

**TECHNISCHE
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Natural Nuclear Fission Reactors (NFRs) older than Oklo: Biogeochemistry, photochemical Constraints, Relationship to ancient Biotas, Design and Applications of similar Arrays

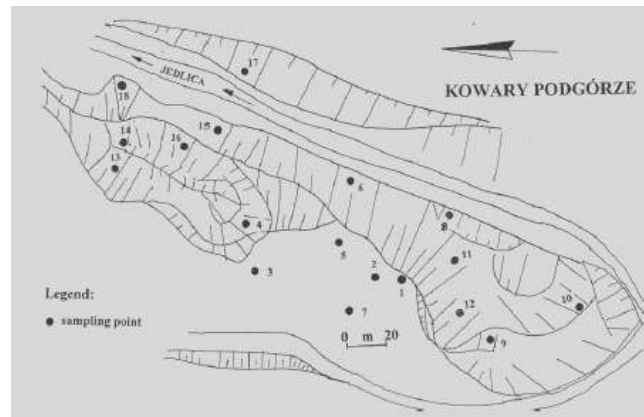
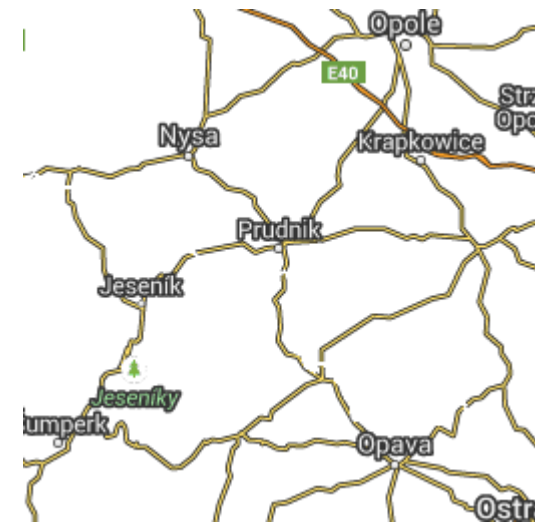
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Where is Zittau?

- Nearby former uranium mining sites ([old times-] GDR, CŠSR, Poland)
- Geochemistry, geological age of these sites
- Reactors at/next to Oklo (Gabon)
- Possible even earlier sites (Kuroda)



Radioactive residue distributions around Kowary mine



Oklo uranium open pit now after U mining was terminated

Recall some facts on early-Earth NFRs

- Oklo (Gabon): 1.8 bio. years old, moderation of NFRs by very hot to supercritical water; some 20 NFRs were excavated and identified
- Older ones: just indirect evidence; probably C-moderated by organics, photochemical „ignition“
- Evidence from scatter of certain element isotopic patterns (cp. ISINN-22 proceedings, p.379 ff.)
- There are specialized bacterial biota which make use of radiogenic compounds for „running“ chemolitho-autotrophy, now distributed worldwide within „low biosphere“



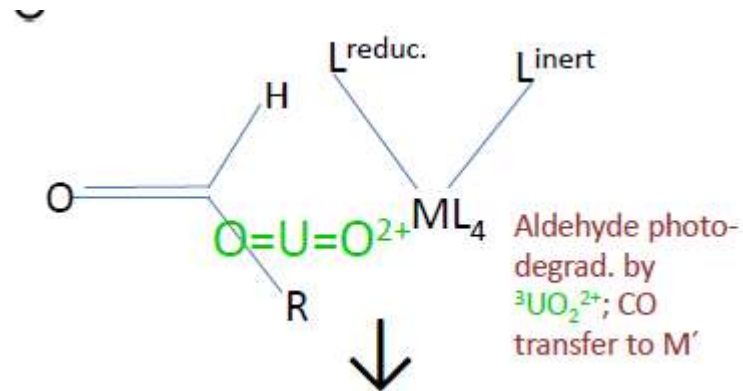
Oklo XV NFR site, now accessible via a tunnel

Photochem. U deposition

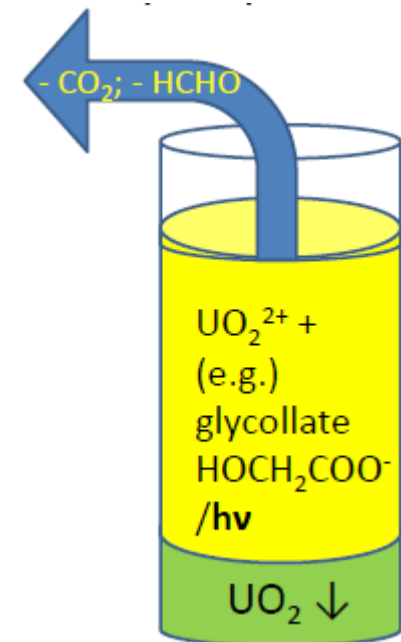
- U(VI) is sole photo-active species → redox potential!
- UO_2^{2+} is activated by visible light ($\lambda \approx 450 \text{ nm}$)
- Spin transfer and decay of triplet states of organics like aldehydes, ketones, amines, alkenes or
- Electron or H atom transfer (e.g. methyl ketones $\text{R-CO-CH}_3 \rightarrow$ - ketene $\text{CH}_2=\text{CO} \rightarrow \text{R}$; $\text{U}^{\text{V}}\text{O}_2^+$ (water)
- ϵ of excited state $\approx 2.4 \text{ V vs. SCE}$, $\tau_{\text{triplet}} < 1 \mu\text{s}$ → high selectivity, redox and spin deexcitation do compete depending on ambient compounds/ions, product UO_2^+ is fairly unstable
- **Only electron transfer** will cause precipitation of UO_2 or other insoluble oxides, U chemical enrichment

→ formation of reactor depends on both presence of appropriate organics (must most likely be afforded by biota) and redox potential levels

Effect of ionizing (ir-)radiation on redox potentials of mineral couples → NFR stability after formation, onset of criticality controlled by environment also



Ligand exchange by photooxidation, introduction of nascent CO



Ion pairs: spin (multiplicity) does matter while many ligands are stable towards photooxidation

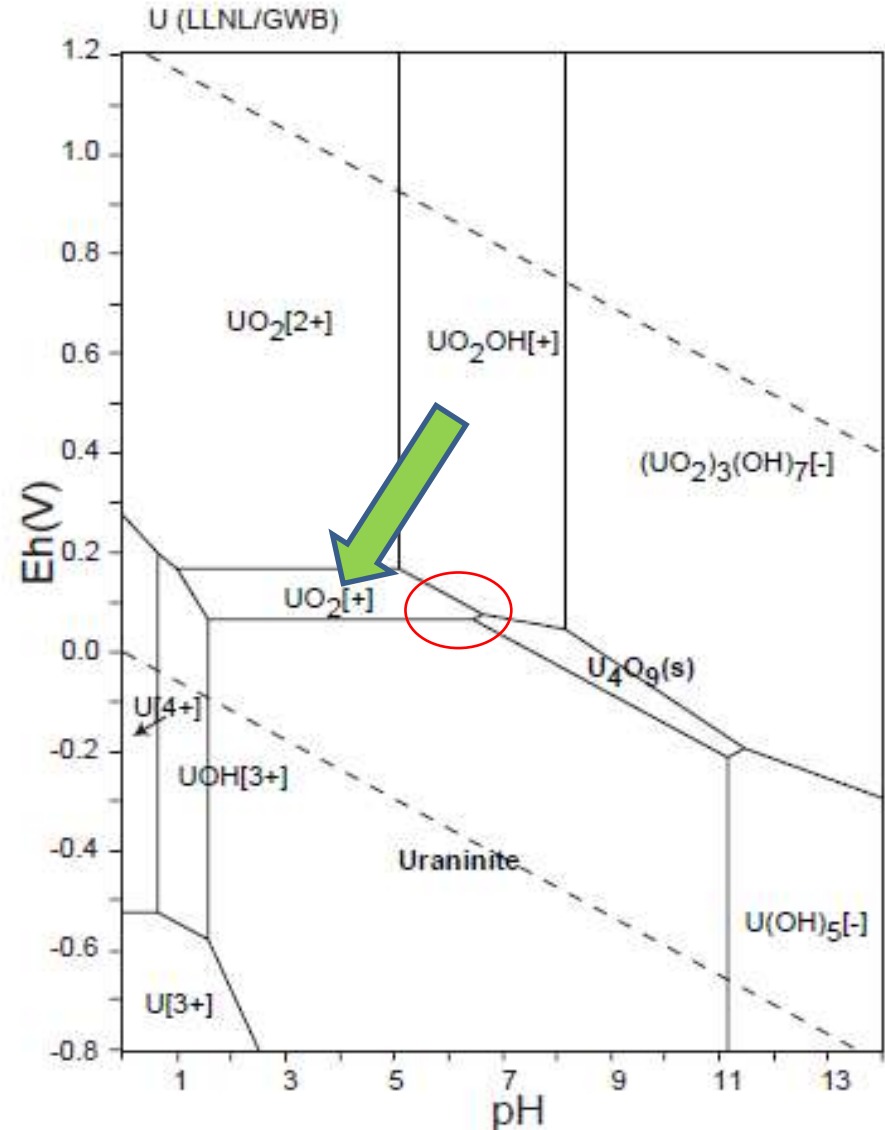
- Photoredox processes in uranyl ion pairs: Os(III) does readily react whereas Ir(III) complexes bearing the same ligands (ox^{2-} , Br^- , I^-) are inert (d^5 vs. d^6 ; electron transfer spin-allowed or not):
- Decomposition of aldehyde (solvent) \rightarrow (several) CO ligands transferred to Os, permitting synthesis of unstable polycarbonyls also
- should likewise apply to Fe(III) vs. Fe(II) [second criterion for external redox potential!]



photochemical H abstraction by $[\text{UO}_2(\text{OH})]^+$ (**pH = 5 – 8**), then elimin. of water;

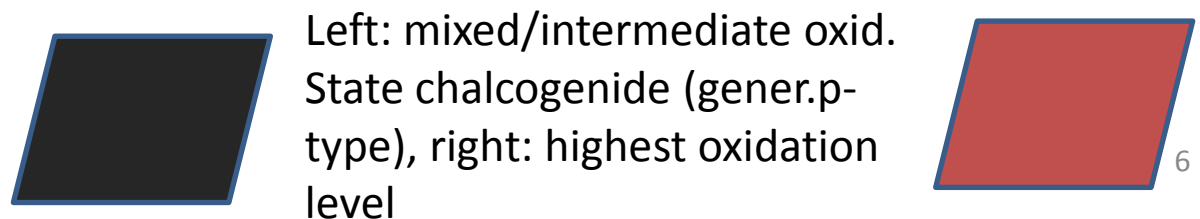
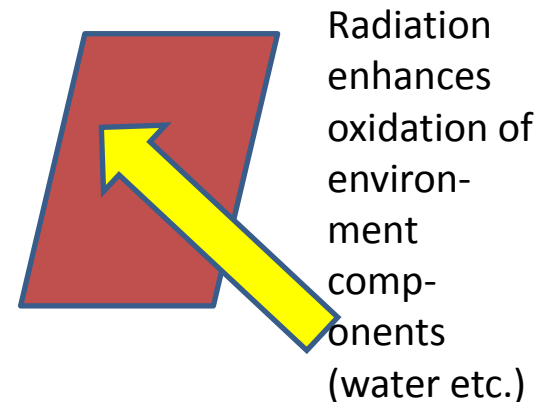
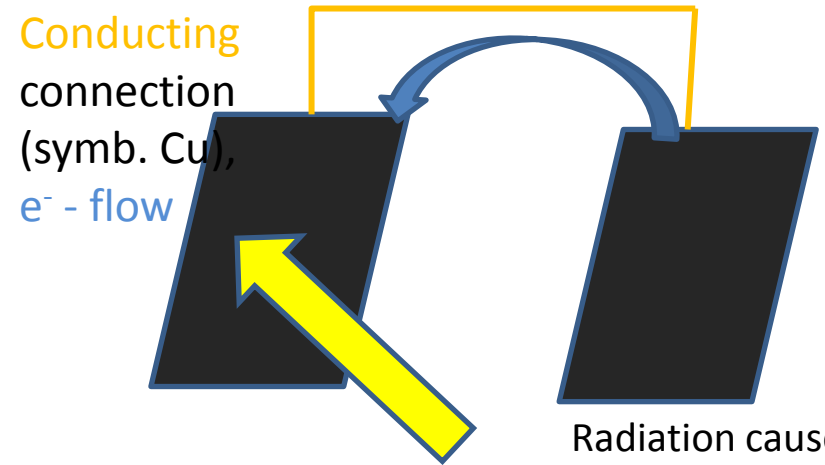


Region of disproportionation of UO_2^+ , oxide precipitation



Radiation chemistry: ε of an electrode does **increase** under β^- , α^- , p- or sometimes n irradiation

- Effect independent of pH
- Some reported work includes effects from nuclear reactions (e.g. for W- or WO_3 electrodes exposed to 260 MeV protons [260-MeV projectiles would overcome $Z = 74$ Coulomb barrier for every projectile up to about Ni]), other
- Results consistent in sign of effect ($\Delta\varepsilon \approx +30\dots+400$ mV)
- Low-T activation by semiconducting catalyst phases doped with radio-nuclides, e.g. ammonoxidation by Bi/Mo(^{99}Mo) oxides or CO oxidation by Ce (^{144}Ce or ^{238}Pu) O_2



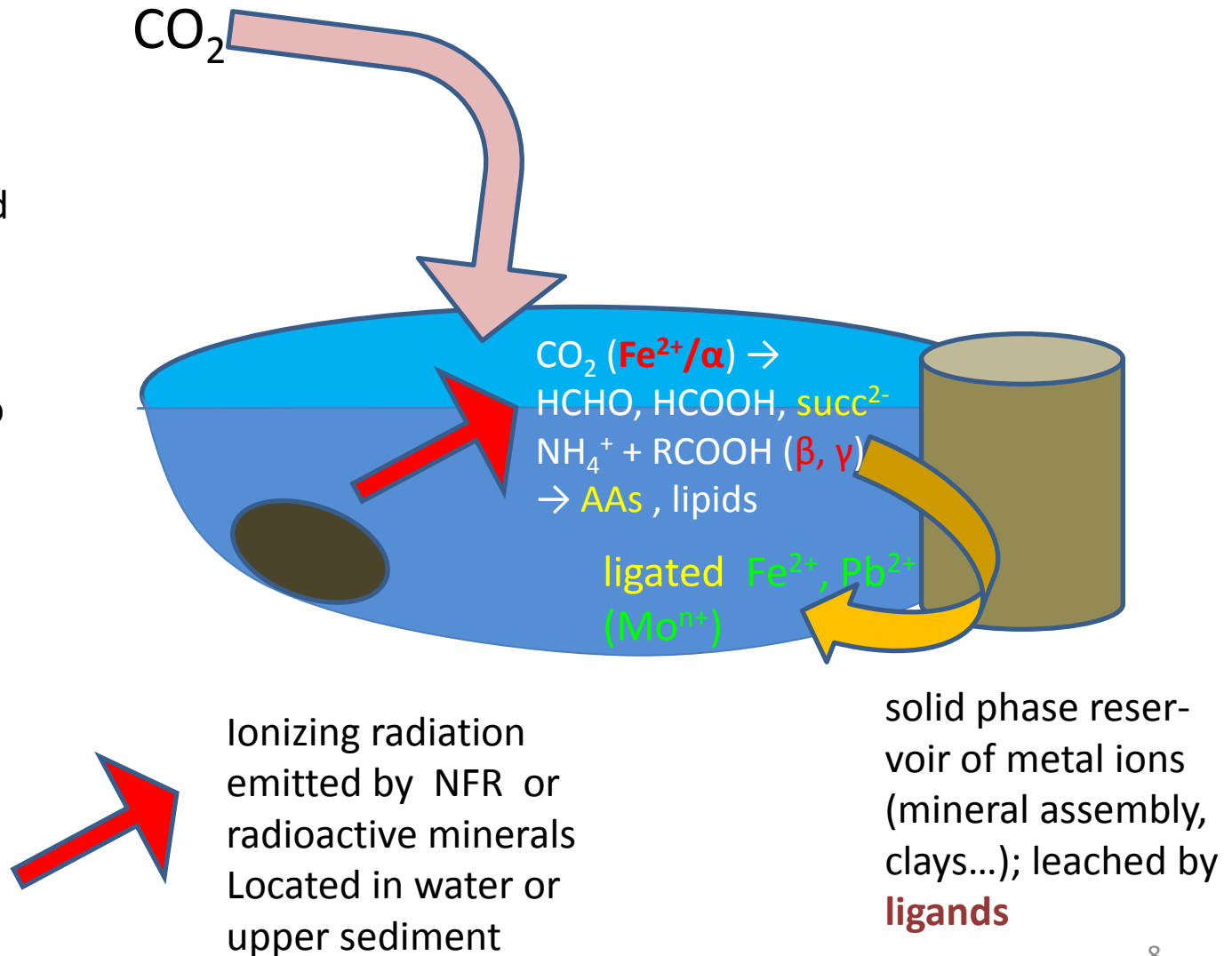
Partition between sediment/NFR and aqueous overlayer by complexation: a blueprint for...?

Once sediment was produced involving biota, it contains lots of lipids and other esters

→ pronounced affinity towards UO_2^{2+} while other ions, including fission products get readily leached into water phase above, there causing radiation-chemical transformations

Principles of radiation-chemical ligand, „food“ production

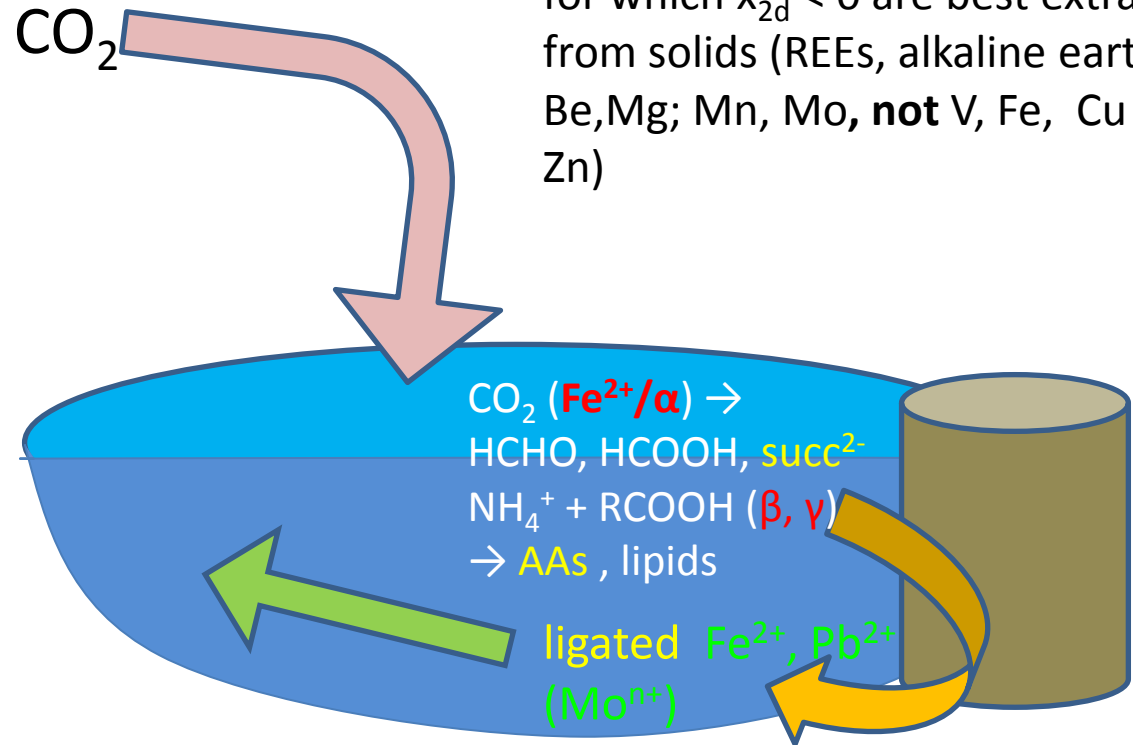
Ionizing radiation does process CO_2 and N_2 , then CN^- , ligands produced mobilize electron source Fe^{2+} and catalysts like Mo salts, Pb^{2+} as complexes



General features of radiation-chemical autocatalysis

Autocatalysis means an active species is multiplied by the very chemical or nuclear process (n in reactors!), with materials taken from some reservoir

catalyze transformations of HCHO, CH₂=N(OH), possibly N₂, CO
Then more ligands increase metal ion leaching unless being eaten by some biota



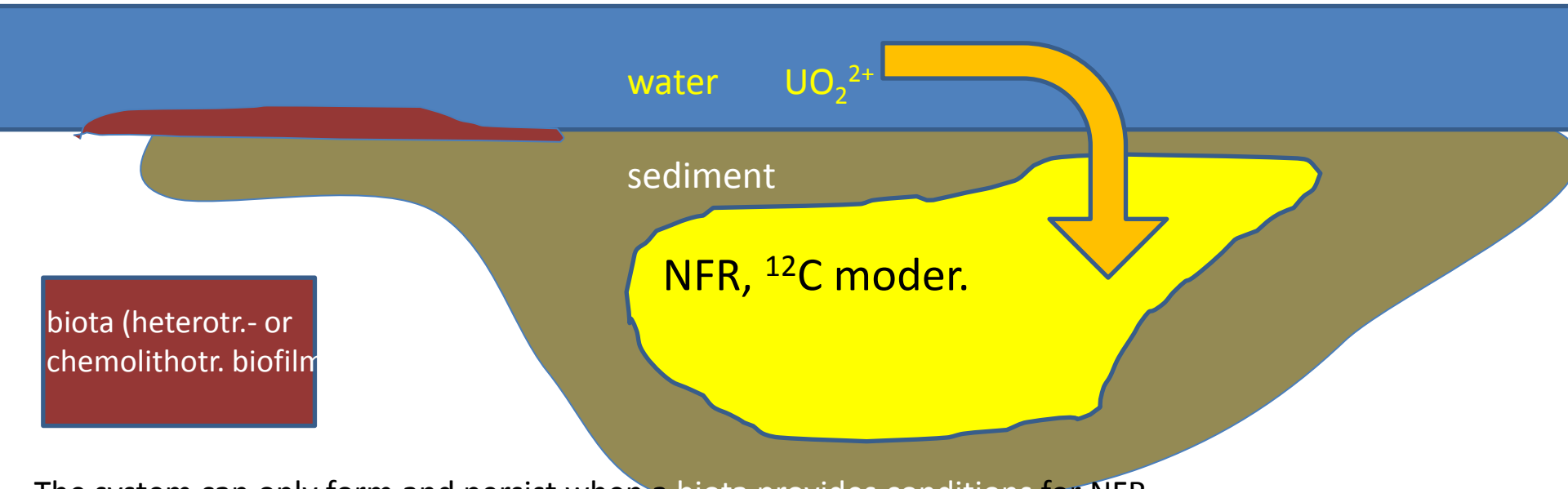
Desamination prevails over N inclusion, whereas HCHO, formate, glyoxalate etc. are readily formed from CO₂ by radiation → elements for which $x_{2d} < 0$ are best extracted from solids (REEs, alkaline earths ≠ Be, Mg; Mn, Mo, **not** V, Fe, Cu or Zn)

Alteration of inorganic species by radiation, change of element extraction (patterns) after onset of NFR activity

Radiation-induced organic chemistry in water layer, air affords organics most of which act as ligands, extracting some metals including fission products to the water layer, causing secondary radiation chemistry

Feedback interaction between some primitive biota and a NFR enabled by it

Distance NFR ↔ biofilm protects the latter from overly radiation while chemical entities can diffuse

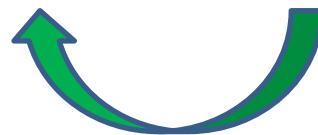


The system can only form and persist when a biota provides conditions for NFR formation without being destroyed by local ionizing radiation (distance for shielding vs. mutual exchange of organics, ions):

$CO, CO_2, (N_2) \rightarrow$ organics \rightarrow feeding biota, leaching metal ions,



fission products



\rightarrow biomass growth \rightarrow lipid accum. in sediment \rightarrow accum. of uranium there \rightarrow support of NFR \rightarrow pos. feedback \rightarrow moderation by organics, neg. feedback by organics eaten

fission-derived decay chains vs. AC feedback in radiation-chemical catalytic chemistry

- Mo through Pd produce hydrolytically stable complex anions; Kr, Xe, Zr, Nb do not
- Radiation chemistry of some intermediate does produce certain ligands, enhancement and autocatalysis **occur if**

- ligands mobilize stable isotopes of same element (not prolific/impossible for Tc, PGMs, Ag but effective for Mo, Ce) and
- some ligand-forming reaction is catalyzed by the very element (e.g. Mo)

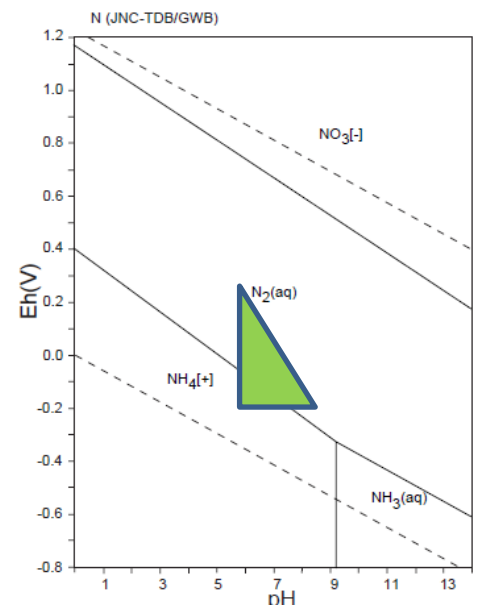
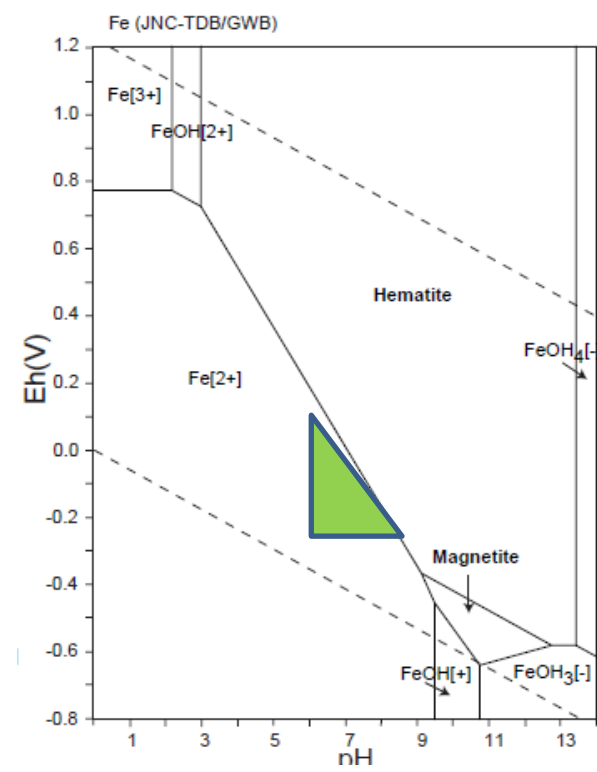
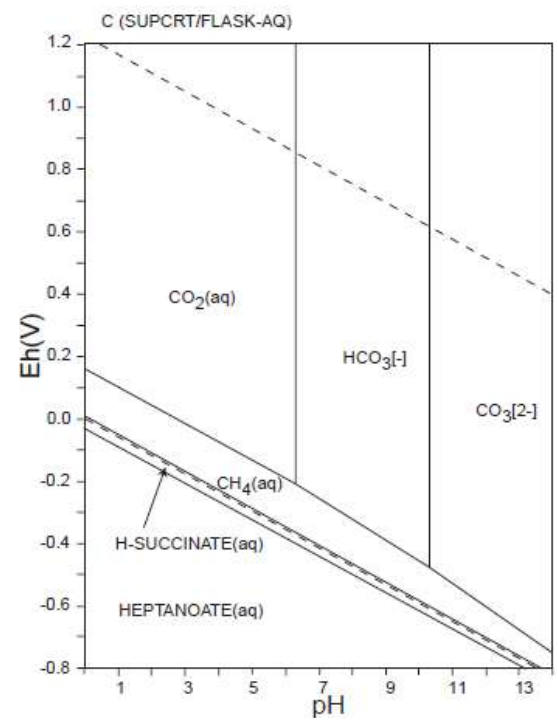
→ production of nutrients then available to biota even rather far from radiation source (NFR)

Fission product elements effective in this respect, their substrates and pertinent products

Ru95 1.643 h β ⁻	Ru96 β ⁻	Ru97 3.74 d β ⁻	Ru98 β ⁻	Ru99 β ⁻	Ru100 β ⁻	Ru101 β ⁻	Ru102 β ⁻	Ru103 39.28 d β ⁻	Ru104 β ⁻	Ru105 4.41 h β ⁻	Ru106 373.59 d β ⁻
Tc94 382 s β ⁻	Tc95 201 h β ⁻	Tc96 4.23 d β ⁻	Tc97 4.21e+3 y β ⁻	Tc98 4.12e+4 y β ⁻	Tc99 2.111e+5 y β ⁻	Tc100 162 s β ⁻	Tc101 1422 ms (β ⁻) ⁺	Tc102 6.29 s β ⁻	Tc103 94.2 s β ⁻	Tc104 16.1 ms (β ⁻) ⁺	Tc105 74 ms (β ⁻) ⁺
Mo93 4.48e+12 y β ⁻	Mo94 β ⁻	Mo95 β ⁻	Mo96 β ⁻	Mo97 β ⁻	Mo98 β ⁻	Mo99 6.64 s β ⁻	Mo100 1.22e+7 y β ⁻	Mo101 34.48 ms β ⁻	Mo102 13.2 s β ⁻	Mo103 47.5 s (β ⁻) ⁺	Mo104 60 s β ⁻
Nb92 1.47e+7 y (β ⁻) ⁺	Nb93 β ⁻	Nb94 1.47e+7 y β ⁻	Nb95 34.779 d β ⁻	Nb96 32.35 s β ⁻	Nb97 71.7 ms β ⁻	Nb99 2.96 s β ⁻	Nb100 10.5 s β ⁻	Nb101 1.8 s β ⁻	Nb102 7.2 s β ⁻	Nb103 1.4 s β ⁻	Nb104 1.4 s (β ⁻) ⁺
Zr91 β ⁻	Zr92 β ⁻	Zr93 1.52e+6 y β ⁻	Zr94 β ⁻	Zr95 64.02 d β ⁻	Zr96 1.62e+7 y β ⁻	Zr97 16.71 h β ⁻	Zr98 88.7 s β ⁻	Zr99 7.1 s (β ⁻) ⁺	Zr100 7.7 s β ⁻	Zr101 2.1 s (β ⁻) ⁺	Zr102 2.8 s β ⁻
Y90 64.1 h β ⁻	Y91 84.61 d β ⁻	Y92 3.24 s β ⁻	Y93 16.25 h β ⁻	Y94 32.7 ms β ⁻	Y95 34.2 ms β ⁻	Y96 1.36 s β ⁻	Y97 1.78 s (β ⁻) ⁺	Y98 4.98 s β ⁻	Y99 470 ms (β ⁻) ⁺	Y100 78 ms β ⁻	Y101 448 ms (β ⁻) ⁺
Sr89 50.51 d β ⁻	Sr90 28.78 y β ⁻	Sr91 5.88 s β ⁻	Sr92 2.71 s β ⁻	Sr93 7.03 ms β ⁻	Sr94 78.3 s β ⁻	Sr95 23.9 s β ⁻	Sr96 1.57 s β ⁻	Sr97 424 ms β ⁻	Sr98 2.463 s β ⁻	Sr99 1.269 s β ⁻	Sr100 302 ms β ⁻
Rb88 17.78 ms β ⁻	Rb89 13.17 ms β ⁻	Rb90 1.8 s β ⁻	Rb91 68.4 s β ⁻	Rb92 4.493 s β ⁻	Rb93 4.84 s β ⁻	Rb94 2.702 s β ⁻	Rb95 377.5 ms β ⁻	Rb96 6.29 s β ⁻	Rb97 186.9 ms (β ⁻) ⁺	Rb98 114 ms (β ⁻) ⁺	Rb99 86.3 ms (β ⁻) ⁺
Kr97 76.3 ms β ⁻	Kr98 3.24 s β ⁻	Kr99 3.14 ms (β ⁻) ⁺	Kr98 32.32 s β ⁻	Kr91 8.37 s (β ⁻) ⁺	Kr92 1.84 s β ⁻	Kr93 7.38 s (β ⁻) ⁺	Kr94 6.23 s β ⁻	Kr95 8.78 s β ⁻	Kr96 β ⁻	Kr97 β ⁻	62

Is there an ($\epsilon + \Delta\epsilon$) interval at near neutral pH which permits all components to co-exist?

- Fe(II) required (not trivalent Fe!), Pb(II) must be stable
- N as NH_4^+ rather than oxidized, N_2
- ϵ close to or above $\text{CH}_4/\text{CO}_2^-$ or $\text{CH}_4/\text{HCO}_3^-$ -limits
- Which is the (redox) state of Mo then?
- Potential and pH range
- Possible precursor minerals; do they exist in Archaean sediments?

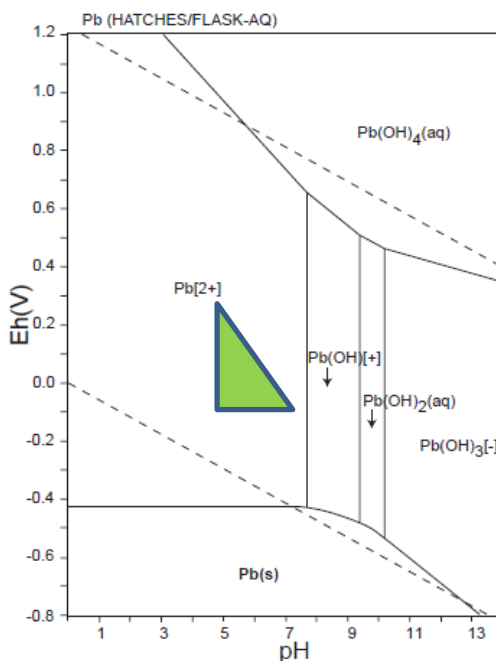
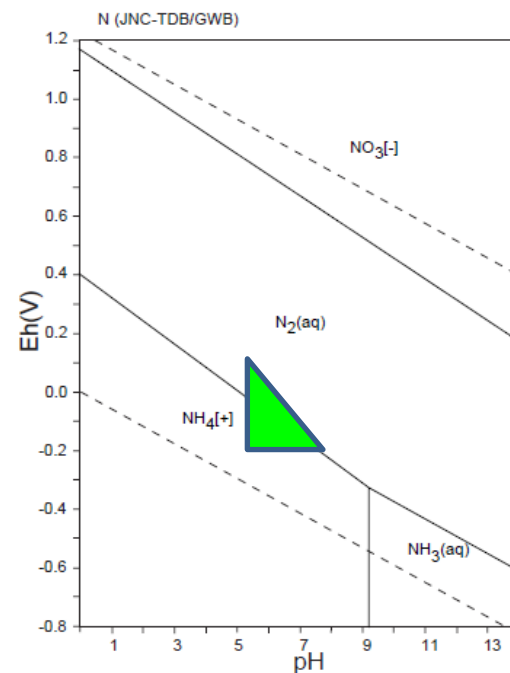


Pourbaix diagrams of C (top left), Fe (top) and N (left): appropriate co-existence in slightly acidic medium at $\epsilon \leq +0.1 \dots -0.25 \text{ V}$

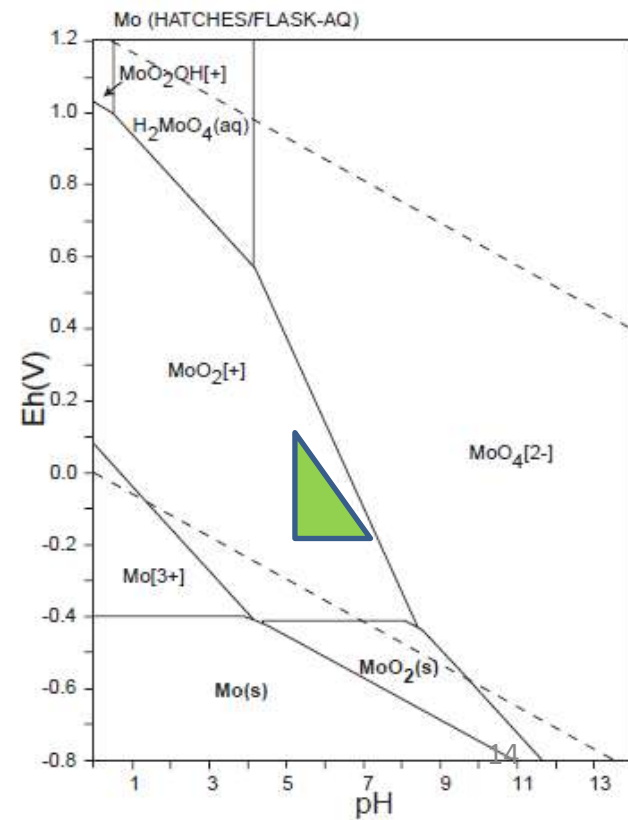
States of Ba, Pb, Mo determine fate of HCHO, yields of amino acids

- Carbonate, sulfate levels, available Ba, Pb and catalysis of formose reaction (contribution by clays?)
- Radiolysis of cyanide (\rightarrow glycine, urea, some polymers) vs. its oxidation

states of Pb, Mo (right)

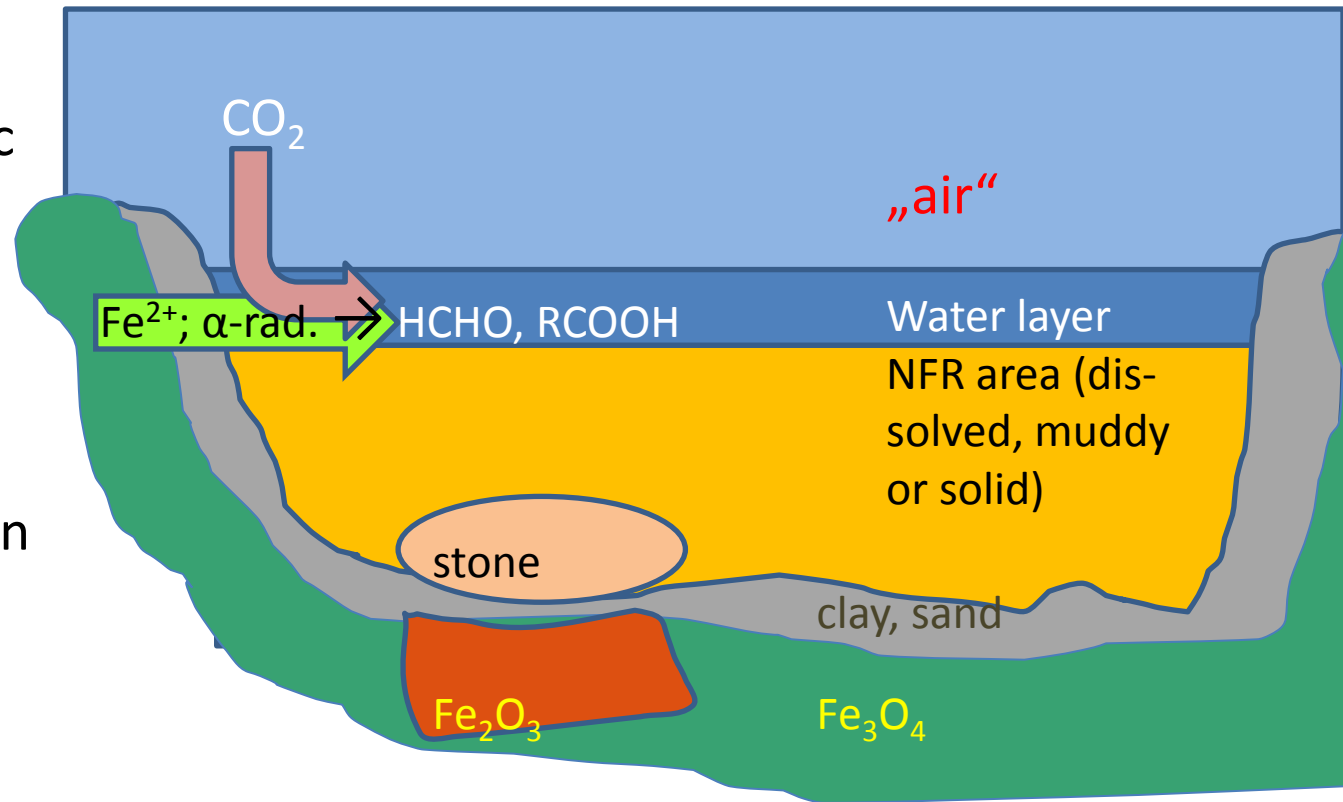


Pb^{2+} , Ba^{2+} are fully stable but anion-sensitive (precip.) while Mo forms MoO_2^+ (prone to disproportionation) but not Mo^{3+} (the latter might reduce both N_2 and oximes)



NFR with partial shielding of surrounding SC minerals

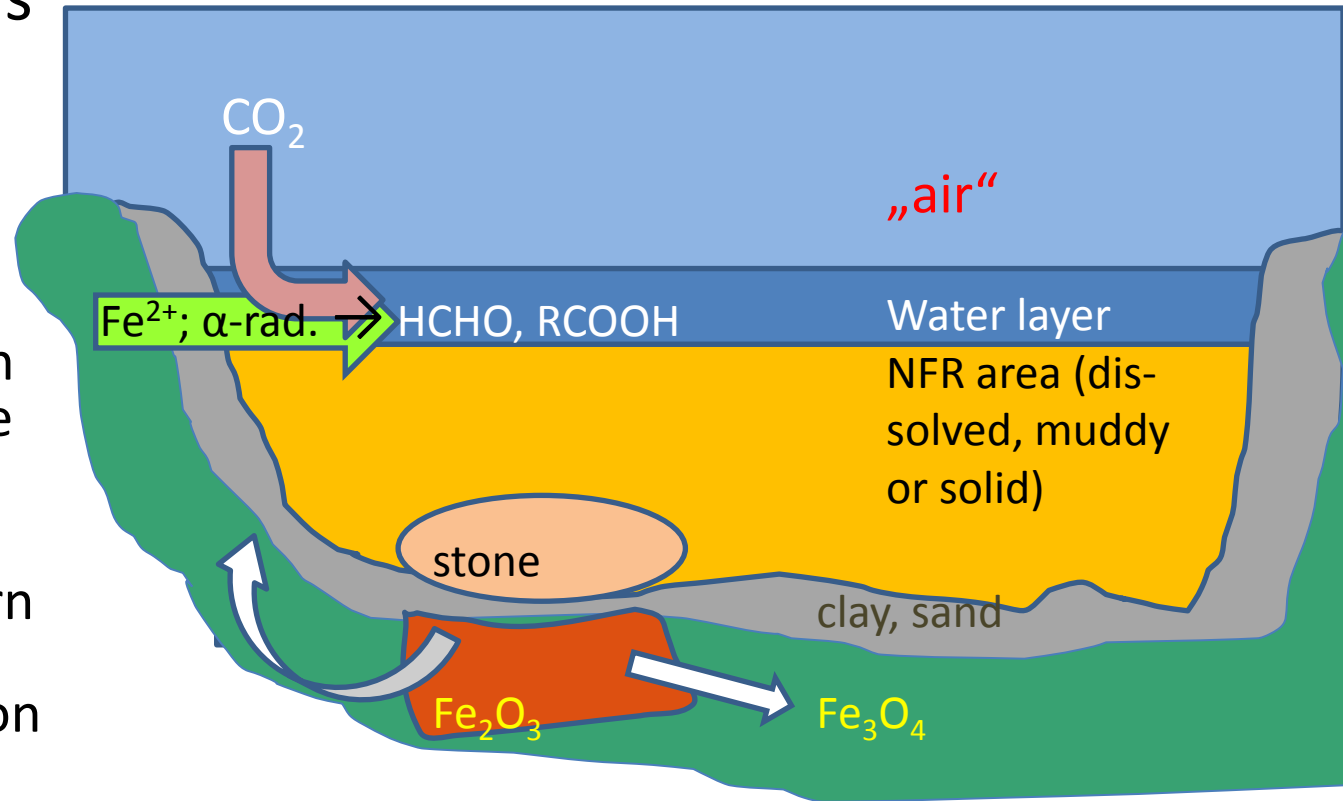
- Uranyl(VI) in lipophilic sediment layer; reoxidation near irradiated oxides → constrains external potential though CO_2 (besides CO) can contribute to radiation syntheses of substrates, ligands, nutrients
- G values for glycine etc. formation
- radiation-chemical processing of cyanide vs. stability of glycinato-, succinato complexes of various metals



HCHO produced from CO_2 would also react with cyanide, eventually both producing glycolate and catalyzing HCN transformations

radiation-chemical potential shift and –shielding spatially organize e flow pathways

- ϵ does **increase** (few exceptions) when exposed to ionizing radiation regardless whether oxide film on metal is a p- or n-type semiconductor;
- hydrogen-activating metals (Pt, Ni, Ru) turn into hydrogen electrodes upon irradiation → electrons will flow from radiation-shielded to –exposed regions in mixed-valence (one- or two-phase) systems, with clay, sand getting conductive in radiation



White arrows: direction of redox/radiation-induced electron flows, eventually releasing Fe²⁺ to water

Energy yields, G values during NFR formation and operation

Educt(s)	product	Kind of ionizing radiation	G value [mol-ec./100 ev]
CO ₂ , Fe ²⁺	HCOOH	α (40 MeV)	
	succinic acid		
CN ⁻ _{aq}	Glycine	β (⁶⁰ Co)	
	Urea		
CO + N ₂ , water vapor	glycine	electron beam (1 MeV)	
	alanine		
Reducing mixture (alkanes, NH ₄ ⁺)	glycine		
Alkanes, CO ₂ , moisture	Fatty acids		
glycine	HCO-COOH, aspartic and diamino succinic acids	α, ⁷ Li (about 1.5 MeV)	

operation

Conversion of „excess“ neutrons into ionizing (and causing radiation chemistry) entities:

- Fission, plus
 - β decay of fission products
 - (n, p)- or (n, α) reactions of ⁶Li, ¹⁰B, ³⁵Cl
- If a radiation-chemistry product does extract metal ions efficiently from NFR „core“, G must be > 10⁻⁴

Radiation-chemical feedback by selective extraction of certain fission products besides of U(IV, VI)

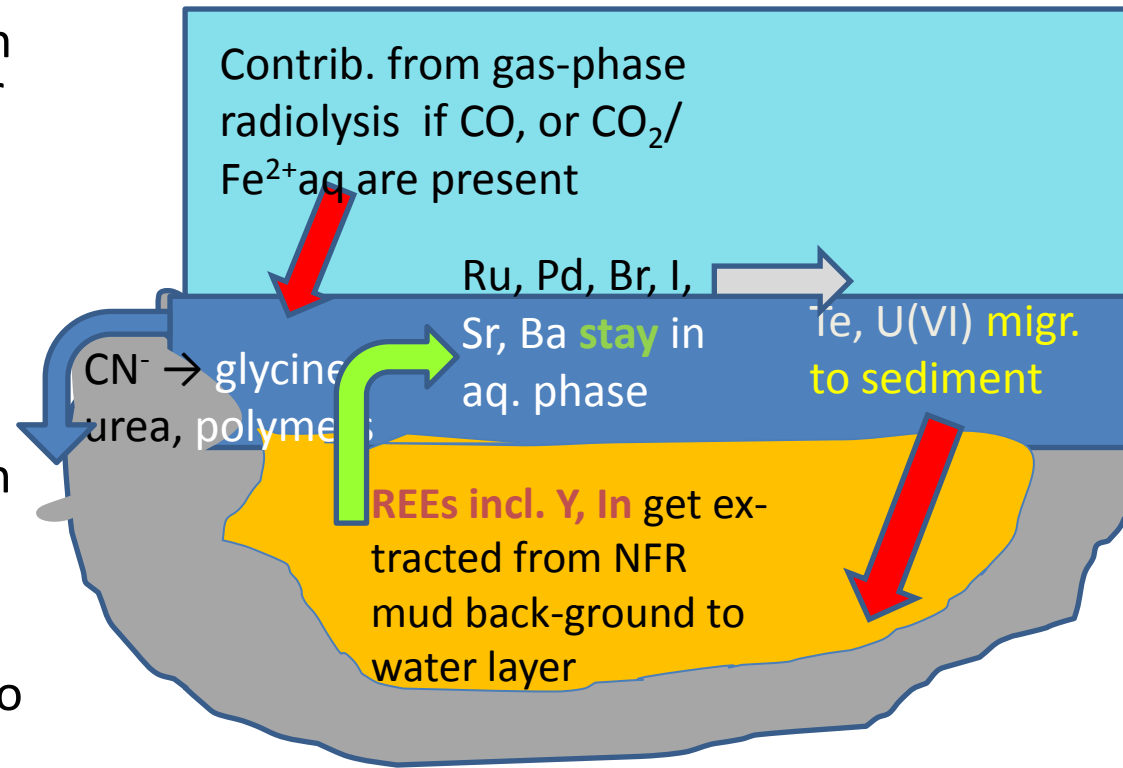
- $\text{CN}^- \rightarrow$ glycine, urea, polymers
- Moist $\text{CO} + \text{N}_2 \rightarrow$ amino acids
- CO_2 α , $\text{Fe}^{2+} \rightarrow$ HCOOH, HCHO, acetic, glycolic, malonic, and succinic acids
- Glycinate does form stable complexes with many metal ions which do not make stable cyano- or oxalato complexes \rightarrow extraction, upwelling \rightarrow fission products contribute to radiation chemistry near water/air interface, besides of halide ions ($^{82-85}\text{Br}$, ^{131}I ...)

Which elements will behave like this (minutes to days after precursors were produced by fission)? -

Mass range for ^{235}U fission 82 – 106 and 128 – 152 – but only some fulfil chemical, radiation- and half-life criteria

The entire system: NFRs obtaining U from surroundings, fission products retained in aqueous phase

- Water over sludge; radiation can penetrate partly into air if water overlayer is sufficiently thin
- Partition changes along decay series and during prolonged irradiation of compounds in aqueous layer, fatty sediments, and air
- No secondary thermal alteration of glycine (stability conditions) but radiolysis
- Reoxidized (e.g. by contact with irradiated Fe oxides) U returns to lipid/ester-containing sediment, increasing NFR efficiency and lifetime
- Radioactive decay series mean isobars will deliver radiation energy to different layers/phases and thus irradiate different comp.



NFRs would leave behind tell-tale isotopic pattern shifts in certain elements

- Isotope patterns from fission are highly dissimilar of common ones (Ru, Nd at Oklo!)
- Even-Z or odd-Z – where to look for the effects?
- Even Z: largest scatter of terrestrial, meteorite isotopic abundances associated with fissiogenic isotopes, such as $^{99};^{101};^{102};^{104}\text{Ru}$ vs. the other (lightest stable and ^{100}Ru) ones

Isotopic shielding in $m = 113$ is reduced by population of isomeric nuclear states \rightarrow compos. (variations) of indium can be used for detection!

Sn112 0+ 0.97	Sn113 115.09 d 1/2+ EC *	Sn114 0+ 0.65	Sn115 1/2+ 0.34	Sn116 0+ 14.53	Sn117 1/2+ 7.68 *	Sn118 0+ 24.23	Sn119 1/2+ 8.59 *
In111 2.8047 d 9/2+ EC *	In112 14.97 m 1+ EC, β^- *	In113 9/2+ 4.3 *	In114 71.9 s 1+ EC, β^- *	In115 4.41E+14 y 9/2+ β^- *	In116 14.10 s 1+ EC, β^- *	In117 43.2 m 9/2+ β^- *	In118 5.0 s 1+ β^- *
Cd110 0+ 12.49	Cd111 1/2+ 12.80 *	Cd112 0+ 24.13	Cd113 5.1E+15 y 1/2+ β^- *	Cd114 0+ 28.73	Cd115 53.46 h 1/2+ β^- *	Cd116 0+ 7.49	Cd117 2.49 h 1/2+ β^- *
Ag109 1/2- 48.161 *	Ag110 24.6 s 1+ EC, β^- *	Ag111 7.45 d 1/2- β^- *	Ag112 3.130 h 2(-) β^- *	Ag113 537 h 1/2- β^- *	Ag114 4.6 s 1+ β^- *	Ag115 10.0 m 1/2- β^- *	Ag116 2.68 m (2)- β^- *
Pd108 0+ 26.46	Pd109 13.7012 h 5/2+ β^- *	Pd110 0+ 11.72	Pd111 23.4 m 5/2+ β^- *	Pd112 21.03 h 0+ β^- *	Pd113 93 s (-2)+ β^- *	Pd114 2.42 m 0+ β^- *	Pd115 25 s (5/2+) β^- *
Rh107 21.7 m 7/2+ β^-	Rh108 6.0 m (5+) β^- *	Rh109 80 s 7/2+ β^-	Rh110 3.2 s 1+ β^-	Rh111 11 s (7/2+) β^-	Rh112 2.1 s 1+ β^- *	Rh113 2.80 s β^-	Rh114 1.85 s 1+ β^-

Isotopic scatter evidence; even-Z elements Ru, Xe,

Sb, Ag

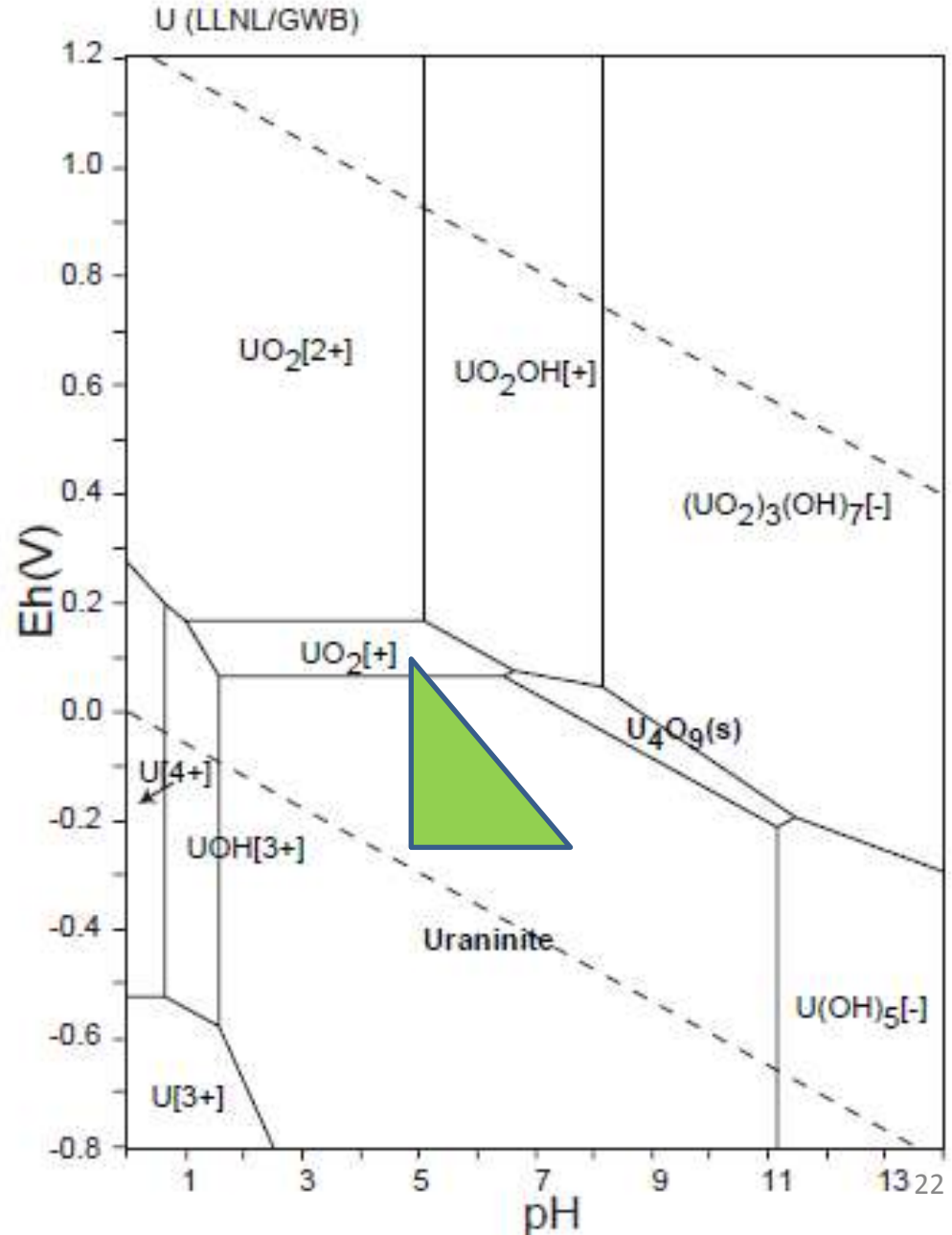
- Odd-Z elements have two stable isotopes at best
- Mattauch's rules preclude isobaric shielding in odd-M fission product decay series, unlike fission yields then cause isotopic shifts vs. „common“ or „standard“ distributions provided $[m_1/m_2] \neq [y_{m1}/y_{m2}]$
- „suitable“ elements: Rb, Ag, In, (Sb), Eu
- Data avail. for Ag, Sb

element	Masses of „stable“ isotopes	Abundance ratio	Fission yield ratio	remarks
Rb	85; (87)	2.593	0.515	Correction for decay of ^{87}Rb
Ag	107; 109	1.076	4.454 (total yields small)	
In	113; (115)	0.0449	1.434 (total yields very small)	36% isobaric shielding by ^{113}Cd , no loss by decay of ^{115}In
Sb	121; 123	1.342	0.816 (total yields very small)	
Eu	(151 [α]); 153	0.916	2.590	no loss by α decay of ^{151}Eu ; ^{151}Sm , ^{151}Eu n capture cross-sections ²¹

But NFRs could **not** contribute to chemical, pre-biotic evolution!

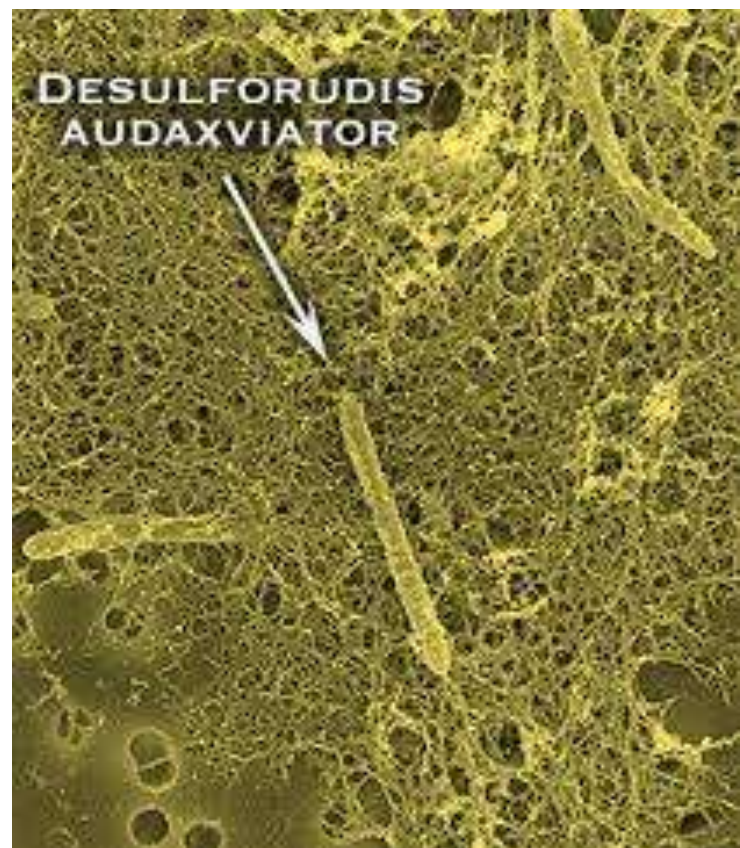
- Uranyl accumulation takes lipid-enriched sediments, and reduced forms of U can only form in appropriate potentials or from U(IV), organic coillumination (photochemistry)
- More heavy xenon (i.e., ^{134}Xe ; ^{136}Xe , possibly fissiogenic) in sediments << 3.0 bio. years old, unlike 3.5 Ga North Pole (W Australia)

Stability region of U in pre-Oklo NFR conditions allows U to stay in its place while local oxidant availability is required to transport to NFR site



No role of NFRs in biogenesis – but might someone feed on the products?

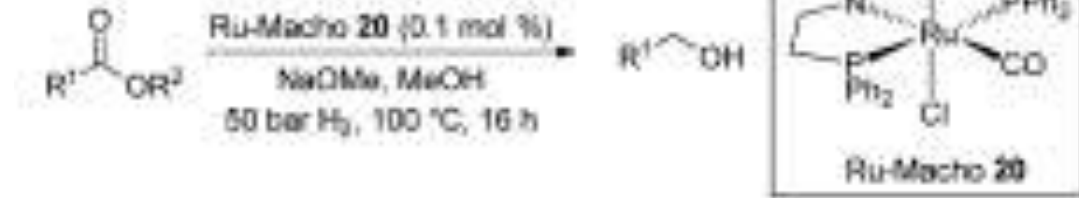
- Productivity, G values of radiation-chemical and/or catalytic transformations
- Carboxylic acids are readily formed in radiation chemistry whereas G for amino acid production is very small while β , α , ^7Li nuclei (from $^{10}\text{B} + n$) cause efficient desamination (directly, not via H_2O_2) \rightarrow any organism which exploits this C^{red} ; (indirectly, by leaching) $\text{M}^{\text{essent.}}$ source must tap another N source, e.g. radiogenic nitrate or NO from lightnings
- M supply from leachable sediment, minerals is reduced by consuming ligands by some biota \rightarrow causes P limitation also, works best if $x_{2d} < 0$ (essent. metals: Mn, Mo)
- *Desulforudis audaxviator*
- A role for radiation chemistry in early nitrogen assimilation, besides making and transforming HCN, amino acids?
- Nitrogenases don't like free oxygen while [C/N] becomes smaller in aerobic organisms
- *D. audaxviator* also can use N_2 !



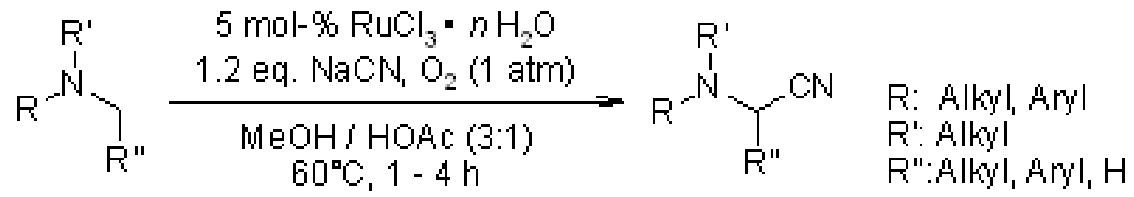
D. audaxviator depends on radiogenic H_2 for sulfate reduction, ATP synthesis while fixing C from CO_2 , carbonate)

Ru as a key fission product and its bio-related chemistry

- $\text{RCN} \leftrightarrow \text{RCH}_2\text{NH}_2 \leftrightarrow \text{RCO-NH}_2$, including aminonitriles, hydantoin formation, $(\text{CN})_2$ into AAN
- Ru complexes attack esters, lactones by hydrogenation but not amides/peptides
- Ru is enriched in laurite $(\text{Ru}; \text{Os})\text{S}_2$, erlichmanite $(\text{Os}; \text{Ru})\text{S}_2$, ruarsite $(\text{Ru}; \text{Fe})\text{AsS}$ particles (laurite pretty much distributed over Earth crust)
- **Cytostatic agent**; Ru(III/II) nucleobase complexes are photoactive
- Fission yields of $^{99};^{101};^{102};^{104}\text{Ru}$
- Ru may do an excellent (hydrogenation or oxidation catalysis) job to bacteria, archaea next to some laurite... particle/crystal (provided ester hydrogenolysis is avoided) – but will a few cm^3 with distinguished chemical properties/Ru accessibility do to support an „exotic“ stem of bacteria?
- (per)halogenates may be replaced with MnO_2 for oxygen transfer
- Ru in chemical evolution (Rasmussen)?



NP_2 replaced with oligopeptide, CO from atmosphere or HCOOH



NH_3 , amines
(red; radiation chemistry of HCs + N_2)



Amino acids, peptides

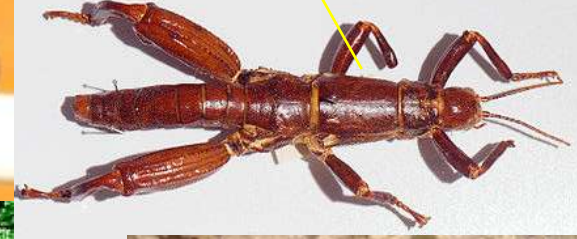
Formation of reduced Rh (Ru, Pd) complexes if amino acids, CO available \rightarrow M insertion into H-OCOR bonds \rightarrow formation of hydrogenation catalyts \rightarrow cleavage of esters

Species of vertebrates, large insects which did survive although restricted to few m² total area for long periods of time

- Fishes, frogs, toads, chameleons
 - „Tree lobster“
- when some m²/m³ will do in sustaining entire species of animals of 3 – 10 cm size (20 – 200 individuals), bacteria can run on much less space/volume (probably ≤ 1 cm³)!
- look for Ru-dependent stems/enzymes around sites where there are laurite particles!!
- Role of Ru in prebiotic evolution?
 - Secondary replacement of Ru in enzymes by Fe, Co, Ni, Mo (nitrogenase)?
 - Steps of evolution (towards chemolithoautotrophy?) around early NFRs?



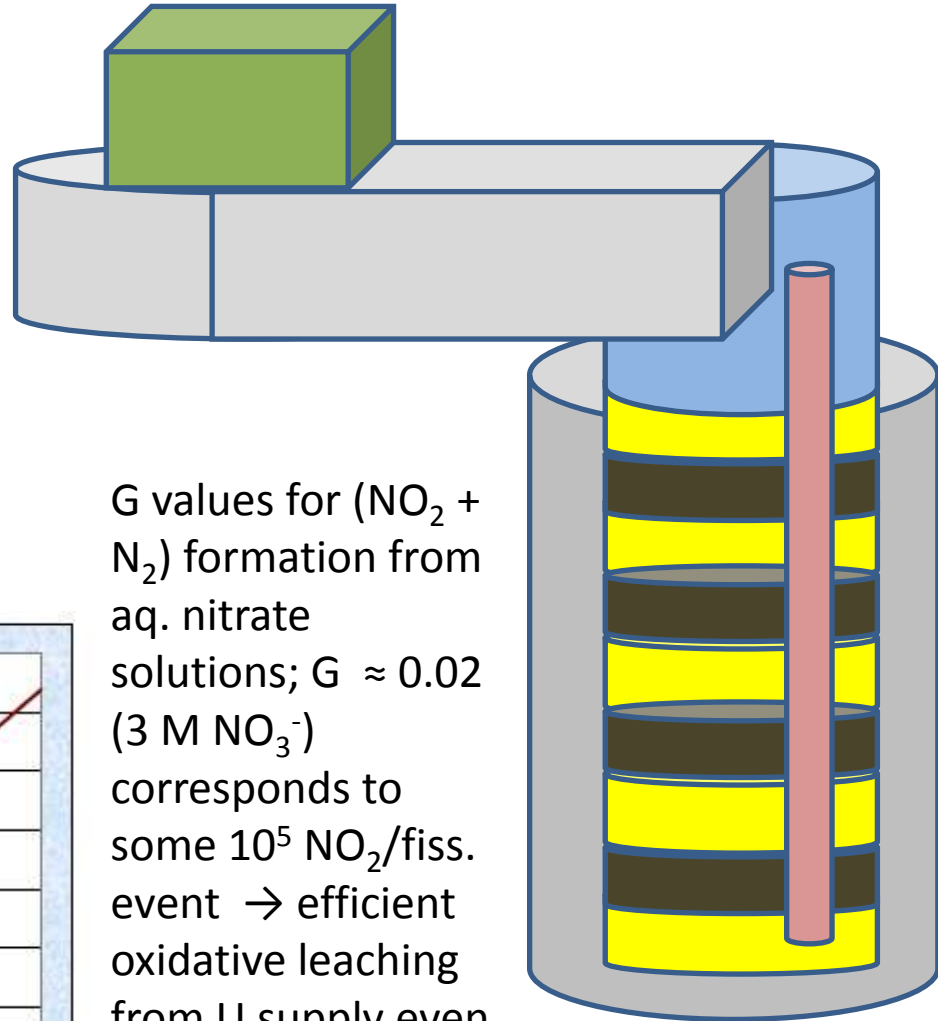
Tiny chameleon *Brookesia micra* living under a single tree at a creek on a small Madegassian island



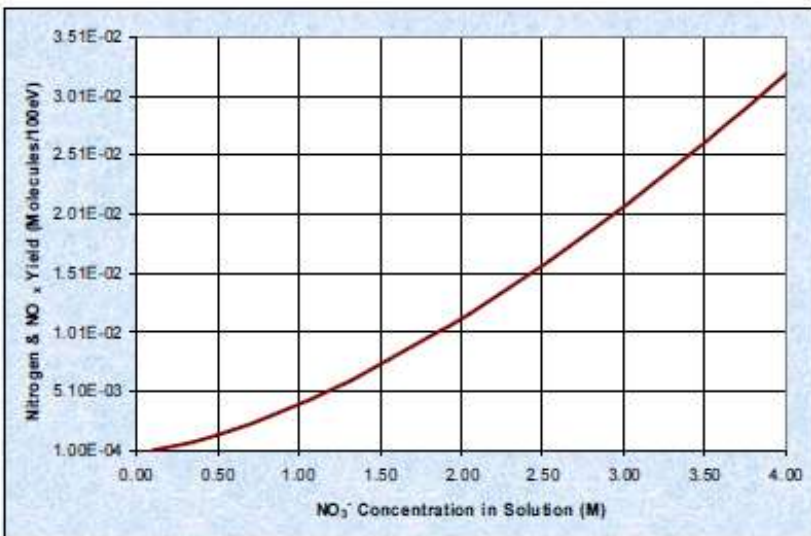
the **entire** habitat of desert pup-fish *Cyprinodon diabolis* – 5 by 1.8 m!

How to build a NFR-similar microreactor – and for what purpose(s)

- Reactors can start on **very much lower** intrinsic radioactivity levels than RTGs (25 kg $^{235}\text{U} \approx 2 \text{ GBq}$, α -emitters releasing some $5 \text{ kW}_{\text{therm}} \approx 6 \text{ PBq}$)
- Criticality is achieved only after secondary blue/violet/NUV irradiation on spot of operation
- Ester/formamide derivative partition, with DMF inducing photoreduction of uranium



G values for ($\text{NO}_2 + \text{N}_2$) formation from aq. nitrate solutions; $G \approx 0.02$ (3 M NO_3^-) corresponds to some $10^5 \text{ NO}_2/\text{fiss. event} \rightarrow$ efficient oxidative leaching from U supply even with dilute nitrate feed solutions

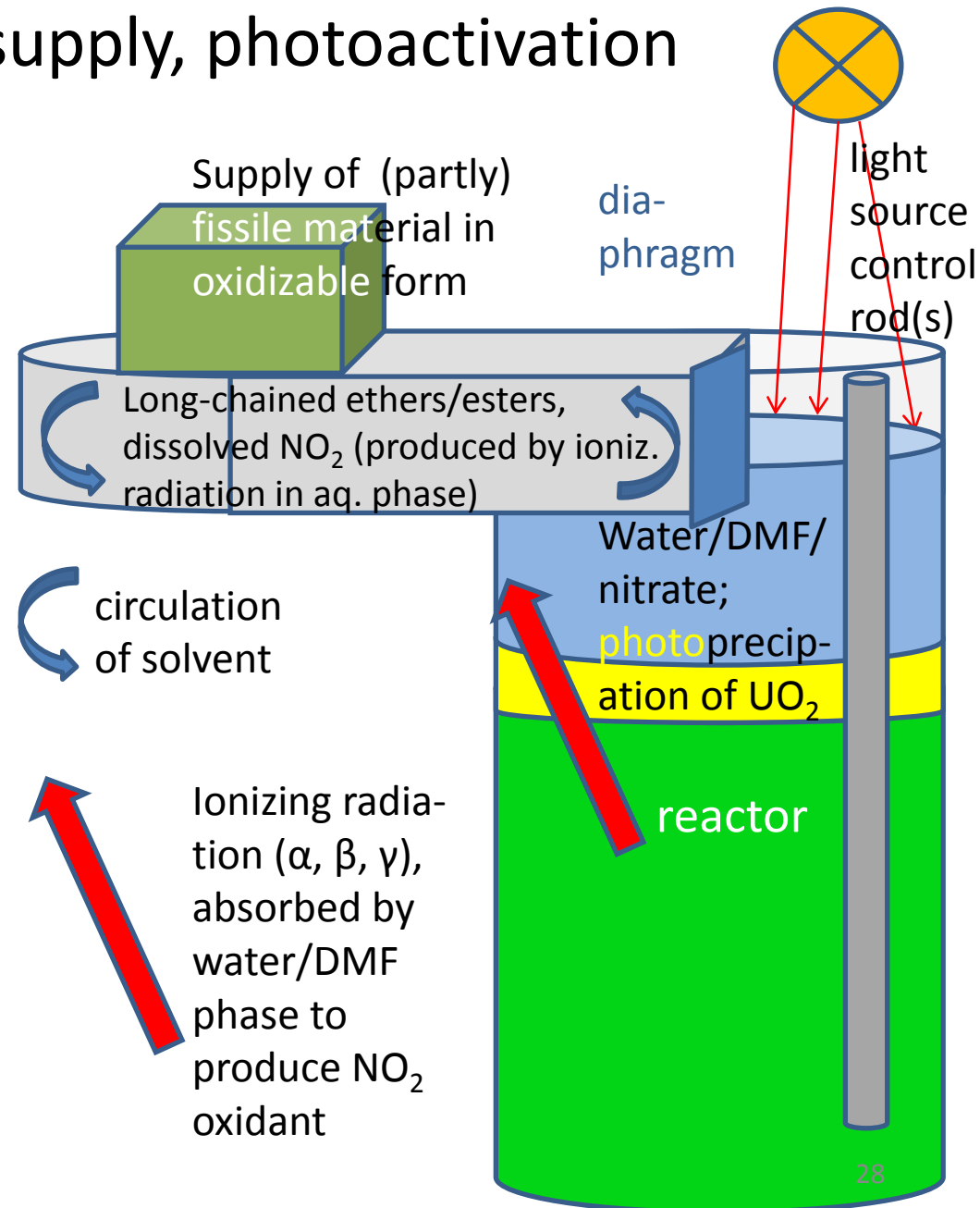


Design, properties of photoactivated NFR-inspired microreactors

- Combines U extraction and –photodeposition
- Subcritical when deployed, „missing“ U then located in remote parts of solution phase(s)
- Photochemical production of extraction agent
- Carbon moderation by high-boiling organic layer to „cap“ region where U is and gets deposited
- Avoiding criticality accidents prior to photochemical activation (in-solvent-moderation!) by e.g. Dy-(phosphate) glass or Ta-tubings for storage, photochemistry washes solid products to deposition
- Steam turbine run with (small part of) organic moderator
- Power output in kW range
- Needs less shielding than a RTG!

Radiation chemistry on top of a reactor and controlled self-supply, photoactivation

- radiation-chemical products oxidize UO_2 and mobilize, lipophilize uranium via UO_2^{2+} , then there is
- reprecipitation by photochemistry directly above reactor, providing controlled supply, „ignition“ of reactor
- ^{233}U (from thorium dioxide blanket) or fissile transuranium isotopes might be transported in a similar manner
- Access of **light** (sun or artificial) **activates reactor** to add fissile matter to compact volume including moderator slabs or –liquids (bright green, bottom right)





Conclusion: neutrons, Fe(II) and uranium and CO₂ make modest food for bacteria, sustaining some NFR system!

Thank you very much for your kind attention!