ISL Mining of Uranium in the Permafrost zone, Khiagda Mine, Russia

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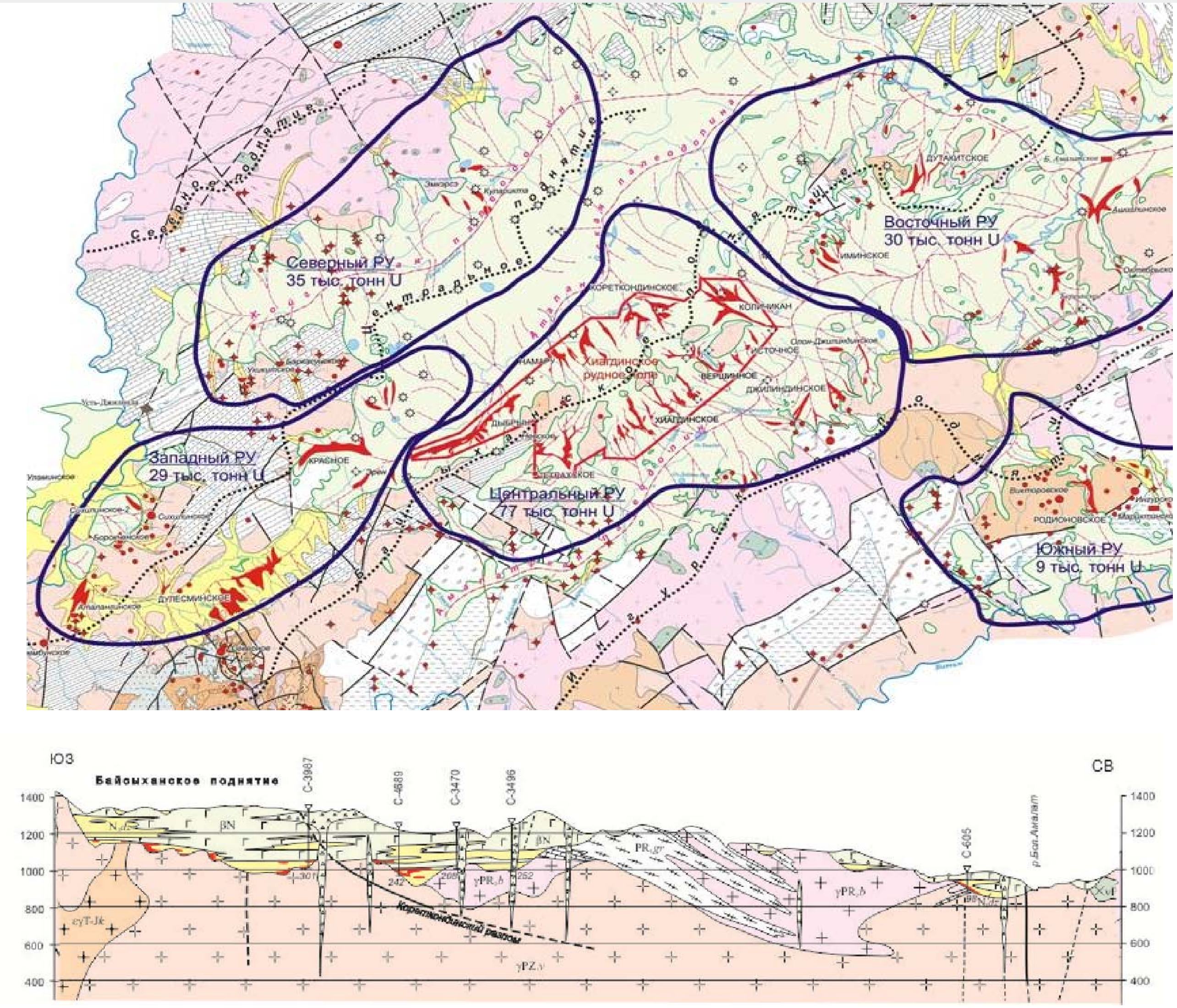
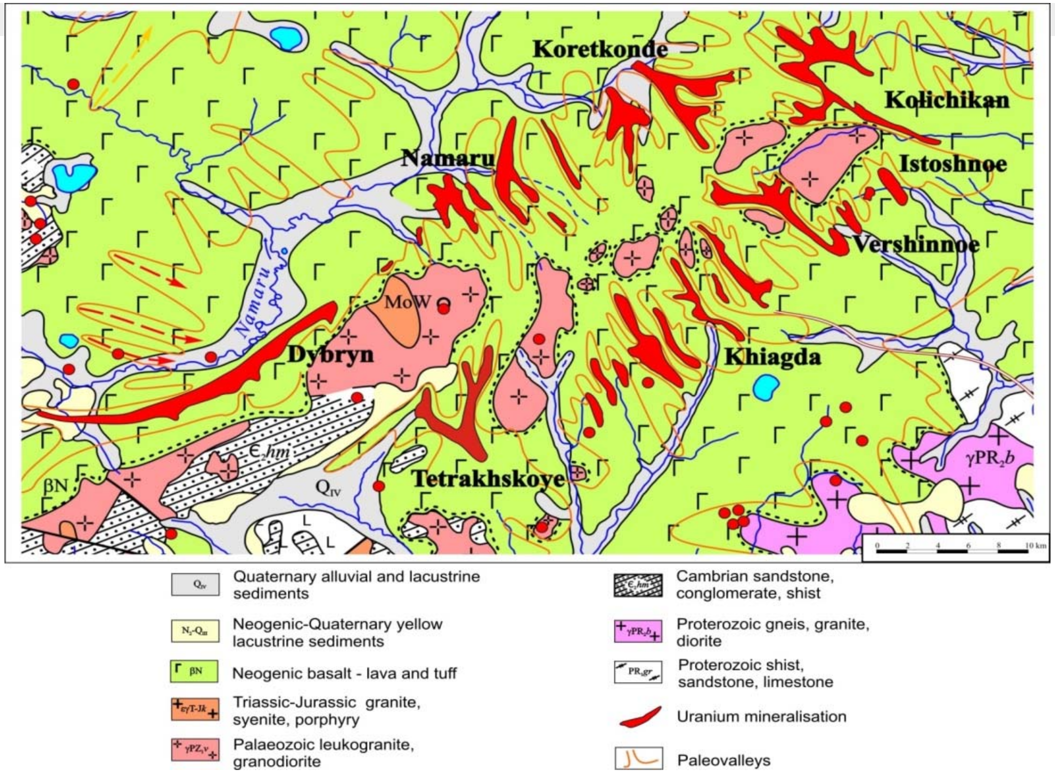
Khiagda mine location and general information



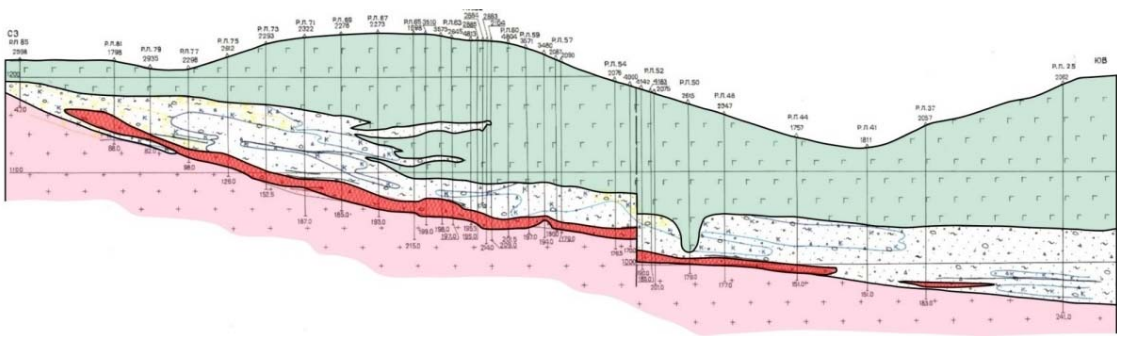
Vitim Uranium District. Geological map and regional cross section.

- Khiagda mine is developing uranium deposits of the Khiagda ore field which is a part of Vitim U district, located about 140 km north of the Chita city in the NE part of Buryatia Autonomous Republic of Russia.
- Known resources of the Vitim district are estimated at 56,000 mt U, while exploration potential is in the order of 100,000 mt U.
- The area is characterized by rigorous climate. In summer time, the air temperature rises up to +35°C, and it falls down in winter up to -45°C. The yearly average temperature is -6°C
- The permafrost is developed everywhere to the 90 m depth.

The Khiagda Uranium Field. Geology and mineralisation



Khiagda Uranium Field. Geological map.



Khiagda deposit, ore body #5. Cross section.

- Khiagda uranium field is the most prospective uranium region in Russia. It contains 8 close located deposits with 48,000 tU of known resources amenable for ISL mining. The distance between deposits is 1.5 to 6.0 km.
- Mineralization occurs in permeable low consolidated Neogene fluvial sediments, which fill paleovalleys of relatively narrow tributaries (sandstone basal channel type).
- The basement is presented by Paleozoic granite. Ore hosting sediments are overlapped by Neogene-Quaternary basalt.
- The mineralization occurs at the depths 90 to 280 m (average is 170m) in lens and lenticular (ribbon-like) ore bodies.
- Single ore bodies are 850 to 4100m long, 15 to 400m wide, 1 to 20m thick.
- ISL mining has been carried out under complicated hydro-geological environment as the mineralization is poorly and irregular watered (the water table is not stable)

Khiagda Mine. Main characteristics

- **Life of Mine:** 2002 to 2036
- **Production 2013:** 440 mtU
- **Production capacity:** 1,000 mtU/year from 2018

Leaching Technology

- **Leaching Agent:** Sulphuric acid
- **Average recovery rate** 80%
- **Acid concentration in pregnant solutions (average):** 12 g/L
- **Average flow rate of recovery well** *4.6 m^3 per hour*
- **Average uranium content in pregnant solutions** 90 mg/L

Wellfields parameters

- **Wellfield patterns shape:** hexagon, row
- **Distance between wells** *35 m*
- **Ratio between recovery and injection wells** 2.3

Processing plant parameters

- **Volume of processed solution:** *500 – 1000 m^3 per hour*
- **Technology of solution processing:** *Ion exchange resin*

Khiagda is the only ISL mine in the world located in a permafrost region

Areas of ISL intensification

- The Uranium production (*D*) is equal to the product of recovered pregnant solutions volume (wells flow rate *Q*) and uranium content in pregnant solutions (C_U). **D = Q x C_U**
- **Intensification of ISL** means increase of these main parameters *(Q* and C_U) using the same amount of exploitation wells (Capex factor) and not exceeding planned sulphuric acid consumption (Opex factor)
- Potential increase of recovery wells flow rate *Q* is limited by permeability and by the condition, when the speed of the leaching solution movement within the ore hosting aquifer is lower or equal to the chemical reaction rate
- Two methods of ISL intensification for the Khiagda mine:
  - How to decrease leaching solutions viscosity?
  - How to oxidize uranium?

Decrease of leaching solutions viscosity (1/2)

Mine	Q, m³/h
Zarechnoye	9,3
Akdala	8,9
Karatau	8,4
S.Inkay-4	7,7
Akbastau	7,1
Kharasan-1	6,3
Dalur	5,4
Khiagda	**4,6**

- **Khiagda has the lowest recovery wells flow rate (4,6 m³/h) in comparison to ISL mines in Kazakhstan**
- **The main factors impacting low flow rate Q:**

1. Irregular and generally poor water abundance the ore-bearing horizons
2. Low sediments permeability
3. High viscosity of leaching solutions

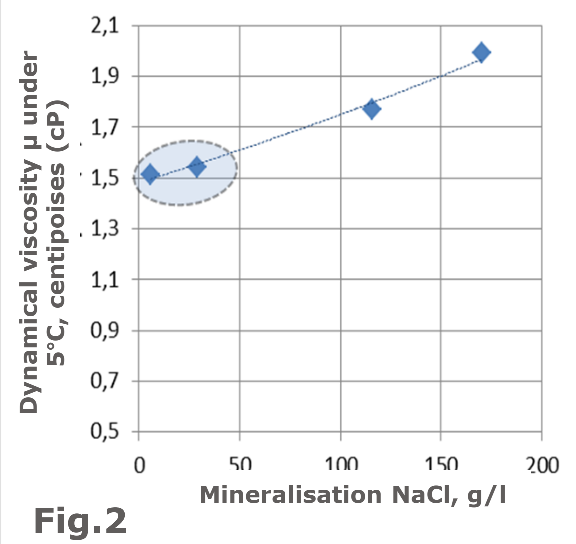


Fig.2

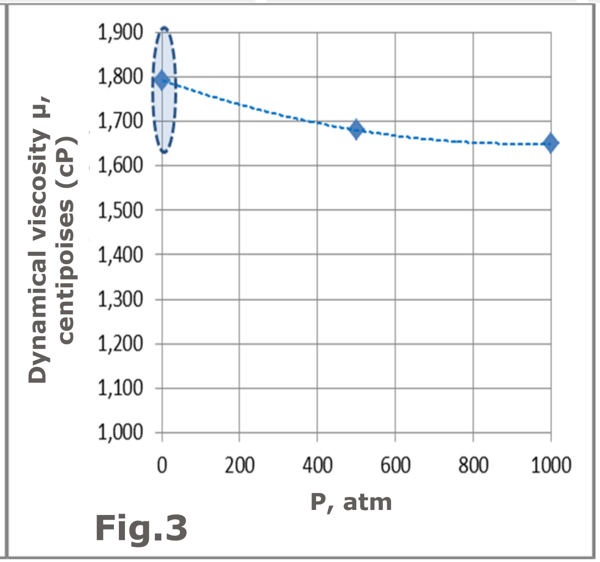


Fig.3

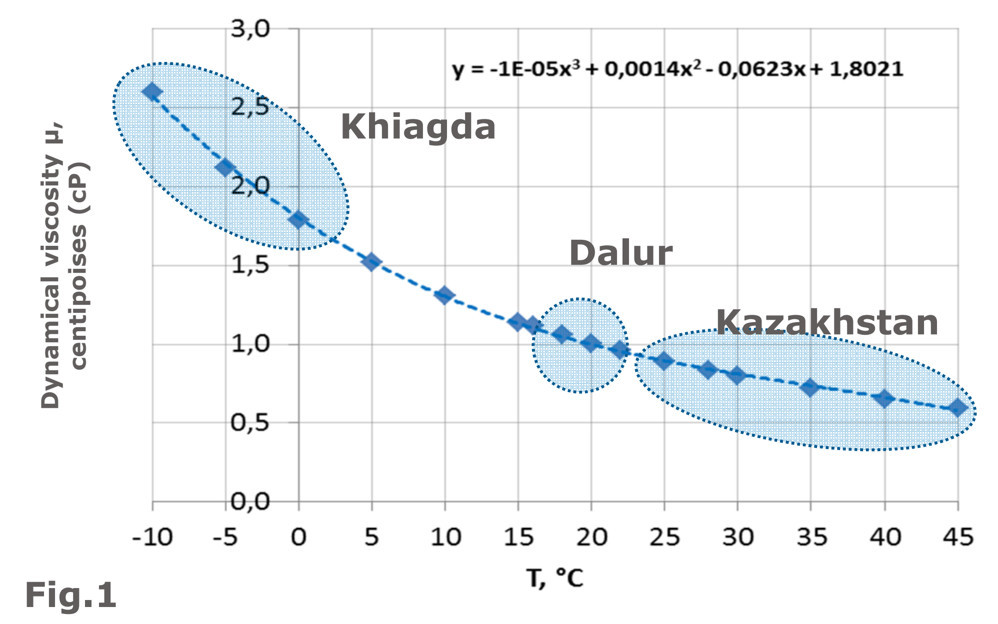


Fig.1

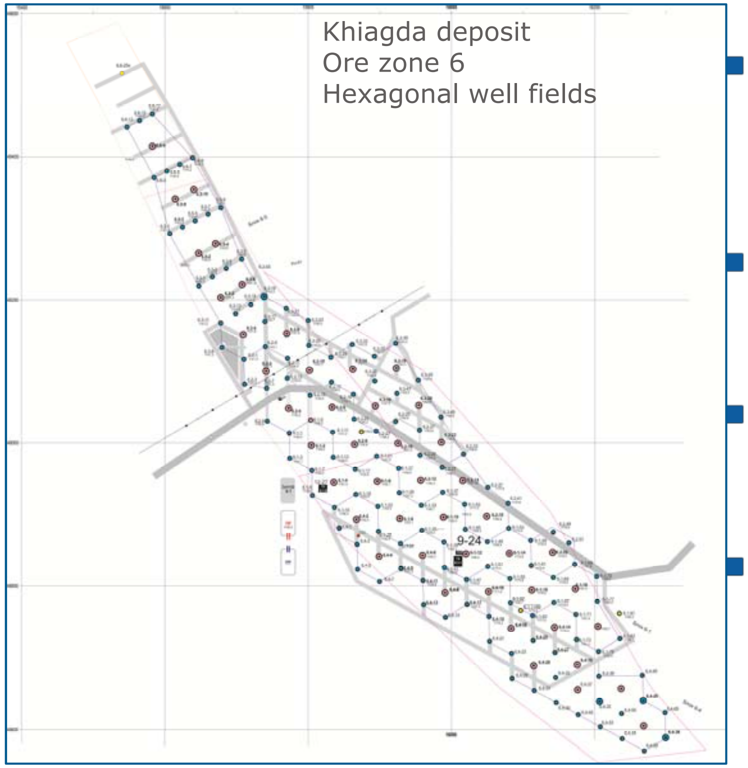
- **Khiagda temperature of ground water is 1-4°C, Dalur - 16-22°C, and at Kazakhstan deposits - 25-45°C (Fig.1)**
- **Viscosity of ground water depends significantly on temperature (Fig.1), slightly on TDS below 50 g/l (Fig.2) and practically not depend on pressure (Fig.3)**
- **Solutions viscosity at Khiagda (1.75 cP) is 2.5 times higher than at Kazakhstan (0.7 cP) due to low temperature(Fig.1)**
- **In winter time, when air temperature goes down to -40°C, the temperature of acid solutions in pipelines may decrease to -10 °C (close to electrolytes freezing point)**
- **Viscosity of cold solutions grows up to 2,6 – 2,9 cP, and hydraulic resistance at the aquifer entrance through injection wells screens rises sharply**

Decrease of leaching solutions viscosity (2/2)

$$K_{\phi} = \frac{\rho}{\mu} K_{\text{пр}} \quad (1)$$

$$K_{\text{пр}} = \frac{Q \, \mu \, \Delta L}{F \, \rho \, \Delta H} \quad (2)$$

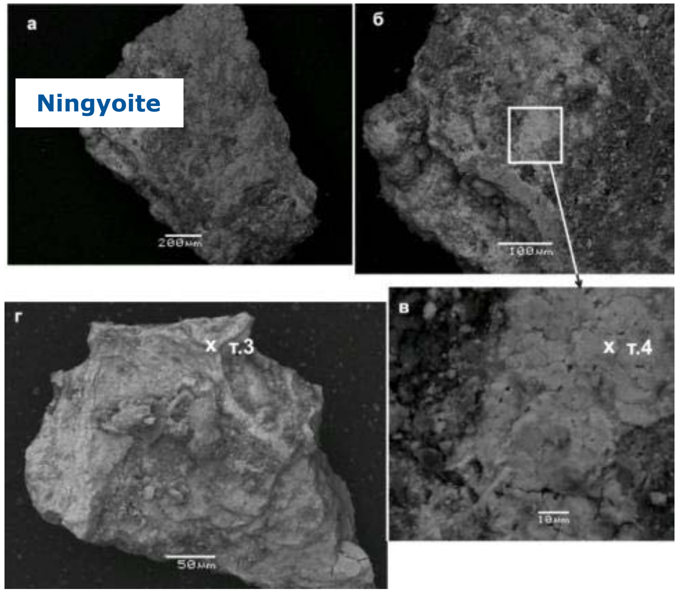
$$Q = \frac{K_{\text{пр}} \, \mu \, \Delta L}{F \, \rho \, \Delta H} \quad (3)$$



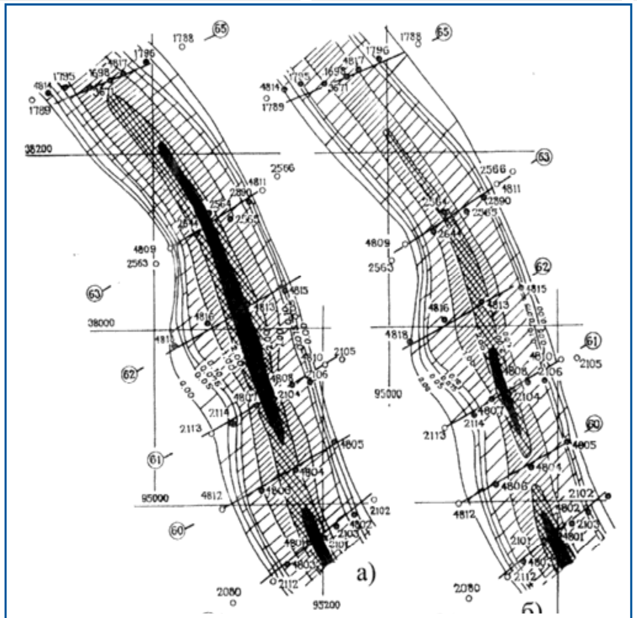
- Low permeability factor (K_f) of the ore-hosting sediments: varies from 1.4 to 3.7m/day with the mean value 2.1 m/day
- Permeability factor depends on liquid properties and mainly on solutions dynamical viscosity (μ), while solutions density (ρ) practically does not influence on filtration factor, because it is rather stable
- The transmissivity factor (K_p) represents a rock property, and it does not depend on solutions properties
- By the formula (1), the K_f value for the normal temperature (20°C) should vary between 2,5÷6,4 m/day with the mean value 3.6 m/day
- In accordance to the formula (3) derived from (2) theoretically it is possible to increase Q flow rate value to 7 m^3/h and thus to increase the rate of Uranium recovery in 1.5 times compared to the actual rate 4.6 m^3/h
- Under high viscosity of solutions, the hexagonal development pattern is the most effective one. It gives highest ratio between injection and recovery wells
- Heating of leaching solutions from 4°C to 20°C is technically impossible due to extremely high thermal capacity of ore horizon. Heating of the leaching solutions in the surface pipelines may slightly decrease viscosity
- **The most promising way to decrease leaching solution viscosity is surfactants adding as they lower the surface tension between two liquids or between a liquid and a solid.**

Uranium Oxidation (1/3)

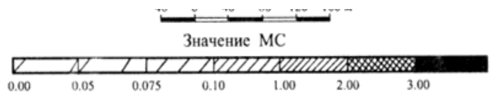
Mineral composition	%
Quartz	35,4
Plagioclase	21,1
Microcline	20,1
Micas	6,6
Fragments of volcanics and ash	1,0
Kaolinite, chlorite, zeolite, montmorillonite	14,4
Pyrite, marcasite	0,4
Phosphates	0,1
Ti minerals	0,7
Carbonates	0.2
Total	100

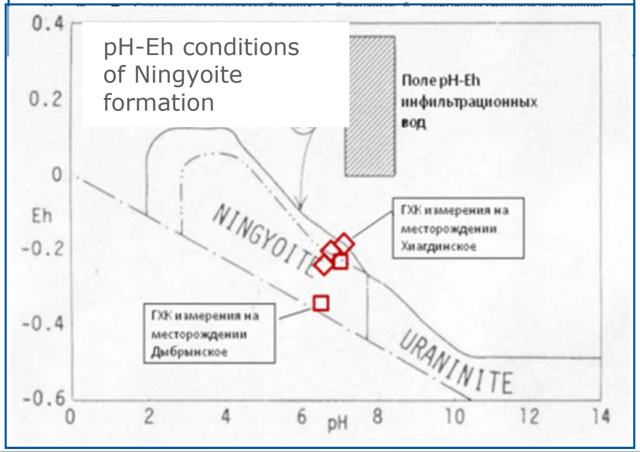


- The ore bearing sands are silica-alumina (SiO_2 – 74,2%, Al_2O_3 – 13,4%), with low content of iron (2%), and practically non-carbonate (CO_2 <0,3%)
- Sands mineral composition - feldspar-quartz. Content of iron disulphides is 0.4%; plant detritus is up to 1% of C_{org}
- **The main uranium mineral is ningyoite**
- **Ningyoite is a tetravalent Uranium phosphate** $CaU_4 + (PO_4)2 \times 2H_2O$
- The following conditions are needed for Ningyoite formation: slightly acidic (pH 5.5-6.5) and strongly reduction (Eh -50 ÷ -400 mV) environment, presence of phosphorus-containing organics and hydrogen-producing micro flora
- All these conditions are typical for Khiagda ore-bearing aquifers
- Most high grade uranium mineralization (up to 3% of U) is located in the mead stream part of paleochannel. It confirms rather sharp redox front conditions for U deposition.



Contrast Uranium ores

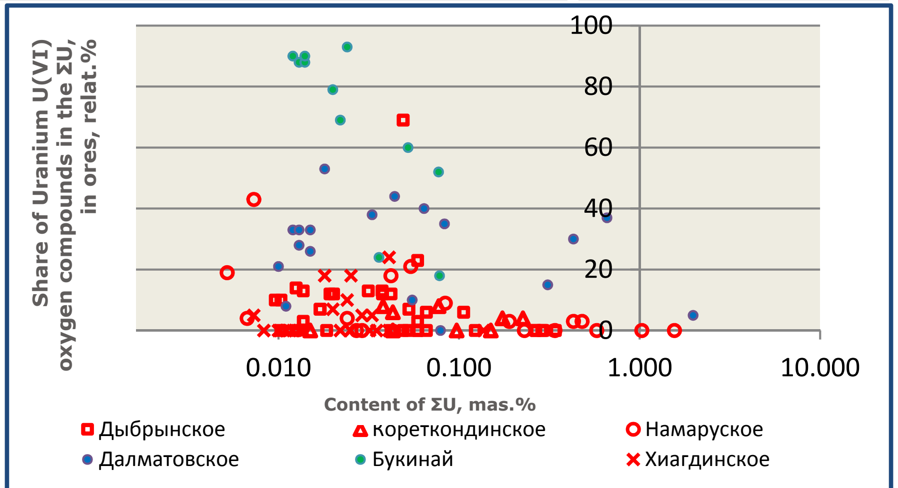




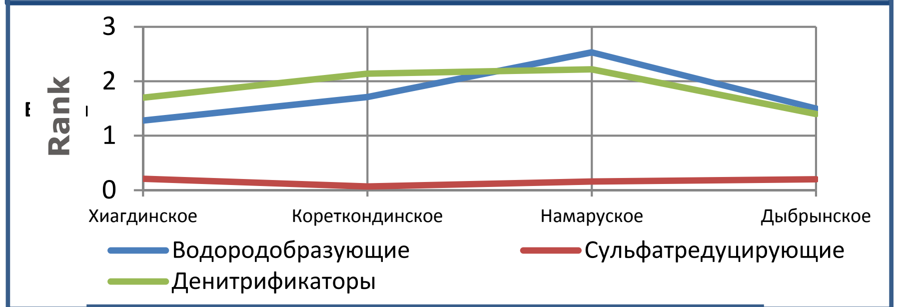
Uranium Oxidation (2/3)

Geochemical properties of mineralisation

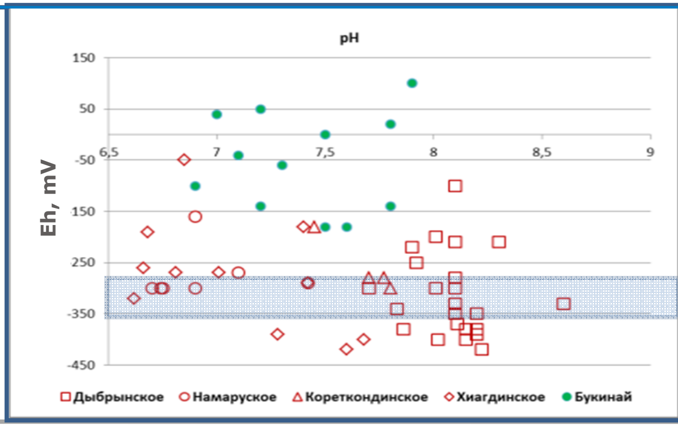
1. High reduction degree of uranium and iron
2. The share of reduced 4 valence Uranium is 90-100%.
3. Deficit of soluble tree valence iron in host sediments which is a natural oxidant – $Fe(III)_{кр}$ = 0 ÷ 15% from total iron (Fe2O3 = 0.73-1.76%)



5. The reduction environment has been created by hydrogen-producing bacteria. Vital biochemical activity of sulphate -reducing bacteria, which is typical for Kazakhstan, is suppressed.



6. Low redox potential Eh -250÷-300 Mv is typical for the hydrogen reduction environment formed by underground microflora



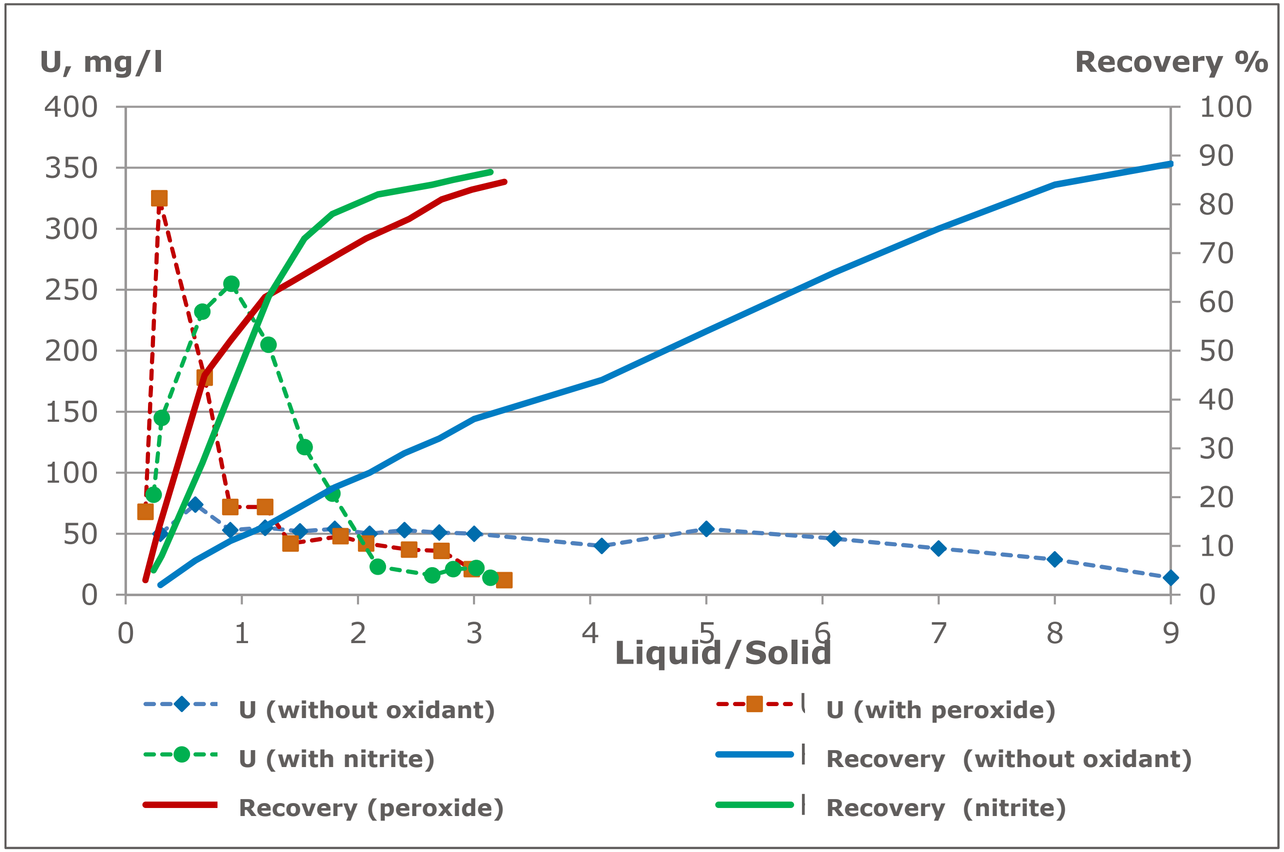
Uranium extraction from Khiagda deposit without oxidants is not effective

Uranium Oxidation (3/3)

Ningyoite Solubility

pH		4,1	1,8	1,3	0,7	0,45	0,3	0 (1N HCl)
Solubility	Mol/l	2,10E-07	2,10E-08	4,00E-06	2,60E-05	6,40E-05	1,60E-04	6,40E-04
	Mg/l	**0,0499**	**0,0499**	**0,95**	**6,19**	**15,23**	**38,1**	**152,3**

Uranium leaching tests in filtration columns



- Studies of U(IV) phosphates solubility in sulfuric acid solutions (see table) has shown that commercial uranium concentration (>10mg/l) appear in concentrated solutions with pH<0,5
- Uranium leaching tests of Khiagda ores in filtration columns has shown very slow recovery without oxidant. The required recovery was reached under Liquid to Solid ratio 8-9. The uranium concentration was 50mg/l
- Oxidants (hydrogen peroxide or nitrite) addition increased uranium concentration to 250-325mg/l and recovery speed thrice. Required recovery occurred under Liquid to Solid ratio 3

Conclusions

1. **High viscosity of leaching solutions is caused by very low underground water temperature (1-4°C) as a permafrost zone affect**
2. **High viscosity negatively affect on injection and recovery wells productivity and flow rate.**
3. **It is possible to increase recovery wells flow rate up to 1.5 times by leaching solutions viscosity reduction**
4. **Major uranium mineralisation is represented by ningyoite (a tetravalent uranium phosphate) which is sparingly soluble in diluted sulphuric acid solutions**
5. **Oxidants (hydrogen peroxide or nitrite) addition to acid solutions increase uranium recovery rate in three times**

Thank you!

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Acknowledgment:

I would like to express my very great appreciation to **Dr. Alexander Boytsov (Uranium One Inc., SVP Exploration)** for his valuable and constructive contribution in the paper drafting, editing and presenting