaboration with the Government of Mongolia through the Ministry of Mining, Mongolia

IAEA-UNECE Interregional workshop on uranium, coal and oil & gas classification: Towards a better understanding of energetic basins and application of UNFC-2009

Industry Best Practice Technology of In-Situ Recovery of Uranium

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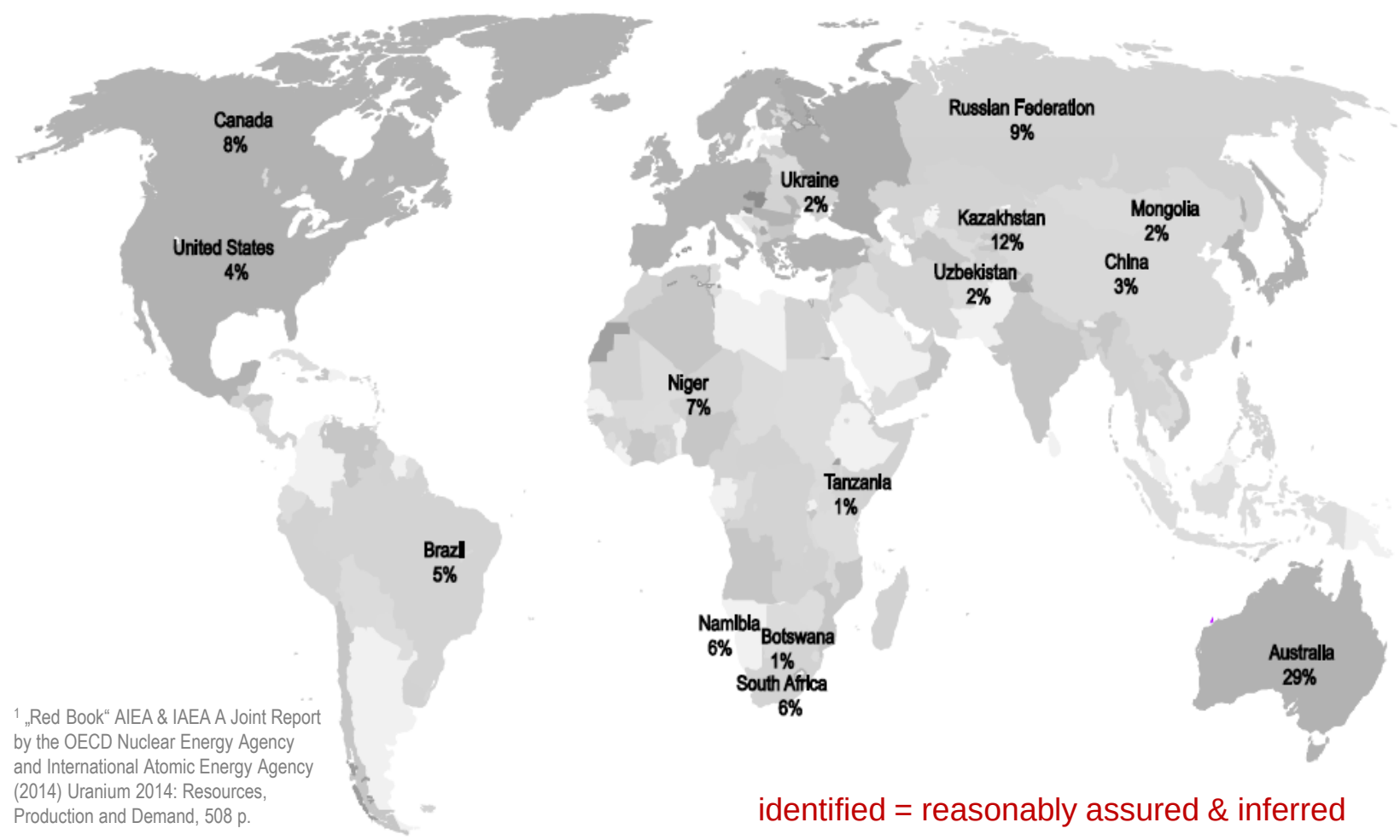
DMT GmbH & Co. KG, Essen, Germany

August 16-19th, 2016

Ulaanbaatar, Mongolia

Global Distribution of Identified Uranium Resources[1]



[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.

identified = reasonably assured & inferred

World Uranium Resources

- **Total identified uranium resources (measured + indicated + inferred) as of Jan. 2013: 5,902,900 t of uranium metal (increase of ~11% compared to Jan. 2011)[1].**
- **Results mainly from re-evaluations of previously identified resources and addition to known deposits (Australia, Canada, Czech Republic, Greenland, Kazakhstan, China and South Africa due to 23% increase in uranium exploration and mine development expenditures 2010-2012).**
- **At the 2012 level of uranium requirements, identified uranium resources are sufficient for over 120 years of supply for the global nuclear power fleet (world reactor requirements 61,980 tU).**

[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.

Geological Types of Uranium Deposits[2]

- Uranium occurs in a number of different geological environments.
- Most Kazakh uranium resources are sedimentary.
- Most Canadian uranium resources are unconformity-related.
- Most Australian uranium resources situated in roll-front, unconformity-related and Fe-oxide breccia complex ore bodies.

[2] www.world-nuclear.org; Feb. 2015

Industry Best Practice U-ISR Technology
Uranium Deposit Types

Geological Types of Uranium Deposits[3]

1. Unconformity-related deposits (e.g. Key Lake, Canada)
2. Sandstone deposits (e.g. Beverley, Australia)
   - Roll-front type deposits
   - Tectonic lithologic type deposits
   - Basal channel type deposits
   - Tabular sandstone type deposits
3. Hematite Breccia Complex deposits (e.g. Olymic Dam, Australia)
4. Quartz-pebble conglomerate deposits (e.g. Witwatersrand, South Africa)
5. Vein type deposits (e.g. Jachymov, Czech Republic)
6. Intrusive deposits (e.g. Rössing, Namibia)
7. Caldera-related volcanic deposits (e.g. Dornod and Gurvanbulag, Mongolia)
8. Metasomatic deposits (e.g. Valhalla and Skal, Australia).
9. Surficial deposits (e.g. Langer Heinrich, Namibia).
10. Collapse breccia pipe deposits (e.g. Arizona Strip, near Grand Canyon, USA).
11. Phosphorite deposits (e.g. Forida, Idaho, USA).
12. Black shale deposits (e.g. Ranstad, Sweden)
13. Metamorphic deposits (e.g. Mary Kathleen, Australia)
14. Other deposit types
    - Uraniferous coal and lignite deposits
    - Limestone and paleokarst deposits
    - By-product copper and gold processing

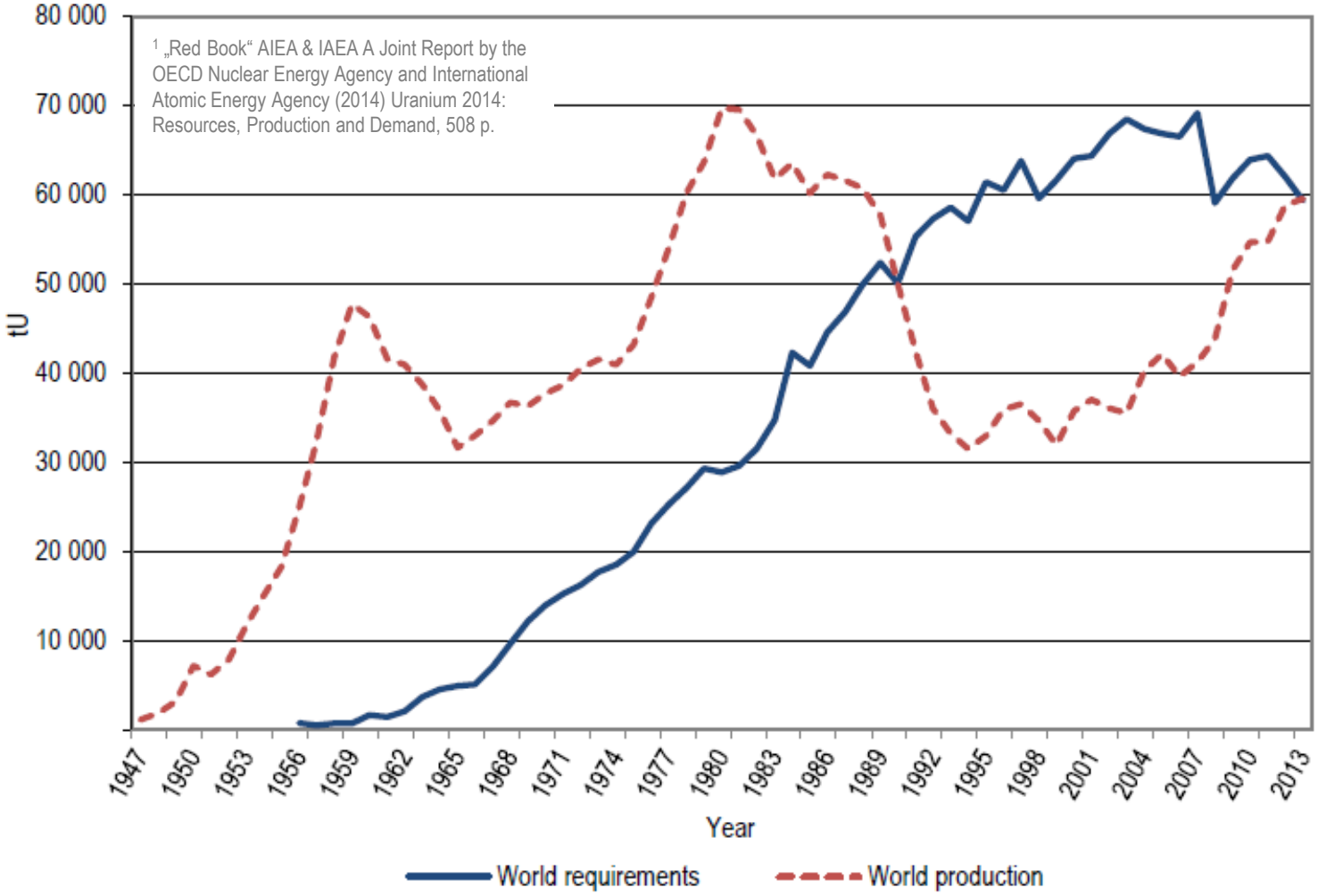
[3] IAEA-TECDOC-1629 (2009 Edition) World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification, 126 p.

World Uranium Demand and Supply[1]

GWe = Gigawatt electric

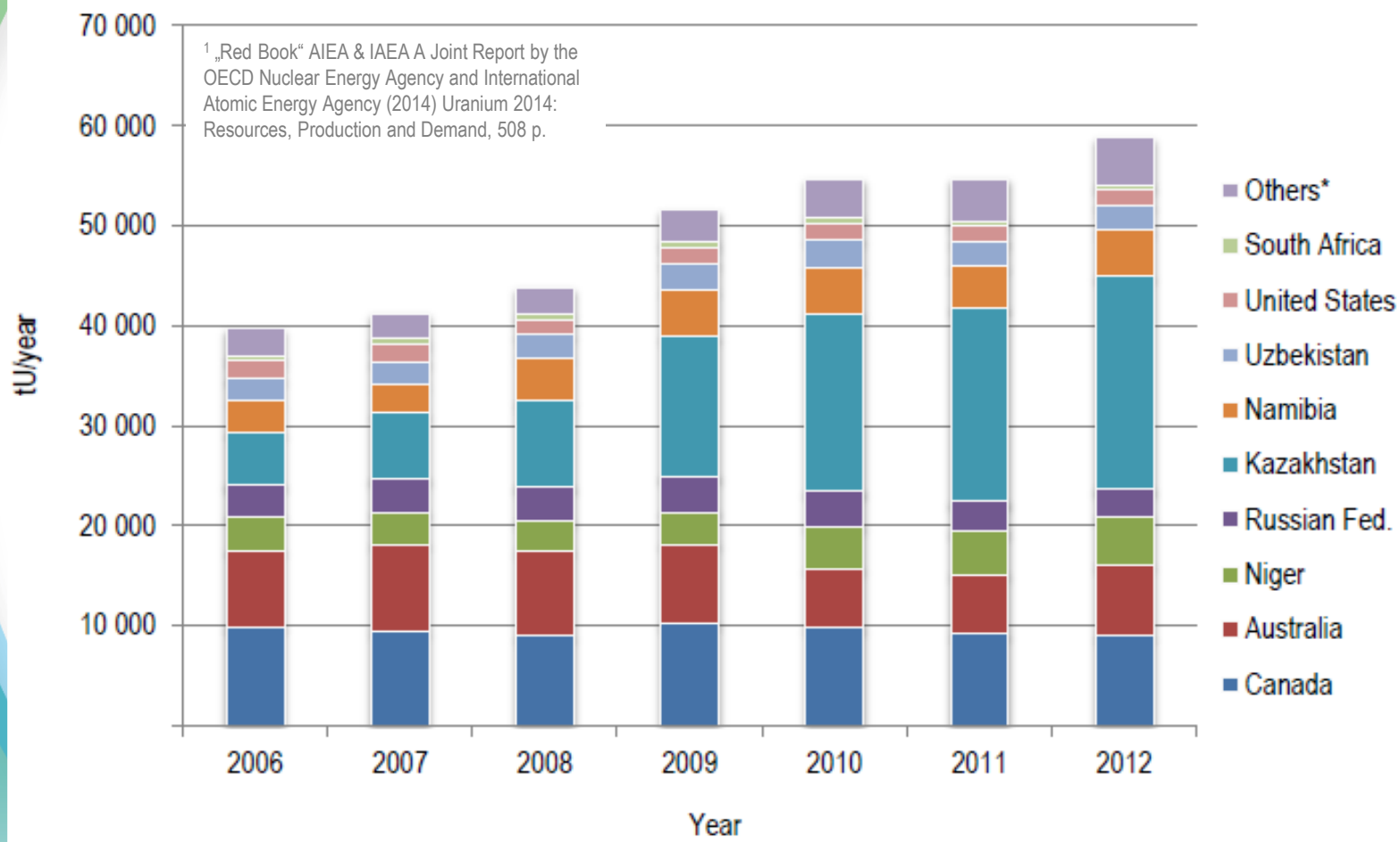
- **In spite of changes in policies in Belgium, France, Germany, Italy, Sweden and Switzerland (following Fukushima power plant accident), world nuclear capacity by the year 2035 is projected to grow to between 400 GWe net (low-demand case) and 680 GWe (high-demand case), representing increases between 7% and 82%.**
- **End of year 2012, 437 commercial nuclear reactors were connected to the grid with a net generating capacity of 372 GWe requiring some 61,980 tU world reactor requirement.**
- **World annual reactor-related uranium requirements are projected to rise to between 72,000 tU and 122,000 tU by year 2035.**
- **East Asia projected to experience the largest increase by year 2035 (between 57 GWe/low demand – and 125 GWe/high demand) representing increases of 65-150% over 2013 capacity.**
- **With uranium production to expand, efforts are increasing for environmentally more sustainable best-practice uranium production.**

Annual Uranium Production and Requirements[1]



[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.

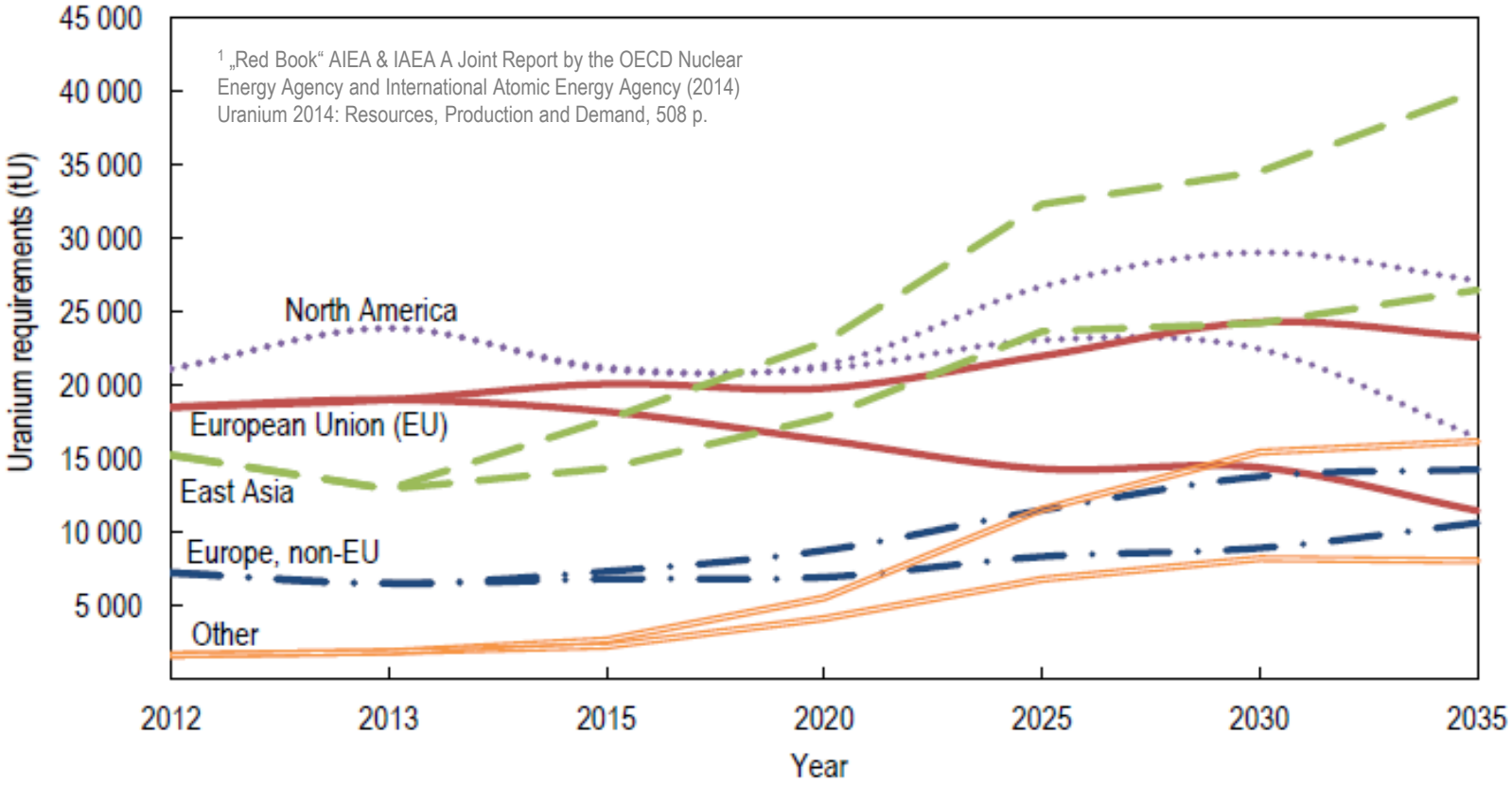
Recent World Uranium Production[1]



[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.

Industry Best Practice U-ISR Technology
Annual Uranium Requirements

Annual reactor-related uranium requirements to 2035[1]



[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.

In-situ Recovery / In-Situ Leaching (ISR/ISL)

- In-Situ Recovery (ISR) is an ore recovery technology suitable for sandstone uranium deposits.
- Sandstone-type uranium deposits contain 18-28% of the world uranium resources.
- Potentially suitable for ISR are those below the water table in weakly lithified or non-consolidated sands.
- Uranium grade is determined by down-hole geophysics, in particular by *prompt fission neutrons* technique (PFN), coupled with sampling and assaying of the drill core.
- The ISR core concept is based on dissolving uranium minerals directly within their host rocks (in-situ) by reactive solutions that are injected through drill holes (injectors).
- The dissolved solution (pregnant lixiviant) is then pumped to the surface through discharge drill holes (extractors).

Uranium Production by Extraction Method 2006-2007[3]

	Uranium Production (%)	
Uranium Production Method	**2006**	**2007**
Underground Mining	39.9	37.7
Open Pit	24.2	23.7
In Situ Leaching	24.9	27.7
Co-product/by-product	8.6	8.4
Others	2.4	2.5
Total	**100.0**	**100.0**

[3] IAEA-TECDOC-1629 (2009 Edition) World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification, 126 p.

Recent World Uranium Production Technology[1]

- **ISR/ISL - 47.5% (2013)**
- **Underground mining - 26% (2012)**
- **Open-pit mining - 20% (2012)**
- **Co-product/by-product - 6% (2012)**
- **Heap leaching - 2% (2012)**
- **Other methods - 1% (2012)**

In-situ recovery **(ISR, also referred to as *in-situ leaching* ISL) has become the dominant method of uranium production accounting for ~48% of world production in 2013, mainly due to increased production in Kazakhstan (+ Australia, China, Russian Federation, U.S. and Uzbekistan).**

[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.

Main differences to non-uranium code-compliant resource projects

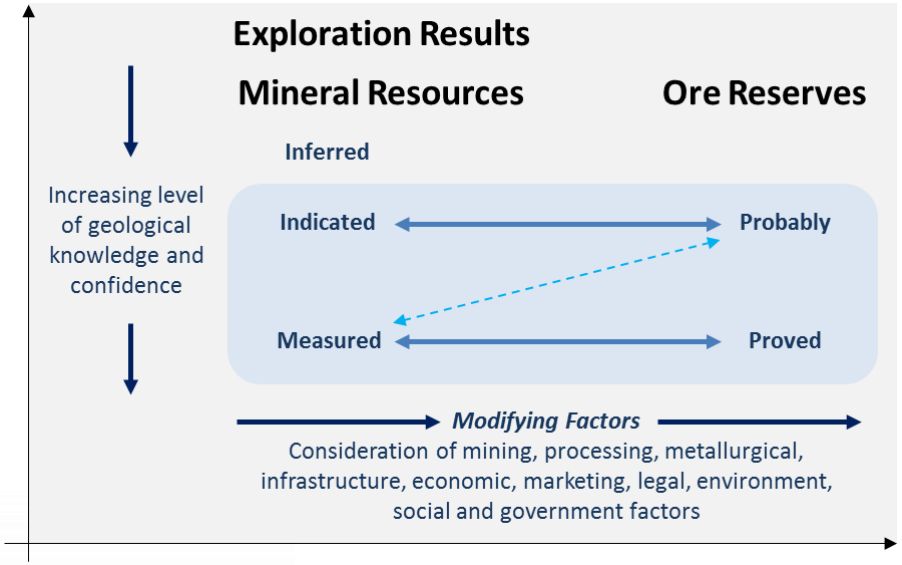
- **Radiometric probes or hand-held devices are commonly used in exploration and evaluation of mineralisation – these need to be appropriately calibrated and adequate correction factors applied.**
- **Uranium can be out of equilibrium with its daughter products (progenies), and the extent of disequilibrium needs to be quantified in estimating uranium grades by gamma-based methods.**
- **‚*Check assays*‘ of representative samples are required. The reliability of probe measurements, number and distribution of measurements, and extent of check essaying will constrain the category of uranium mineral resources that can be reported[5].**

[5] McKay, A.D., Stoker, P., Bampton, K.F., Lambert, I.B. (2007) Resource estimates for In-Situ Leach Uranium Projects and Reporting Under the JORC Code, Bulletin, p. 58-67.

Typical Resource Classification Grid for Uranium Resources

Example: Kazakhstan[6]

- **Measured[7] – av. 50x100m** (range from 25x50m to 50x100m)
- **Indicated[7] – av. 50x200m** (range from 50x100m to 50x200m)
- **Inferred[7] – av. 50x400m** (range from 50x400m to 100x800m)



[6] Abzalov, M.Z., Drobov, S.R., Gorbatenko, O., Vershkov. A.F., Bertoli, O., Renard, D., Beucher, H. (2014) Resource estimation of in-situ leach uranium projects, Applied Earth Science (Trans. Inst. Min. Metall. B), vol. 123, no. 2, p. 71-85

[7] CRIRSCO (2012) The JORC Code, 2012 Edition.

Main ISR Parameters to be Considered[6]

(1) Grade and geometry of mineralization (accuracy sufficient for supporting remote mining).

(2) If grade is estimated using gamma logging technique, then the disequilibrium should be studied and reported.

(3) Hydrogeological confinement of the mineralized horizon.

(4) Permeability of the mineralized horizon.

(5) Composition of the host rocks (carbonate content) to estimate if U mineralization is amenable to dissolution by acid or alkaline solutions.

(6) Groundwater flow.

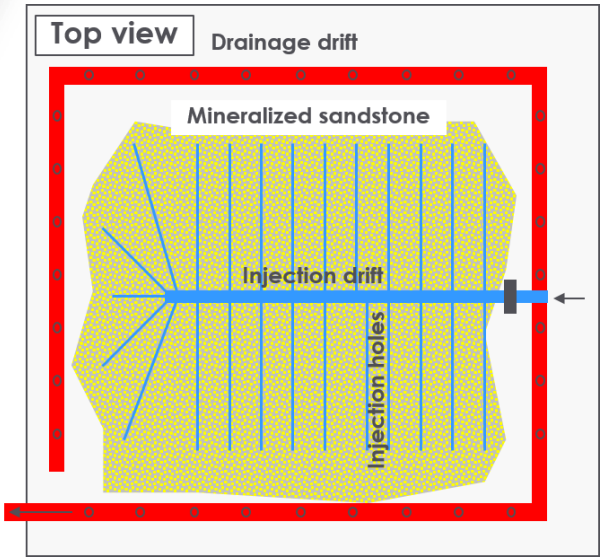
(7) Aquifer salinity.

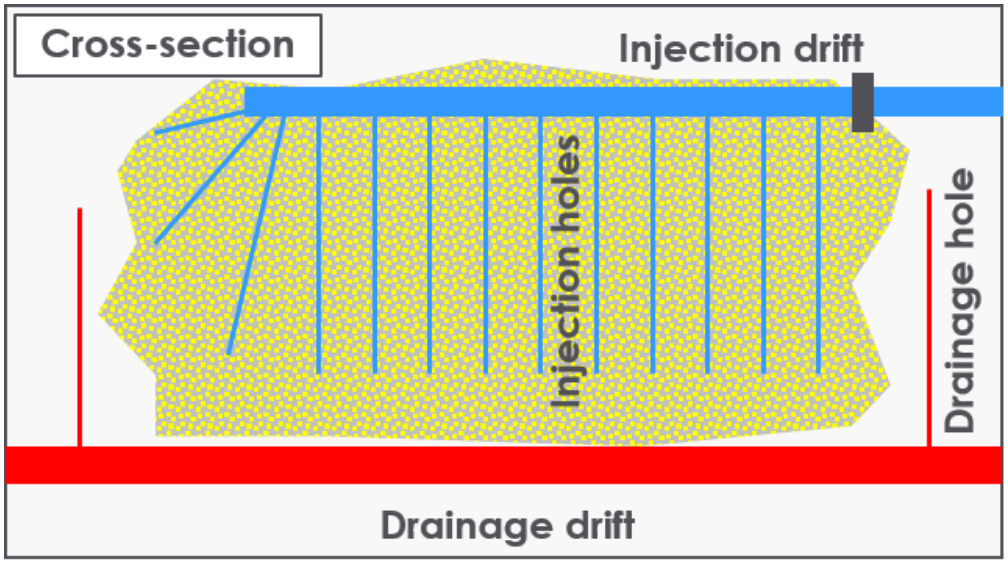
(8) Rate of *in-situ* dissolution of the U minerals.

[6] Abzalov, M.Z., Drobov, S.R., Gorbatenko, O., Vershkov. A.F., Bertoli, O., Renard, D., Beucher, H. (2014) Resource estimation of in-situ leach uranium projects, Applied Earth Science (Trans. Inst. Min. Metall. B), vol. 123, no. 2, p. 71-85.

U-Leaching Technology Option

Underground block leaching (example Königstein, Germany)





Leaching principle:

- Percolation (gravity-driven lixiviant flows through uranium ore)
- Condition: sufficient permeability for quantitative flow
- Alternative measure: fracturing by explosives (as performed by Wismut)

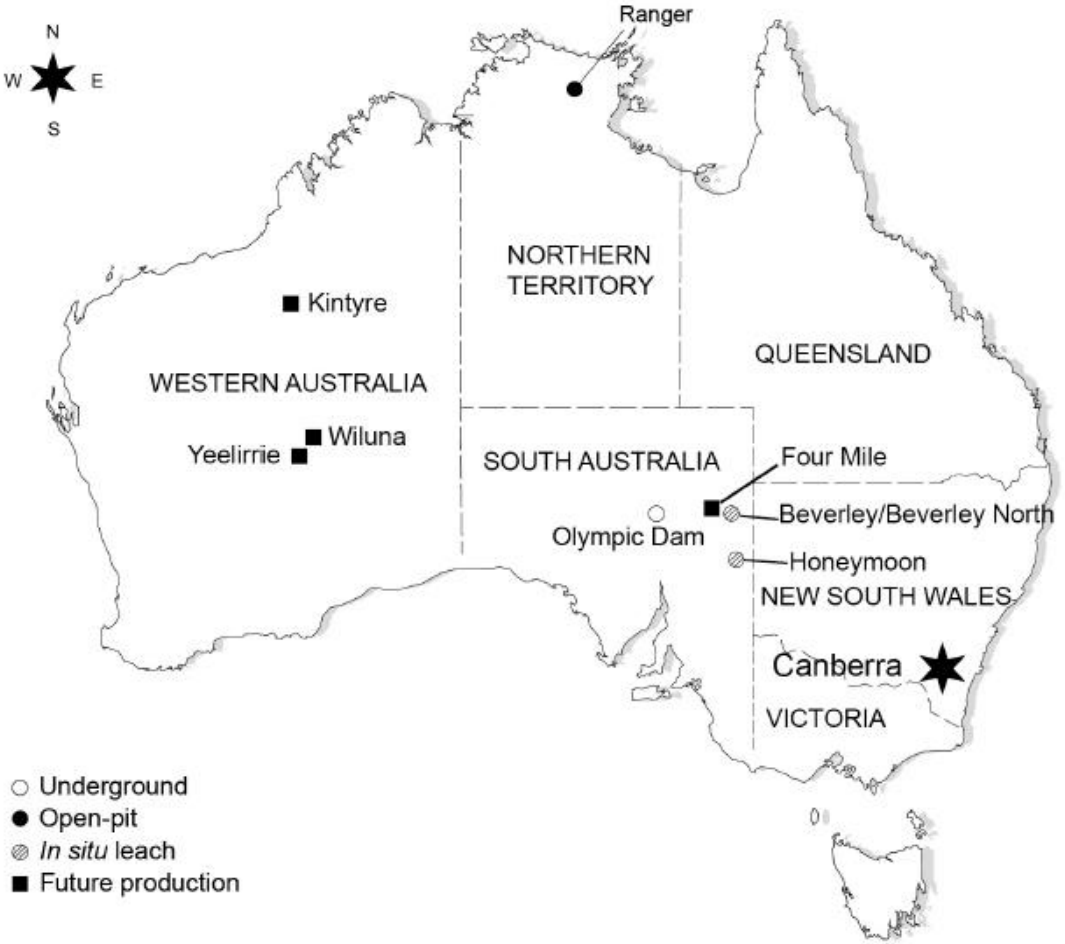
Requires:

- Development of drifts around defined leaching blocks
- Injection drifts with injection holes
- Drainage system (drainage drifts with drainage holes) to collect pregnant lixiviant

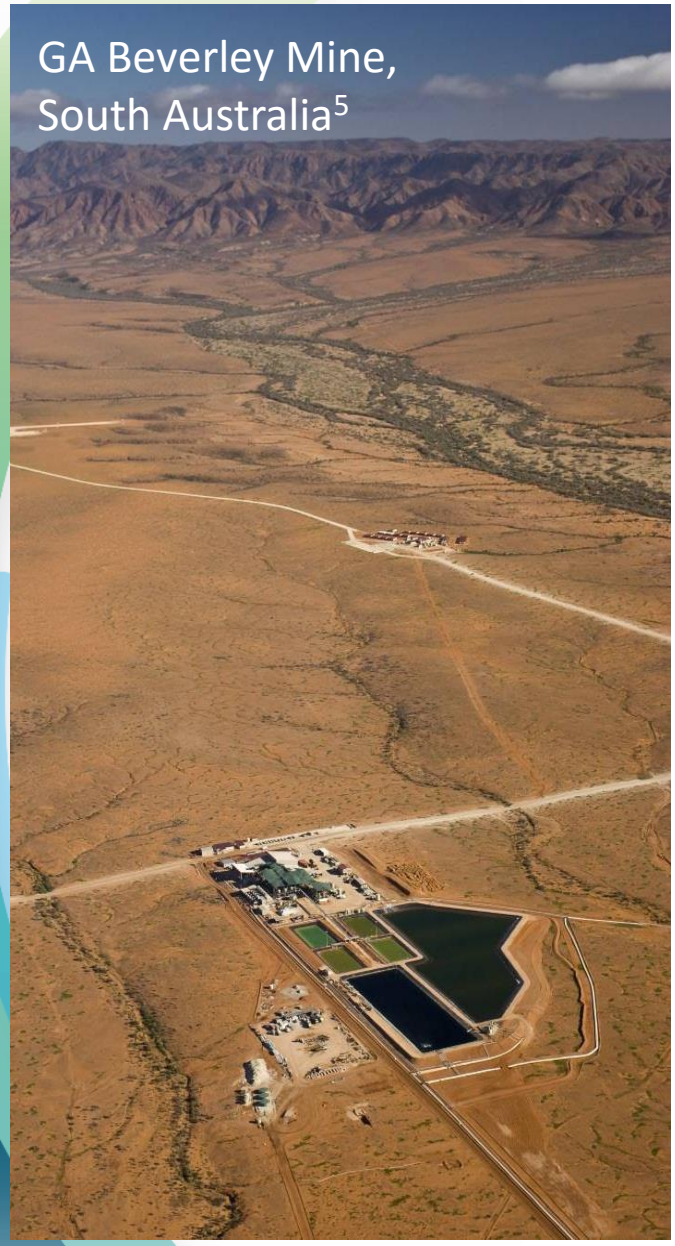
Future ISR Production Centers, Australia

example: Four Mile W+E, Beverley[1]

- Av. ISR mining recovery Beverley/Beverley North: ca. 65% (0.26% U grade; incl. combined losses due to ISR mining and hydrometallurgical processing)



[1] „Red Book“ AIEA & IAEA A Joint Report by the OECD Nuclear Energy Agency and International Atomic Energy Agency (2014) Uranium 2014: Resources, Production and Demand, 508 p.



Industry Best Practice U-ISR Technology

Beverley Mine, Australia

The Uranium In-Situ Recovery Process

1. Groundwater pumped to surface
2. Small amount of acid and oxidant added
3. Water pumped back into aquifer
4. Uranium dissolved
5. Water pumped to surface
6. Uranium extracted from water
7. Water recycled back to “2.”

[5] McKay, A.D., Stoker, P., Bampton, K.F., Lambert, I.B. (2007) Resource Estimates for In-Situ Leach Uranium Projects and Reporting under the JORC Code, Bulletin, p. 58-67.

Industry Best Practice U-ISR Technology
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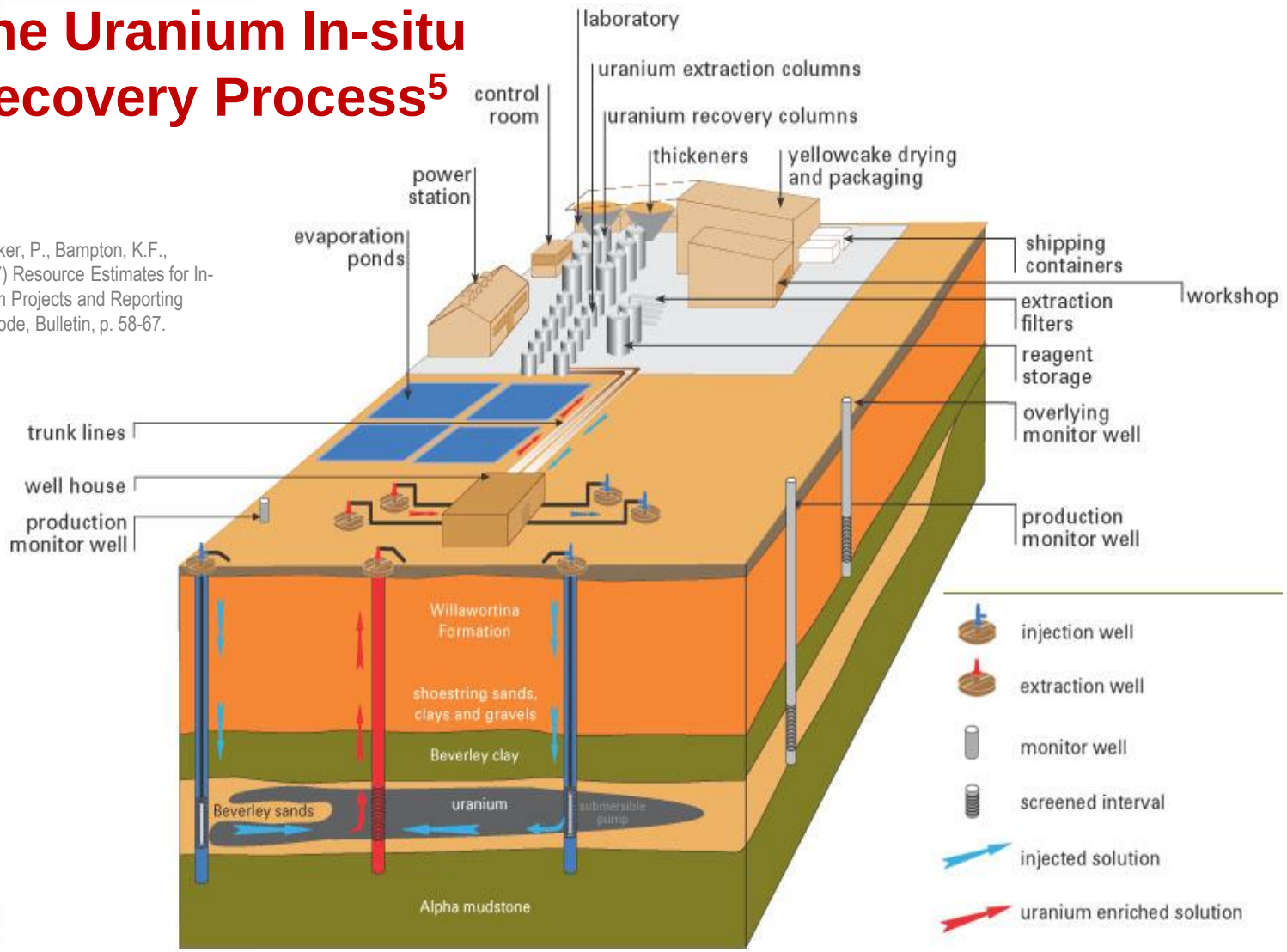
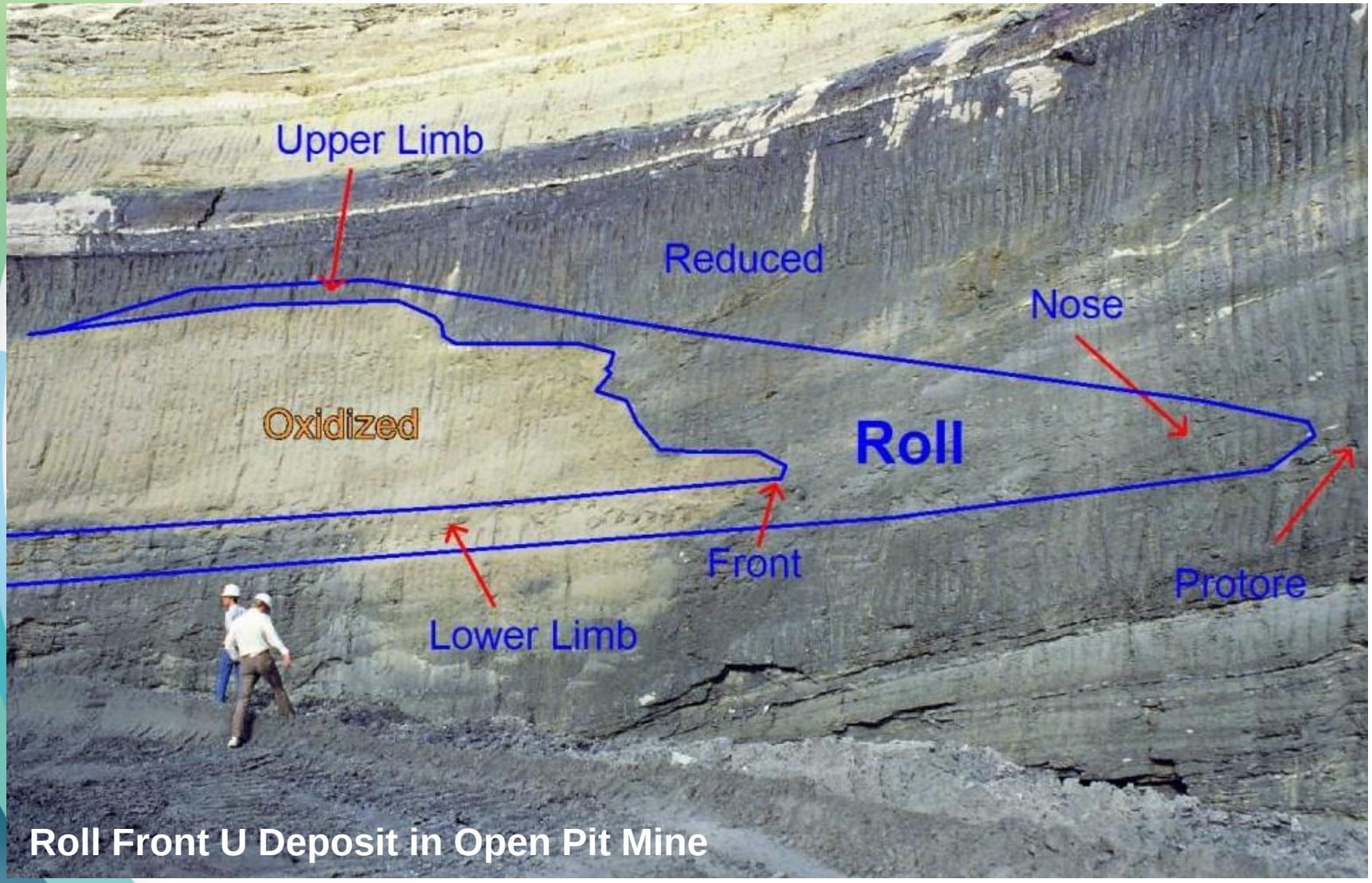


Industry Best Practice U-ISR Technology

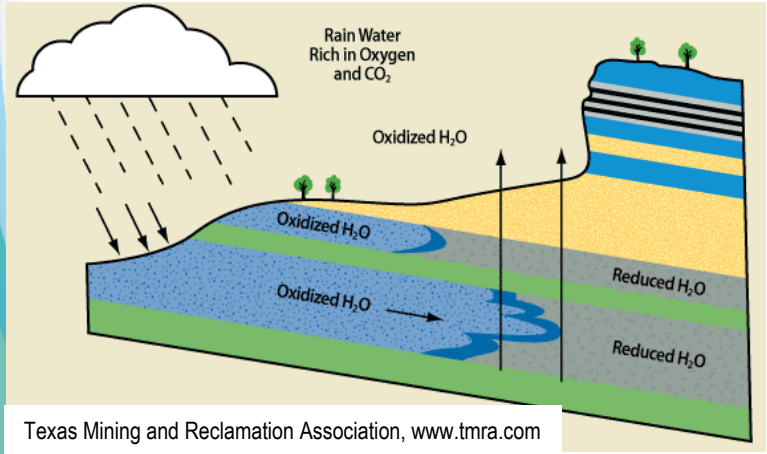
Roll-front Deposit



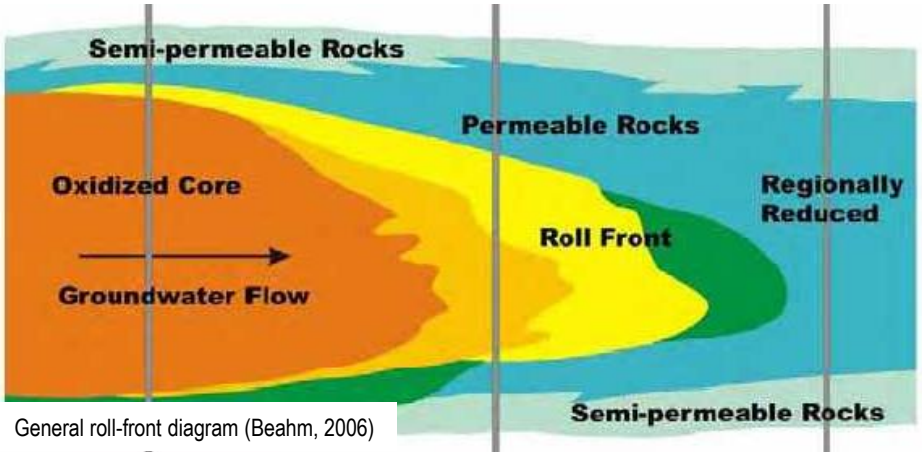
Roll Front U Deposit in Open Pit Mine

Formation of Roll-Front Deposits[8]

- Also known as „ore-rolls“, solution fronts, geochemical cells, and reduction-oxidation (redox) fronts.
- Typically form by mixing of groundwater fluids of varying chemistry (e.g. oxidizing groundwater interfacing/mixing with reducing groundwater).
- May contain a variety of accessory metals (e.g. Mo, V, Se).



Texas Mining and Reclamation Association, www.tmra.com



General roll-front diagram (Beahm, 2006)

[8] Beahm, D. (2006) Mineral Resource Report (NI43-101), Converse County, Wyoming, Energy Metals Corporation, 35 p.

Conditions to form a Uranium Roll-Front Deposit

- **A transportation system**
  - **Surficial water flow (to transport U to groundwater recharge)**
  - **Groundwater flow**
    - **Regionally transmissive host sandstone (good porosity and permeability)**
    - **Oxygenated groundwater**
    - **Focused groundwater flux (confined aquifer, bounding shales/clays, paleochannel systems)**
- **A hydrogeological ‚trap' (i.e. suitable hostrock)**
  - **Fluvial or marine sandstones with good porosity and permeability**
  - **Regional chemically reducing environment**
  - **Development of reduction-oxidation interface**
- **Time (continuity of favorable conditions to build deposit)**

General Characteristics of Uranium Roll-Front Deposits[12]

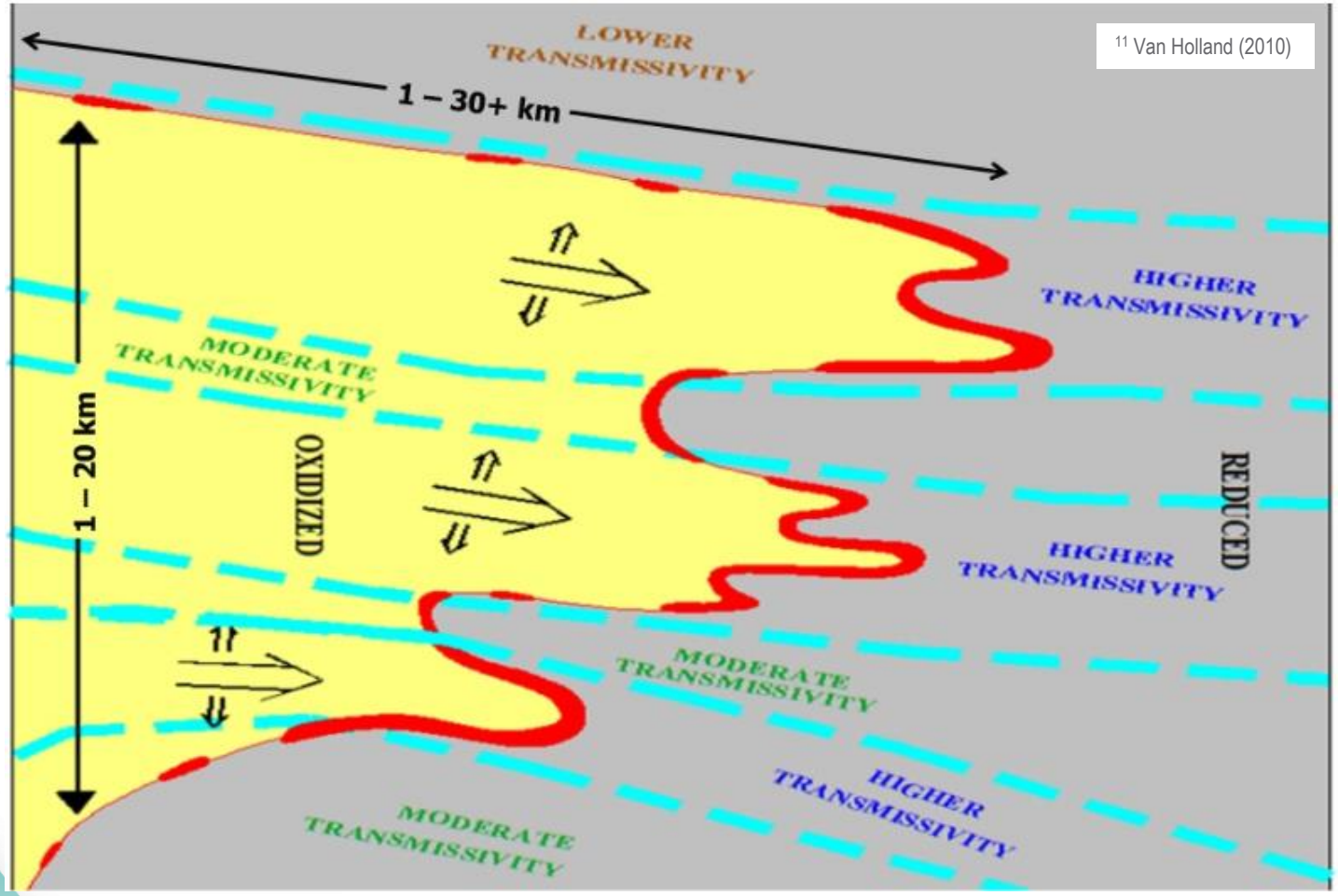
- **Genesis – Epigenetic (introduced after host rock formation)**
- **Mineralization**
  - Commonly uraninite UO_2 (pitchblende) and coffinite $U^{4+}[(SiO_4),(OH)_4]$
  - Commonly as amorphous coating on sand grains and fillings in interstitial spaces
- **Deposits**
  - typical ore grade: 0.05 – 0.26% U_3O_8 (up to 7% U_3O_8)
  - size: economic deposits contain 2-25+ million lbs U_3O_8
  - depth: 60-600 m
- **Roll-front Geometry**
  - **Map view**
    - Narrow: Commonly 3 – 40 m wide
    - Long: Continuous over long distances (km‘s to 10‘s km‘s) but not equal ore quality along length
    - Sinuous: Extreme, often complex sinuousity
  - **Cross-sectional view**
    - Crescent (convex downdip) shape, commonly 2-8 m thick
    - Commonly in a complex stacked system of multiple roll-fronts

[12] Boberg (2012) IAEA Meeting Vienna

Typical ISR Resource Parameters

Project	Resource (tU)	Grade (%U)	Thickness (m)	Depth (m)
1	2,500	0.09%	3.5	250
2	4,300	0.17%	2.0	200
3	2,700	0.04%	2.5	120
4	20,000	0.04%	3.0	250
5	4,300	0.04%	6.0	160
6	7,000	0.08%	2.0	150
7	8,400	0.04%	5.5	100

Roll-Front Oxidized ‚Nose‘ in Map View[11]



[11] Van Holland (2010)

Mineralogical Assessment

- U mineralization in sandstone deposits mainly uraninite UO_2 (pitchblende) and coffinite $U^{4+}[(SiO_4),(OH)_4]$ [6].
- Mineralogical analysis of U ore and host rock includes MLA and SEM, and determination of carbonate content.

[6] Abzalov, M.Z. (2012) Sandstone-hosted uranium deposits amenable for exploitation by in-situ leaching technologies, Appl. Earth Sci. (Trans. Inst. Min. Metall.), vol. 121, no. 2, p. 55-64.

Dimensions, Figures, Thresholds of Roll-Front Deposits[13]

- **Groundwater**
  - Bulk flow rate of ground water = 58m³/yr thru 1m²
  - Ground water velocity = 290 m/yr
  - Oxygen content = 5 ppm
  - Uranium content = 50 ppb
- **Sedimentary Unit**
  - Porosity = 20%
  - Rate of advance of roll-front = 1.4 cm/yr
- **Time required to form**
  - 10 km long oxidized tongue = 700.000 yrs
  - 10 m wide, 0.28% U_3O_8 grade deposit = 50.000 yrs

[13] Granger & Warren (1978) USGS

Typical ISR Characteristics

Hydrology (uncertainty)

- Permeability ~200 mD (50-500) at ~20% (10-30%) porosity
- Extraction rate ~40 gpm (10-100) at ~30 m spacing, Δ ~8m
- PVE (pore volume exchange) rate ~0.06 d^{-1} (0.015-0.15), or ~17 d (7-66)

Leaching chemistry (↔ mineralogy/texture)

- Effective kinetic rate for U leaching and effective recovery (typically 0.001-0.01 d^{-1}/70%)
- Interfering reaction kinetics for pyrite, organics, oxidant concentration – typically unknown
- Temperature effects (leaching, IX), ~55°C

Both hydrology and chemistry determine wellfield lifetime

- Uncertainty ~1-10 years

Tasks to investigate ISR feasibility

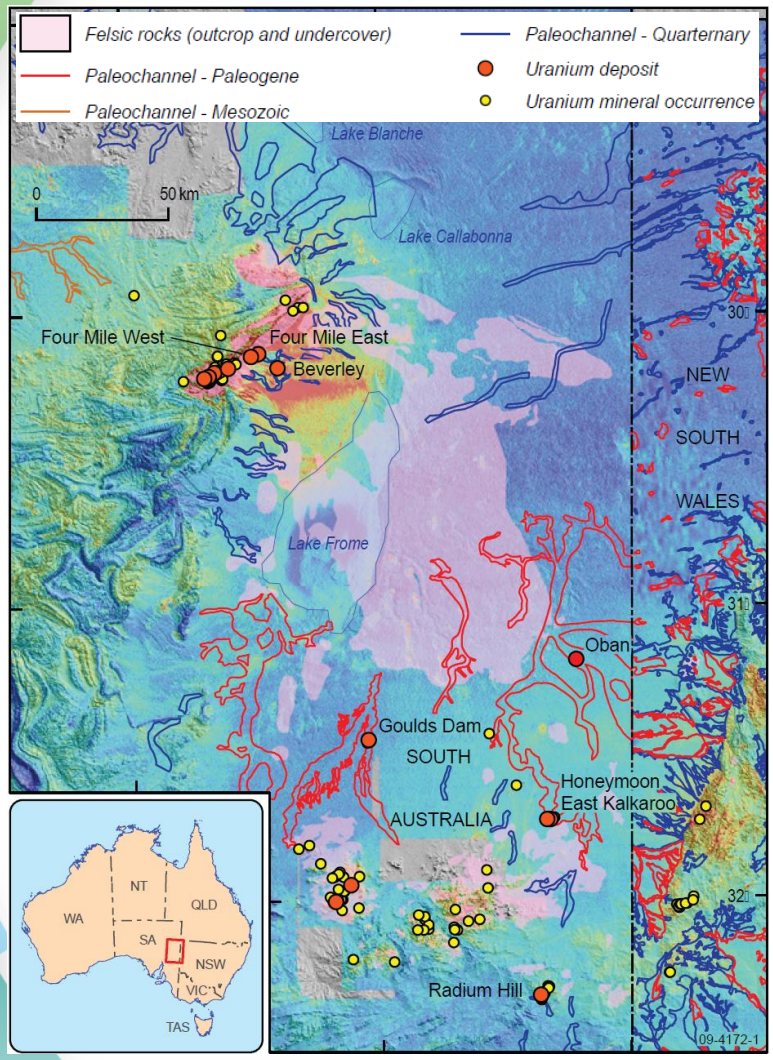
- Quantify critical parameters more accurately → ISR simulation/testwork
- Develop economic model including uncertainties

In-Situ Recovery Mining Considerations[11,12]

- **High-grade ‚limb ore‘ tied up in mudstones (or with organics) will not be ISR mined but often considered for conventional mine planning.**
- **Cut-off grade 0.02/0.03% U_3O_8, minimum GT 0.09% for depths <300m, or minimum GT of 0.15% for depths >300m.**
- **Sand unit must be saturated, porous and permeable.**
- **Uranium must be in porous and permeable sand, not organics or mudstones.**
- **Each production pattern (e.g. 5-point cell = 1 production well and 4 injection wells) covering a surface area of approximately 450-900m^2, will commonly address a resource of ca. 5,000-10,000 lbs U_3O_8.**

[11] Van Holland (2010); [12] Boberg (2012) IAEA Meeting Vienna

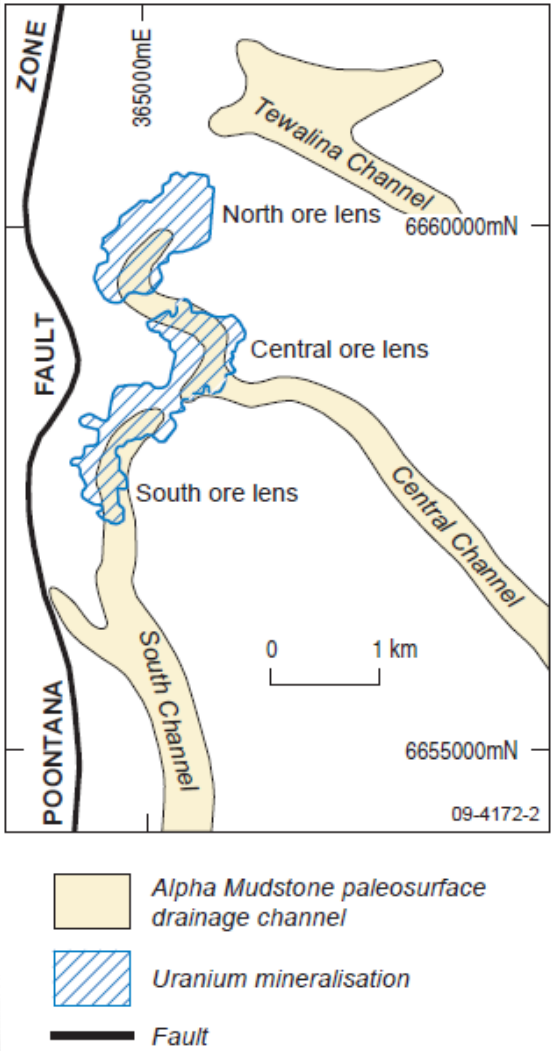
Industry Best Practice U-ISR Technology
Paleochannel Deposits



Paleochannel Deposits

- Sandstone-uranium deposits in fluvial (river) sediments filling ancient river channels as paleochannels.
- Commonly localised at the confluences and intersections of channels and/or near bends.
- Typically caused by abundance of organic material and pyrite, predominance of coarse-grained sediments, presence of basement scours[3].

[3] Jaireth, S., Clarke, J., Cross, A. (2010) Exploring for sandstone-hosted uranium deposits in paleovalleys and paleochannels, AUSGEO News, Australian Government – Geoscience Australia, vol. 97, 5 p.

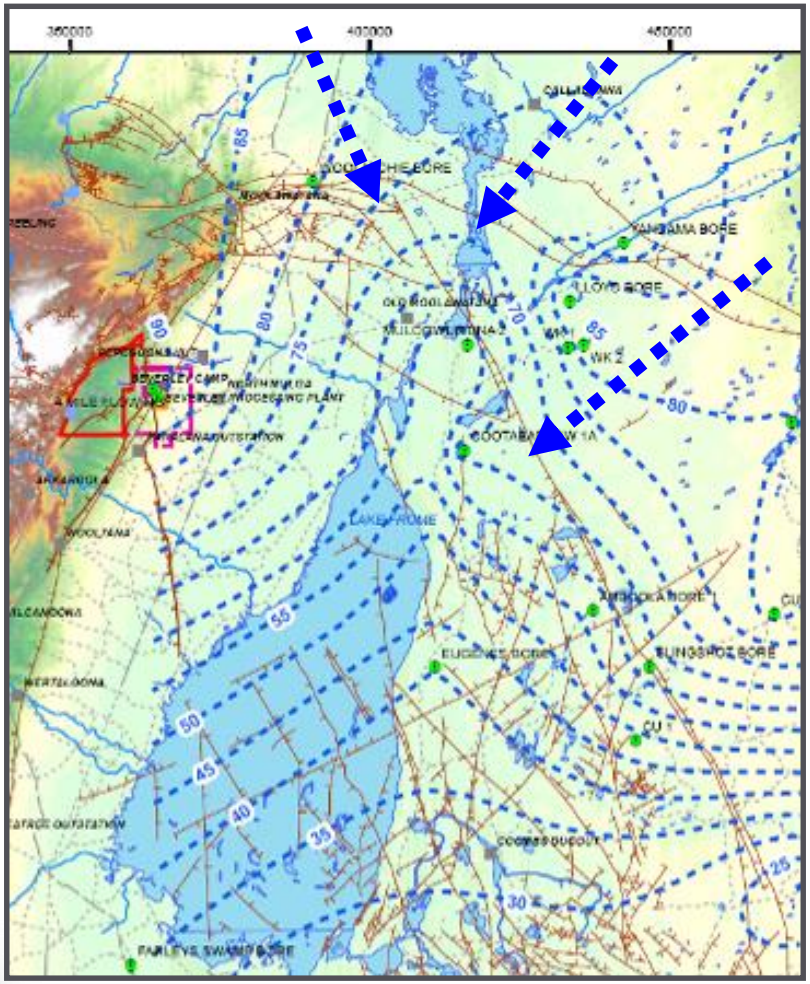


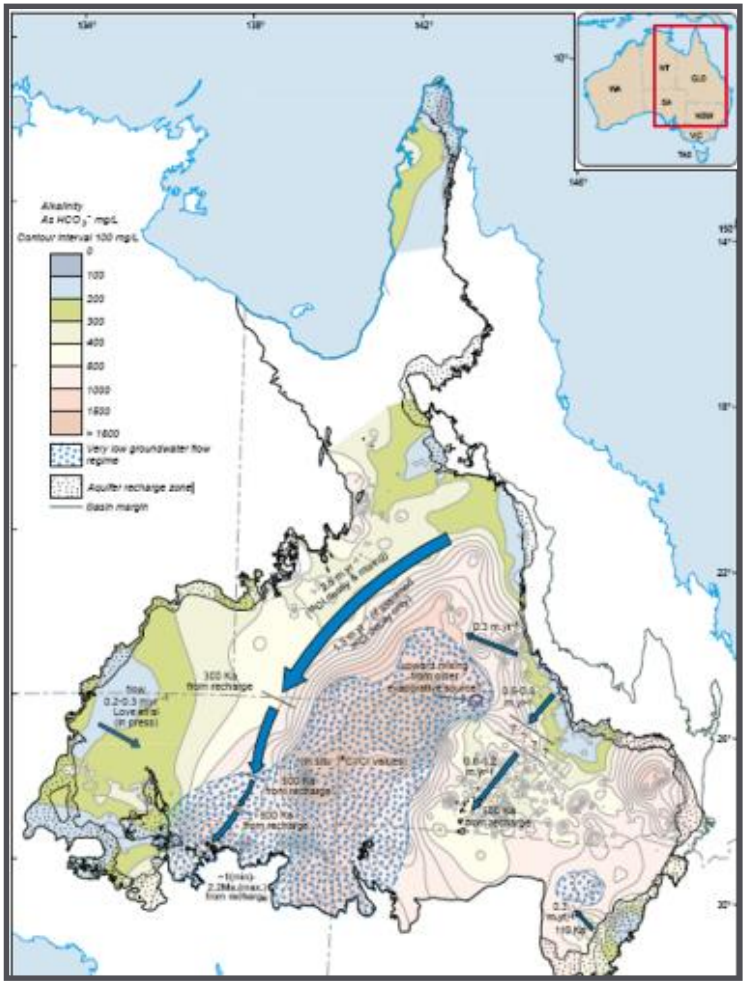
Paleochannel U Deposits

- Main channels typically 5-10km wide, ~200km long, joined by smaller tributaries, N-S gradients from 1.2 to 2.1 m/km.
- General shape and orientation of the channels controlled by basement rocks and structures; e.g. where channel breached a ridge along a fault zone[3].
- Other sites show U-mineralised sand and mudstone eroded into organic-rich clay-mudstone (plant fragments, carbonised wood). Anomalously high U concentrations concentrated at bends and/or points of confluence with tributaries (channel up to 1km wide, 80-150m thick).

[3] Jaireth, S., Clarke, J., Cross, A. (2010) Exploring for sandstone-hosted uranium deposits in paleovalleys and paleochannels, AUSGEO News, Australian Government – Geoscience Australia, vol. 97, 5 p.

Regional Hydrogeology





Typical ISR Challenge: Historical Data

Permeability

- Vast differences in permeability (the younger the study, the more permeable).

Site Location

- Ca. 60 km NW off mine site.
- Depth: 610 m (significantly shallower than ore site).

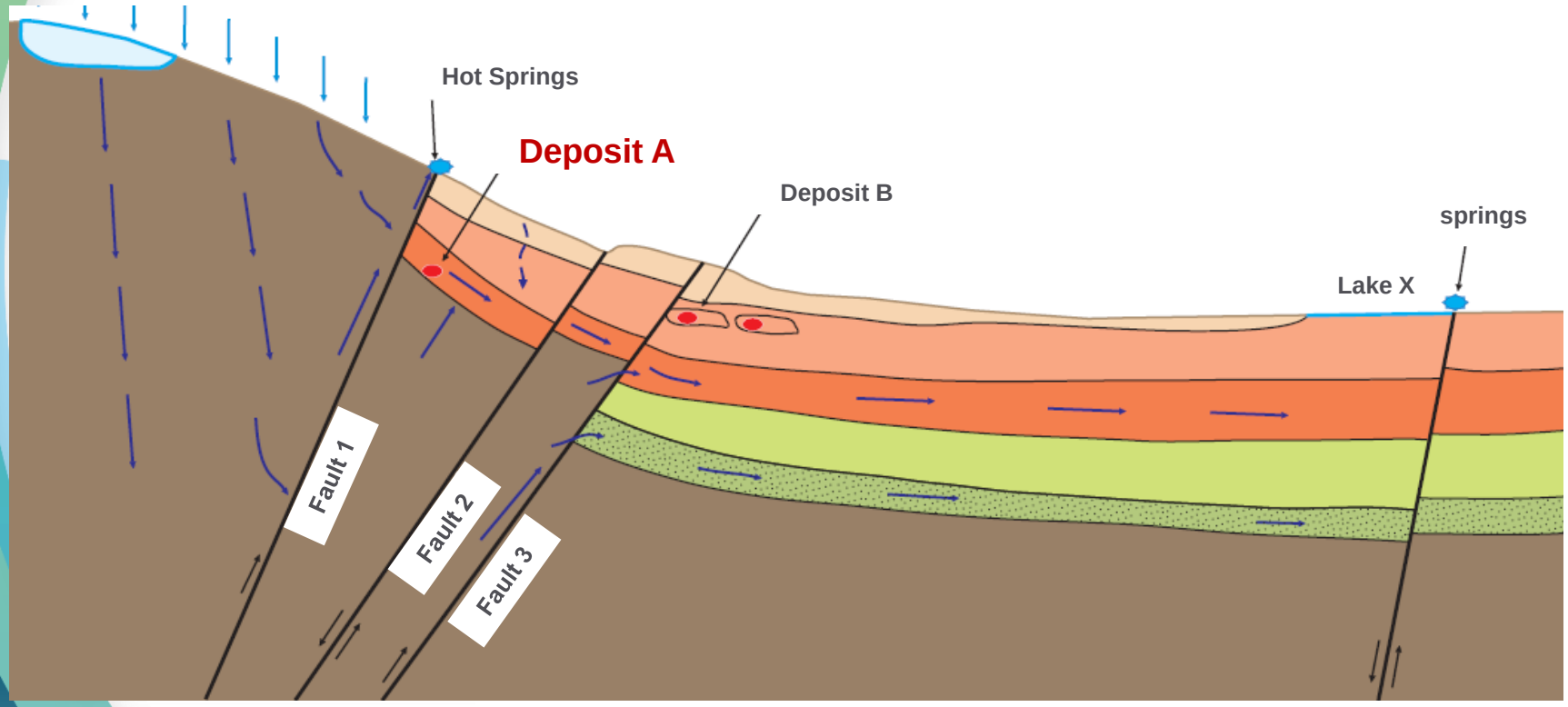
In-Situ Leach Test Incomplete

- Leaching and recovery ceased after 10 months (permitting and remediation constraints).
- Only ~15% U recovery level @ av. 100 ppm U (within 3 months) due to premature end of field leach trials → can only reflect min. recovery
- Lab recovery rates 65-87%.

Test site vs. Mine site	Permeability (md)	Porosity (%)
CP Northeast	1,750	21
CP Southeast	850	23
CP Southwest	750	16
CP Northwest	640	20
Mine Site	477	20-30
	280	20-30
	193	20-30

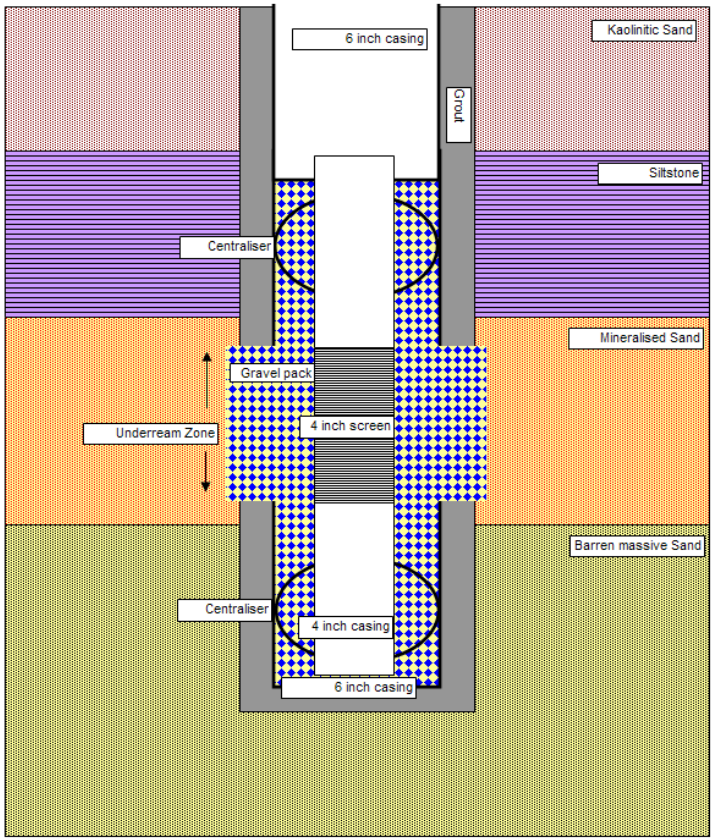
Typical ISR Challenge

Geological Setting of ISR Site



Industry Best Practice U-ISR Technology
Hydrogeology

Typical ISR Challenge



- Well field design requires test puming.
- Test pumping comprises variable speed drive pump steps and electronic flow control.
- Typical test pumping results: Within the nose area (thick mineralization) available drawdown is greatest, reasonable flow rates ranging from 1 to 4 L/s can be achieved.
- In the limbs (thin mineralization 1-2m thick) drawdown is reduced, flow rates are close to zero.

Test production well flow rates

Well ID	Achieved flow (L/s)		Maximum est. flow (L/s)
4MT001	Nose Central	1.6	2
4MT002r	Nose Central	0.8	1.1
WC04	Nose East	3	4
WC02	Limbs West	<0.1	-
WC07	Limbs NW	<0.1	-

Typical results: The predicted well flow rates in the ore body nose and high grade, thicker parts of the limbs are greater than **0.5 L/s** which **is considered sufficient to allow ISR mining**. Thinner, elevated limbs, and highly elevated unsaturated areas west of the fault zones are not likely to produce flow rates feasible for ISR mining using conventional 7 spot patterns and vertical wells.

Mine Closure

Typical Environmental Requirements

1. Uppermost sedimentary formation (surface) non-critical
2. Sedimentary formations/aquifers overlying and underlying the ore aquifer being long-term monitored (→ results reported to Ministry of Mining/Environment).
3. Potential use category of groundwaters unchanged.
4. Assessment of potential for impact on fossil groundwater aquifers above/below the ore zone aquifer.
5. Assessment of liquid waste capacity (→ environmental assessment report prior to mining approval).
6. Remediation strategies (see above).
7. Compliance monitoring (see above).

Hydrogeology – Compliance Monitoring

Excursion Control Parameters

The proposed parameters of:

- pH, SO_4, EC (for lateral wells)

  and

- pH, SO_4 and uranium (for overlying and underlying wells)

are selected because these parameters will exhibit the greatest contrast between native groundwater and mining solution, whilst being readily and reliably measured.

Hydrogeology – Mine Closure & Rehabilitation

Aquifer remediation methods available

If required to meet outcomes

- Groundwater flush (creates waste stream)
- Pump, treat and re-inject
  - Batch treatment
  - RO (reverse osmosis) or electrodialysis (creates waste stream)
- Mixing
- Non-mineralized leaching
- Addition of remediation agents
  - H_2S
  - CSIRO's *Virtual Curtain Technology* (lime-based additives – hydrotalcites - to remediate acidic and contaminated waste water in one step; e.g. pre-treatment for RO)

ISR Hydrogeology – Current State of Knowledge

1. **Current state of knowledge is robust and suitable to ensure that ISR mining can be undertaken without unacceptable impacts.**
2. **Good understanding required of:**
   - ore zone hydrogeology
   - regional hydrogeological setting
   - natural attenuation processes
3. **Arguably a more robust understanding than for any approved uranium mine (including Beverley mine).**
4. **Mining → more knowledge → enhanced mining and management practices → enhanced (environmentally sustainable) mine closure.**

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Thank you for your attention!

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