Identification and Quantitation of ^{232}Th and ^{238}U Decay Series Members

Analytical Peculiarities due to Sampling and Sample Origin

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Identification and Quantitation of ^{232}Th and ^{238}U Decay Series Members

1. Naturally Occurring Radionuclide's (NOR's) in the *Earth*'s Crust
2. Activity Concentration vs. Elemental Concentration
3. Chemistry – Members of ^{232}Th and ^{238}U decay series
4. Mineral Mining, Beneficiation/Treatment and Processing
   a. Mobile Phase - Gas/Oil/Water Production,
   b. Ore

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Naturally Occurring Radionuclide’s (NOR’s) in the *Earth*’s Crust

Earth's Crust – Element Concentrations (ppm[w])

Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)
1	8	O	460000,000	21	23	V	160,000	41	62	Sm	6,500	61	69	Tm	0,490
2	14	Si	280000,000	22	28	Ni	120,000	42	64	Gd	5,700	62	53	I	0,470
3	13	Al	82000,000	23	37	Rb	75,000	43	66	Dy	5,700	63	49	In	0,210
4	26	Fe	57000,000	24	30	Zn	75,000	44	92	U	4,200	64	51	Sb	0,200
5	20	Ca	43000,000	25	74	W	69,000	45	68	Er	3,200	65	48	Cd	0,150
6	11	Na	25000,000	26	29	Cu	64,000	46	72	Hf	3,000	66	47	Ag	0,078
7	12	Mg	24000,000	27	58	Ce	63,000	47	70	Yb	2,700	67	80	Hg	0,076
8	19	K	21000,000	28	60	Nd	37,000	48	35	Br	2,500	68	34	Se	0,050
9	22	Ti	6100,000	29	57	La	37,000	49	55	Cs	2,400	69	83	Bi	0,017
10	1	H	1400,000	30	39	Y	31,000	50	4	Be	2,400	70	46	Pd	0,011
11	15	P	1100,000	31	27	Co	28,000	51	50	Sn	2,300	71	78	Pt	0,004
12	25	Mn	980,000	32	21	Sc	24,000	52	33	As	2,000	72	79	Au	0,004
13	6	C	980,000	33	7	N	20,000	53	63	Eu	1,900	73	75	Re	0,002
14	9	F	470,000	34	31	Ga	19,000	54	73	Ta	1,900	74	76	Os	0,002
15	16	S	430,000	35	3	Li	18,000	55	32	Ge	1,500	75	52	Te	0,001
16	56	Ba	420,000	36	41	Nb	18,000	56	67	Ho	1,300	76	44	Ru	0,001
17	38	Sr	370,000	37	90	Th	12,000	57	42	Mo	1,200	77	45	Rh	0,001
18	17	Cl	260,000	38	82	Pb	12,000	58	65	Tb	1,100	78	77	Ir	0,001
19	24	Cr	200,000	39	5	B	9,400	59	81	Tl	0,690				
20	40	Zr	180,000	40	59	Pr	9,000	60	71	Lu	0,500		Total Crust		101%

Earth’s Crust– Element Concentrations (ppm[w])

incl. Elements with Naturally Occurring Radioisotopes (I)

Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)
1	8	O	460000,000	21	23	V	160,000	41	62	Sm	6,500	61	69	Tm	0,490
2	14	Si	280000,000	22	28	Ni	120,000	42	64	Gd	5,700	62	53	I	0,470
3	13	Al	82000,000	23	37	Rb	75,000	43	66	Dy	5,700	63	49	In	0,210
4	26	Fe	57000,000	24	30	Zn	75,000	44	92	U	4,200	64	51	Sb	0,200
5	20	Ca	43000,000	25	74	W	69,000	45	68	Er	3,200	65	48	Cd	0,150
6	11	Na	25000,000	26	29	Cu	64,000	46	72	Hf	3,000	66	47	Ag	0,078
7	12	Mg	24000,000	27	58	Ce	63,000	47	70	Yb	2,700	67	80	Hg	0,076
8	19	K	21000,000	28	60	Nd	37,000	48	35	Br	2,500	68	34	Se	0,050
9	22	Ti	6100,000	29	57	La	37,000	49	55	Cs	2,400	69	83	Bi	0,017
10	1	H	1400,000	30	39	Y	31,000	50	4	Be	2,400	70	46	Pd	0,011
11	15	P	1100,000	31	27	Co	28,000	51	50	Sn	2,300	71	78	Pt	0,004
12	25	Mn	980,000	32	21	Sc	24,000	52	33	As	2,000	72	79	Au	0,004
13	6	C	980,000	33	7	N	20,000	53	63	Eu	1,900	73	75	Re	0,002
14	9	F	470,000	34	31	Ga	19,000	54	73	Ta	1,900	74	76	Os	0,002
15	16	S	430,000	35	3	Li	18,000	55	32	Ge	1,500	75	52	Te	0,001
16	56	Ba	420,000	36	41	Nb	18,000	56	67	Ho	1,300	76	44	Ru	0,001
17	38	Sr	370,000	37	90	Th	12,000	57	42	Mo	1,200	77	45	Rh	0,001
18	17	Cl	260,000	38	82	Pb	12,000	58	65	Tb	1,100	78	77	Ir	0,001
19	24	Cr	200,000	39	5	B	9,400	59	81	Tl	0,690				
20	40	Zr	180,000	40	59	Pr	9,000	60	71	Lu	0,500		Total Crust		101%

Cosmogenic **Primordial**

Earth's Crust– Element Concentrations (ppm[w])

incl. Elements with Naturally Occurring Radioisotopes (II)

Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)	Rank	Z	Symbol	ppm(w)
1	8	O	460000,000	21	23	V	160,000	41	62	Sm	6,500	61	69	Tm	0,490
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8	19	K	21000,000	28	60	Nd	37,000	48	35	Br	2,500	68	34	Se	0,050
9	22	Ti	6100,000	29	57	La	37,000	49	55	Cs	2,400	69	83	Bi	0,017
10	1	H	1400,000	30	39	Y	31,000	50	4	Be	2,400	70	46	Pd	0,011
11	15	P	1100,000	31	27	Co	28,000	51	50	Sn	2,300	71	78	Pt	0,004
12	25	Mn	980,000	32	21	Sc	24,000	52	33	As	2,000	72	79	Au	0,004
13	6	C	980,000	33	7	N	20,000	53	63	Eu	1,900	73	75	Re	0,002
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15	16	S	430,000	35	3	Li	18,000	55	32	Ge	1,500	75	52	Te	0,001
16	56	Ba	420,000	36	41	Nb	18,000	56	67	Ho	1,300	76	44	Ru	0,001
17	38	Sr	370,000	37	90	Th	12,000	57	42	Mo	1,200	77	45	Rh	0,001
18	17	Cl	260,000	38	82	Pb	12,000	58	65	Tb	1,100	78	77	Ir	0,001
19	24	Cr	200,000	39	5	B	9,400	59	81	Tl	0,690				
20	40	Zr	180,000	40	59	Pr	9,000	60	71	Lu	0,500		Total Crust		101%

Cosmogenic **Primordial >>>>> Secundary** (*ex* decay series)

^{232}Th & ^{238}U Decay Characteristics

^{232}Th	10^{10} y	
^{228}Ra	6 y	
^{228}Ac		γ
^{228}Th	2 y	(γ)
^{224}Ra	4 d	(γ)
^{220}Rn		
^{216}Po		
^{212}Pb		γ
^{212}Bi		γ
^{212}Po & ^{208}Tl		γ
^{208}Pb	stable	

Primordial **N**aturally **O**ccurring **R**adionuclide's (**NOR's**) ^{232}Th and ^{238}U are special as they are heading a series of successive nuclear decays, thereby transmuting nuclei and changing chemical behaviour

Listed in *Earth's Crust Element Concentrations*: ***Th*, *Pb*, *U*, *Tl*, *Bi***
not listed: Ra, Ac, *Rn*, Po, Pa

if undisturbed > secular equilibrium
(on a geological time scale)

^{238}U	10^{9} y	
^{234}Th		(γ)
^{234m}Pa		
^{234}U		(γ)
^{230}Th		(γ)
^{226}Ra	1600 y	(γ)
^{222}Rn	4 d	
^{218}Po		
^{214}Pb		γ
^{214}Bi		γ
^{214}Po		
^{210}Pb	22 y	(γ)
^{210}Bi		
^{210}Po	138 d	
^{206}Pb	stable	

(radio)isotopes: (radio)isotopes within a specified element, *e.g.* ^{38}K, ^{39}K, ^{40}K, ^{41}K, ^{42}K, ^{43}K
(radio)nuclides: (radio)nuclides of various elements, e.g. ^{1}H, ^{12}C, ^{35}Cl, ^{40}K, ^{57}Fe

Specific Activity vs. Activity Concentration

In agreement with the general use of the term *specific* and the definition of *activity* the **specific activity** (SA) should be the activity of 1 g of the radionuclide itself. Consequently **specific activity** is a constant physical quantity or physical property of a naturally occurring radionuclide *e.g*.

^{40}K $SA = \lambda \times N_{Av} / M_A[^{40}K] = ln(2) \times N_{Av} / (M_A[^{40}K] \times T_{1/2}) = 2.59 \times 10^5\ Bq[^{40}K]/g[^{40}K]$

Activity concentration (AC) is a measurable quantity of an identified naturally occurring radionuclide in a product / residue / waste matrix. The naturally occurring radionuclide is present at an impurity level, whereas the product / residue / waste matrix is determining the chemical and physical properties of the "material". AC may be expressed as the (radio)activity in an identified naturally occurring radionuclide (subseries) per unit of mass or volume *e.g*. 300 $Bq[^{222}Rn]/Nm^3$[natural gas], 5 $Bq[^{228}Ra]/L$[effluent] or 3 $Bq[^{226}Ra_{eq}]/g$[scale].

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Activity Concentration
vs.
Element Concentration

Basic Units & Terminology

Activity Concentration vs. Element Concentration in a Matrix

RADIOACTIVITY

Becquerel SI unit for radioactivity (Bq); concentration (Bq per unit of mass/volume):
1 Bq equals 1 nuclear disintegration per second

Half-Life time period, in which the total activity, is reduced to half its value
(*e.g.* ^{238}U $5x10^9$ years, ^{226}Ra 1600 years, ^{222}Rn 4 days, ^{218}Po 3 minutes, ^{210}Pb 22 years)

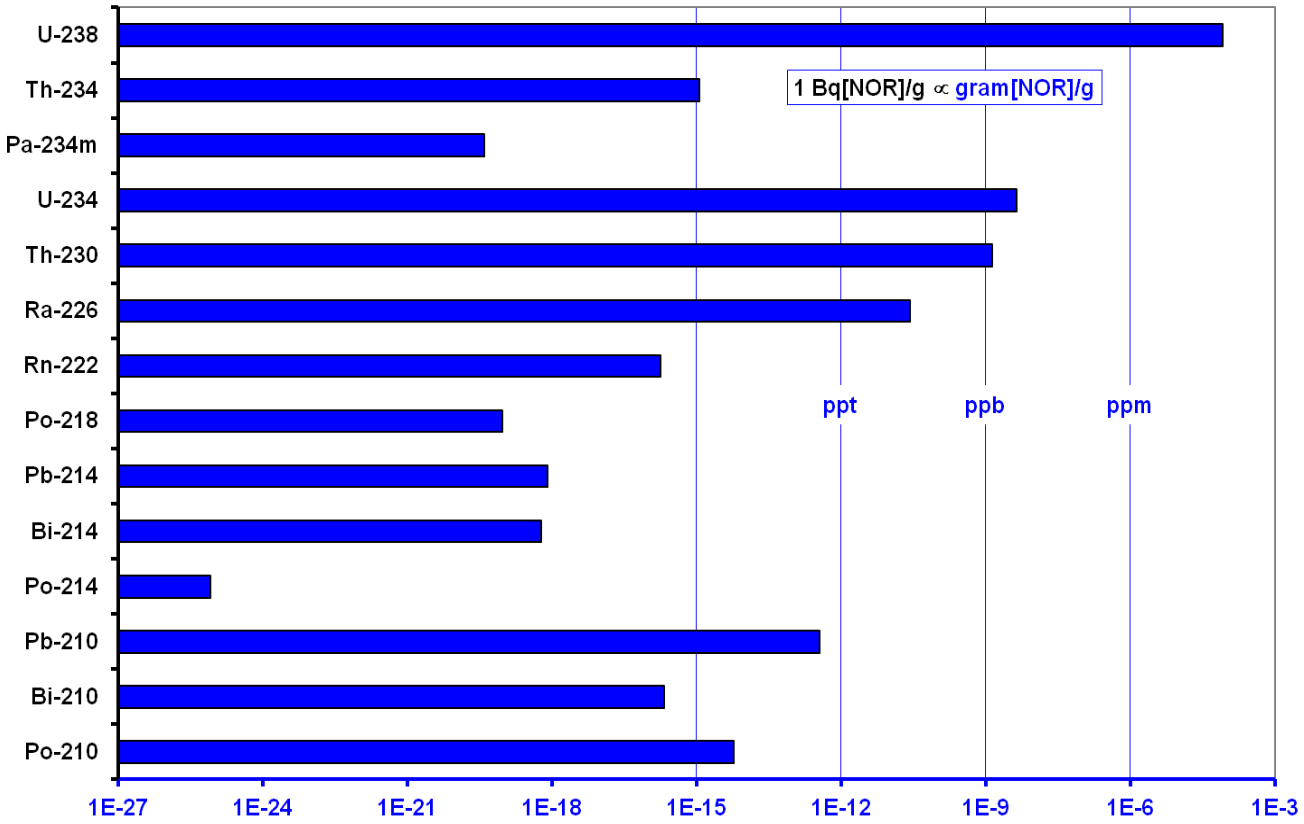
Equilibrium (secular -) can be reached in a 'closed' system between long-lived radioactive parent and substantially shorter-lived progeny.

PHYSICS/CHEMISTRY

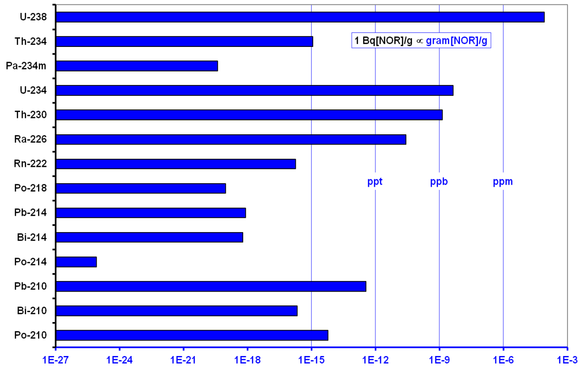
mass/volume Avogadro's number: 6 x 10^{23} atoms/mole
0,0224 Nm^3/mole = M_A (g/mole)

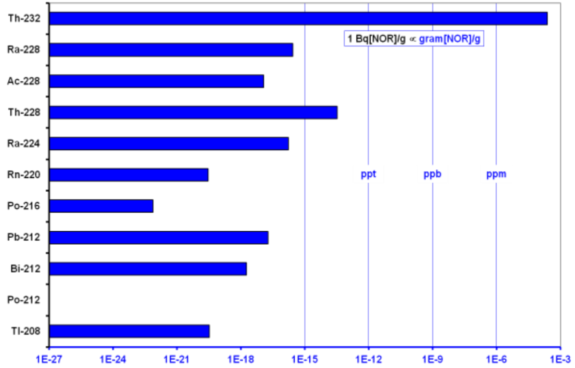
RADIOACTIVITY	corresponds to	PHYSICS/CHEMISTRY
300 Bq[^{222}Rn]/Nm^3[NG]		5 x 10^{-18} Nm^3[^{222}Rn]/Nm^3[NG]
10 Bq[^{226}Ra]/g[sample]		3 x 10^{-10} g[^{226}Ra]/g[sample]

Activity Concentration vs. "Chemical" Concentration

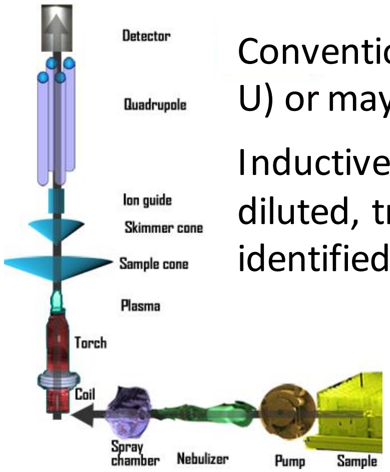


Element Analysis





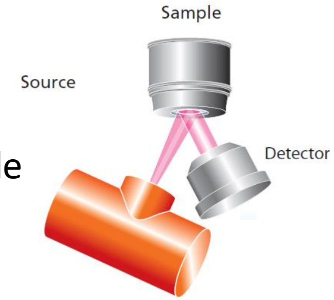
ICP/MS



Conventional Element Analysis techniques are a good indicator, if NOR's are (Th and U) or may be (Pb, S in combination with group II ions) present in a sample

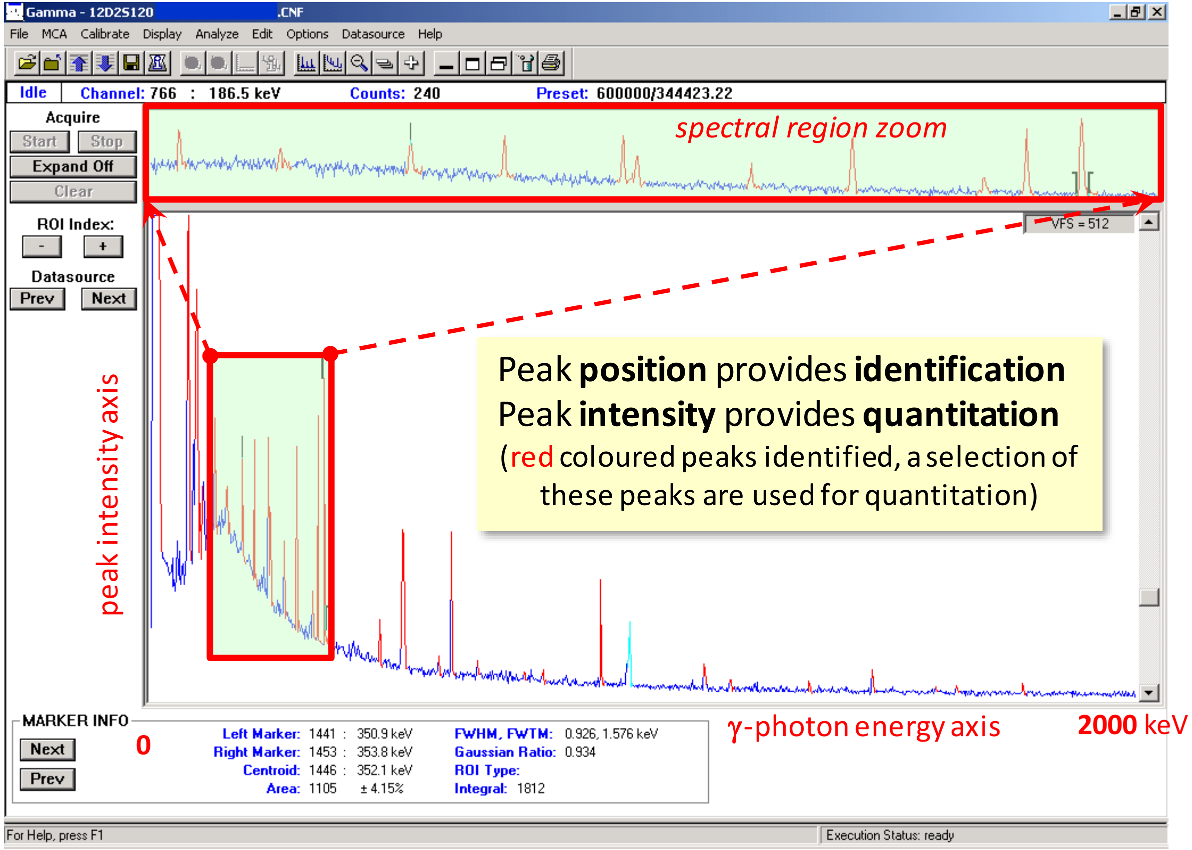
Inductively Coupled Plasma/Mass Spectroscopy (**ICP/MS**): sample digested and diluted, treated sample introduced into plasma, ionised element (isotopes) identified (mass) and quantified (peak area)

XRF



X-ray Fluorescence (**XRF**): sample milled (solids), transferred to sample cup (ultra thin mylar foil bottom), 40 keV X-ray irradiation, elements identified (energy fluorescent lines) and quantified (peak area)

Identification and Quantitation by γ-Spectrometry



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Chemistry – Members of ^{232}Th and ^{238}U decay series

Periodic System

Metalloids

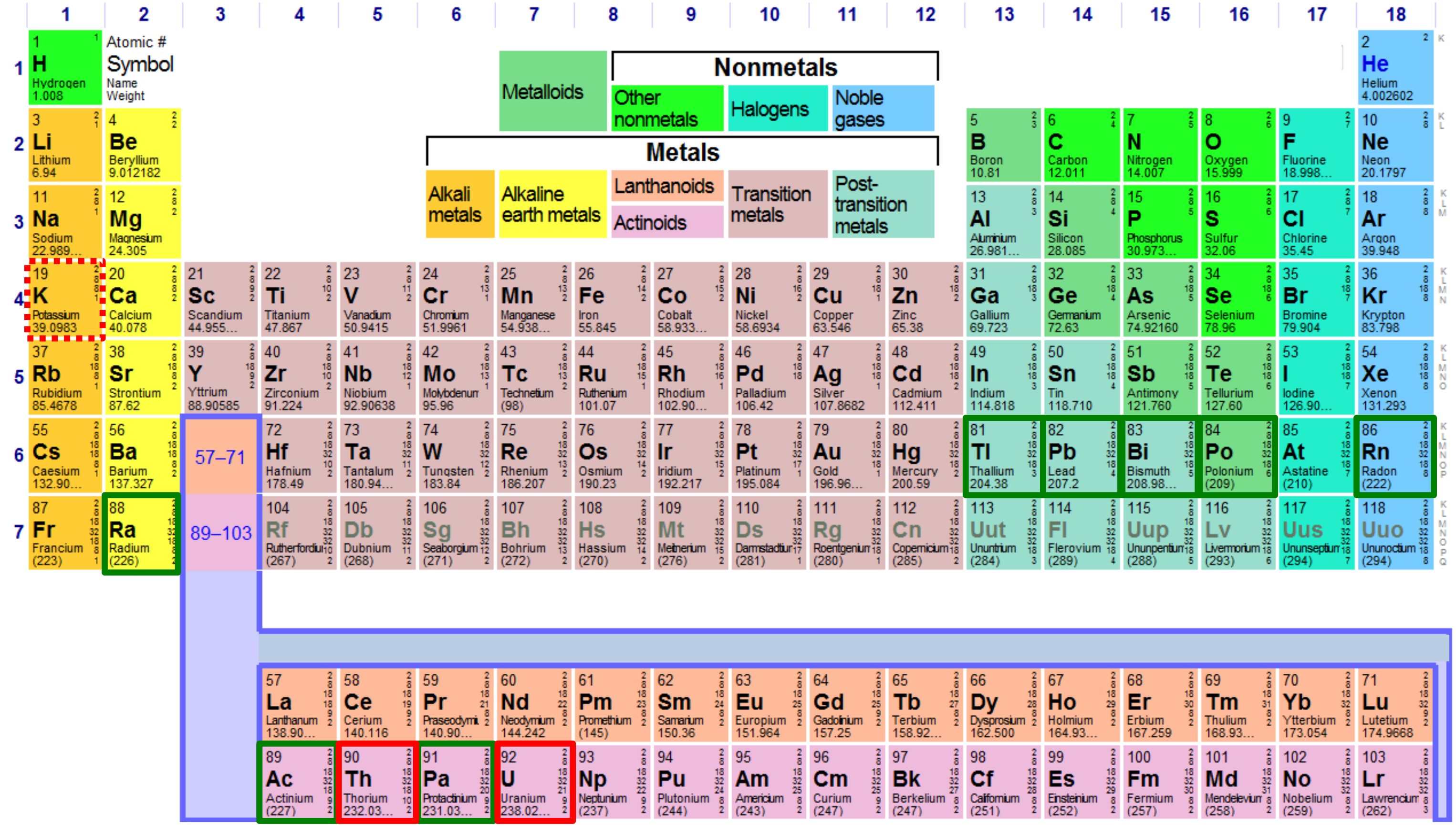
Nonmetals: Other nonmetals | Halogens | Noble gases

Metals: Alkali metals | Alkaline earth metals | Lanthanoids | Actinoids | Transition metals | Post-transition metals

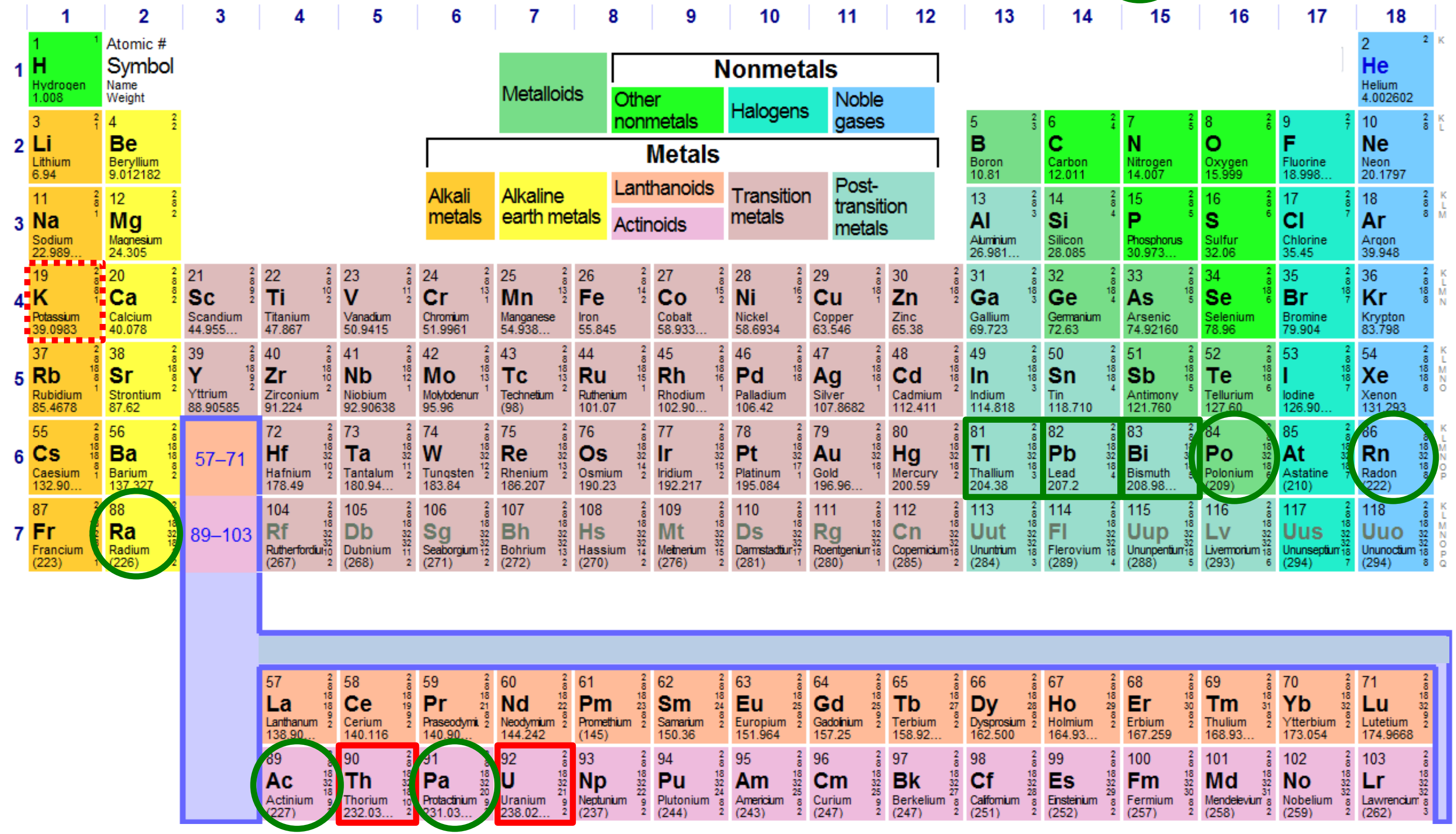
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.008	Atomic # Symbol Name Weight																2 He Helium 4.002602
2	3 Li Lithium 6.94	4 Be Beryllium 9.012182											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998...	10 Ne Neon 20.1797
3	11 Na Sodium 22.989...	12 Mg Magnesium 24.305											13 Al Aluminium 26.981...	14 Si Silicon 28.085	15 P Phosphorus 30.973...	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955...	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938...	26 Fe Iron 55.845	27 Co Cobalt 58.933...	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90...	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90...	54 Xe Xenon 131.293
6	55 Cs Caesium 132.90...	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94...	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.96...	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98...	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordiu (267)	105 Db Dubnium (268)	106 Sg Seaborgium (271)	107 Bh Bohrium (272)	108 Hs Hassium (270)	109 Mt Meitnerium (276)	110 Ds Darmstadtiu (281)	111 Rg Roentgeniu (280)	112 Cn Copernicium (285)	113 Uut Ununtrium (284)	114 Fl Flerovium (289)	115 Uup Ununpentium (288)	116 Lv Livermorium (293)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

57 La Lanthanum 138.90...	58 Ce Cerium 140.116	59 Pr Praseodymi 140.90...	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92...	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93...	68 Er Erbium 167.259	69 Tm Thulium 168.93...	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03...	91 Pa Protactinium 231.03...	92 U Uranium 238.02...	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Periodic System – Primordial and Secundary NOR's



Periodic System – Carrier vs. Carrier Free



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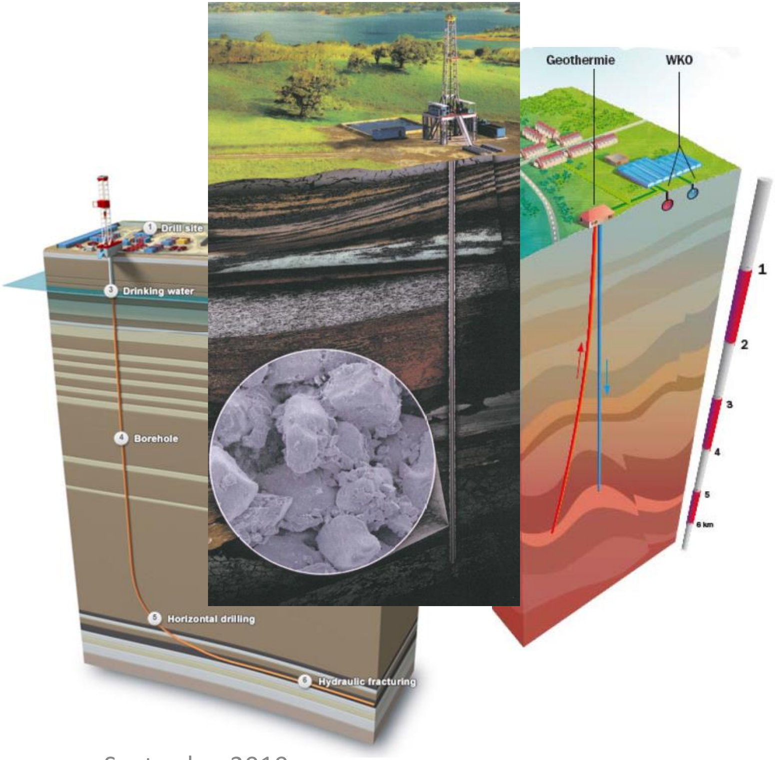
Mineral Mining, Beneficiation/Treatment and Processing

Earth's Crust & Natural Resources - Mining

Mobile Phase (Gas/Oil/Water)

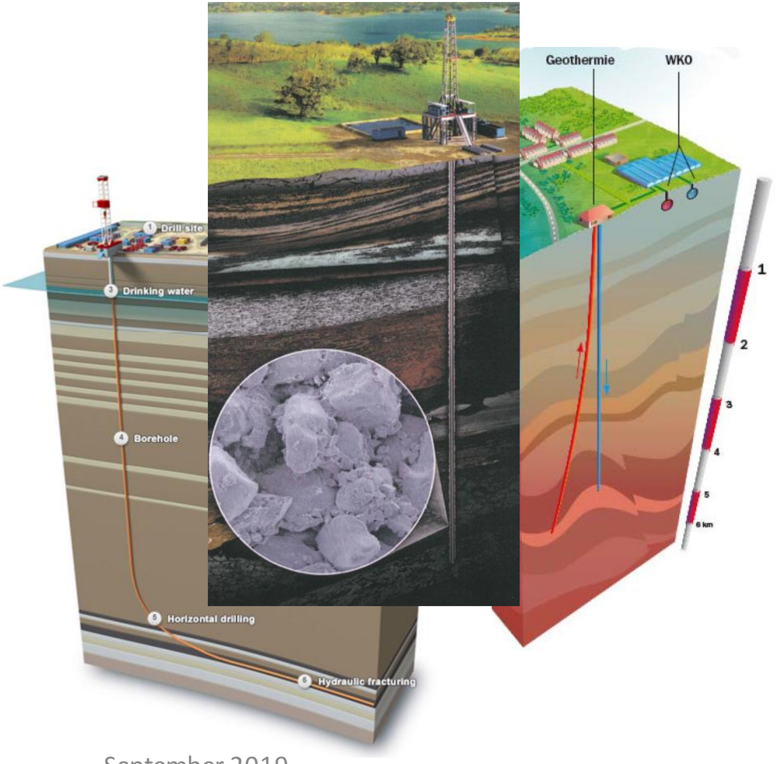


Surface Mine

Sub-surface Mine

Earth's Crust & Natural Resources – Mobile Phase Mining

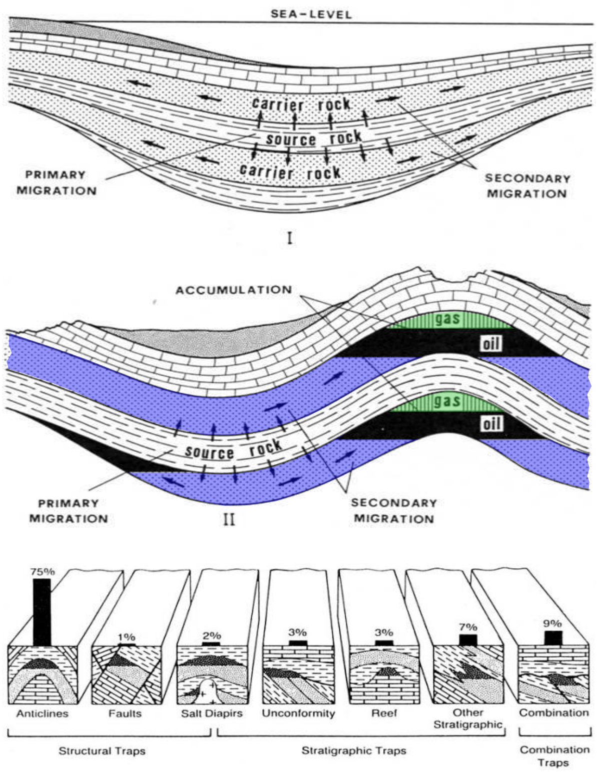
Mobile Phase (Gas/Oil/Water)



Surface Mine

Sub-surface Mine

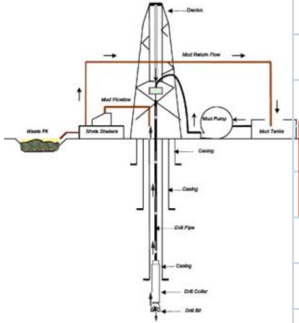
Gas/Oil Formation – Geological Time Scale



- hydrocarbon **source rocks** are sediments containing large amounts of organic matter (*e.g*. coal, organic rich shale)
- source rocks to have been buried to depths of at least 3 kilometers for a significant period of geological time (say up > **10^6 years**) before gas/oil is formed
- geological strata should be shaped in such a way that gas/oil escaping/seeping from source rock may be come **trapped** in a '***conventional***' reservoir
- most common **sandstone reservoir** with gas/oil/formation-water in the pores sealed by a dome-shaped sealing (salt [evaporite], shale) layer
- geological shale strata may contain gas/oil, that may be released by hydraulic fracturing ('***unconventional***' reservoir, e.g. shale gas/oil)

NOR's in Sedimentary Rocks (Gas/Oil Reservoirs)

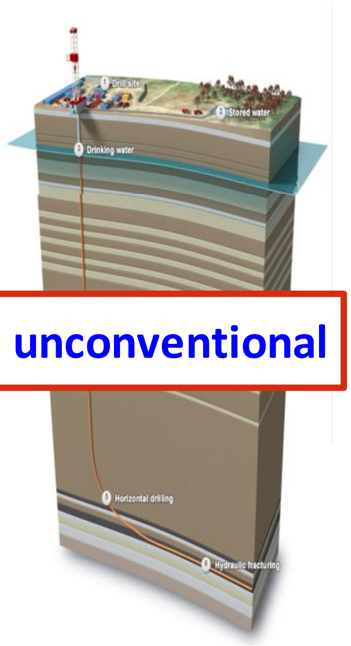
K, Th & U - Element and Activity Concentrations



conventional

SEDIMENTARY ROCK CLASS	Potassium (K) %w	Potassium (K) Bq/g	Thorium (Th) ppm (w)	Thorium (Th) Bq/g	Uranium (U) ppm (w)	Uranium (U) Bq/g
DETRITAL	2,1	0,66	12,4	0,050	4,8	0,059
Sandstone & Conglomerates	1,2	0,37	9,7	0,039	4,1	0,050
Orthoquartzites	2,0	0,62	1,5	0,006	0,5	0,006
Arkoses	2,5	0,78	5,0	0,020	1,5	0,018
Shale						
Grey/Green	3,5	1,09	16,3	0,066	5,9	0,072
Black	3,0	0,94	13,0	0,053	3,0	0,037
Clay	0,6	0,19	8,6	0,035	4,0	0,049
CHEMICAL	0,6	0,19	14,9	0,060	3,6	0,044
Carbonates	0,3	0,09	1,8	0,007	2,0	0,025
Limestone	0,5	0,16	3,0	0,012	13,0	0,159
Evaporites					< 0.1	< 0.001
EARTH's CRUST	2,1	0,66	12,4	0,050	4,2	0,051
Top soil	1,5	0,47	9,0	0,037	8,0	0,098
Beach sands (unconsolidated)			6,0	0,024	3,0	0,037

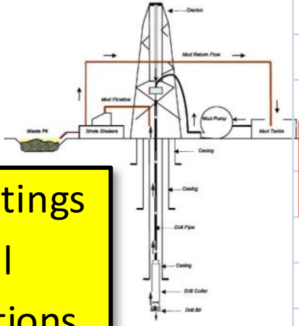
unconventional



NOR's in Sedimentary Rocks (Gas/Oil Reservoirs)

K, Th & U - Element and Activity Concentrations

conventional



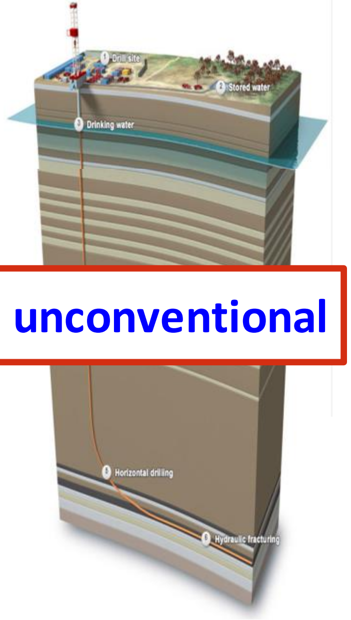
Drilling Cuttings Natural Concentrations

of **K**, **Th** & **U**

NORM?

SEDIMENTARY ROCK CLASS	Potassium (K) %w	Potassium (K) Bq/g	Thorium (Th) ppm (w)	Thorium (Th) Bq/g	Uranium (U) ppm (w)	Uranium (U) Bq/g
DETRITAL	2,1	0,66	12,4	0,050	4,8	0,059
Sandstone & Conglomerates	1,2	0,37	9,7	0,039	4,1	0,050
Orthoquartzites	2,0	0,62	1,5	0,006	0,5	0,006
Arkoses	2,5	0,78	5,0	0,020	1,5	0,018
Shale						
Grey/Green	3,5	1,09	16,3	0,066	5,9	0,072
Black	3,0	0,94	13,0	0,053	3,0	0,037
Clay	0,6	0,19	8,6	0,035	4,0	0,049
CHEMICAL	0,6	0,19	14,9	0,060	3,6	0,044
Carbonates	0,3	0,09	1,8	0,007	2,0	0,025
Limestone	0,5	0,16	3,0	0,012	13,0	0,159
Evaporites					< 0.1	< 0.001
EARTH's CRUST	2,1	0,66	12,4	0,050	4,2	0,051
Top soil	1,5	0,47	9,0	0,037	8,0	0,098
Beach sands (unconsolidated)			6,0	0,024	3,0	0,037

unconventional



NOR's in Sedimentary Rocks (Gas/Oil Reservoirs)

K, Th & U - Element and Activity Concentrations

SEDIMENTARY ROCK CLASS	Potassium (K) %w	Potassium (K) Bq/g	Thorium (Th) ppm(w)	Thorium (Th) Bq/g	Uranium (U) ppm(w)	Uranium (U) Bq/g
DETRITAL	2,1	0,66	12,4	0,050	4,8	0,059
Sandstone & Conglomerates	1,2	0,37	9,7	0,039	4,1	0,050
Orthoquartzites	2,0	0,62	1,5	0,006	0,5	0,006
Arkoses	2,5	0,78	5,0	0,020	1,5	0,018
Shale						
Grey/Green	3,5	1,09	16,3	0,066	5,9	0,072
Black	3,0	0,94	13,0	0,053	3,0	0,037
Clay	0,6	0,19	8,6	0,035	4,0	0,049
CHEMICAL	0,6	0,19	14,9	0,060	3,6	0,044
Carbonates	0,3	0,09	1,8	0,007	2,0	0,025
Limestone	0,5	0,16	3,0	0,012	13,0	0,159
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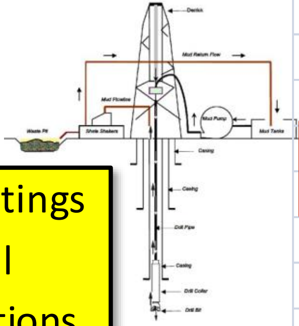
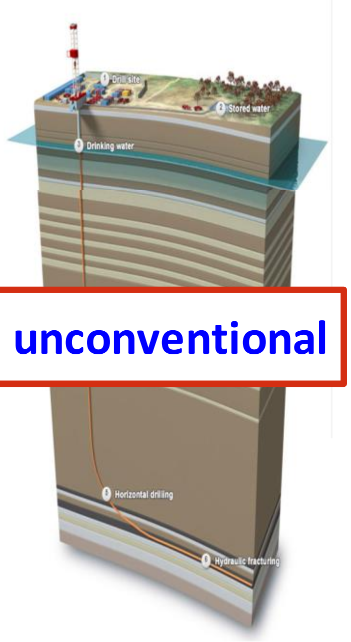
conventional

unconventional





Drilling Cuttings
Natural
Concentrations
of **K, Th & U**

NORM?

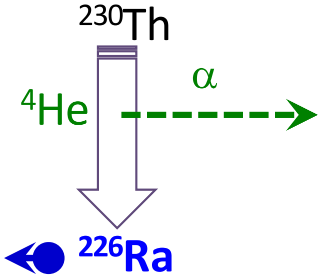
NOR Geochemistry

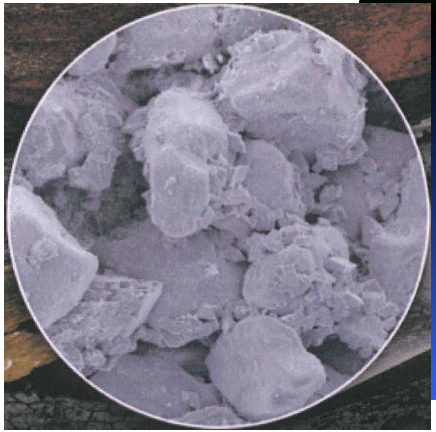
Gas/Oil/Water and Water Reservoir Conditions

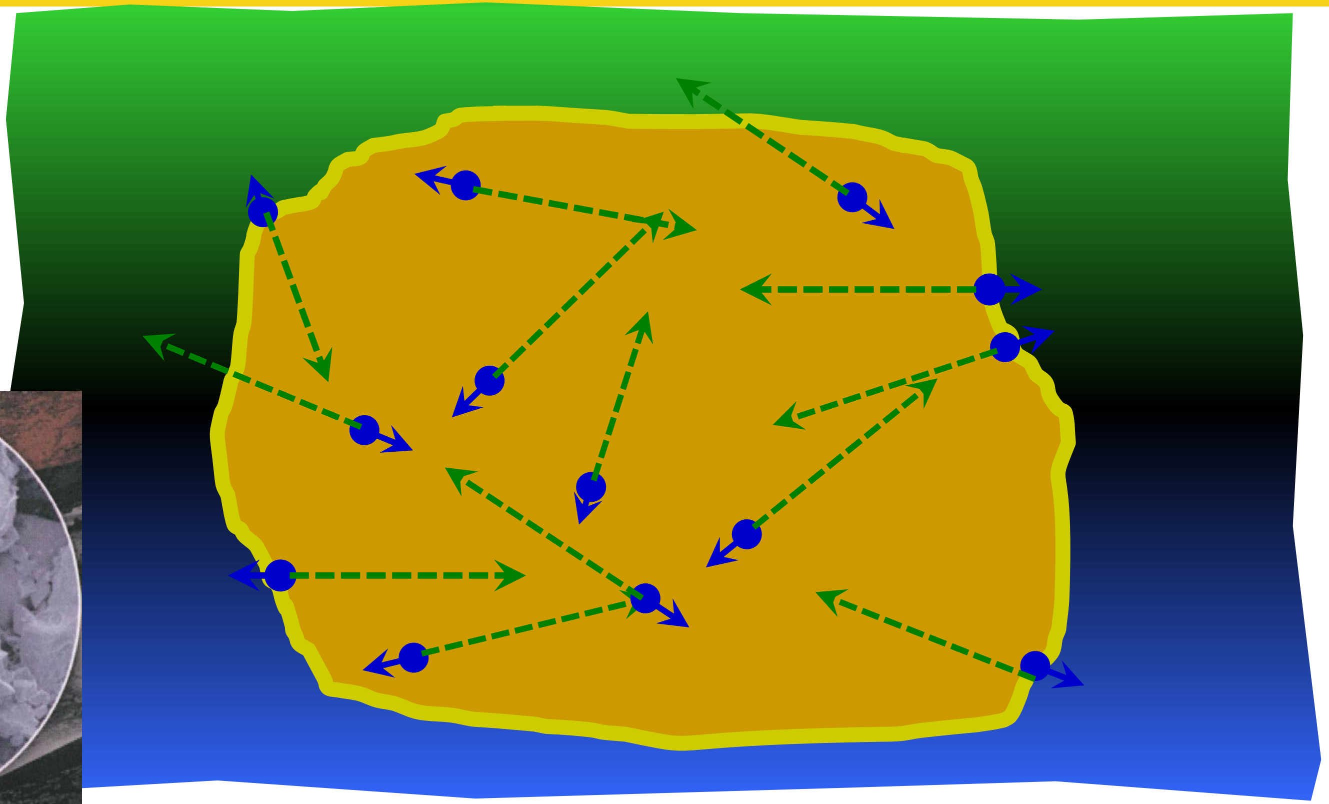
element	^{232}Th-series	^{238}U-series	chemical behaviour	Diagenesis/ Accumulation
U uranium		^{238}U, ^{234}U	reducing environment: U^{4+} insoluble, no UO_2^{2+}	remains inside or at surface of reservoir grains
Th thorium	^{232}Th, ^{228}Th	^{234}Th, ^{230}Th	reducing environment: Th^{4+} very insoluble	
Ra radium	^{228}Ra, ^{224}Ra	^{226}Ra	alkaline-earth (Mg, Ca, Sr, Ba)$^{2+}_{aq}$ carrier for Ra^{2+} ions	preference for and geo-chemically transported by aqueous phase
Rn radon	^{220}Rn	^{222}Rn	noble gas, very polarisible atoms	water/oil/gas phase partitioning
Pb lead		^{210}Pb	stable Pb^{2+}_{aq} carrier for $^{210}Pb^{2+}$ ions	preference for and geo-chemically transported by aqueous phase

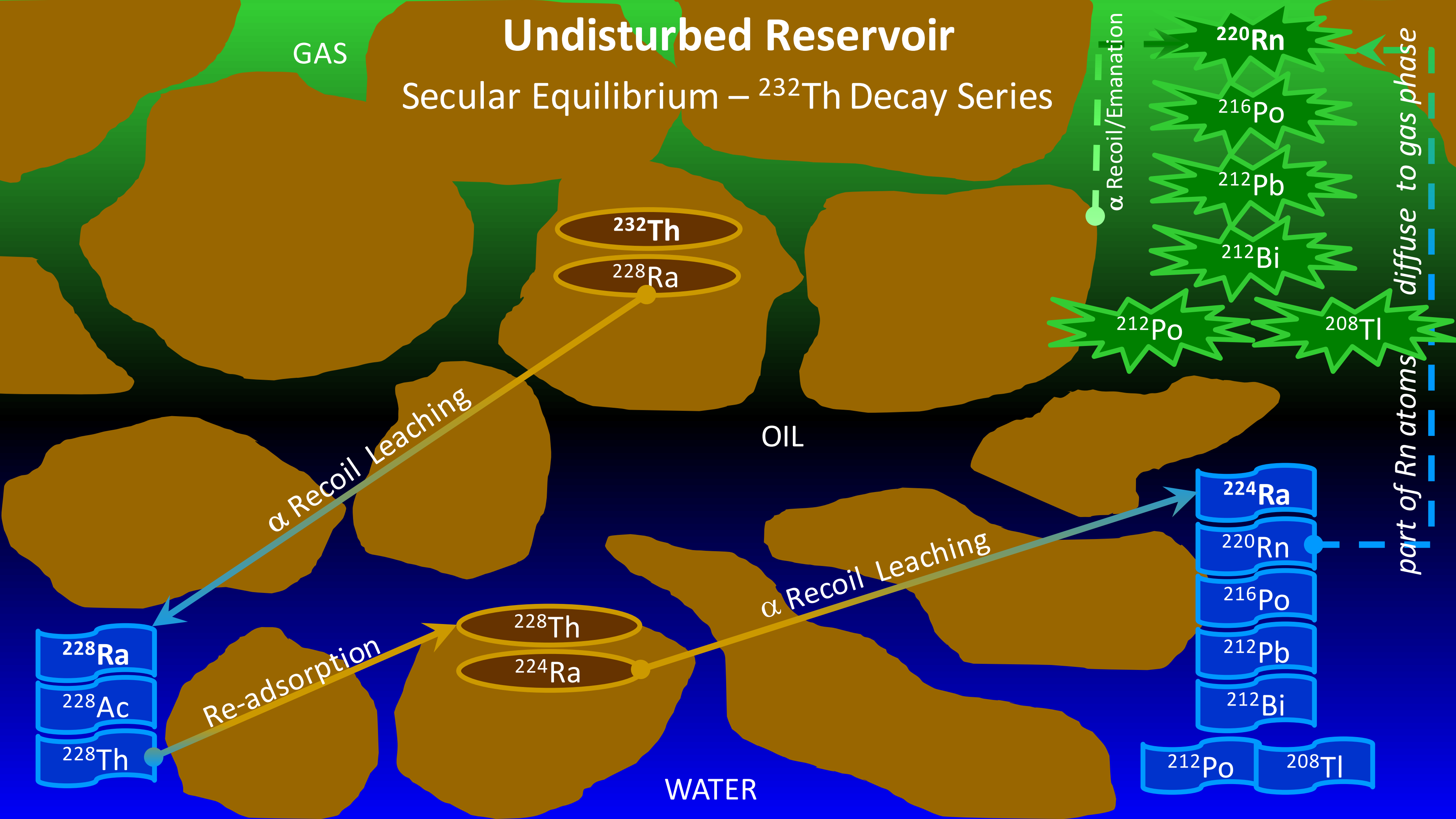
Radiophysical and Radiochemical Phenomena

α Recoil Stimulated Dissolution from/around a Sand Grain





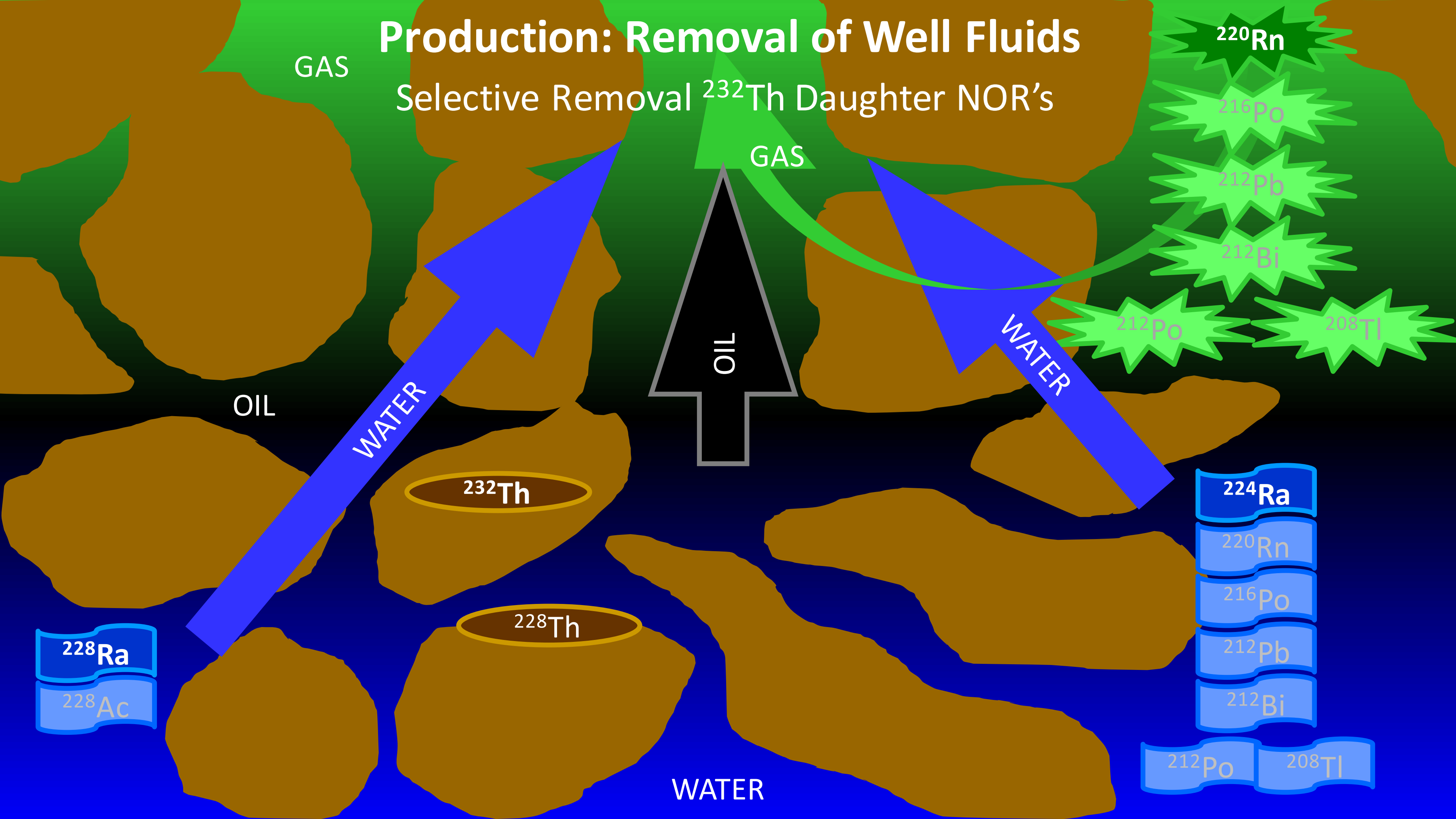




Undisturbed Reservoir
Secular Equilibrium – ^{232}Th Decay Series
GAS
OIL
WATER
^{232}Th
^{228}Ra
α Recoil Leaching
^{228}Ra
^{228}Ac
^{228}Th
Re-adsorption
^{228}Th
^{224}Ra
α Recoil Leaching
^{224}Ra
^{220}Rn
^{216}Po
^{212}Pb
^{212}Bi
^{212}Po
^{208}Tl
α Recoil/Emanation
^{220}Rn
^{216}Po
^{212}Pb
^{212}Bi
^{212}Po
^{208}Tl
part of Rn atoms diffuse to gas phase

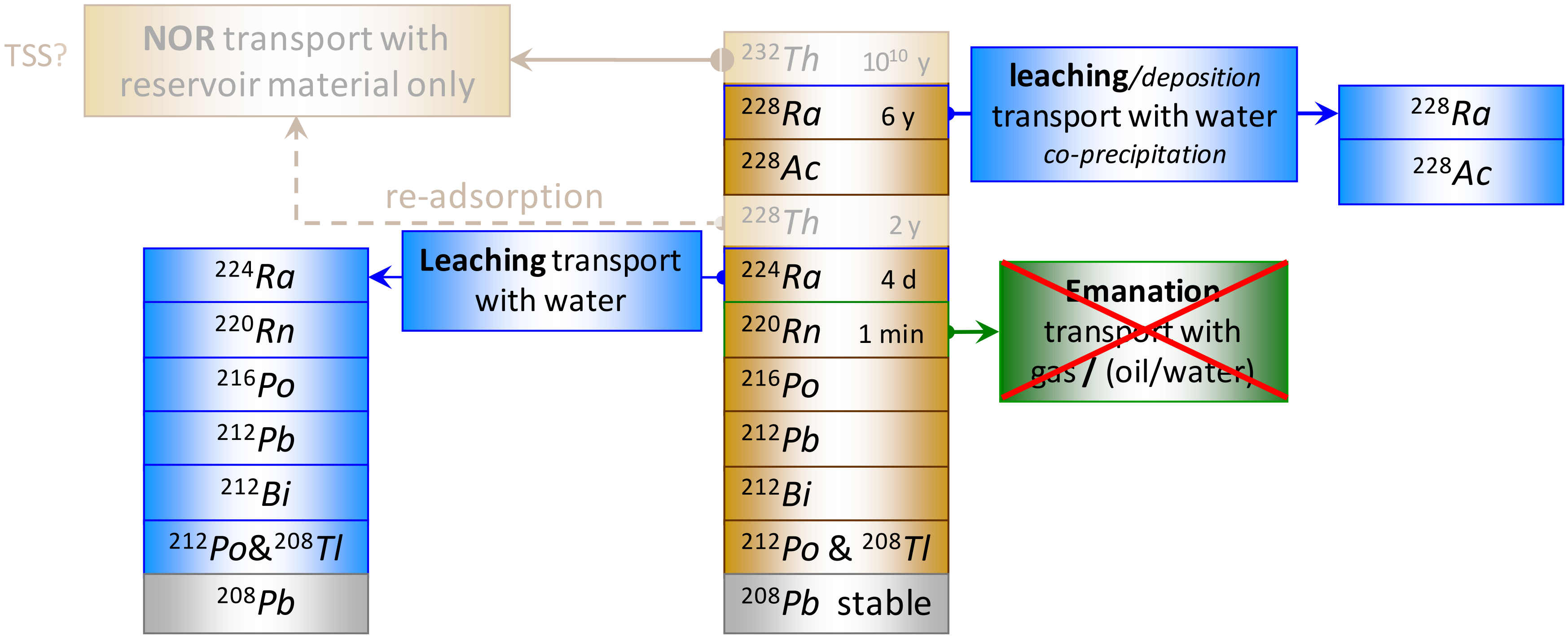
Production: Removal of Well Fluids

Selective Removal ^{232}Th Daughter NOR's



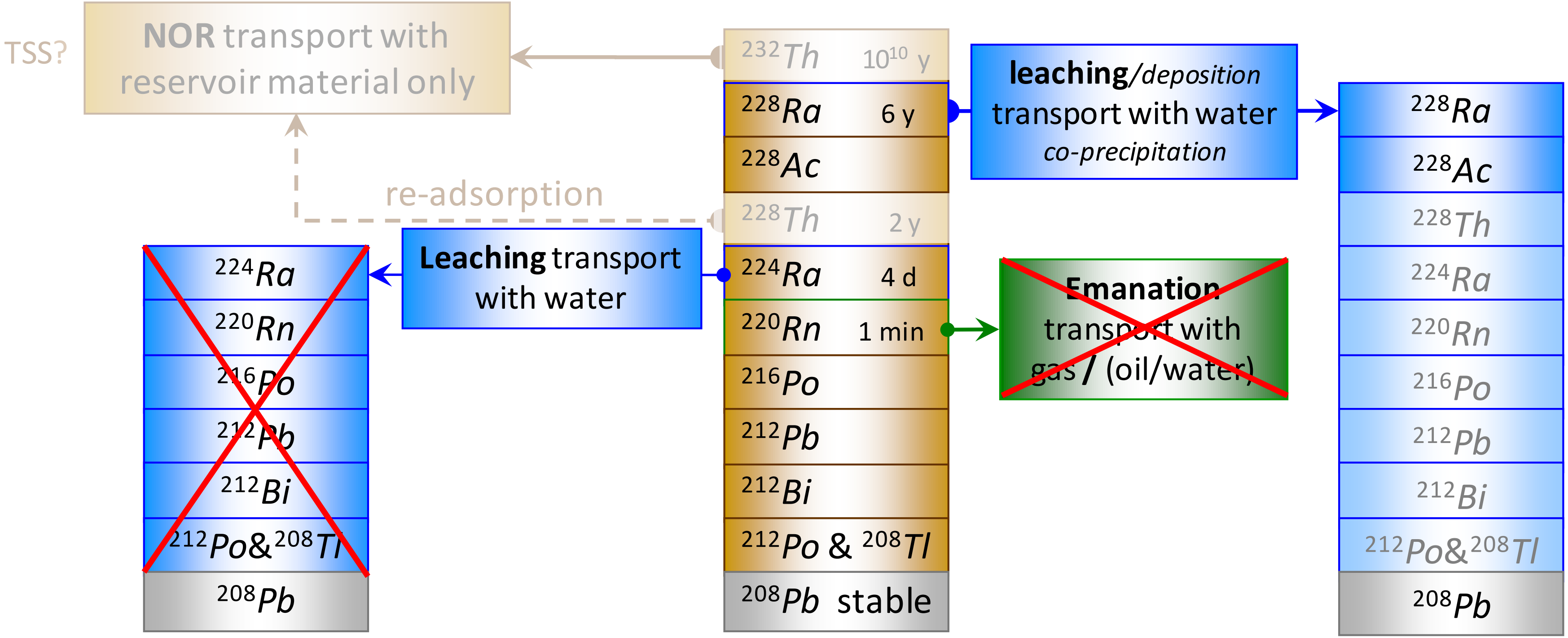
NOR Characteristics – Well Fluids/Produced Water

^{232}Th Decay Series 1 day after production



NOR Characteristics – Well Fluids/Produced Water – Scale/Sludge

^{232}Th Decay Series — 1 year after production



NOR Characteristics – Mobile Phase Mining

^{232}Th Decay Series overview

Notation ^{232}Th-series
$^{228}Ra_{eq}$ and $^{228}Th_{eq}$

TSS?

NOR transport with reservoir material only

re-adsorption

^{232}Th	10^{10} y
^{228}Ra	6 y
^{228}Ac	
^{228}Th	2 y
^{224}Ra	4 d
^{220}Rn	1 min
^{216}Po	
^{212}Pb	
^{212}Bi	
^{212}Po & ^{208}Tl	
^{208}Pb	stable

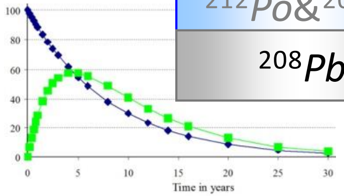
leaching/*deposition* transport with water *co-precipitation*

^{228}Ra	$^{228}Ra_{eq}$
^{228}Ac	
^{228}Th	$^{228}Th_{eq}$
^{224}Ra	
^{220}Rn	
^{216}Po	
^{212}Pb	
^{212}Bi	
^{212}Po&^{208}Tl	
^{208}Pb	

Leaching transport with water

^{224}Ra	$^{224}Ra_{eq}$
^{220}Rn	
^{216}Po	
^{212}Pb	
^{212}Bi	
^{212}Po&^{208}Tl	
^{208}Pb	

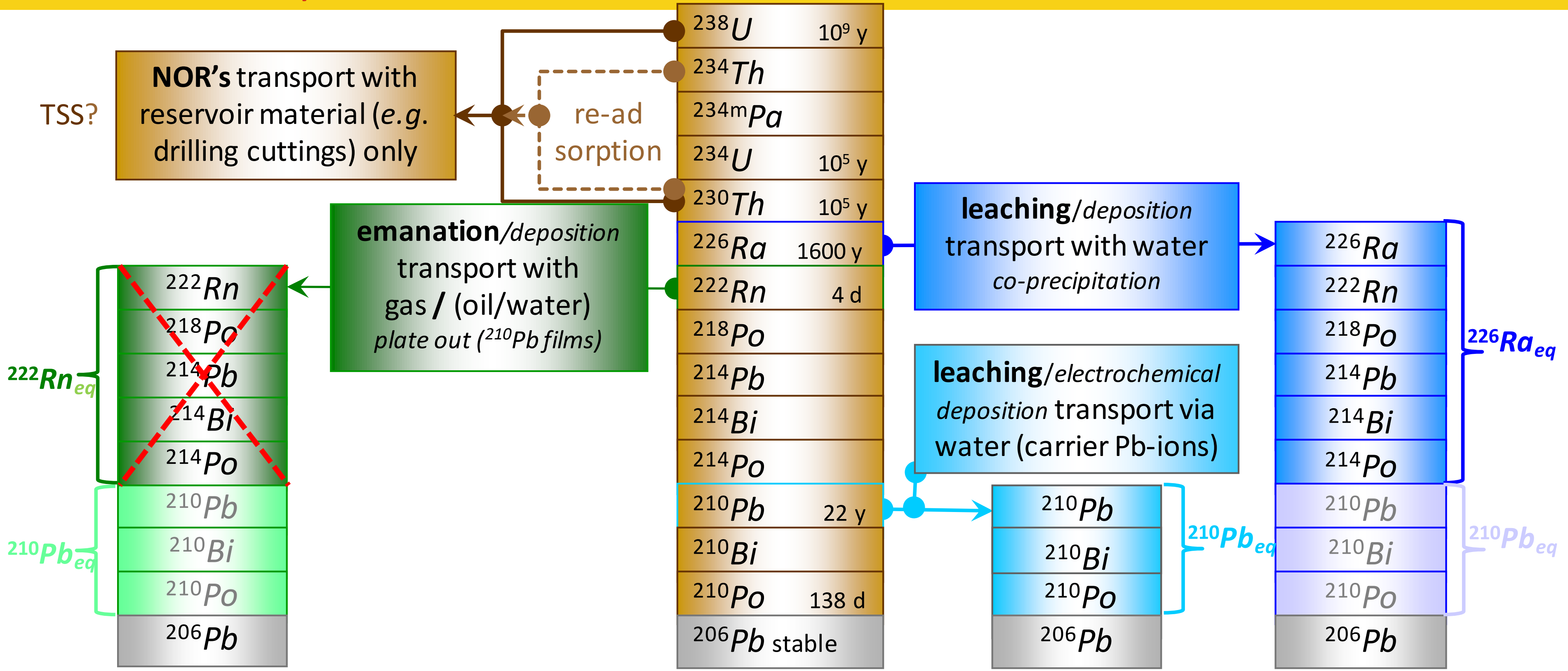
~~**Emanation** transport with gas / (oil/water)~~



NOR Characteristics – Mobile Phase Mining

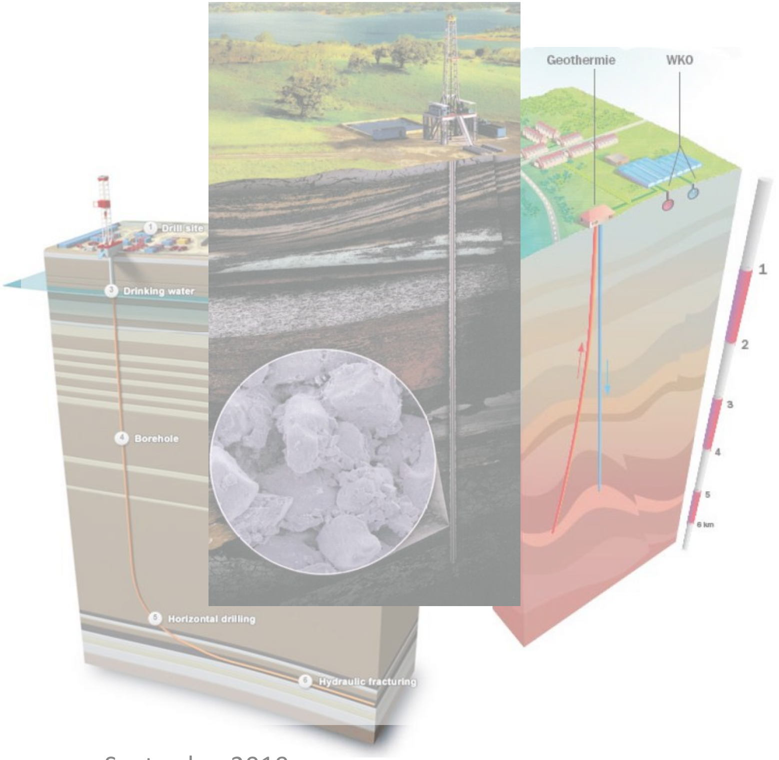
^{238}U Decay Series overview

Notation ^{238}U-series
$^{226}Ra_{eq}$ and $^{210}Pb_{eq}$



Earth's Crust & Natural Resources – Ore Mining

Mobile Phase (Gas/Oil/Water)



Surface Mine

Sub-surface Mine

Mining & Beneficiation



- Commercially exploited sedimentary phosphate deposits close to Earth's surface (± 10 m).
- Overburden (set aside for mine remediation) and phosphate ore will be broken up.
- Truck loading and transport to nearby crushing facility and beneficiation plant.
- Beneficiation via wet screening ('washing'), flocculation, and other special physical-chemical treatments to enhance the phosphate rich fraction
- All NOR's are still there, no (severe) disturbance of secular equilibria.

Wet Processing – Phosphoric Acid Production

- Beneficiated phosphate ore digested by H_2SO_4 (sulphuric acid), thereby producing $CaSO_4$ (phosphogypsum) and H_3PO_4 (phosphoric acid)

$$Ca_3(PO_4)_2 + 3\ H_2SO_4 \longrightarrow 2\ H_3PO_4 + 3\ CaSO_4$$

- ➢ **U**: present in phosphate rock as U^{4+} and U^{6+}. Digestion reduces any U^{6+} to U^{4+}, open air acid filtration oxidises U^{4+} to U^{6+}, forming uranyl ions (UO_2^{2+}) complexing with phosphates.
  - 90%–95% U in rock migrates to H_3PO_4 .
  - 5%-10% U in rock migrates to phosphogypsum (unreacted rock)
- ➢ **Th**: partitions depending on the actual process conditions and characteristics of phosphate rock. Either 75% to H_3PO_4 or 75% to phosphogypsum
- ➢ **Ra**: 75% to 95% in phosphate rock migrates to phosphogypsum
- ➢ **Pb**: conflicting reports, either all to H_3PO_4 or to phosphogypsum
- ➢ **Po**: is reported to migrate for 80% to 100% to phosphogypsum

Conclusions

- **Refrain from the term Specific Activity**
- Take account of the type of industry unwillingly producing NORM

  U, Th only relevant during ore mining, beneficiation and processing; not relevant for mobile phase mining industry (excl. U solution mining)

  Ra, Pb dissolves in aqueous process streams, deposits (exceeding solubility products/electrochemically) from aqueous process streams

  Rn only relevant for open industrial systems

  Pb, Po expelled from high temperature processes, deposits at cooler places (ducts, vents)
- α-recoil stimulates chemical leaching into the mobile phase (*geochemical time scale*)
- Transport carrier vs. carrier-free (*production/processing time scale*)
- NOR's may appear both in product and by-product (waste/residue) streams
- Have only relevant NOR's (in sub-equilibrium) reported

Q&A