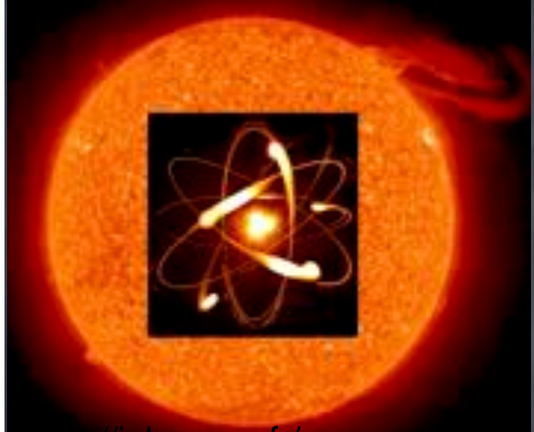


//iphc.cnrs.fr/

Physique pour tous

Briques & Fabriques nucléaires

Mardi 18 octobre 2022

 / 

Les chaudrons nucléaires

Dans quels lieux la nature fabrique des nouveaux éléments et/ou les transforme : nucléosynthèse primordiale, stellaire et explosive, radioactivité naturelle et tellurique et réacteurs naturels

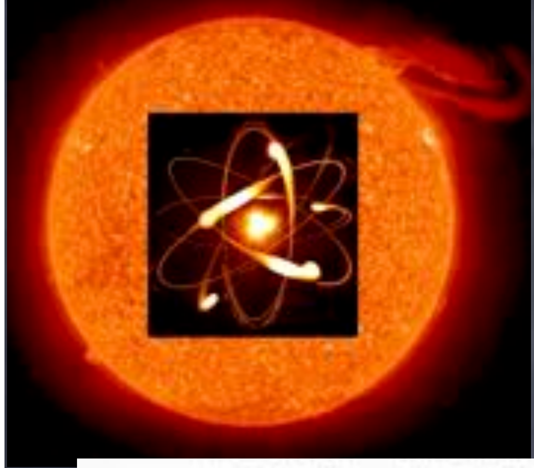
USIAS

Emma MONPRIBAT Benoît GALL

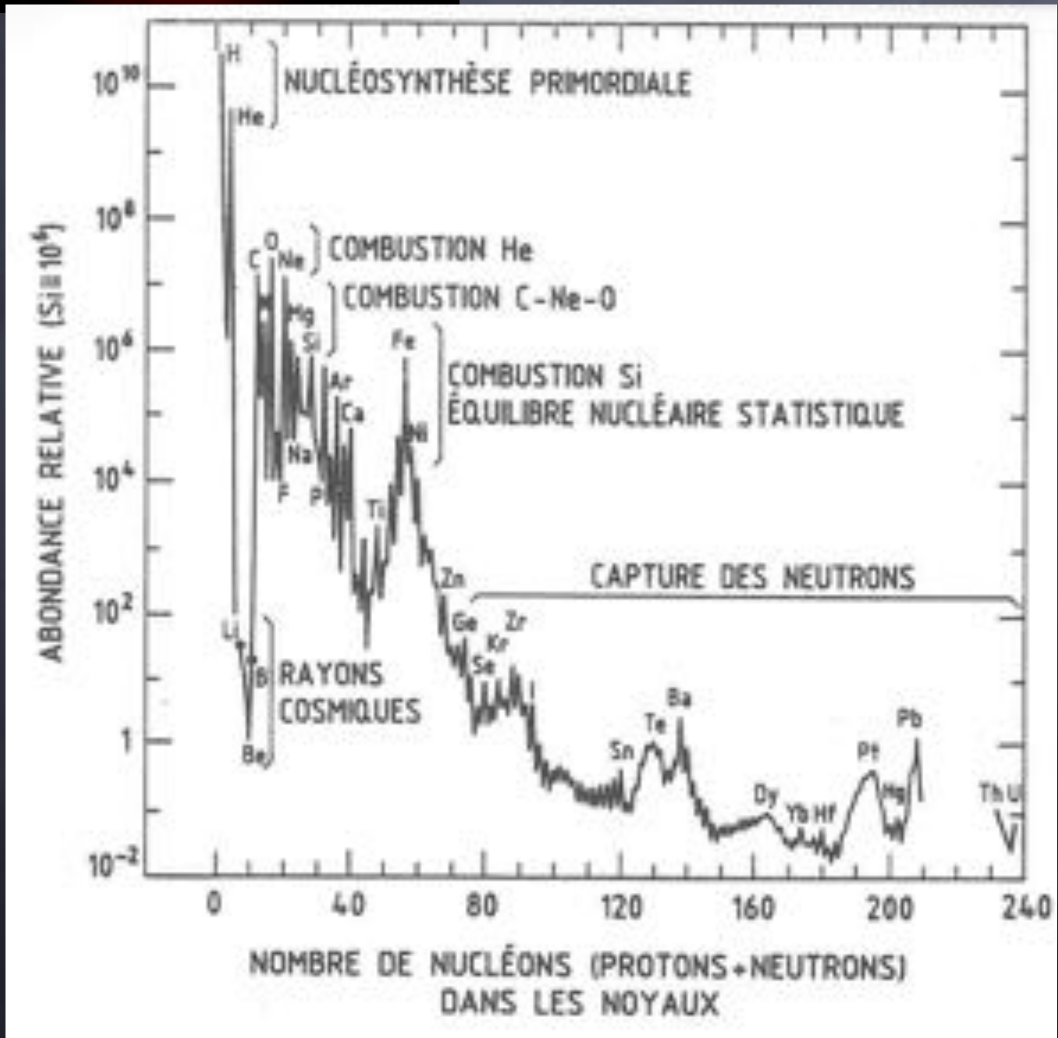
Faculté de Physique & Ingénierie

iPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

Université de Strasbourg



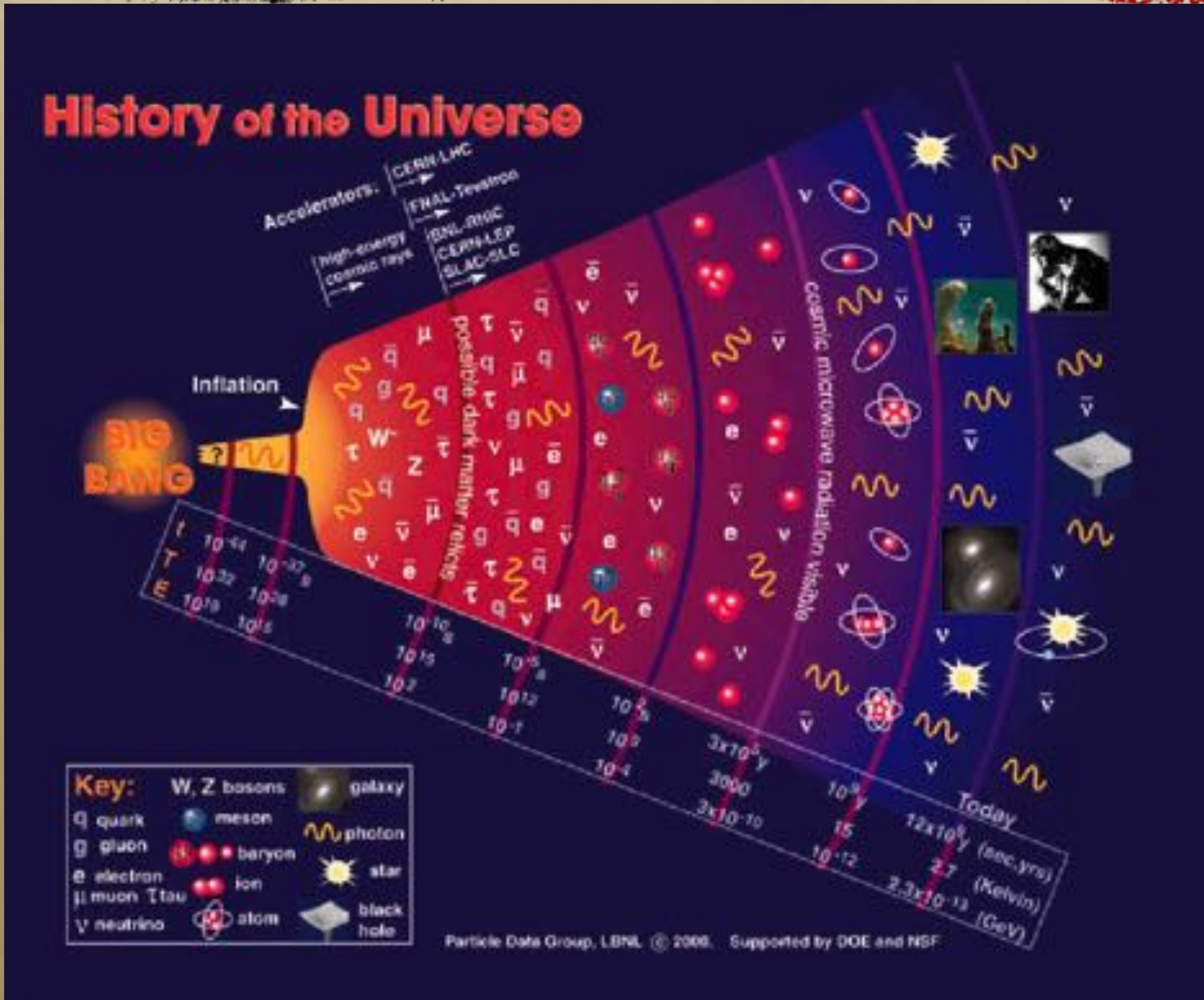
Les réacteurs naturels à fusion....



- Big-bang & Nucléosynthèse primordiale
- Nucléosynthèse stellaire
- Nucléosynthèse explosive

Au début il y avait …

le big bang ?

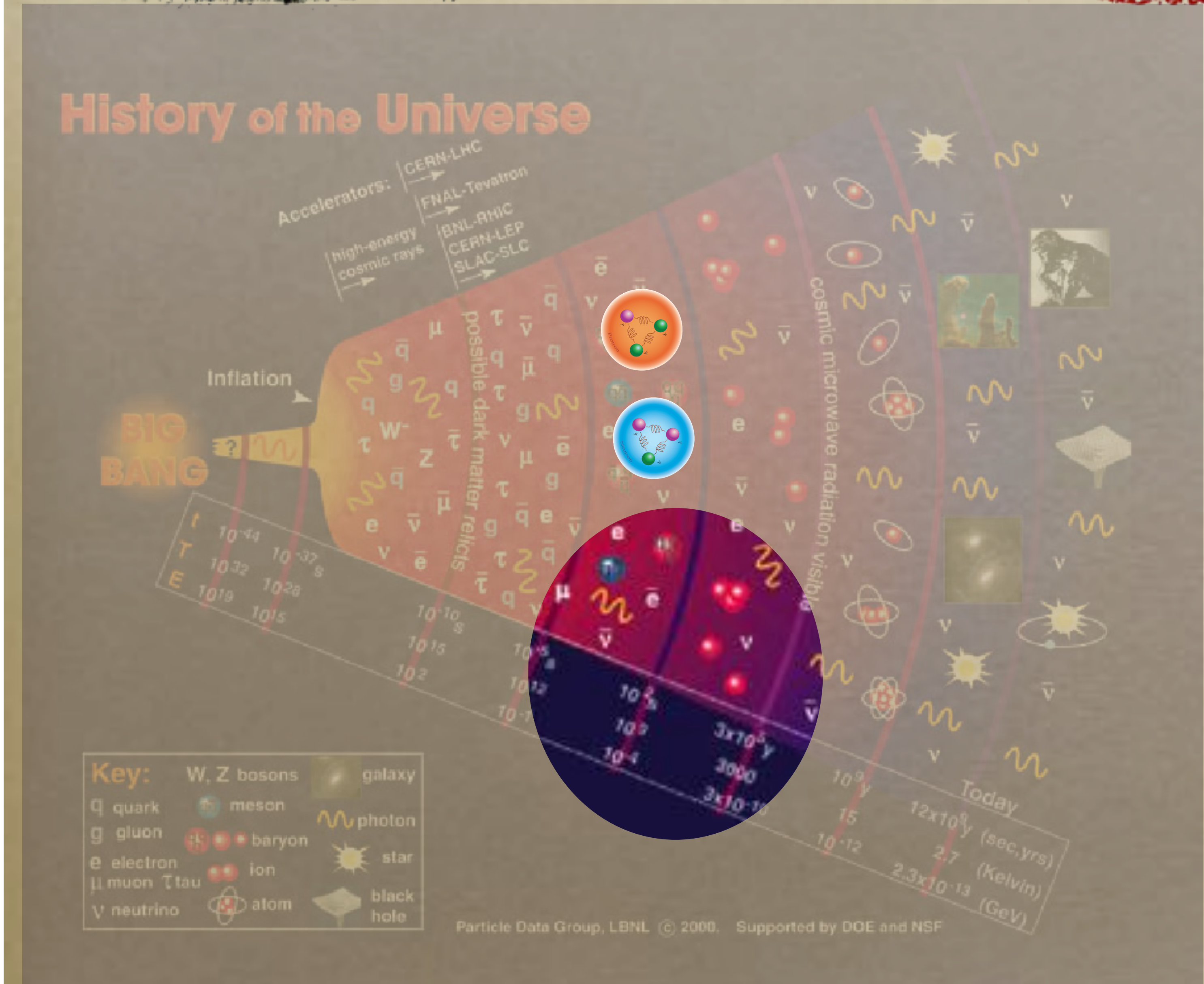


$E=mc^2$…
des particules aux protons & neutrons

Le Big-bang induit la nucléosynthèse

Au début il y avait …

le big bang ?



$E=mc^2$…
des particules aux protons & neutrons

Le Big-bang induit la nucléosynthèse primordiale

Nucléosynthèse primordiale

On forme quoi ? où ? quand ?

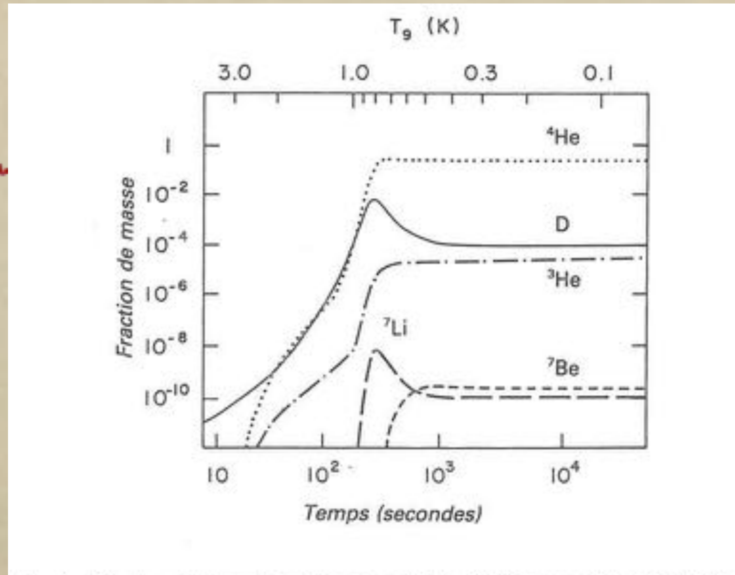


Fig. 2. – *Déroulement de la nucléosynthèse primordiale.* Le deutérium apparaît le premier, formé qu'il est par la réaction d'absorption des neutrons par les protons. Une partie du deutérium se transforme ensuite en hélium-3 et 4. Il faut attendre 200 secondes pour que le lithium-7 puis le béryllium-7 apparaissent. Le béryllium-7 en capturant un électron se transformera cinquante jours plus tard (environ !) en lithium-7. T_9 (K), température en unités de 10^9 K.

Chaîne PP I

$$p + p \longrightarrow d + e^+ + \nu$$

$$p + d \longrightarrow {}^3He + \gamma$$

$${}^3He + {}^3He \longrightarrow {}^4He + 2p + \gamma$$

Chaîne PP II

$${}^3He + {}^4He \longrightarrow {}^7Be + \gamma$$

$${}^7Be + e^- \longrightarrow {}^7Li + \nu$$

$${}^7Li + p \longrightarrow 2\,{}^4He$$

Chaîne PP III

$${}^3He + {}^4He \longrightarrow {}^7Be + \gamma$$

$${}^7Be + p \longrightarrow {}^8B + \gamma$$

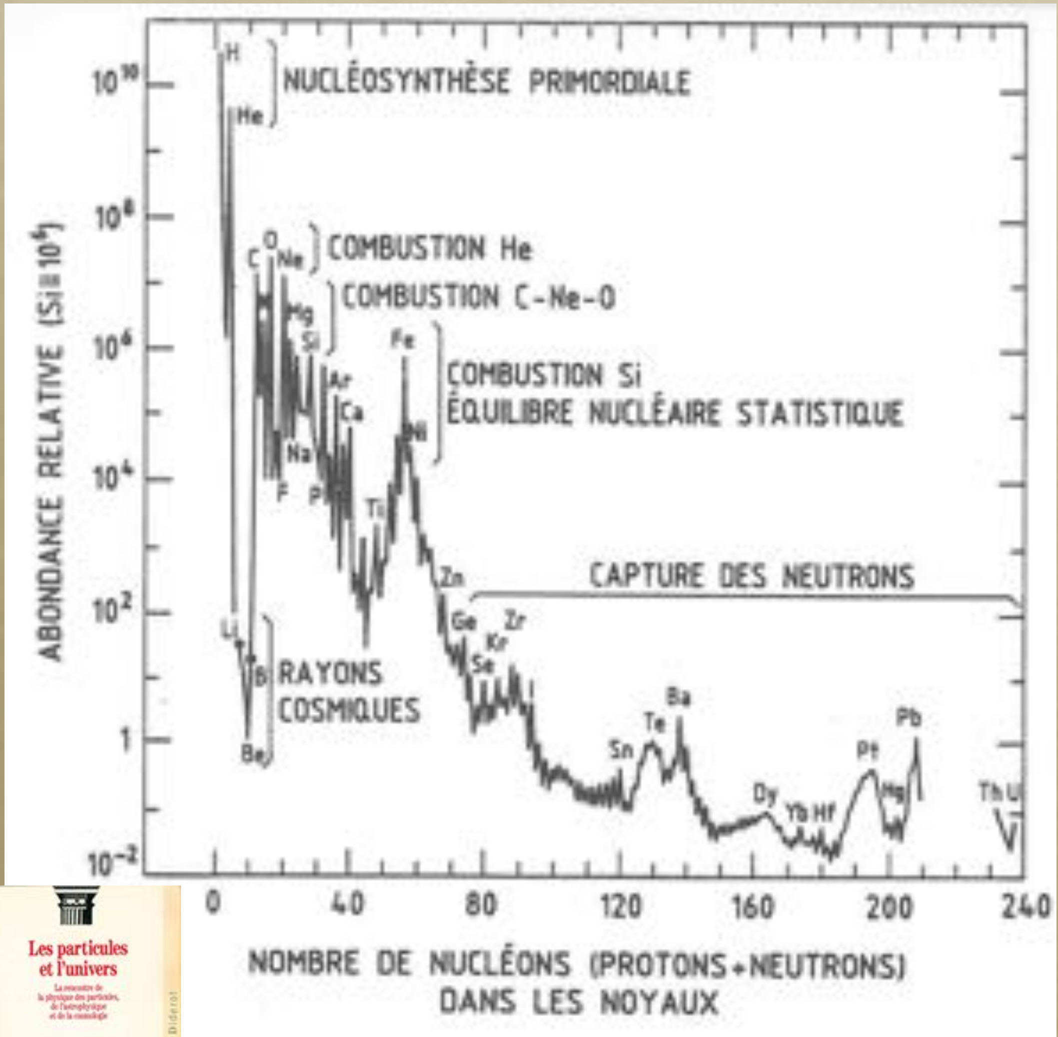
$${}^8B \longrightarrow {}^8Be + e^+ + \nu$$

!!! ^{8}Be pas stable –> $${}^8Be \longrightarrow 2\,{}^4He$$

On bloque à 8 !!!

Abondance des éléments

On forme quoi ? où ? quand ?



- *Large domination de H (71 %) He(27%)*
- *Pic du Fer*
- *pics « magiques »*
- *Bas fonds pour Li, Be et B*

! le reste constitue 2% … après 15 10^9 ans

En accord avec les modèles de processus stellaires

Nucléosynthèse primordiale

On forme quoi ? où ? quand ?

Chaîne PP I

$$p + p \longrightarrow d + e^{+} + \nu$$

$$p + d \longrightarrow {}^{3}He + \gamma$$

$${}^{3}He + {}^{3}He \longrightarrow {}^{4}He + 2p + \gamma$$

TABLEAU 2. – Abondances « primordiales » des éléments légers

Elément	*Abondance (en nombre)*	*Abondance (en masse)*
H	1,00	0,75
D	$(1,6 \pm 1,0)10^{-5}$	$(2,5 \pm 1,5)10^{-5}$
^{3}He	$(1,8 \pm 1,2)10^{-5}$	$(4,2 \pm 2,8)10^{-5}$
^{4}He	$(7,5 \pm 0,9)10^{-2}$	$0,23 \pm 0,02$
^{6}Li	$\left(7,0 {}^{+7}_{-3,5}\right)10^{-11}$	$\left(3,0 {}^{+3,0}_{-1,5}\right)10^{-10}$
^{7}Li	$\left(9,0 {}^{+9,0}_{-4,5}\right)10^{-10}$	$\left(4,6 {}^{+4,5}_{-2,5}\right)10^{-9}$

Chaîne PP II

$${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$$

$${}^{7}Be + e^{-} \longrightarrow {}^{7}Li + \nu$$

$${}^{7}Li + p \longrightarrow 2\,{}^{4}He$$

Chaîne PP III

$${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$$

$${}^{7}Be + p \longrightarrow {}^{8}B + \gamma$$

$${}^{8}B \longrightarrow {}^{8}Be + e^{+} + \nu$$

!!! ^{8}Be pas stable —> $${}^{8}Be \longrightarrow 2\,{}^{4}He$$ *décroit en 10^{-16} s !*

Nucléosynthèse primordiale

On forme quoi ? où ? quand ?

^{8}Be pas stable !!!

Pas d'isobare stable de masse 5 et 8 !!!

Il faut T > 10^8K pour passer ce fossé !

La nucléosynthèse primordiale s'arrête au ^{7}Li !!!

Equilibres & réactions stellaires :

Réactions nucléaires stellaires

Entre le Big-bang et les premières étoiles il faut $10^{6 \text{ à } 9}$ ans

Photo Hubble :
Formation de jeunes étoiles

Rôle de la gravité

Equilibres & réactions stellaires :

Réactions nucléaires stellaires

Mais comment passer A=8 ???

—> Pourquoi pas $^4He + ^4He + ^4He$ —> ^{12}C ?

La collision simultanée de 3 ^4He est trop peu probable

—> Pourquoi pas ($^4He + ^4He$ —> ^8Be)+ ^4He—> ^{12}C ?

Salpeter souligne en 1952 que la durée de vie de ^8Be (résonance) $T_{1/2}(^8Be) = 2.6\ 10^{-16}s$ est peut être suffisante

… à comparer au temps que mettra un ^4He à passer $8\ 10^{-21}s$ … qui accélère

=> on a un équilibre $^4He + ^4He$ <—> ^8Be

Equilibres & réactions stellaires :

Réactions nucléaires stellaires

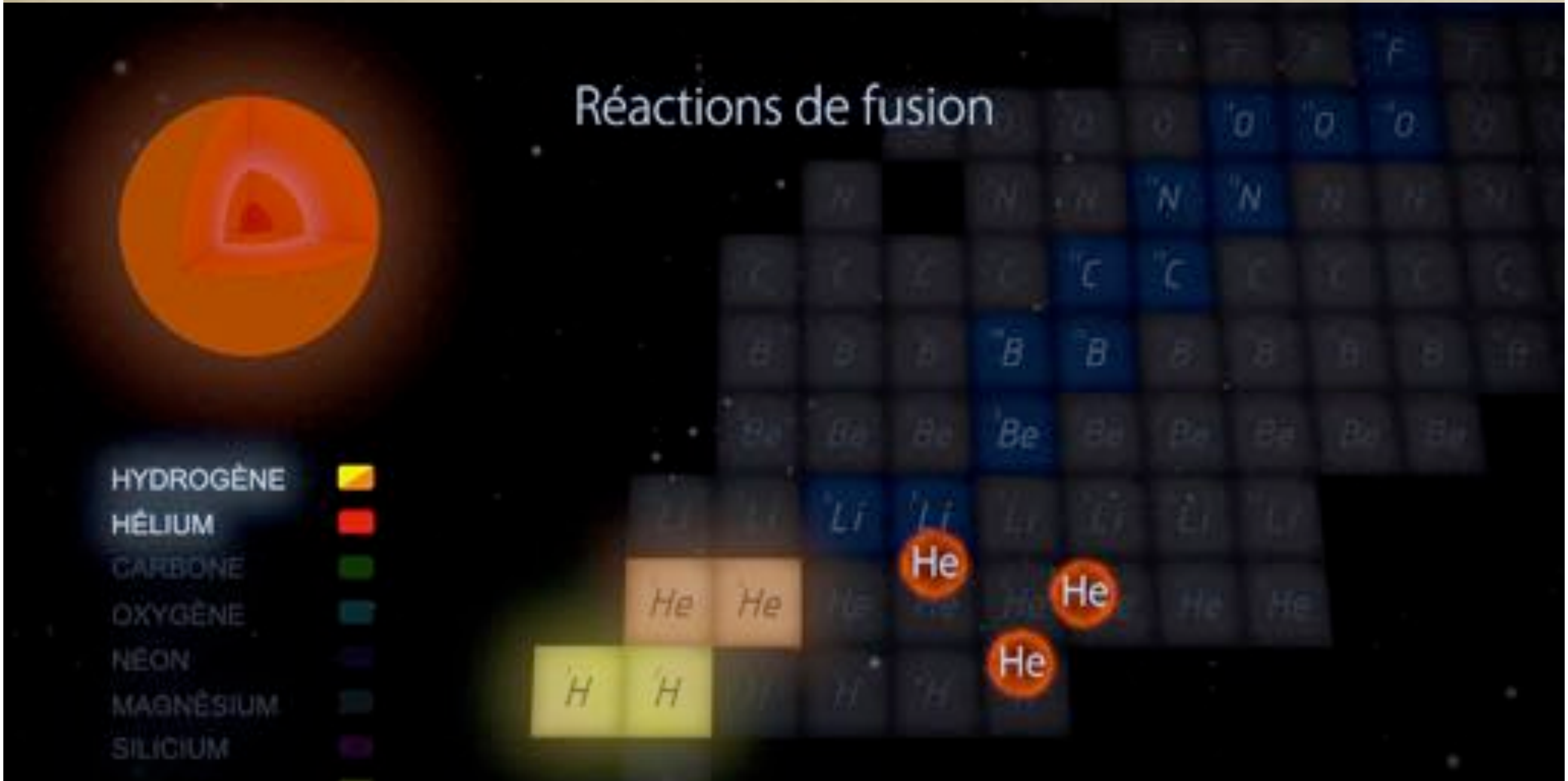
Une fois le carbone créé, les cycles CNO s'enclenchent

Cycle CNO « froid »	*Cycle CNO « tiède »*	*Cycle CNO « chaud »*
T< 10⁸K	*10⁸K < T< 2. 10⁸K*	*2.10⁸K T< 5.10⁸K*
$^{12}C + p \longrightarrow {}^{13}N + \gamma$	$^{12}C + p \longrightarrow {}^{13}N + \gamma$	$^{12}C + p \longrightarrow {}^{13}N + \gamma$
$^{13}N \longrightarrow {}^{13}C + e^+ + \nu$	$^{13}N \longrightarrow {}^{13}C + e^+ + \nu$	$^{13}N + p \longrightarrow {}^{14}O + \gamma$
$^{13}C + p \longrightarrow {}^{14}N + \gamma$	$^{13}C + p \longrightarrow {}^{14}N + \gamma$	$^{14}O \longrightarrow {}^{14}N + e^+ + \nu$
$^{14}N + p \longrightarrow {}^{15}O + \gamma$	$^{14}N + p \longrightarrow {}^{15}O + \gamma$	$^{14}N + p \longrightarrow {}^{15}O + \gamma$
$^{15}O \longrightarrow {}^{15}N + e^+ + \nu$	$^{15}O \longrightarrow {}^{15}N + e^+ + \nu$	$^{15}O \longrightarrow {}^{15}N + e^+ + \nu$
$^{15}N + p \longrightarrow {}^{12}C + {}^{4}He$	$^{15}N + p \longrightarrow {}^{12}C + {}^{4}He$	$^{15}N + p \longrightarrow {}^{12}C + {}^{4}He$

Les proportions finales dépendent de la T° …

Equilibres & réactions stellaires :

Réactions nucléaires stellaires.



http://irfu.cea.fr/la-vallee-de-stabilite/

Réactions stellaires explosives:

quand la nature fait des haut flux ....

Réactions stellaires explosives:

quand la nature fait des haut flux …

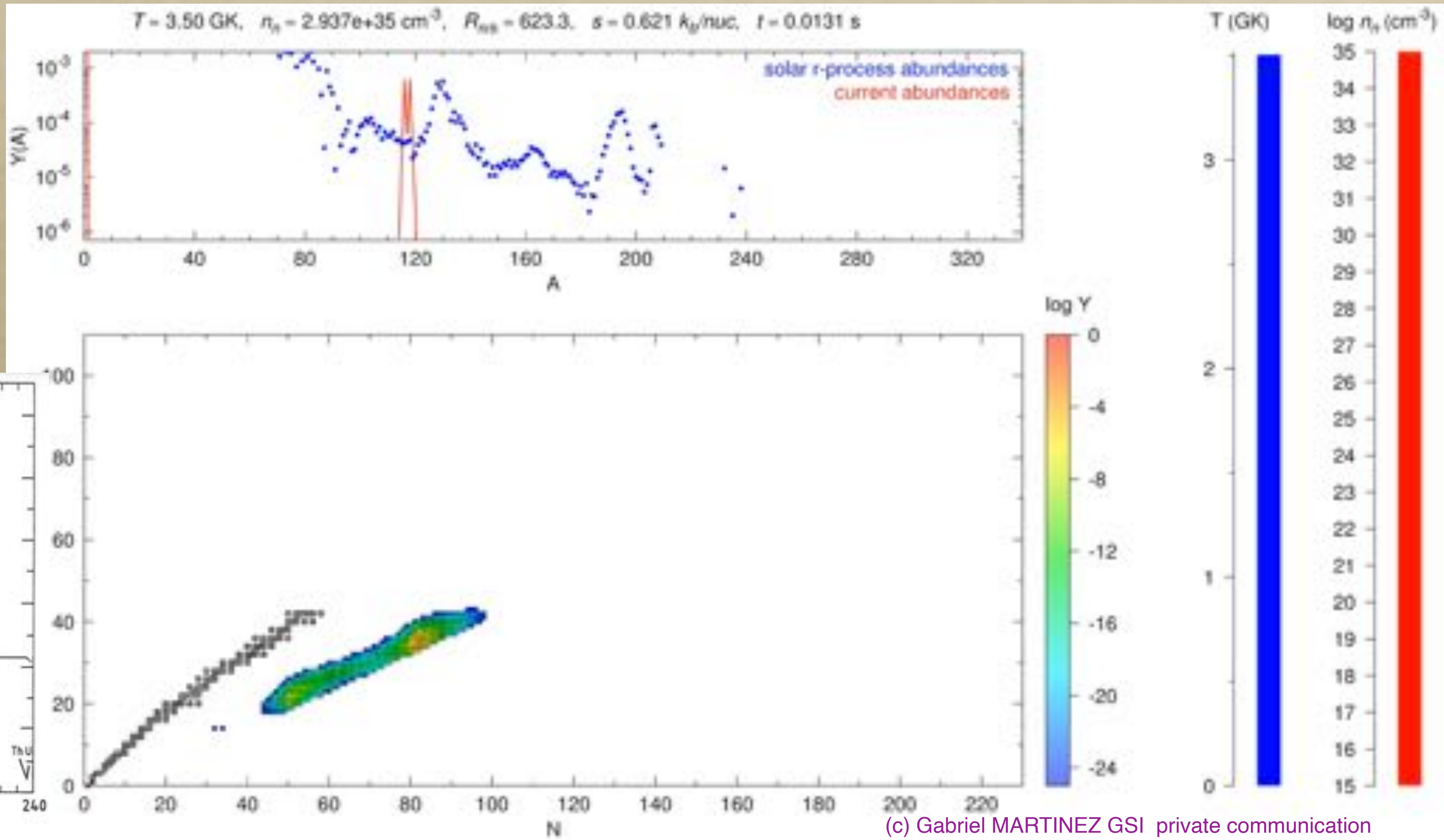
***Merge de 2 étoiles à neutrons** => Très haut flux neutronique*

Brassage

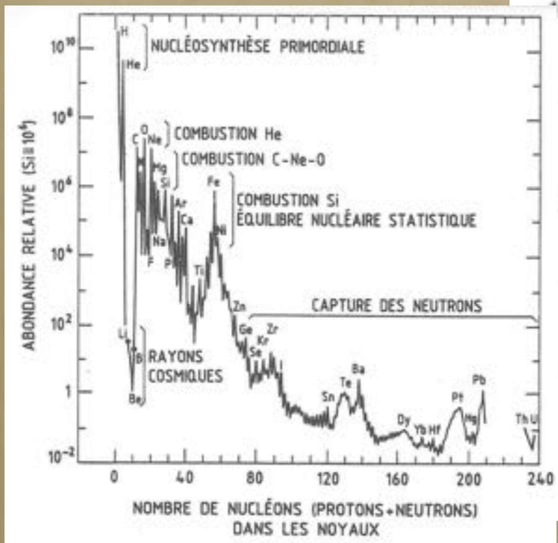
=> résultat

indépendant

de l'état



(c) Gabriel MARTINEZ GSI private communication



Nuclear robustness of the r-process in neutron-star mergers

Meng-Ru Wu, Karlheinz Langanke, Gabriel Martínez-Pinedo, Andreas Bauswein, and Hans-Thomas Janka et al.,
Phys. Rev. C **92**, (2015) 055805

see also https://arxiv.org/abs/1901.01410

Les réacteurs naturels à fission
Réacteurs d'Oklo ...

Criticality achieved by human …

First artificial nuclear reactor

After discovery of fission process by Otto Hahn, Fritz Strassmann and Lise Meitner in december 1938

E. Fermi starts CP1 (Chicago Pile 1) in december 1942

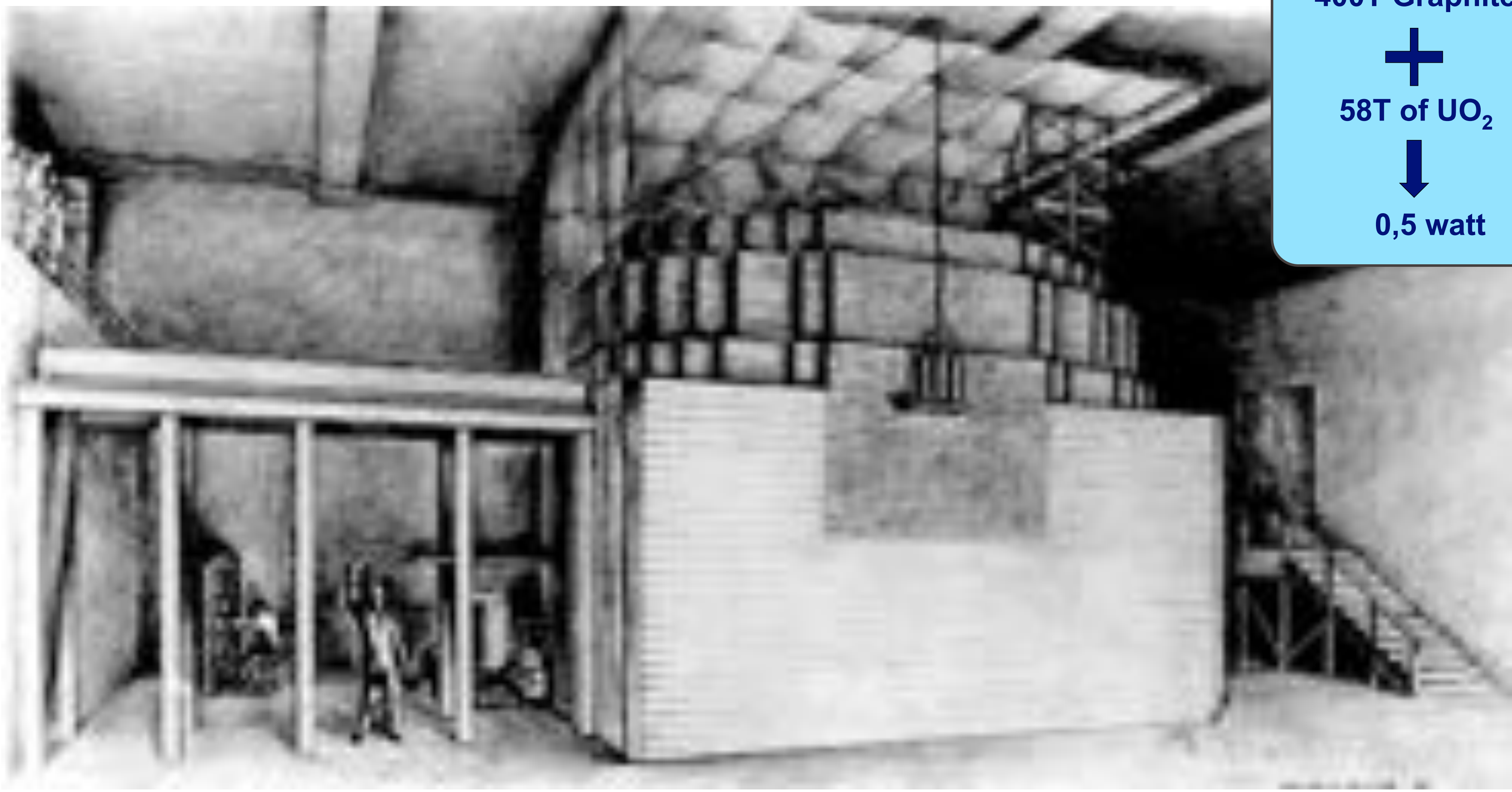
400T Graphite

+

58T of UO_2

↓

0,5 watt



Natural criticality already predicted in 1956...

On the Nuclear Physical Stability of the Uranium Minerals

P. K. Kuroda
Department of Chemistry, University of Arkansas, Fayetteville, Arkansas
(Received July 26, 1956)

1917-2001

It is generally accepted that the deposition of the uranium minerals took place at the pegmatitic-pneumatolytic and early hydrothermal stages. Hence, one may consider that the crystallization of the uranium minerals represents the following sequence of events. An aqueous solution of uranium (U^{-235} enriched) is gradually converted to an assemblage of uranium plus n moles of water ($n=1, 2, 3, \cdots n$) and finally to an almost water-free uranium mineral.

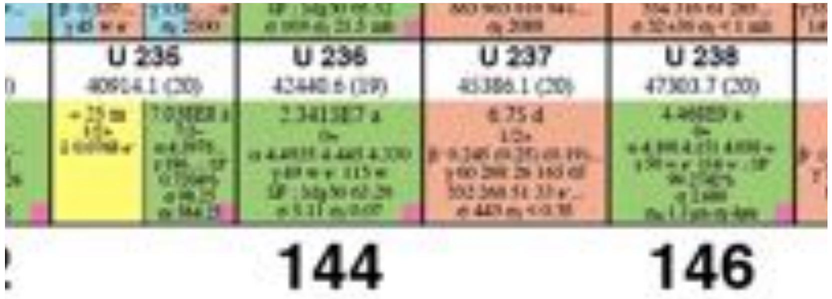
Let us imagine that the crystallization of the Johanngeorgenstadt pitchblende took place 2100 million years ago. The calculated values of p, f, η, and k_∞ are shown in Table II. Table II shows that the assemblages of the Johanngeorgenstadt pitchblende plus water were nuclear physically "unstable" 2100 million years ago, and the critical uranium chain reactions could have taken place, if the size of the assemblage was greater than, say, a thickness of a few feet. The effect of such an event could have been a sudden elevation of the temperature, followed by a complete destruction of the critical assemblage.

The effect of the ground water or the water vapor from the molten magma could have resulted in the formation of a nuclear physically "unstable" assemblage of uranium plus n moles of water. Such mechanism might explain the fact that the ages of the large uranium deposits never exceed 2000 million years, or the

Table II. The water-uranium ratio and the values of p, f, η, and k_∞ (Johanngeorgenstadt pitchblende, 2100 million years ago).

n	1/4	1/2	1	2	3	4	5	10
p	0.29	0.47	0.62	0.74	0.79	0.82	0.84	0.86
f	0.99	0.98	0.97	0.95	0.93	0.91	0.89	0.81
η	1.91	1.91	1.91	1.91	1.91	1.91	1.91	1.91
k_∞	0.55	0.88	1.15	1.34	1.40	1.42	1.43	1.33

Oklo industrial site

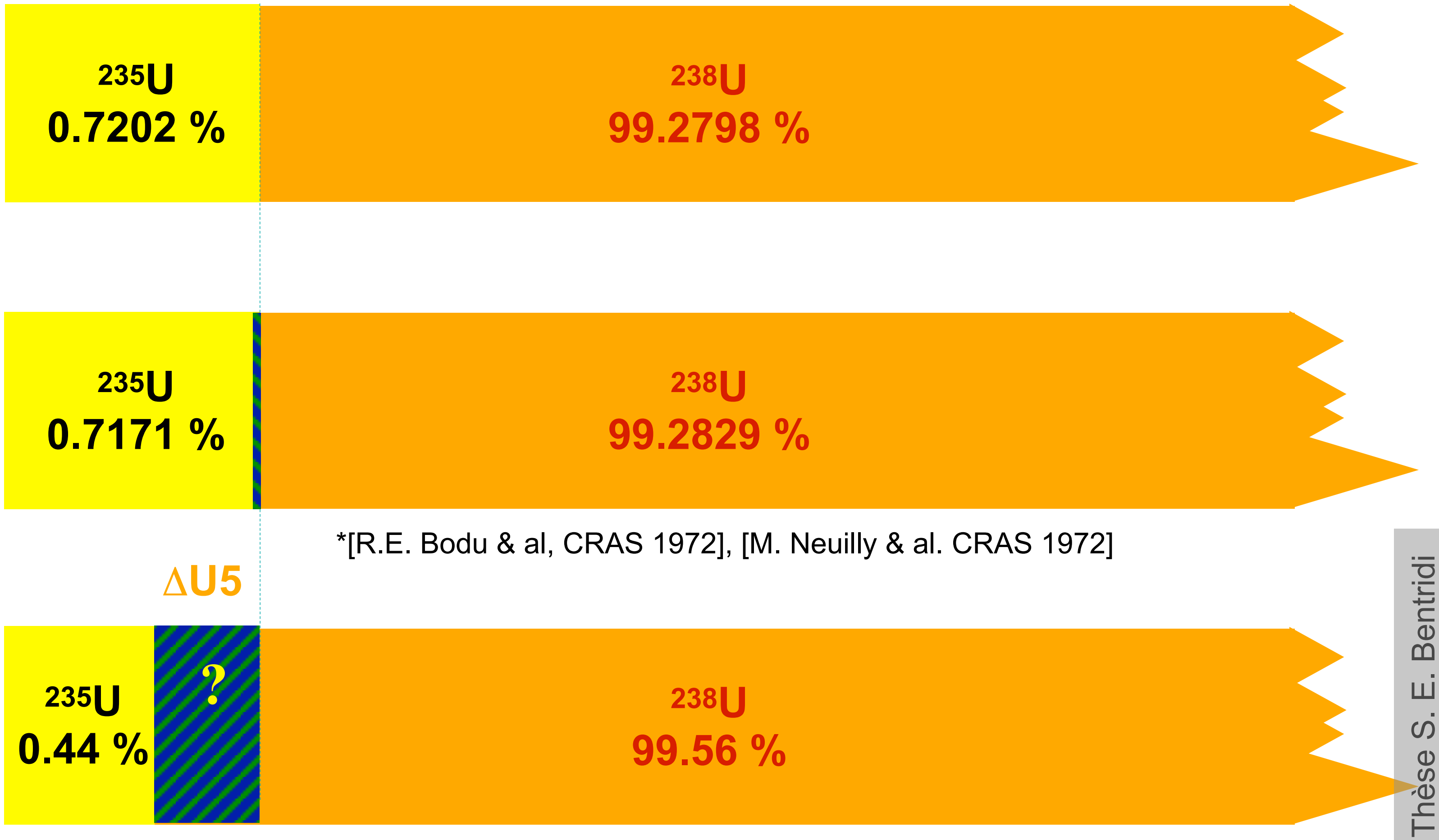


The discovery ...

Isotopic content of earth natural Uranium (% atm.):

First observation
7 Juin 1972*:

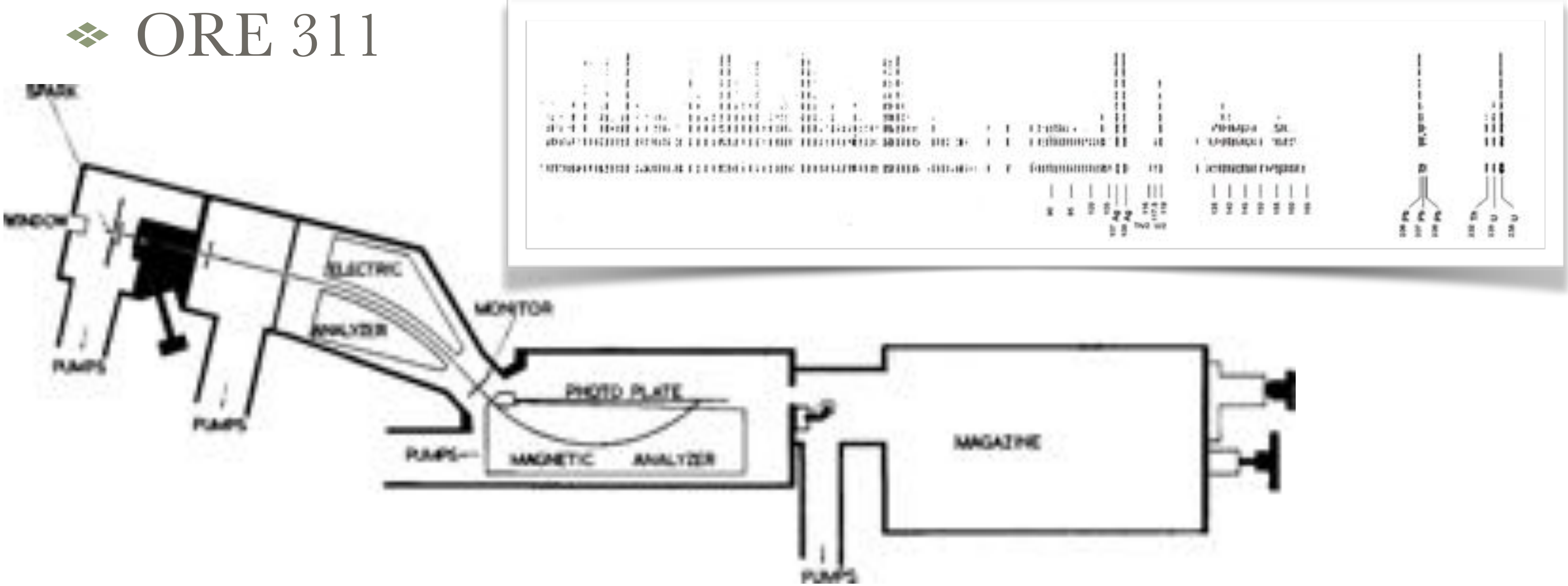
Some weeks later



*[R.E. Bodu & al, CRAS 1972], [M. Neuilly & al. CRAS 1972]

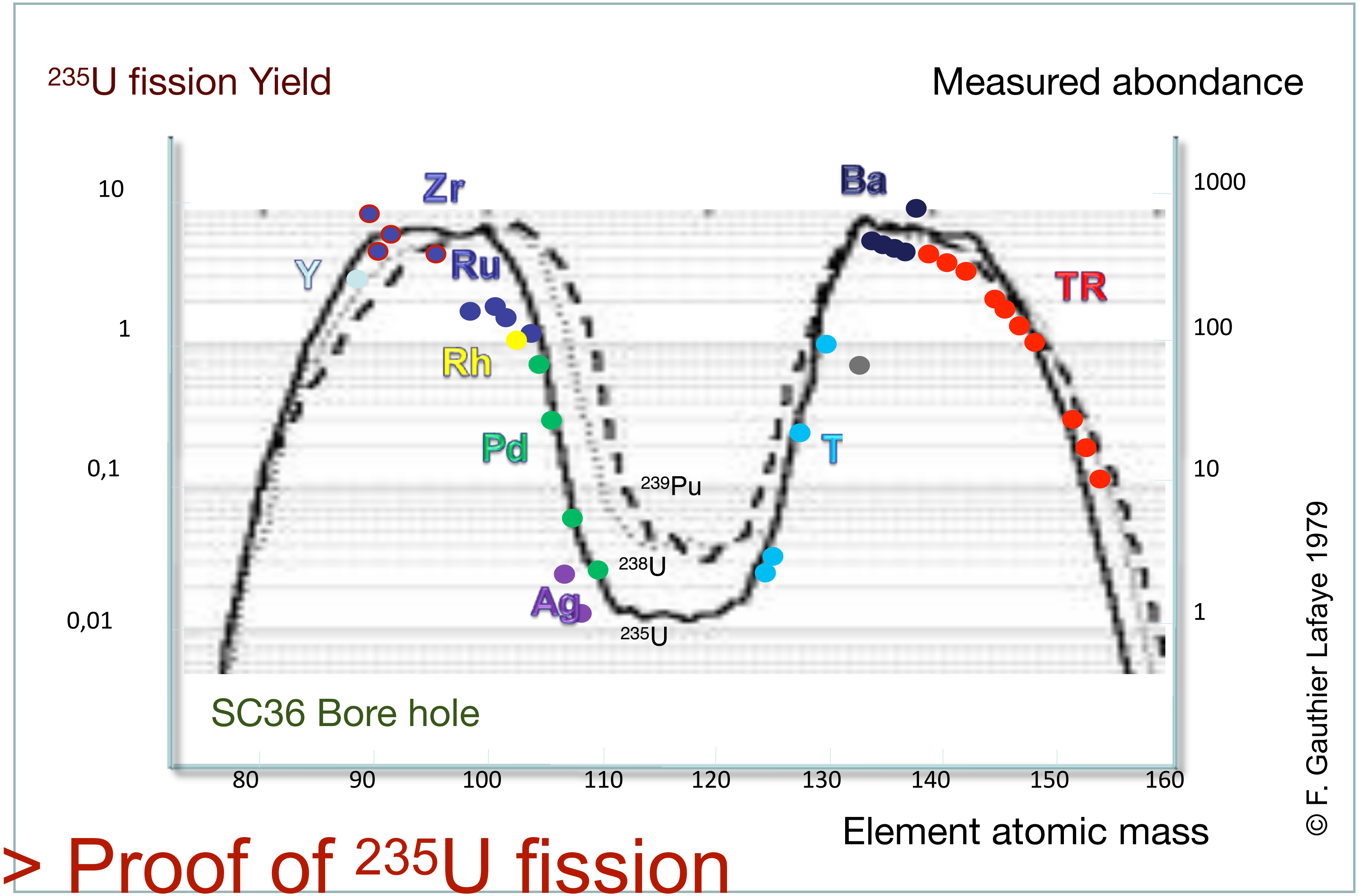
Uranium 235 content went down to 0,29% in RZ2 !!!

ORE 311



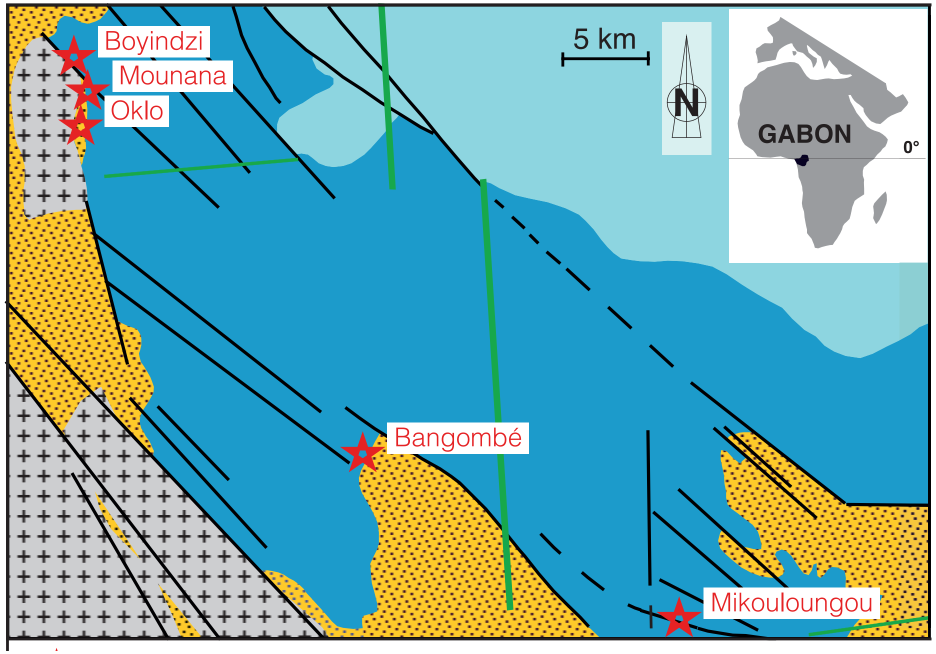
Nd	Natural %	Ore 311 %	Sm	Natural %	Ore 311 %
^{142}Nd	27.11	5.75	^{144}Sm	3.09	0.45
^{143}Nd	12.17	23.46	^{147}Sm	14.97	50.89
^{144}Nd	23.85	27.39	^{148}Sm	11.24	3.86
^{145}Nd	8.30	16.42	^{149}Sm	13.83	1.25
^{146}Nd	17.22	15.32	^{150}Sm	7.44	25.62
^{148}Nd	5.73	7.74	^{152}Sm	26.72	12.6
^{150}Nd	5.62	3.92	^{154}Sm	22.71	5.17

Elementary analysis of Oklo rocks

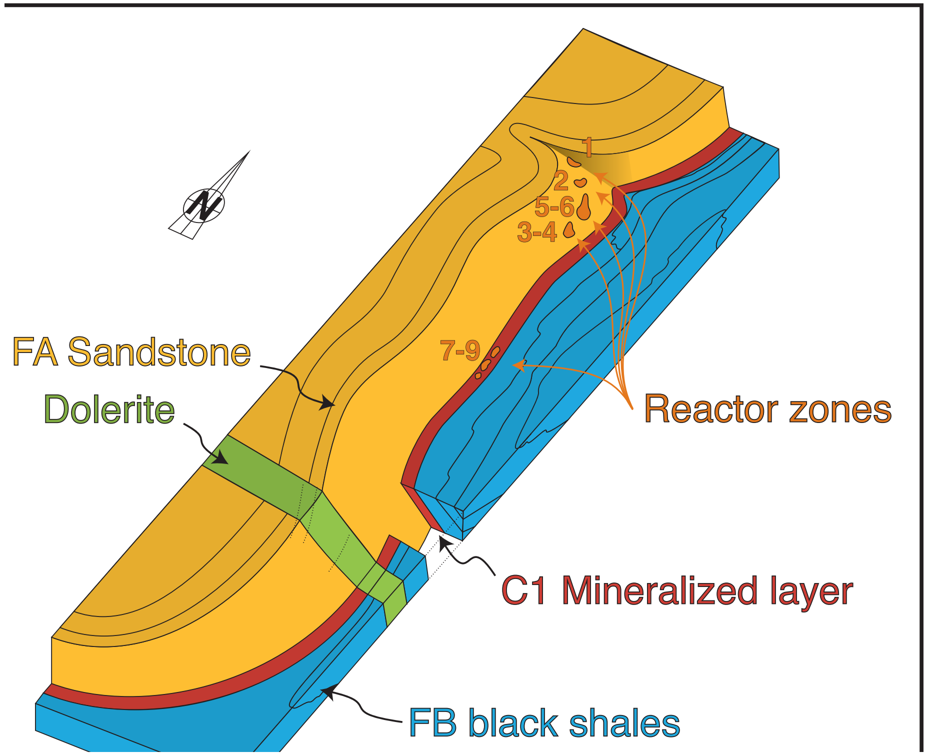


=> Proof of ^{235}U fission

Fission data from England and Rider (1994)

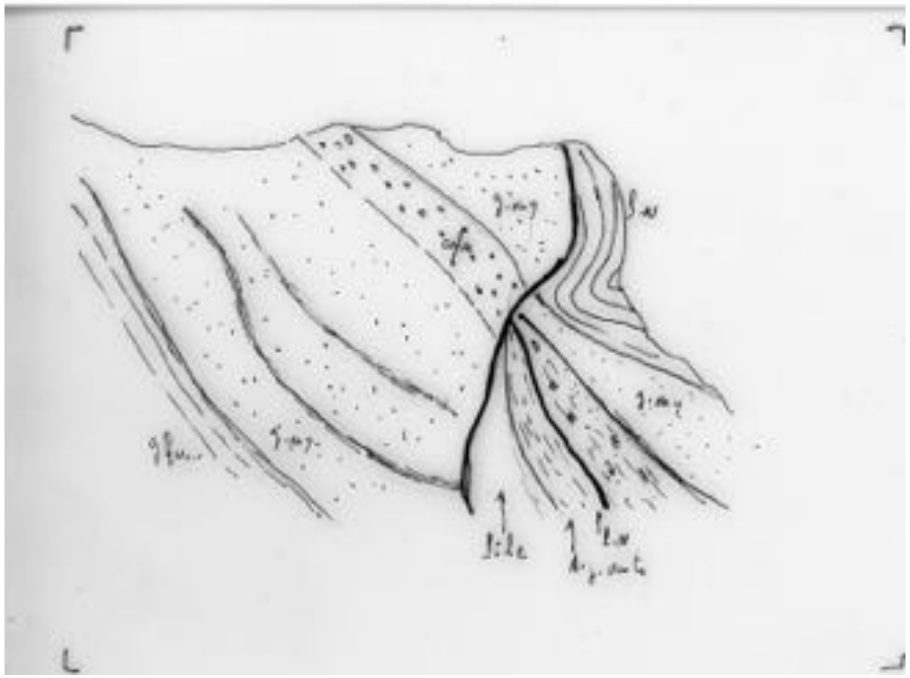


Boyindzi
Mounana
Oklo
5 km
N
GABON
0°
Bangombé
Mikouloungou

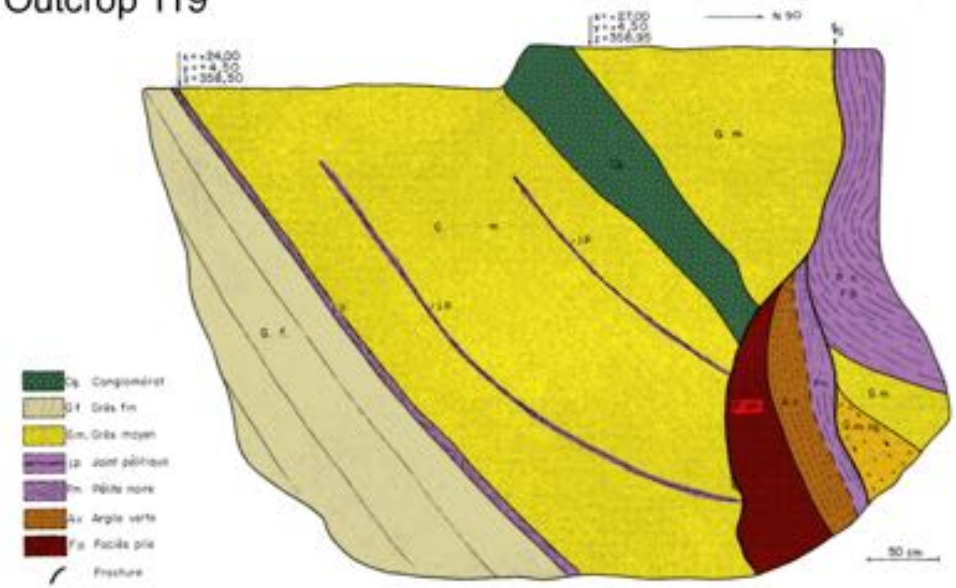


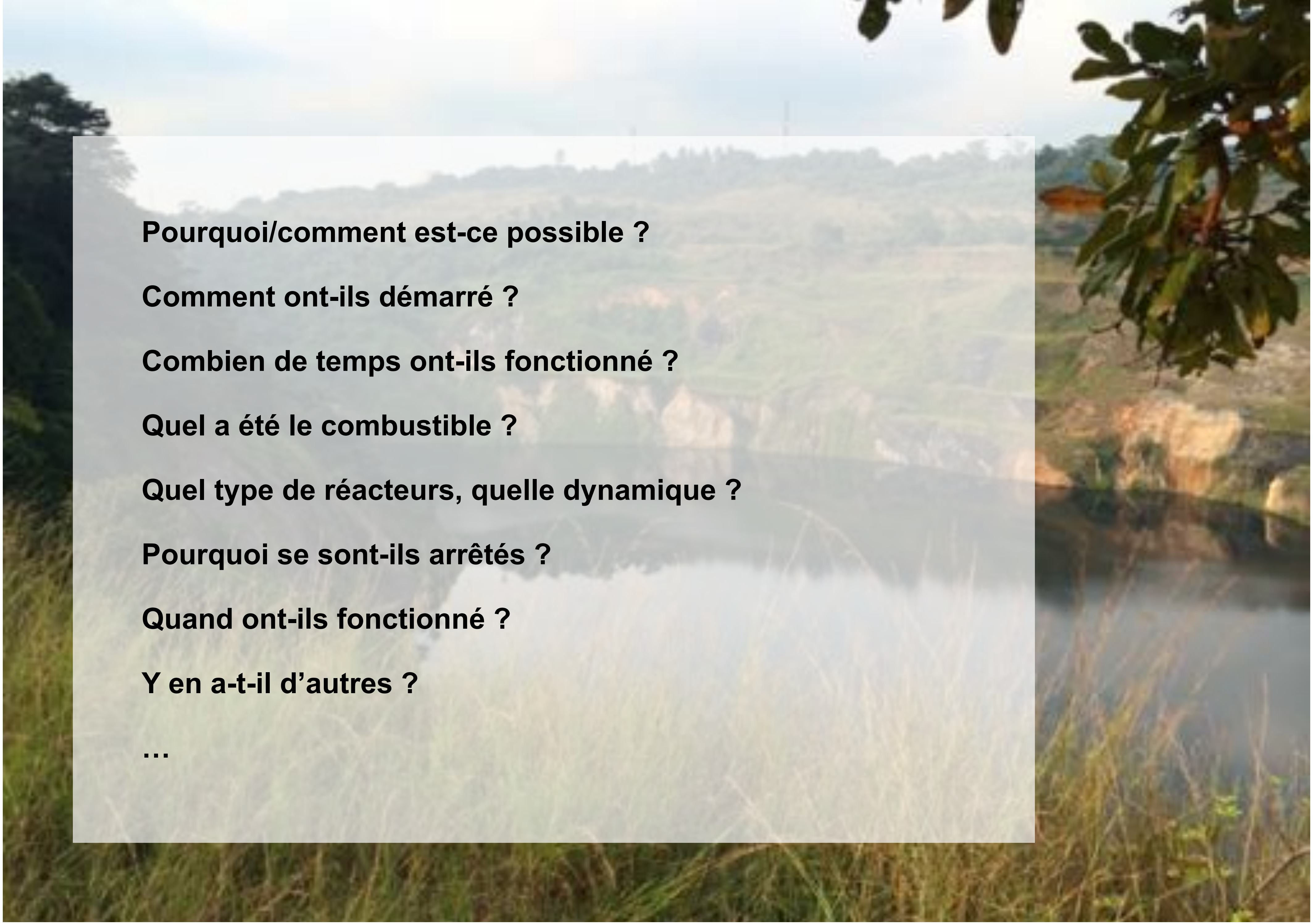
N
1
2
5-6
3-4
7-9
FA Sandstone
Dolerite
Reactor zones
C1 Mineralized layer
FB black shales

Front 119



Outcrop 119





Pourquoi/comment est-ce possible ?

Comment ont-ils démarré ?

Combien de temps ont-ils fonctionné ?

Quel a été le combustible ?

Quel type de réacteurs, quelle dynamique ?

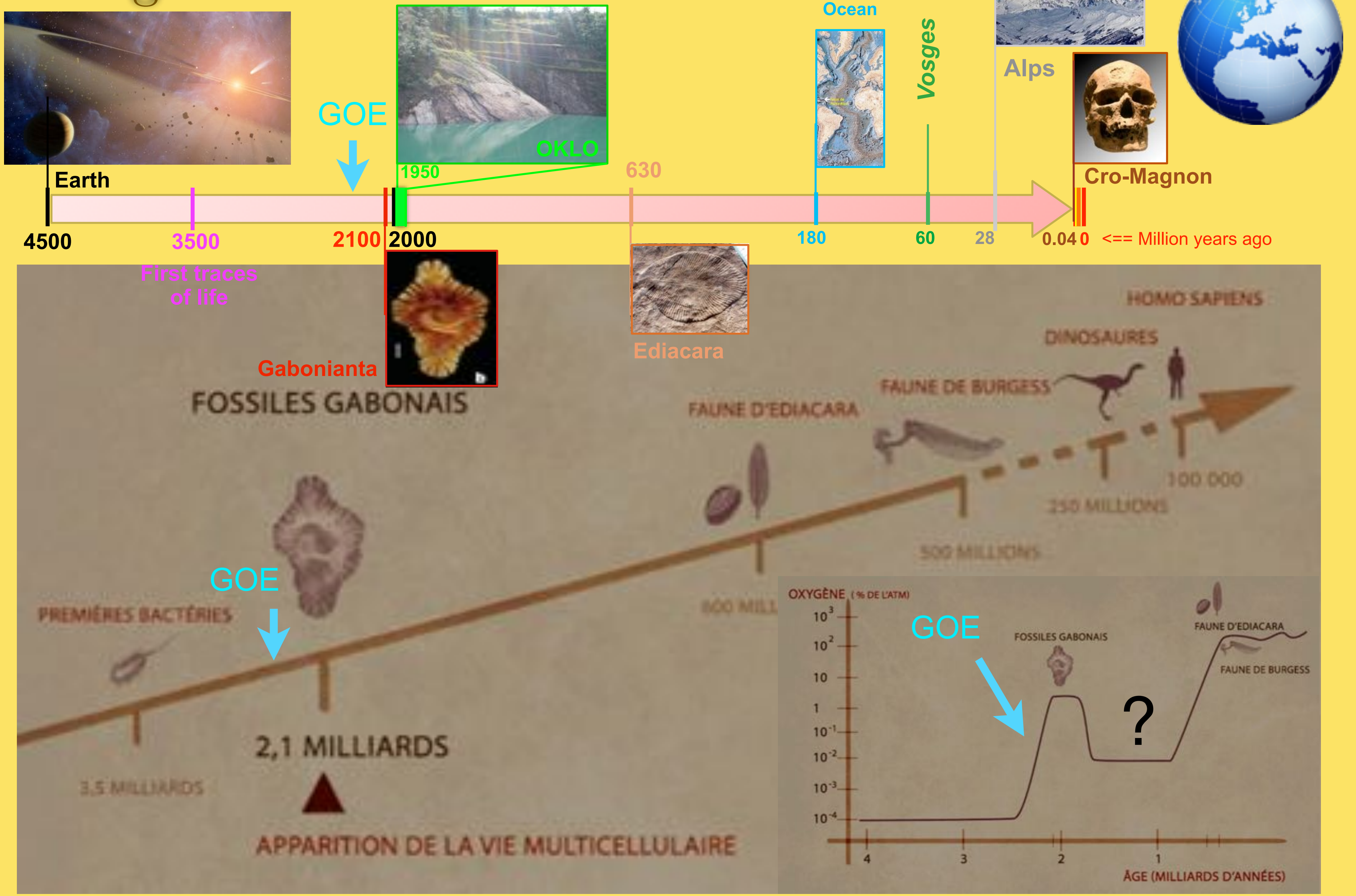
Pourquoi se sont-ils arrêtés ?

Quand ont-ils fonctionné ?

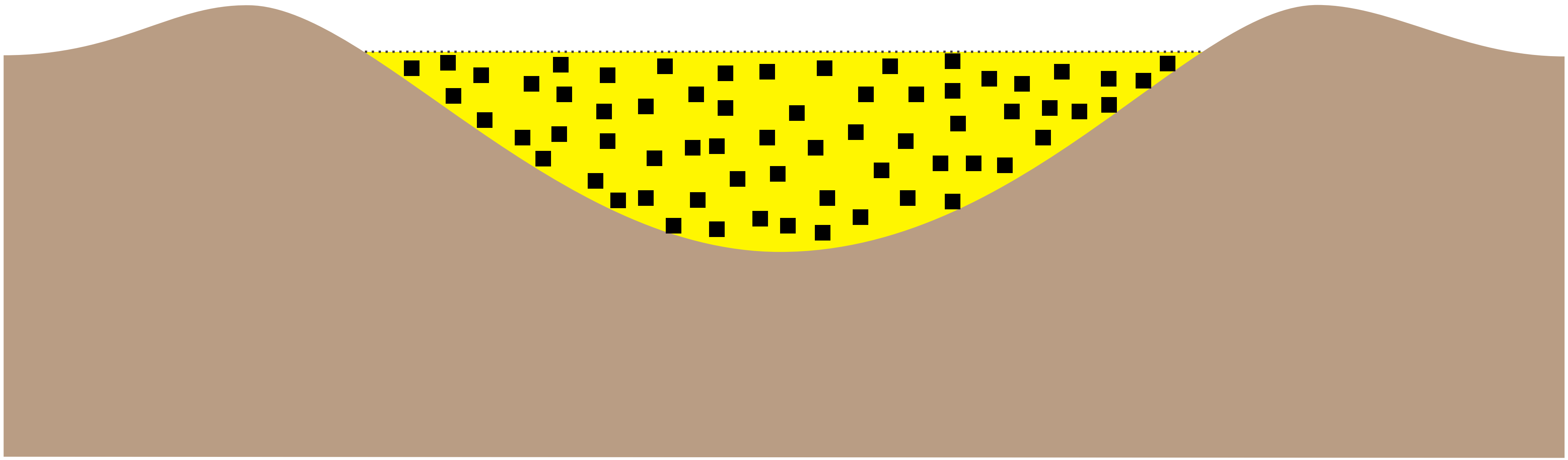
Y en a-t-il d'autres ?

…

Geological time scale …



Below sea sedimentary follows



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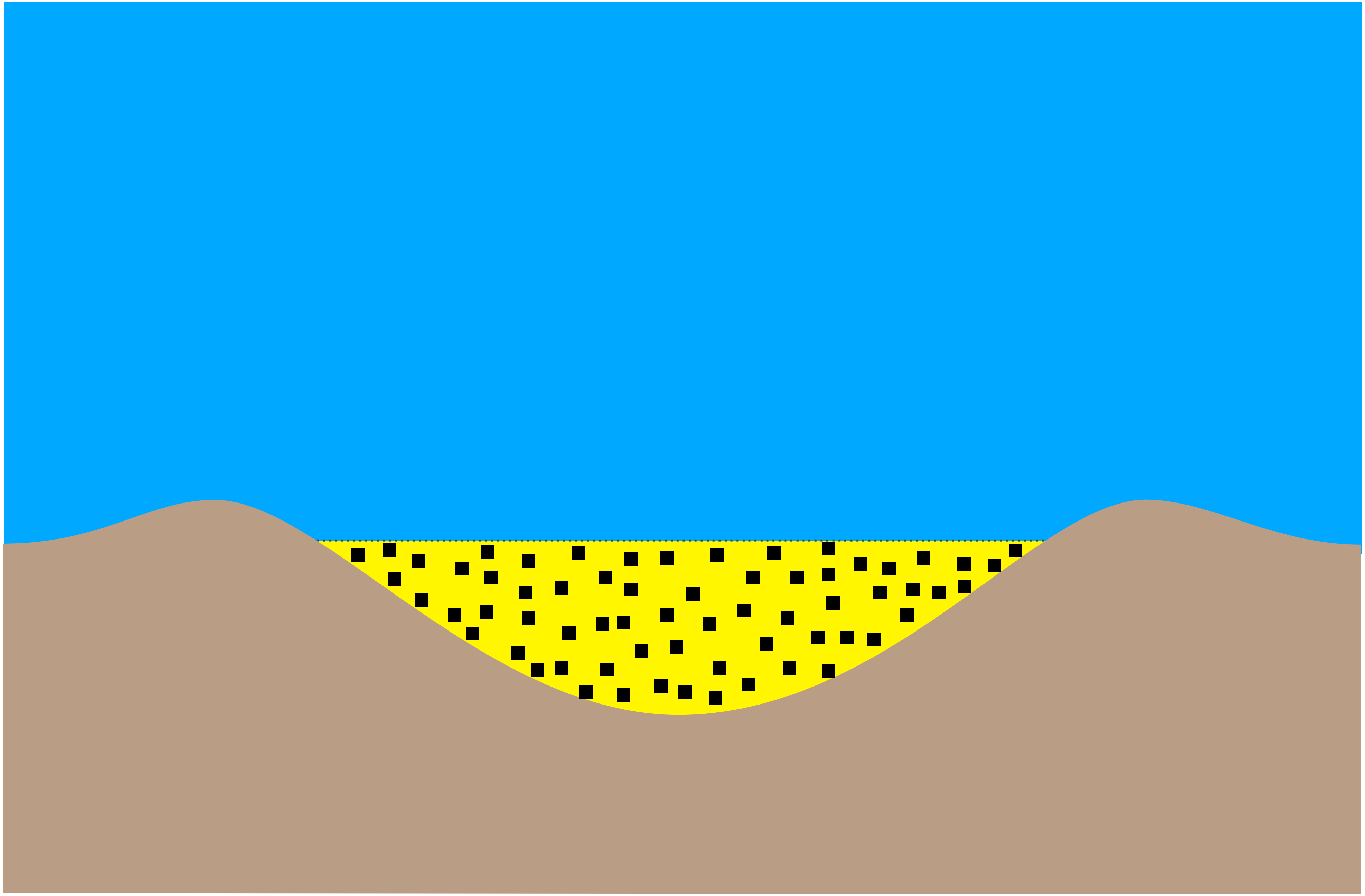
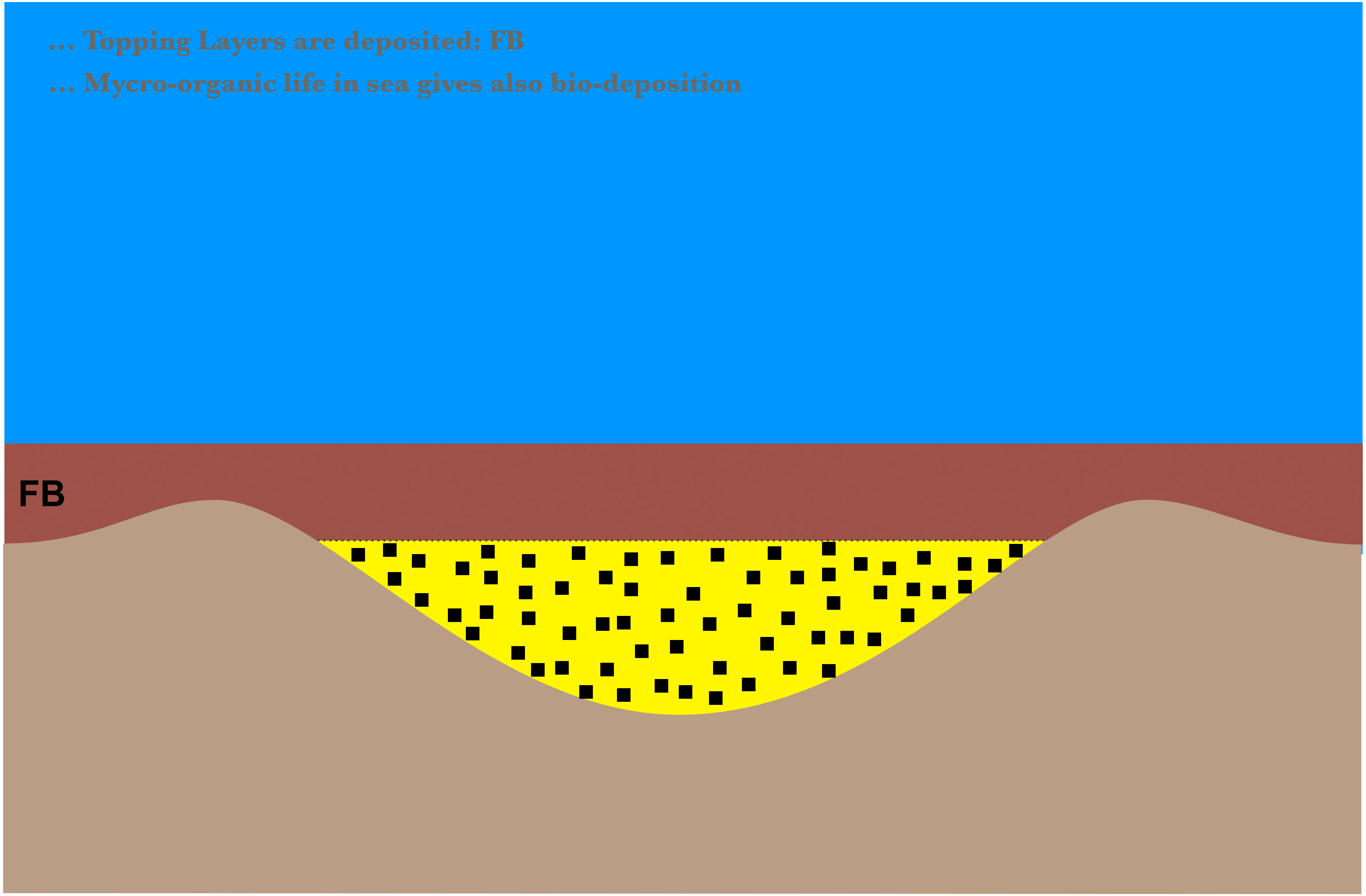


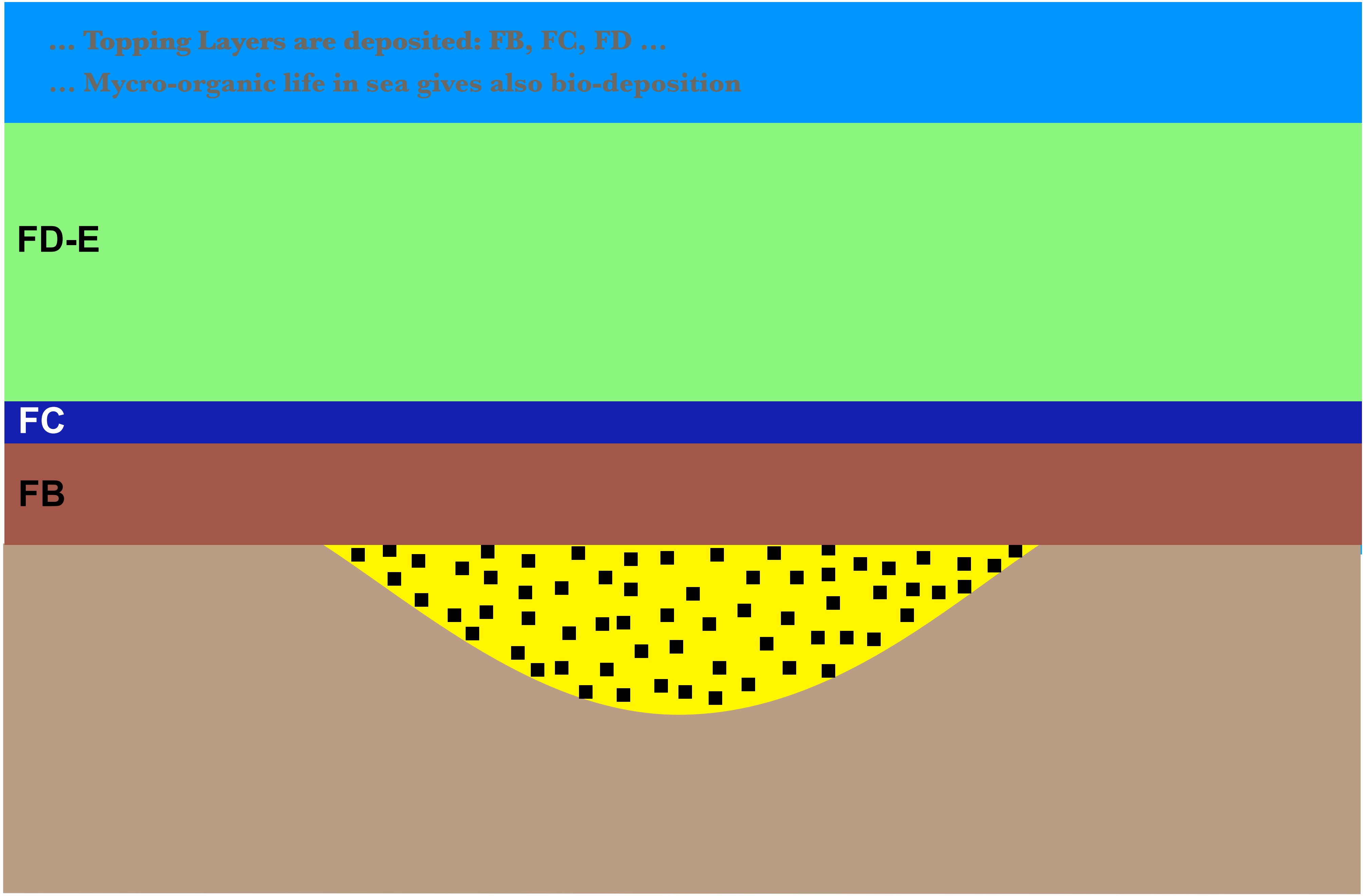
Below sea sedimentary follows

… Topping Layers are deposited: FB

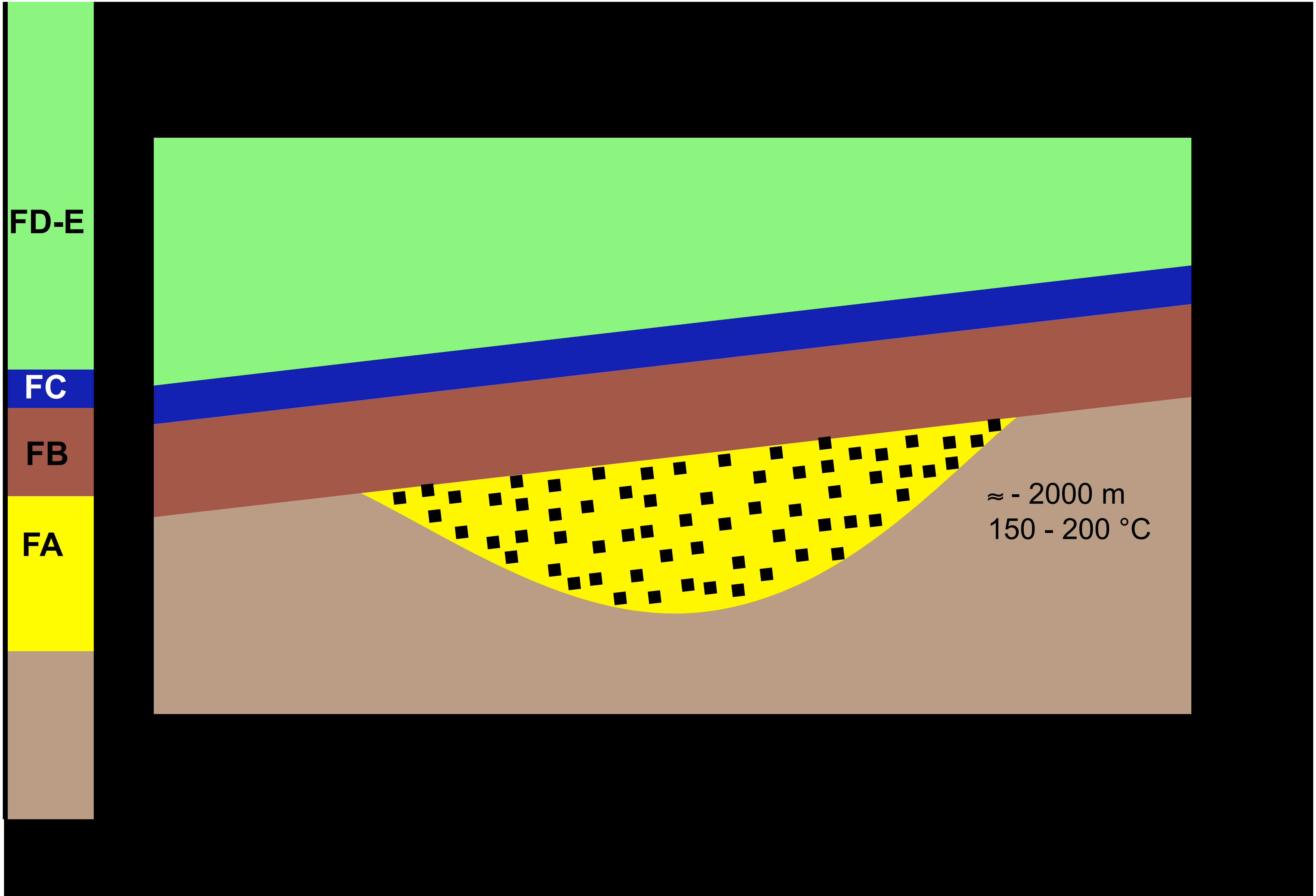
… Mycro-organic life in sea gives also bio-deposition



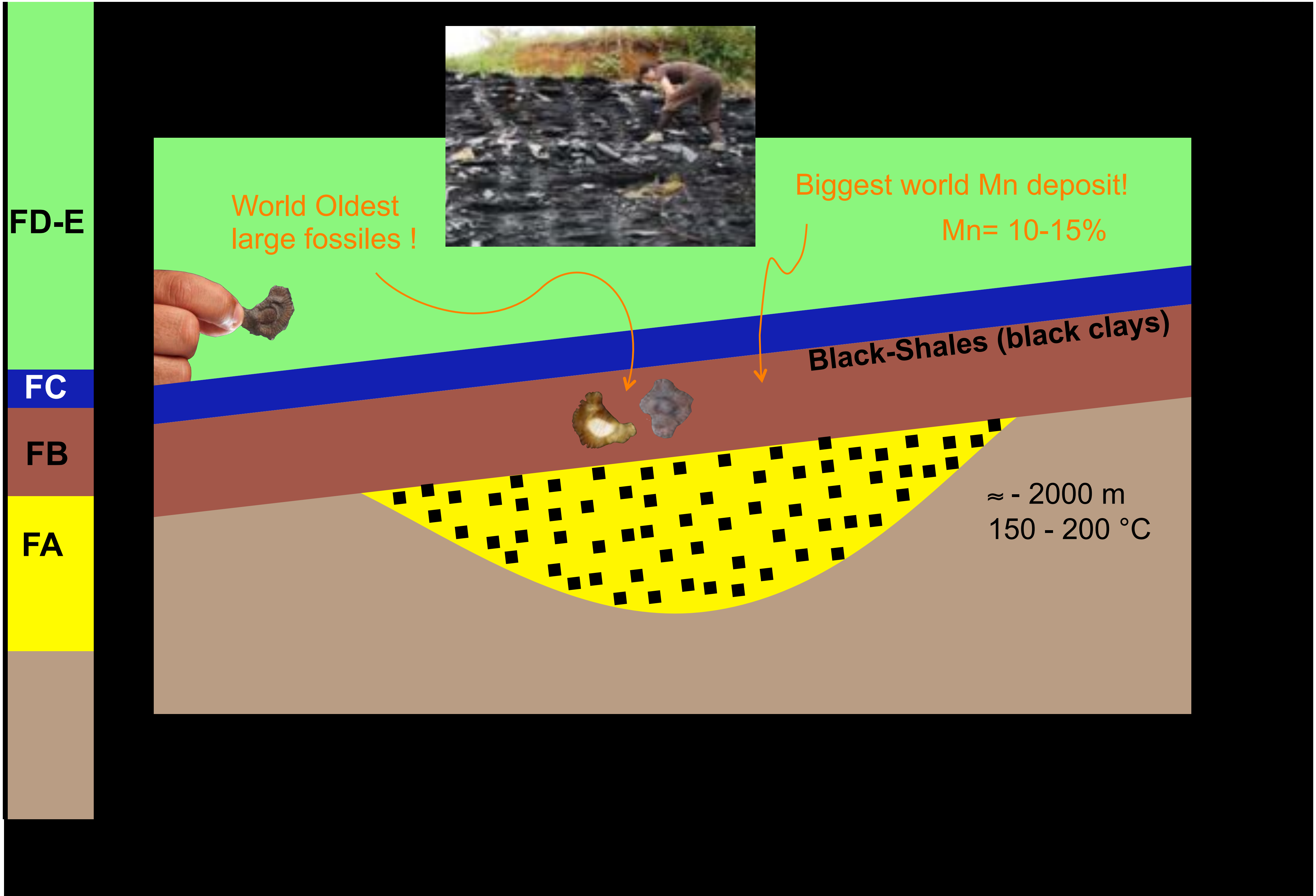
Below sea sedimentary follows



Diagenesis of the deposit -1950 MY ago



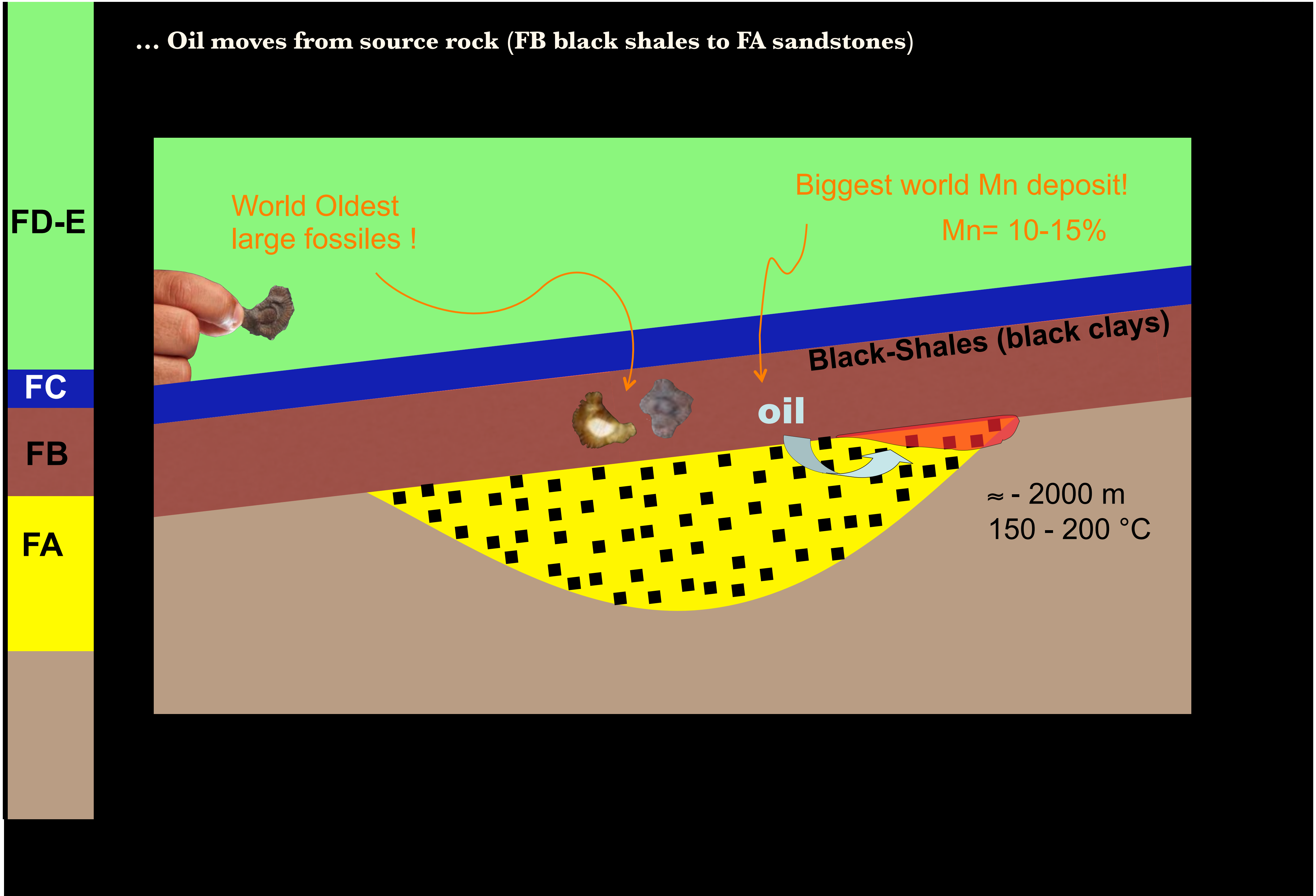
Diagenesis of the deposit -1950 MY ago




Nature, Vol. 466, July 2010
© F. Gauthier-Lafaye

Diagenesis of the deposit -1950 MY ago

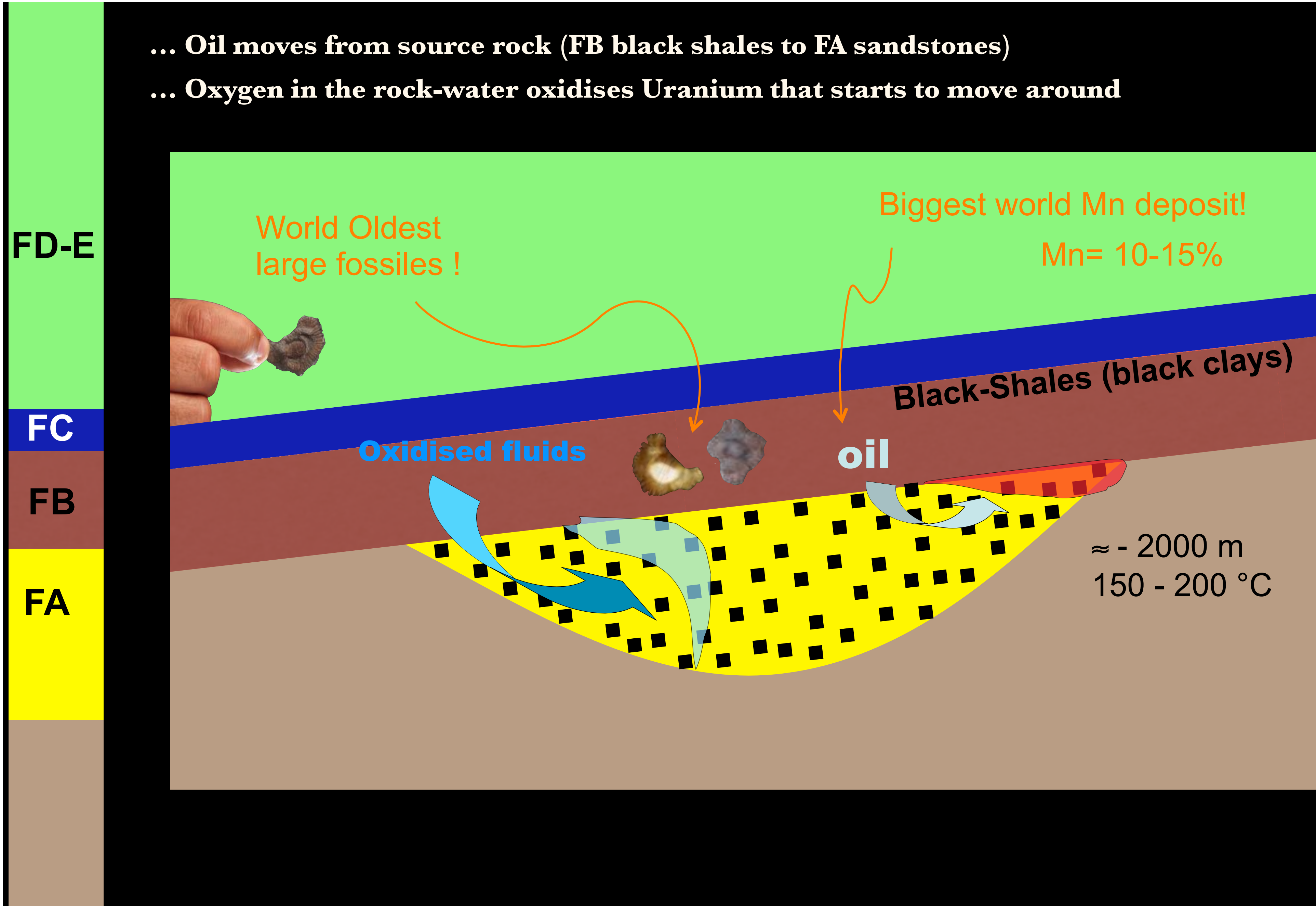
… Oil moves from source rock (FB black shales to FA sandstones)



Diagenesis of the deposit -1950 MY ago

… Oil moves from source rock (FB black shales to FA sandstones)

… Oxygen in the rock-water oxidises Uranium that starts to move around

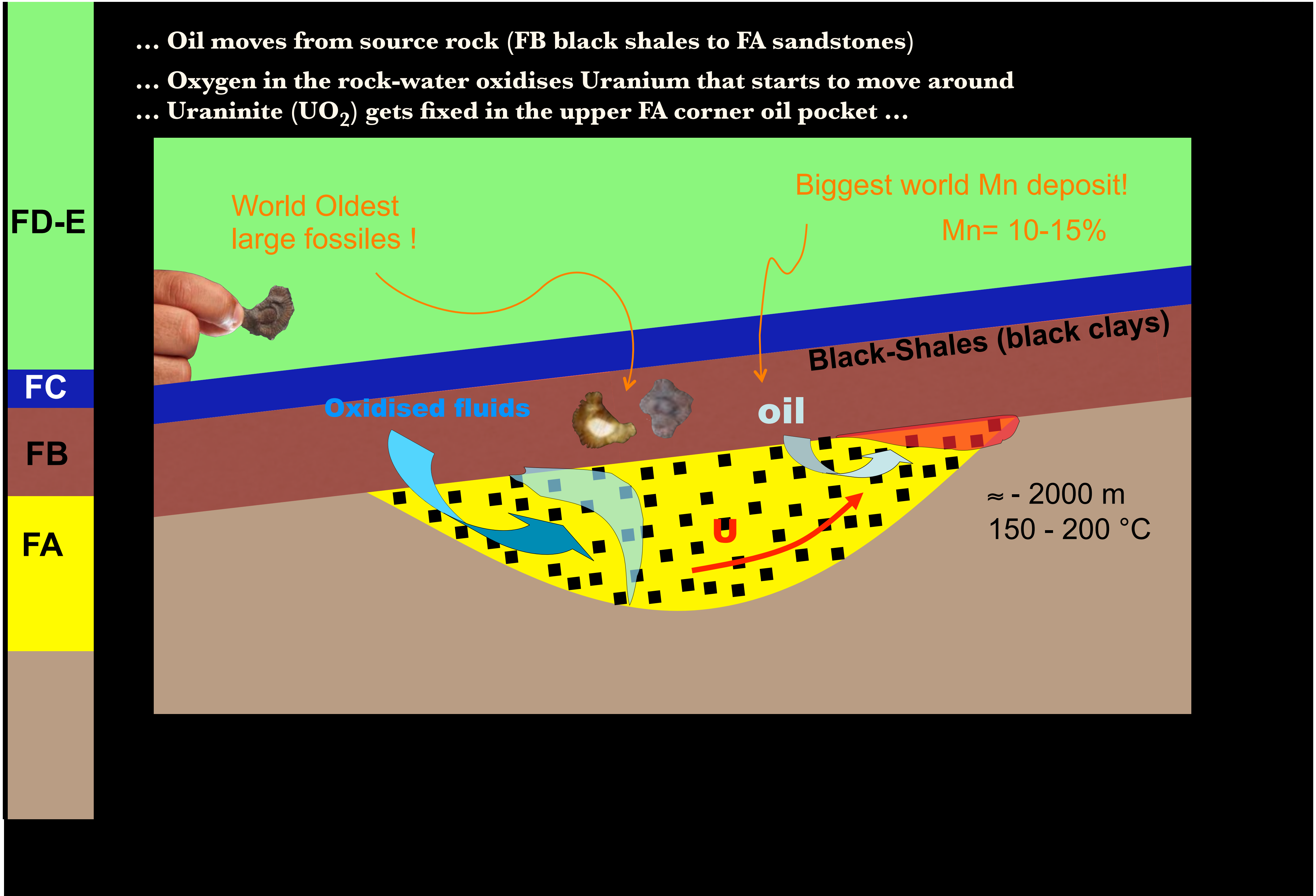


Diagenesis of the deposit -1950 MY ago

… Oil moves from source rock (FB black shales to FA sandstones)

… Oxygen in the rock-water oxidises Uranium that starts to move around

… Uraninite (UO_2) gets fixed in the upper FA corner oil pocket …



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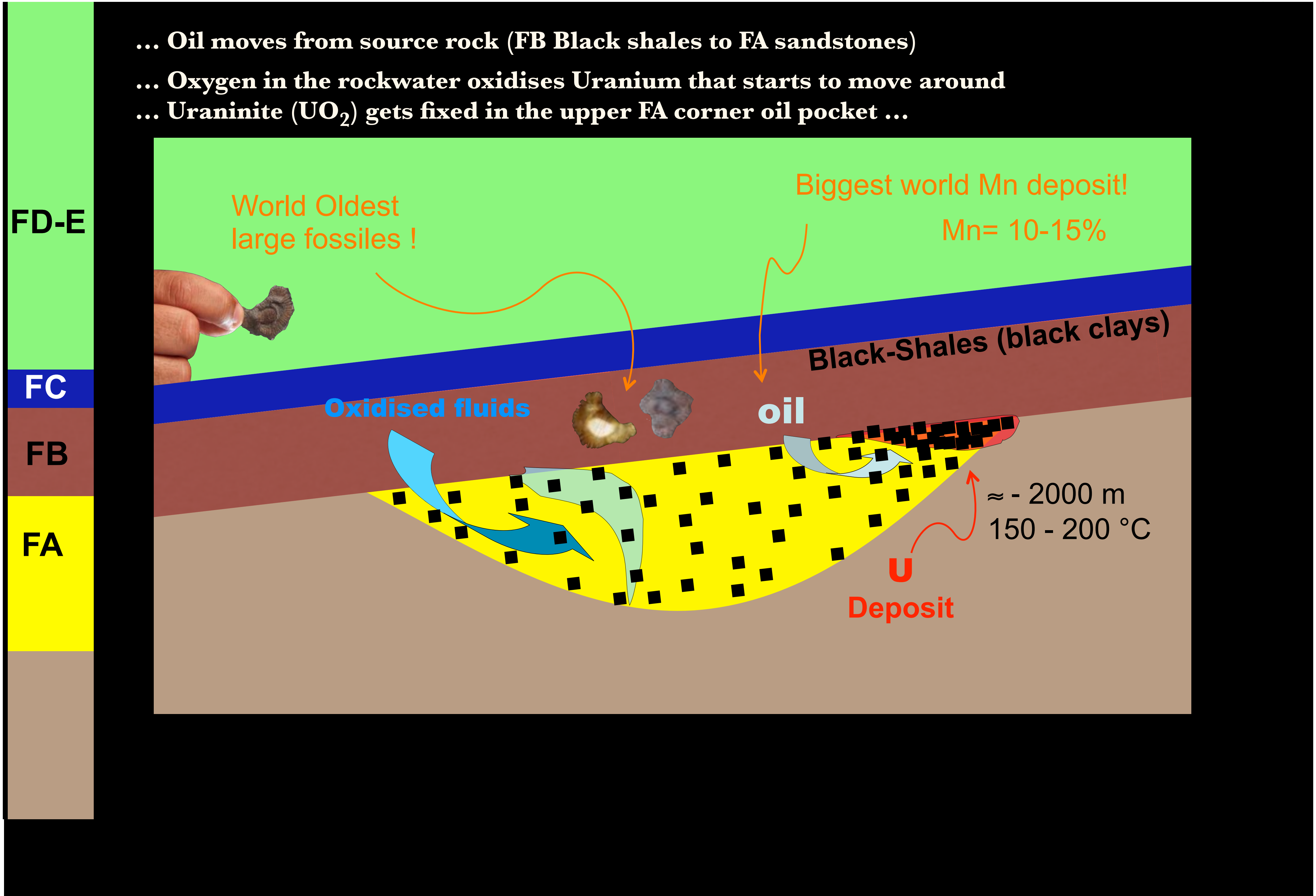
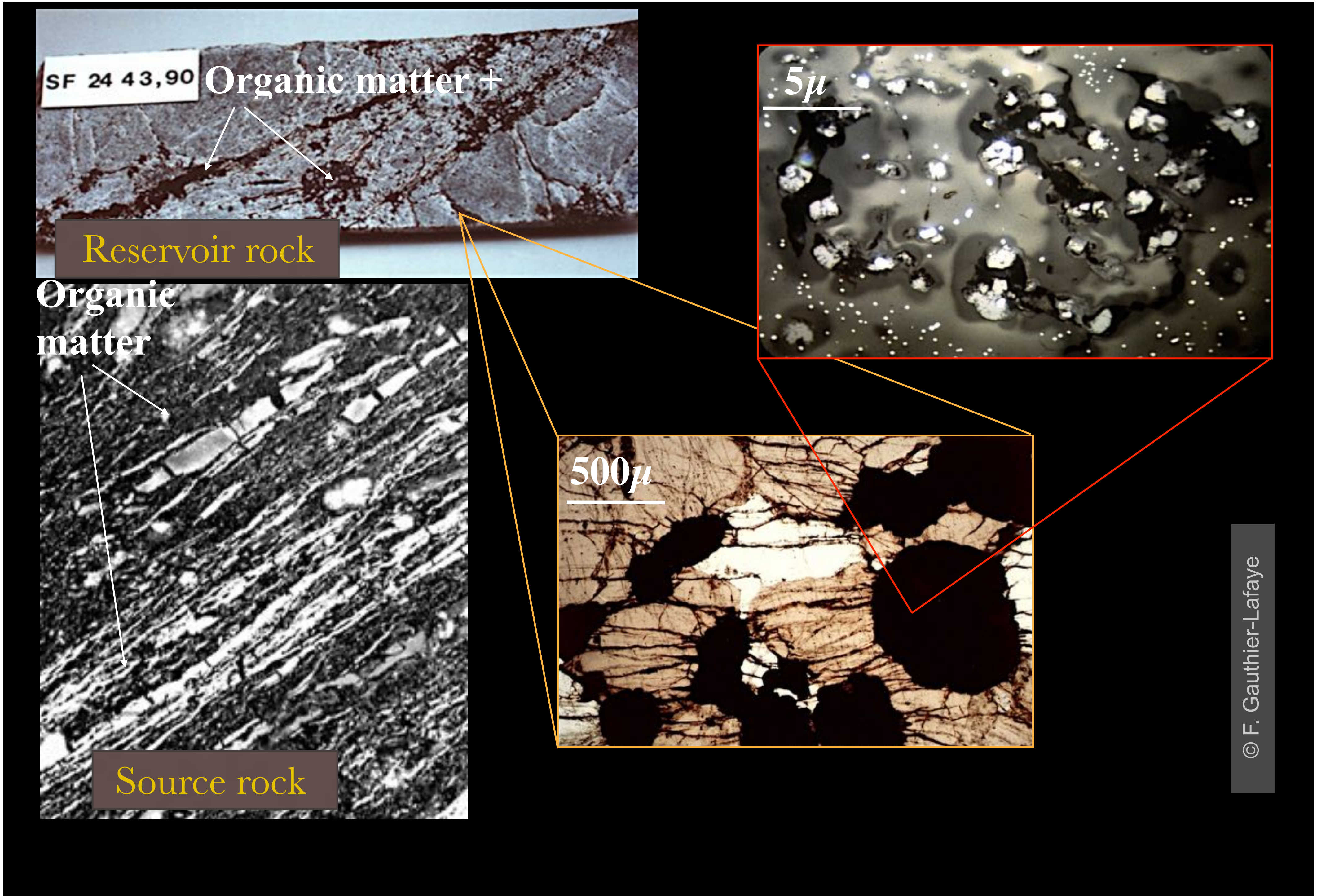
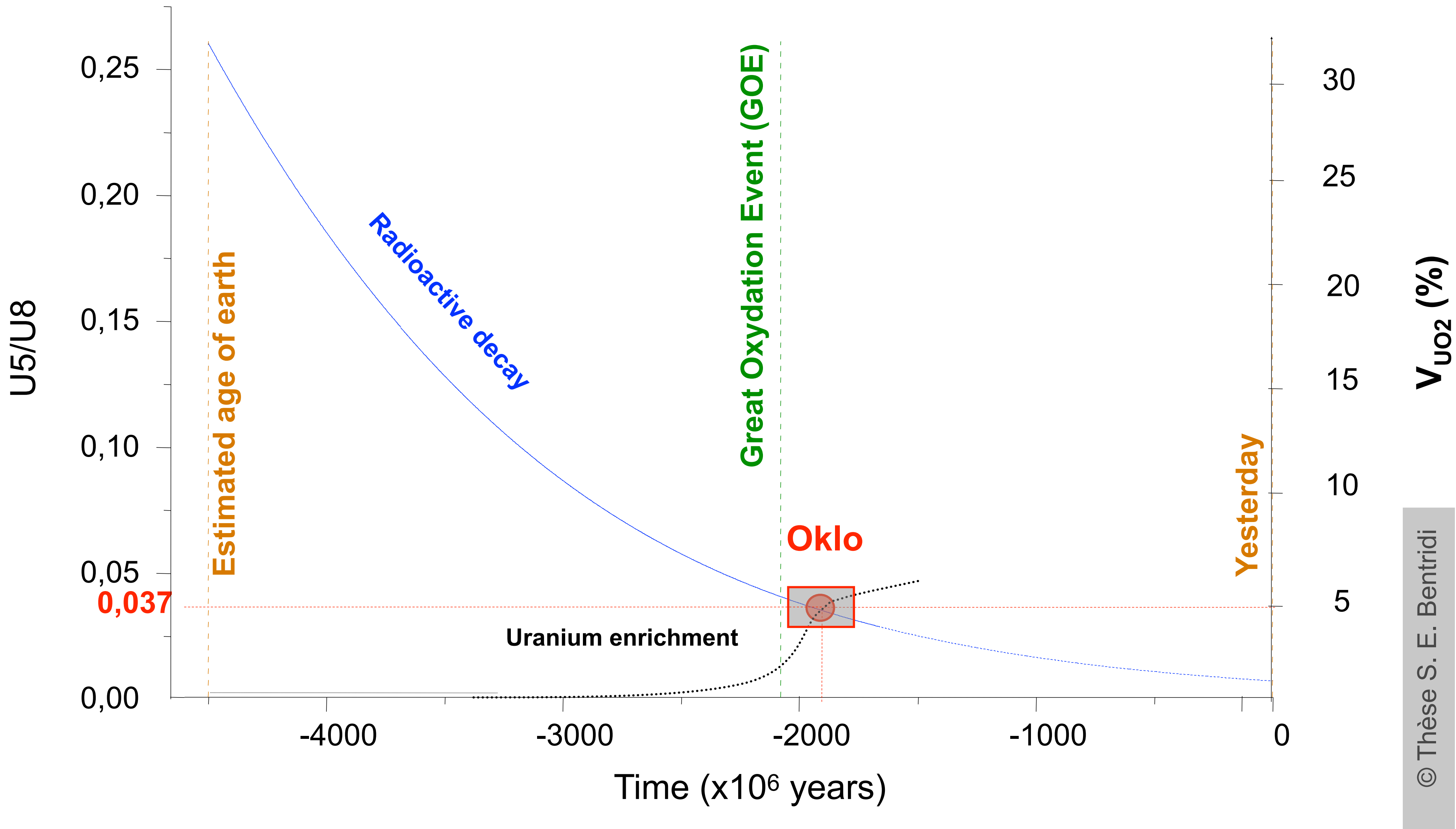


Oklo reactor ore in FA sandstones:



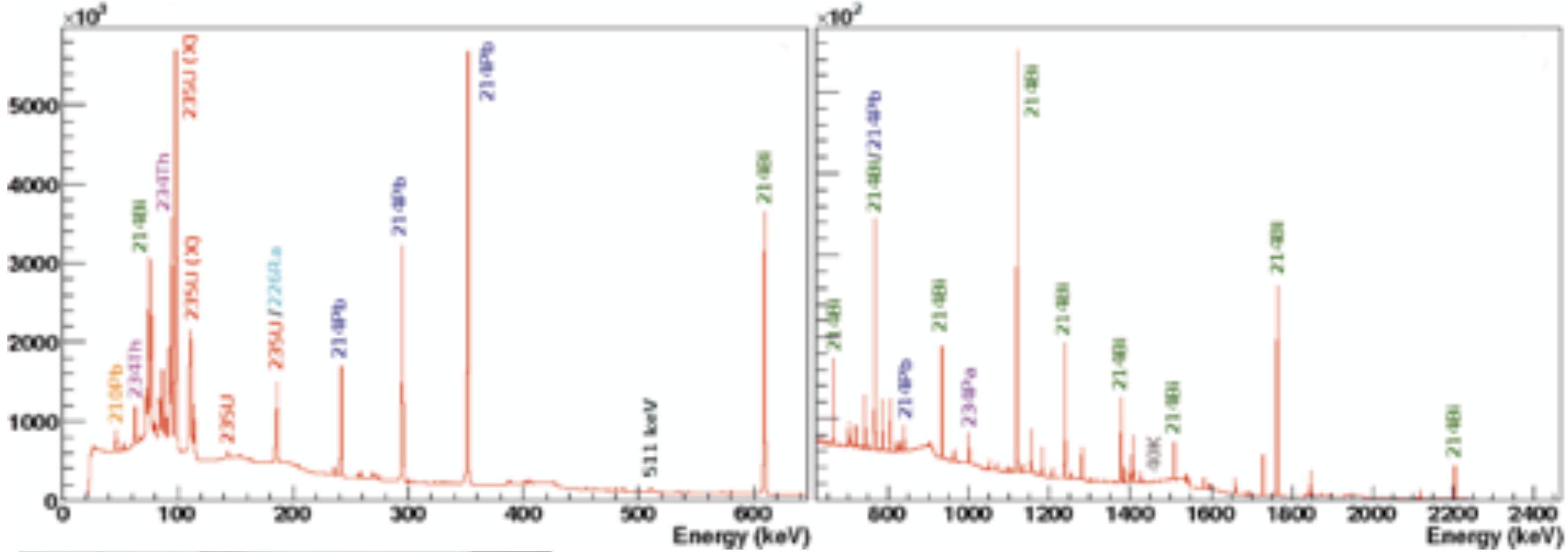
Genesis of the phenomenon

GOE... U concentration and U5 / U8 ratio



Oklo Samples Spectra

RZ13 sample



γ signature of natural Uranium

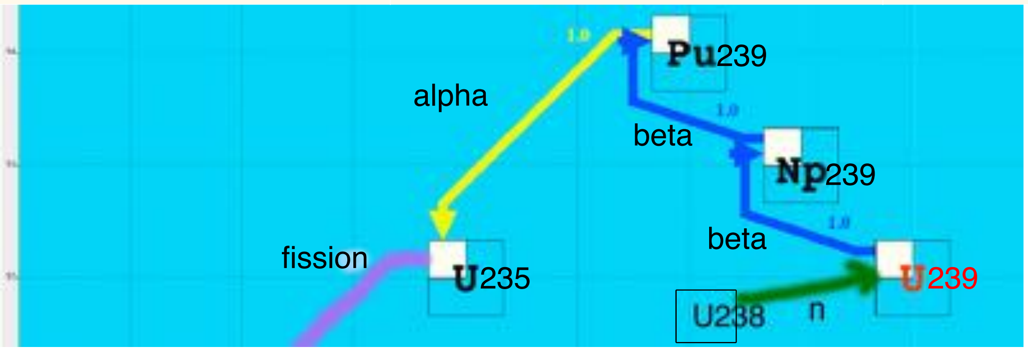
No traces of fission products

Isotopic ratio of U5 et U8 families

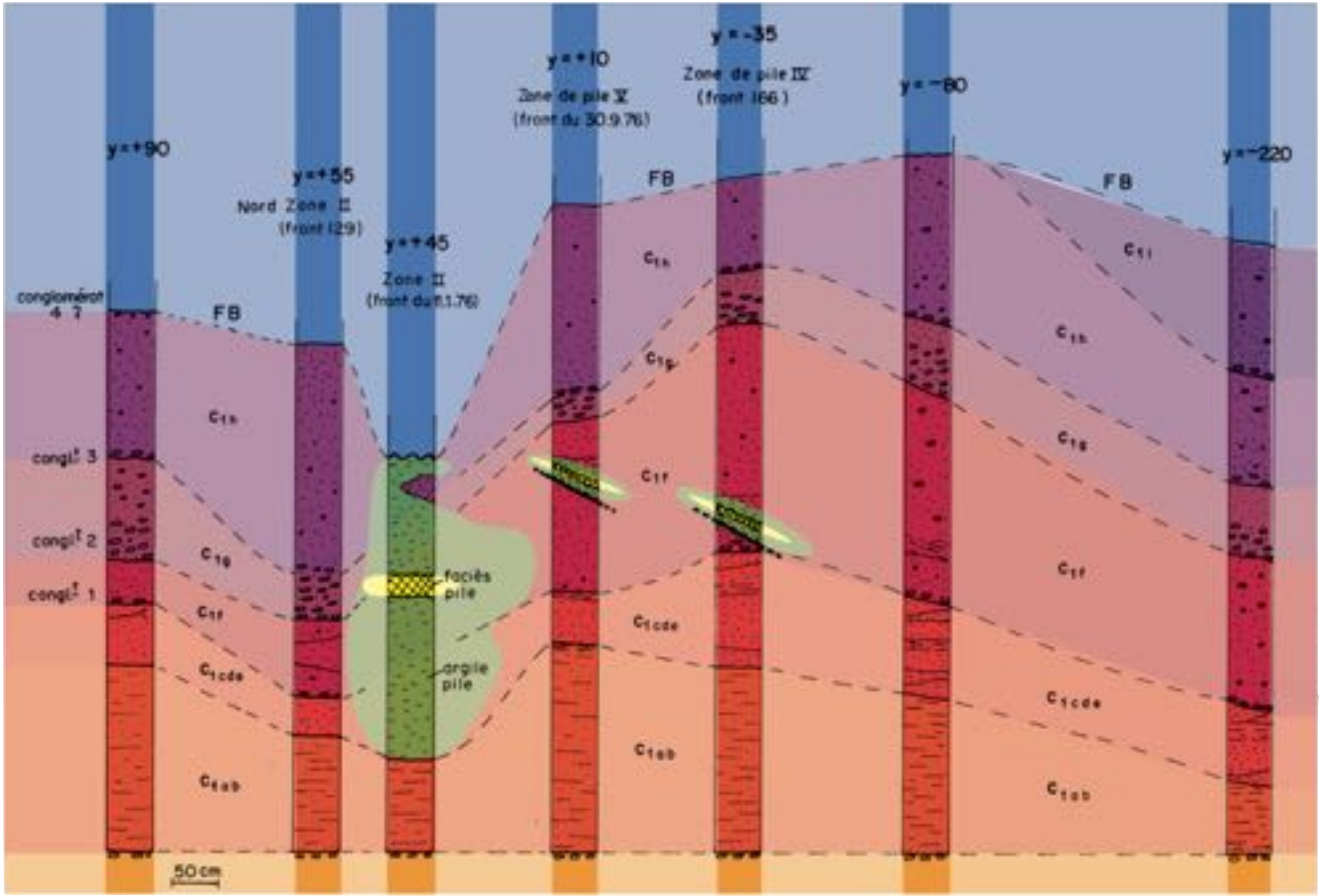
© J. Rubert Master Thesis

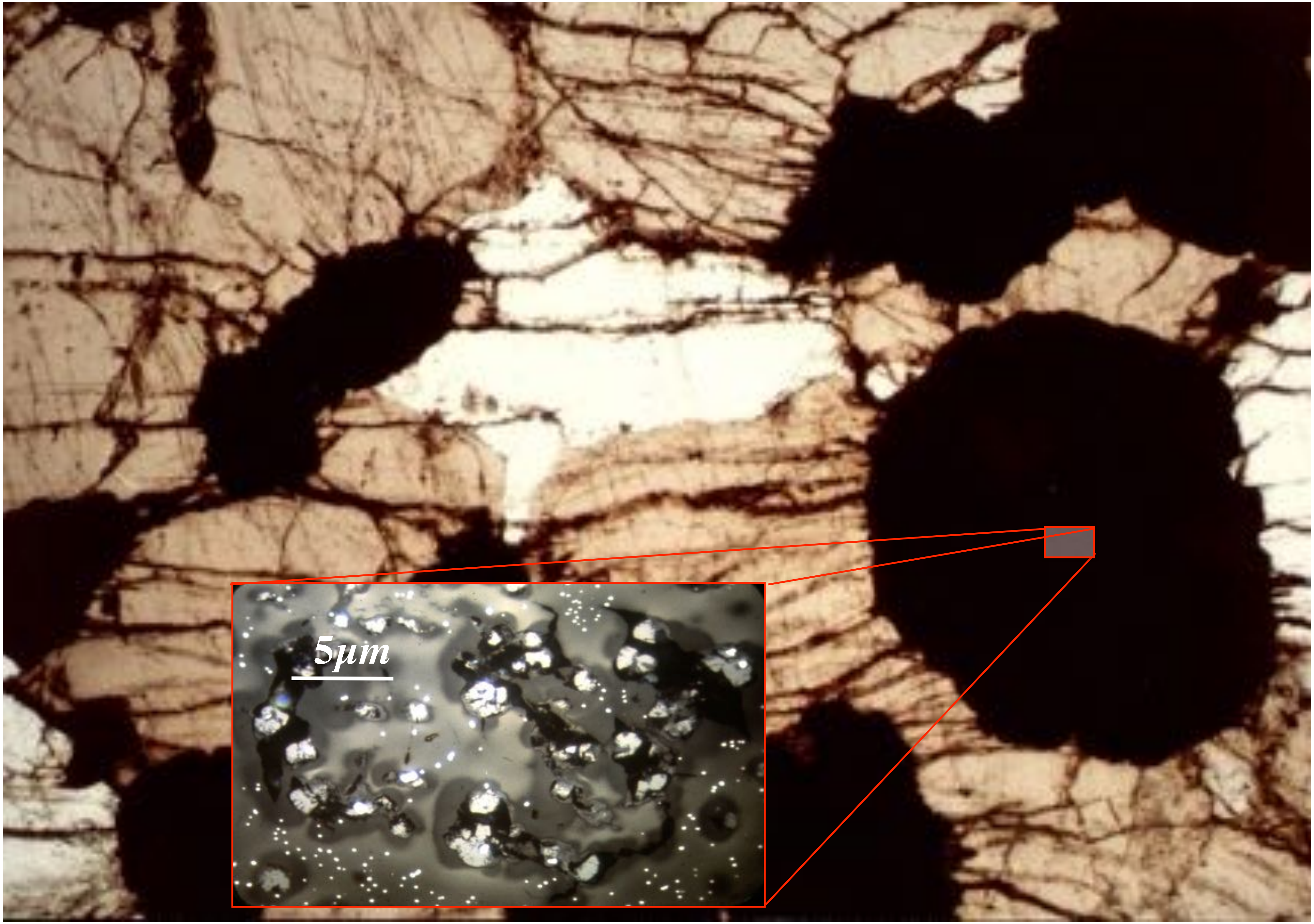
Average power

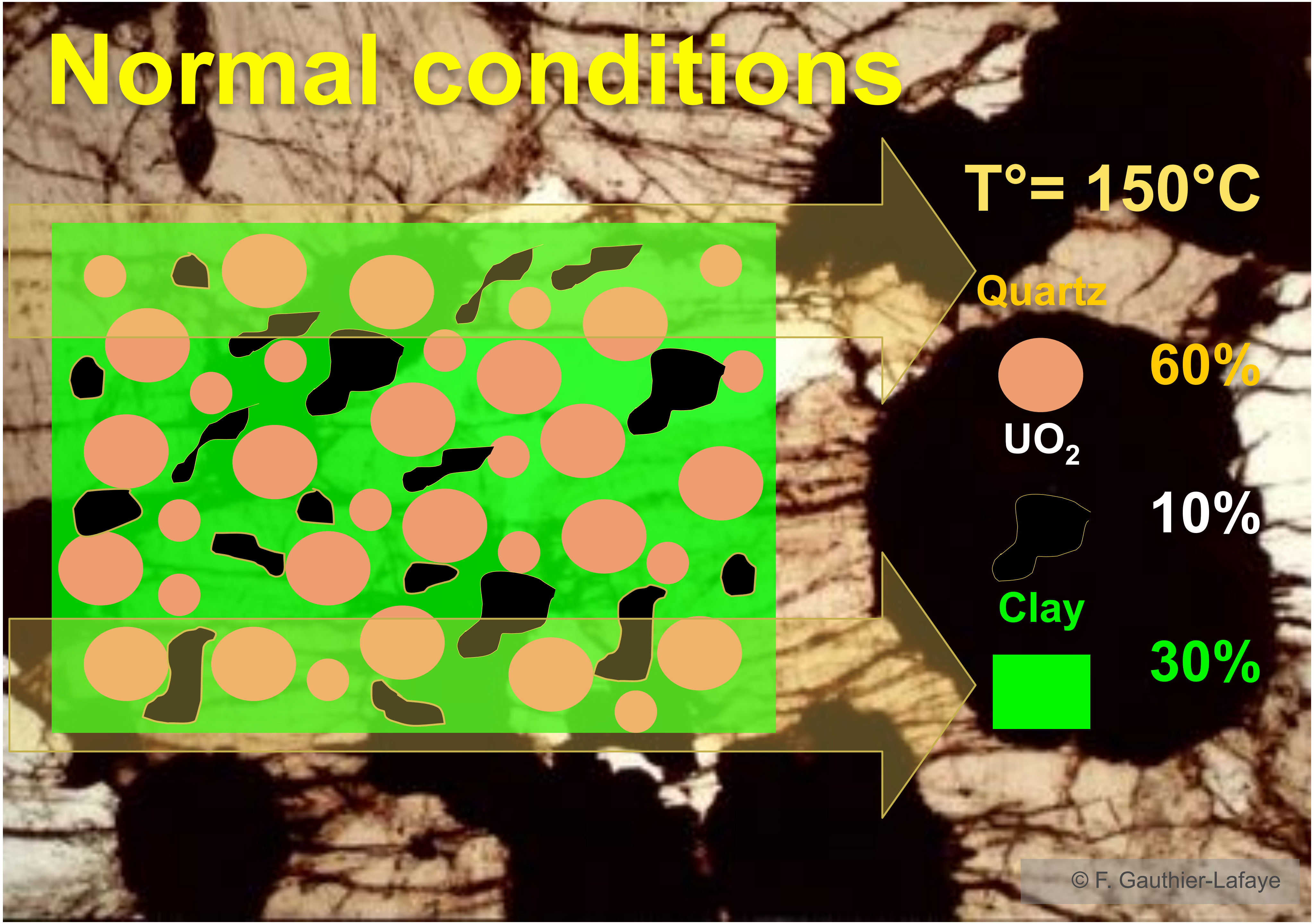
Operation	RZ13	RZ16
Natural isotopic ratio at the start up	3.680 %	3.680 %
isotopic ratio at the shut down	2.593 %	3.381 %
fraction of the fissioned ^{235}U	29.26 %	8.125 %
Released Energy (MJ/g)	917.3	254.4
Restitution Factor of ^{239}Pu	11.1 %	48.4 %
Fission contribution of ^{238}U and ^{239}Pu	25 %	7.7 %
Total released energy (Mj/g)	1345	409
Burn-up Rate (GWj/t)	15.9	4.89
Duration (year)	24 200	111 000
Power (W)	1 700	118



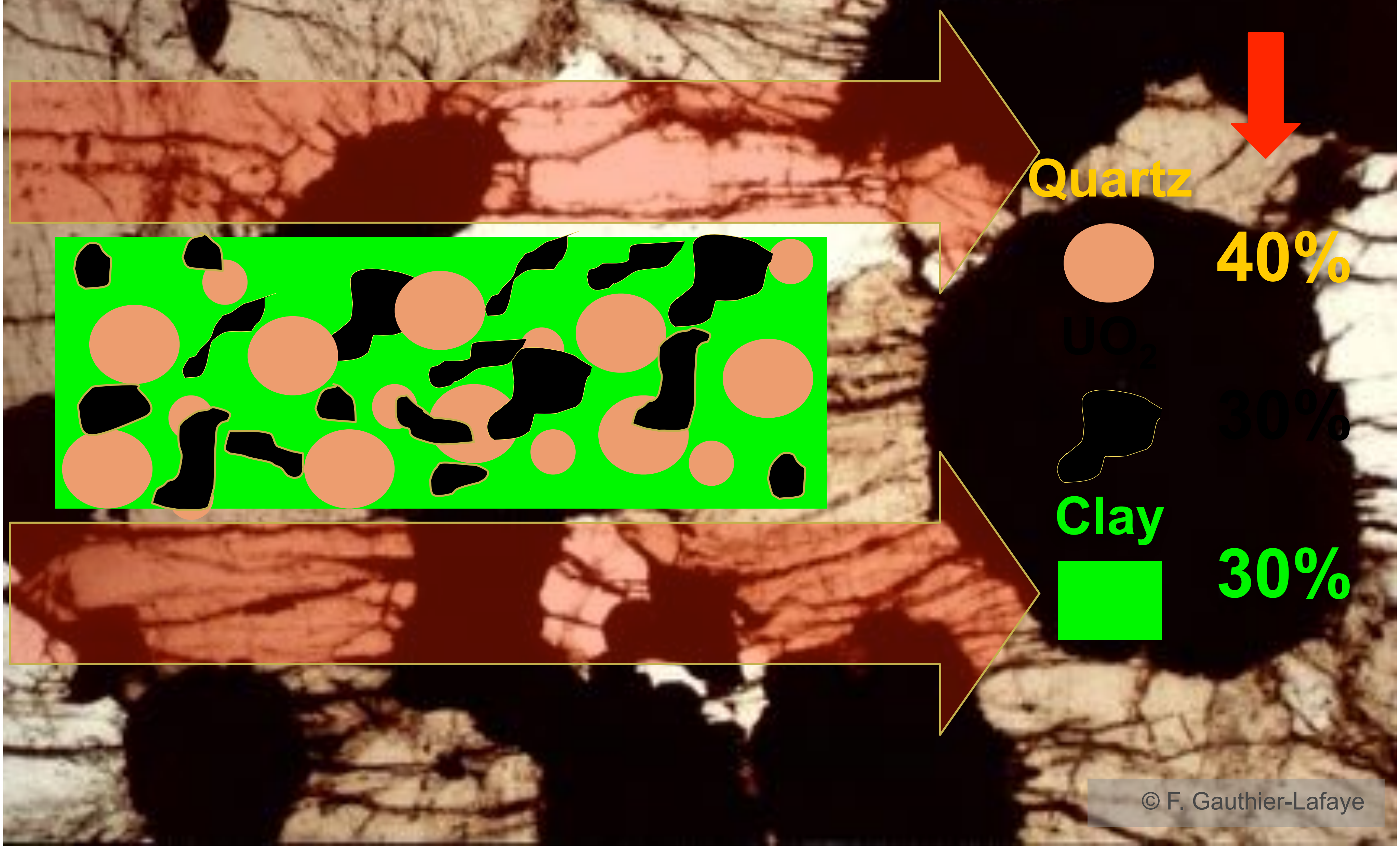
❖ Oklo mistery …



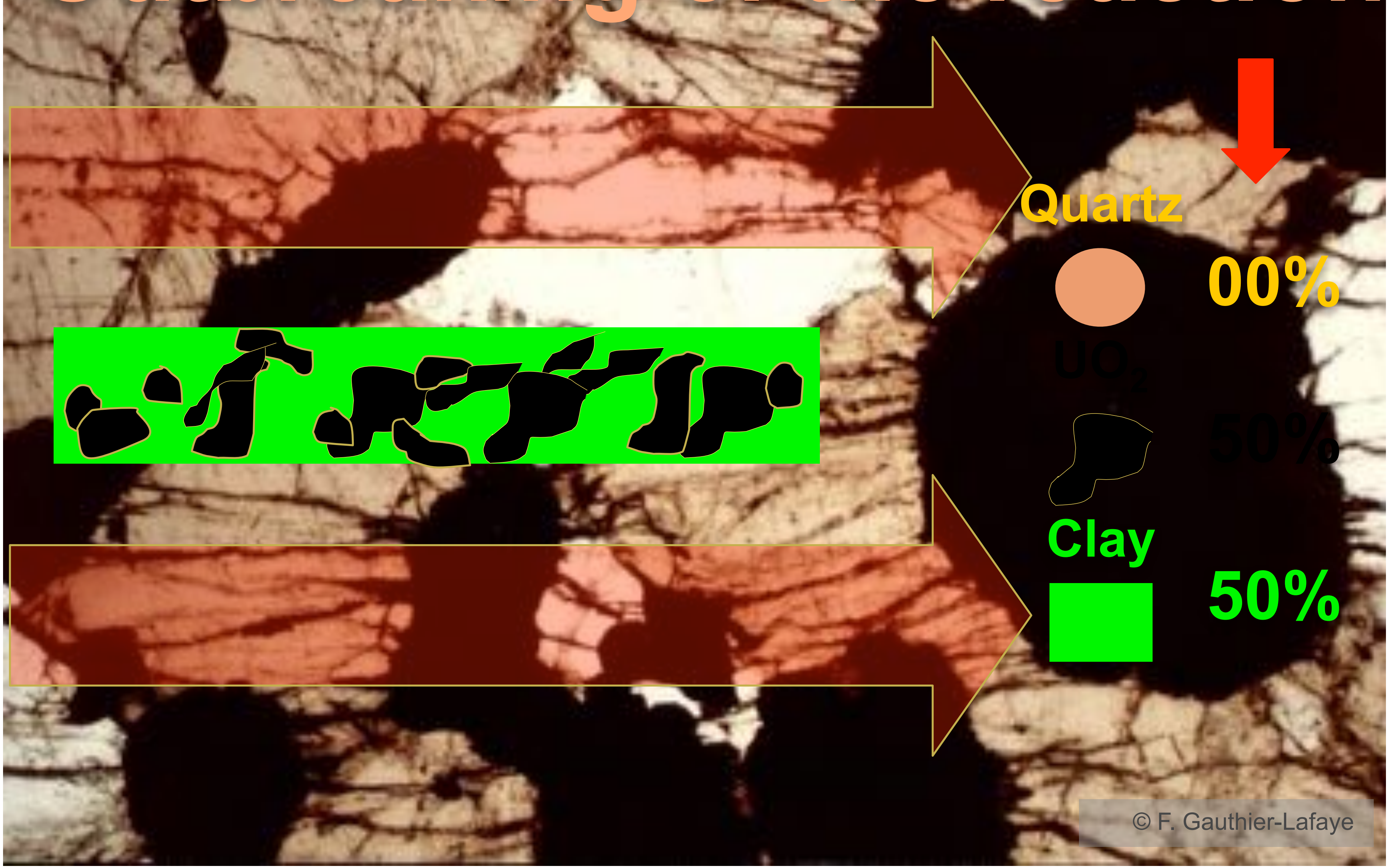

5μm

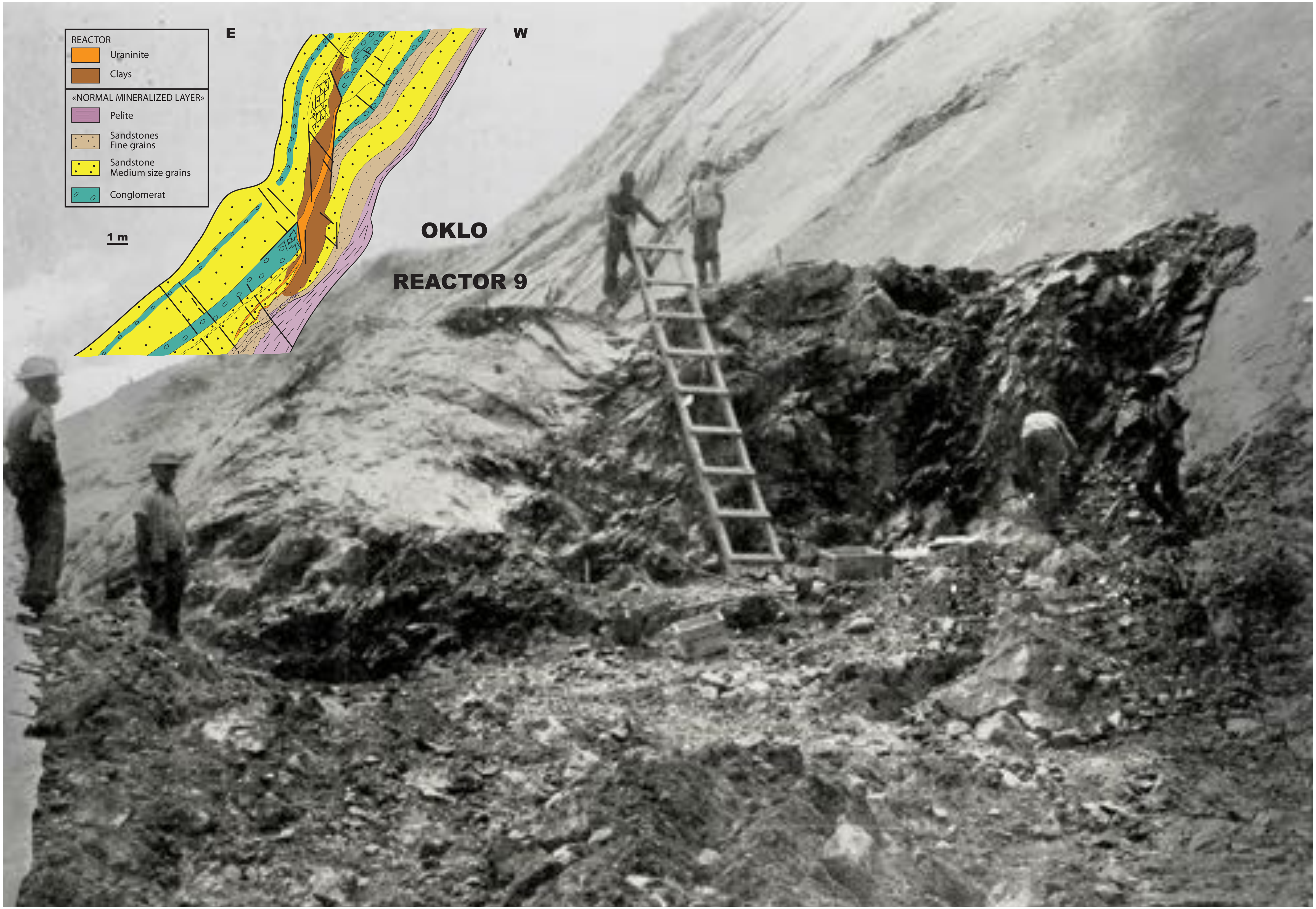

Normal conditions
T°= 150°C
Quartz
60%
UO2
10%
Clay
30%
© F. Gauthier-Lafaye

Outbreaking of the reaction

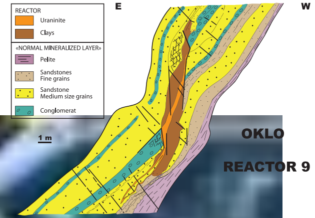


Outbreaking of the reaction




REACTOR
Uraninite
Clays
«NORMAL MINERALIZED LAYER»
Pelite
Sandstones
Fine grains
Sandstone
Medium size grains
Conglomerat
1 m
E
W
OKLO
REACTOR 9

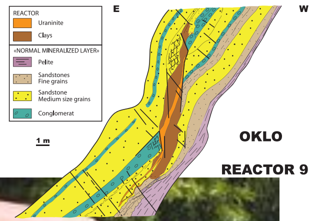
Oklo mistery ...



... how to go backward in time ?

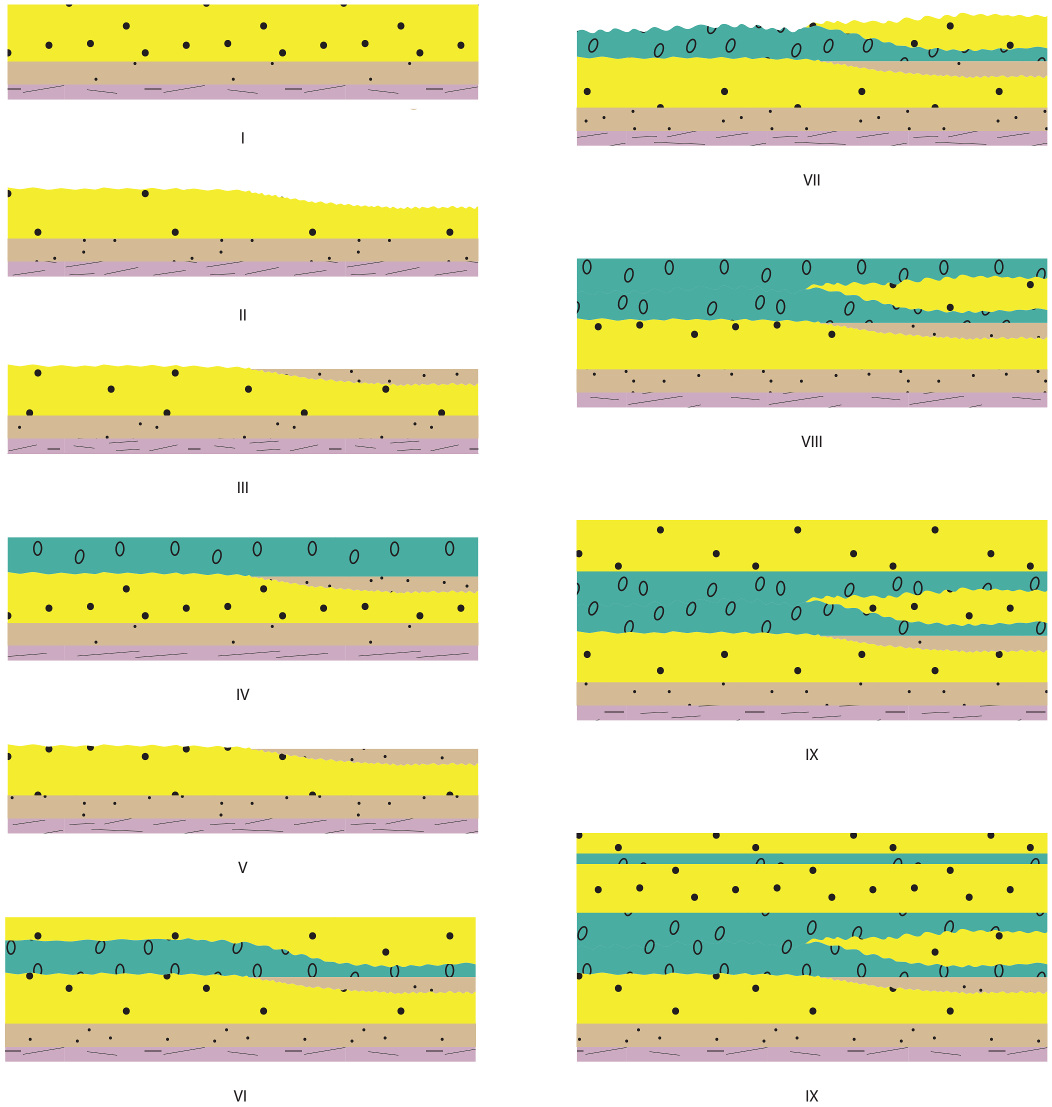
Oklo mistery …

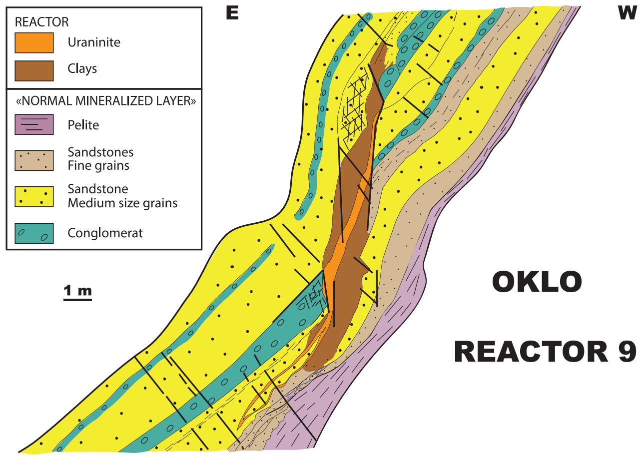
… how to go backward in time ?



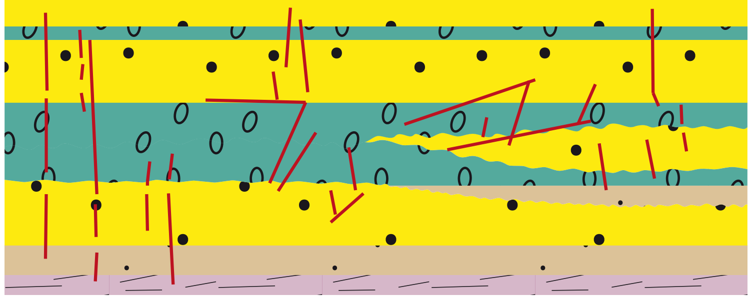
Modeling the reactor : RZ9

RZ9 site genesis before Great Oxydation Event

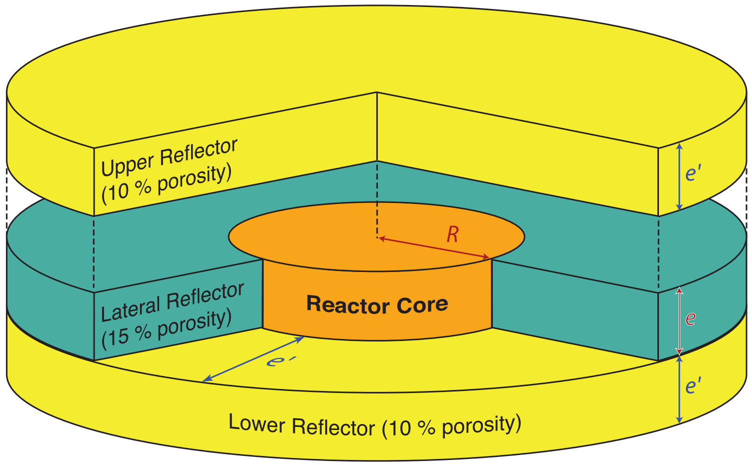


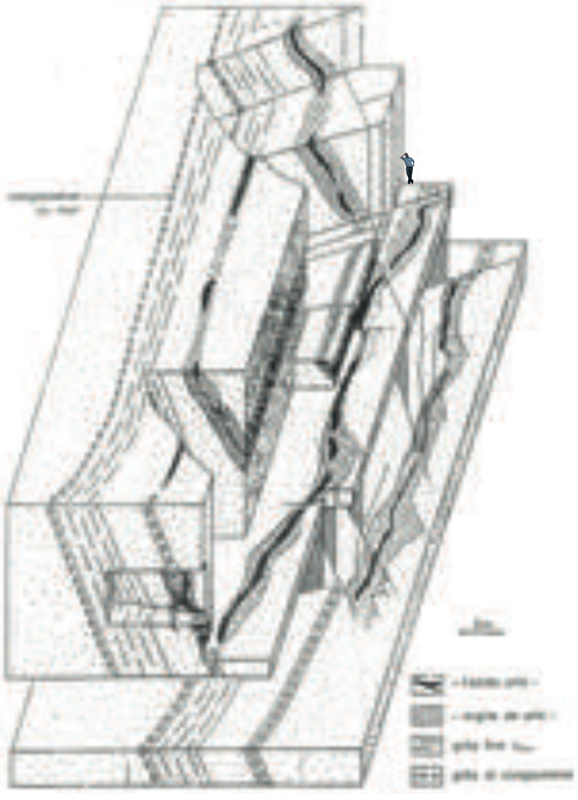


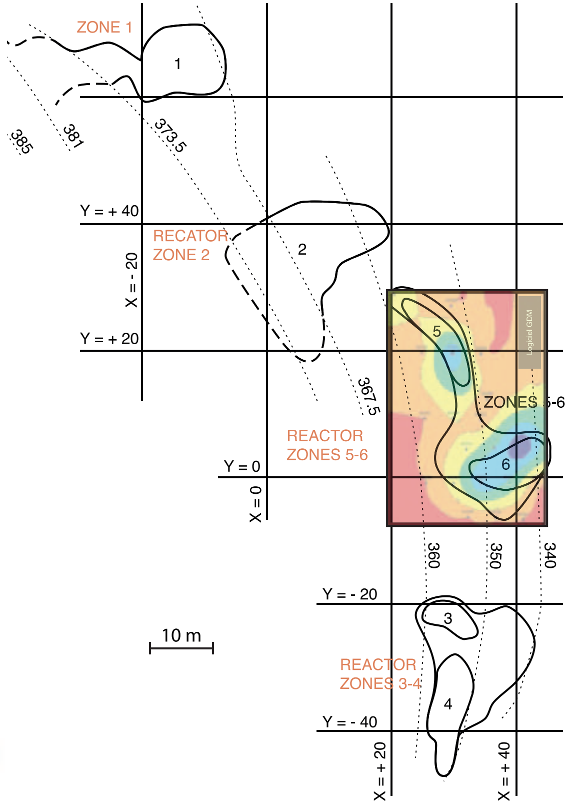
The genesis is understood, ...



... start up explained







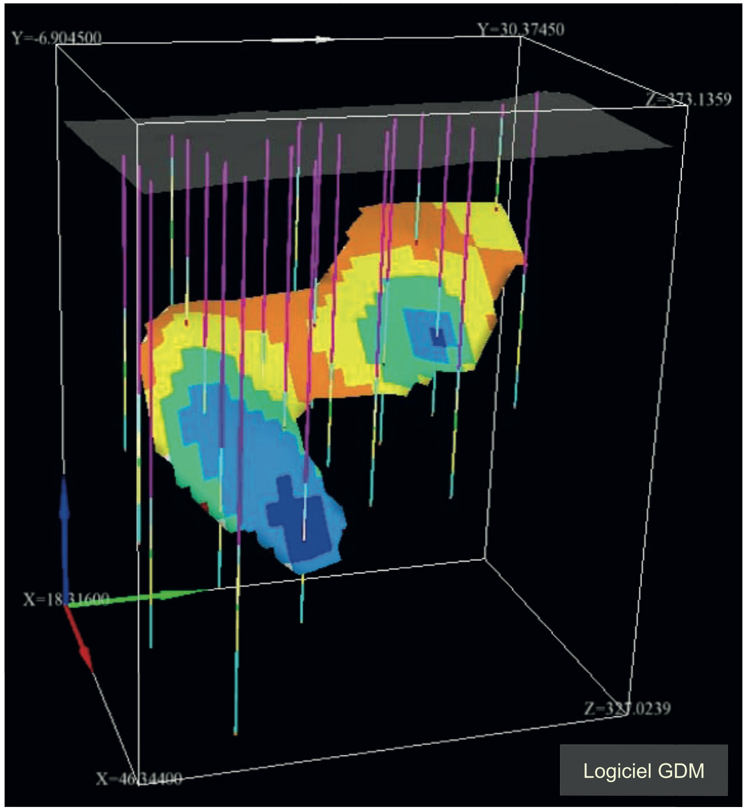
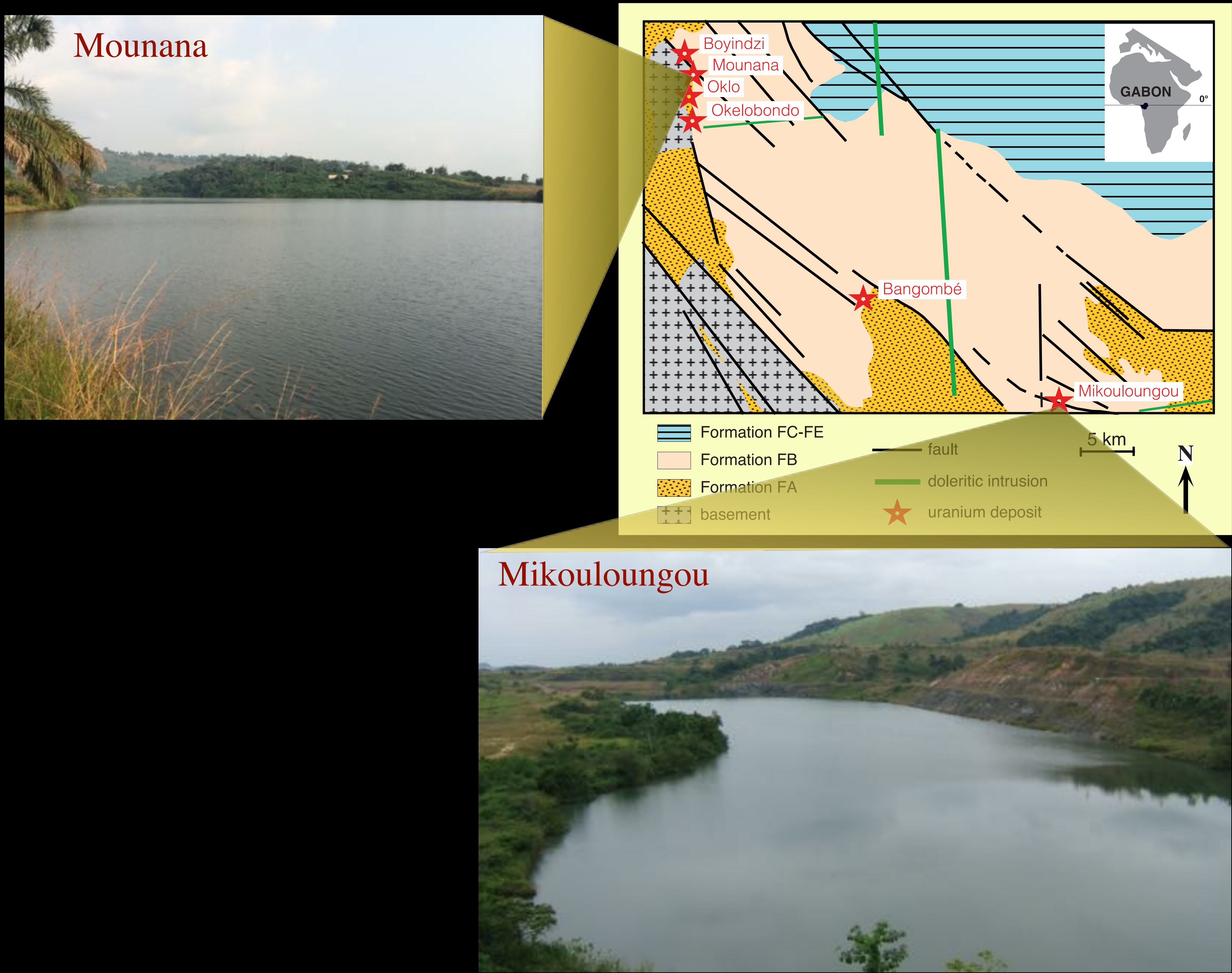
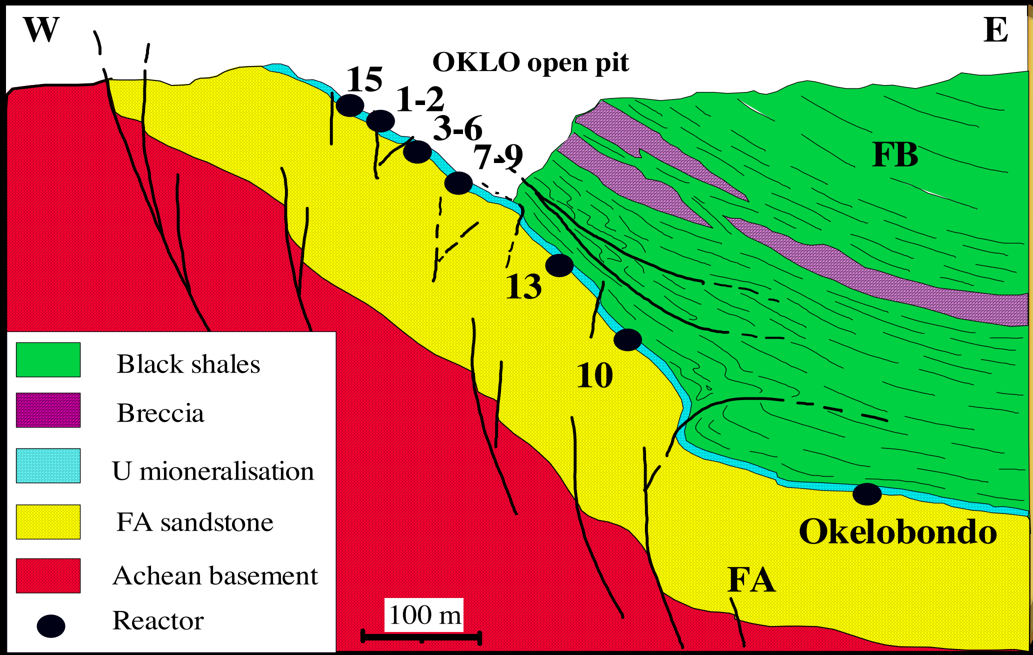
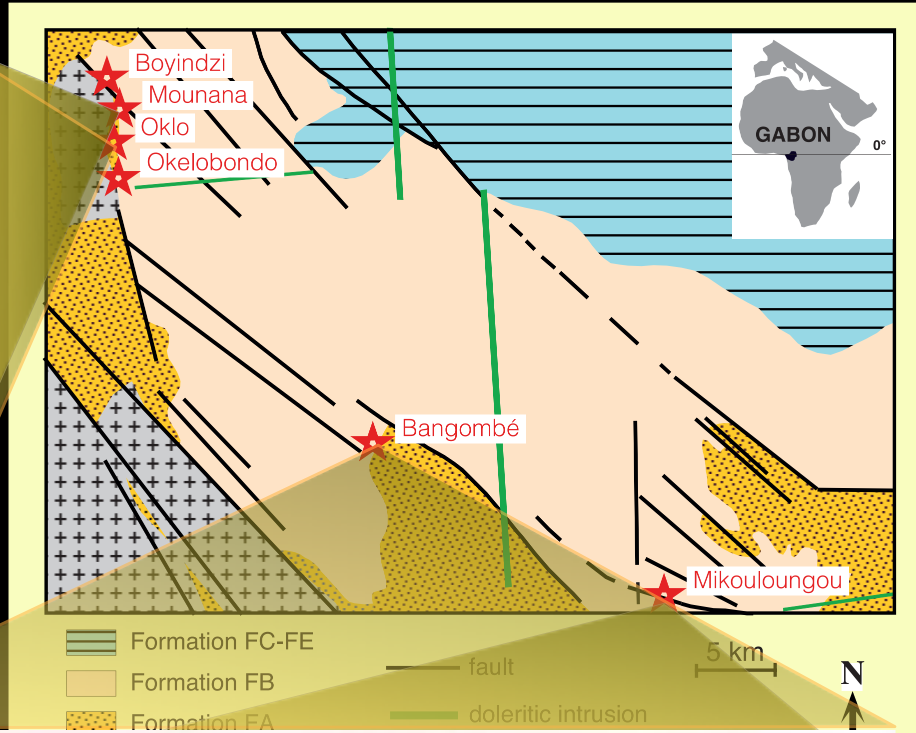


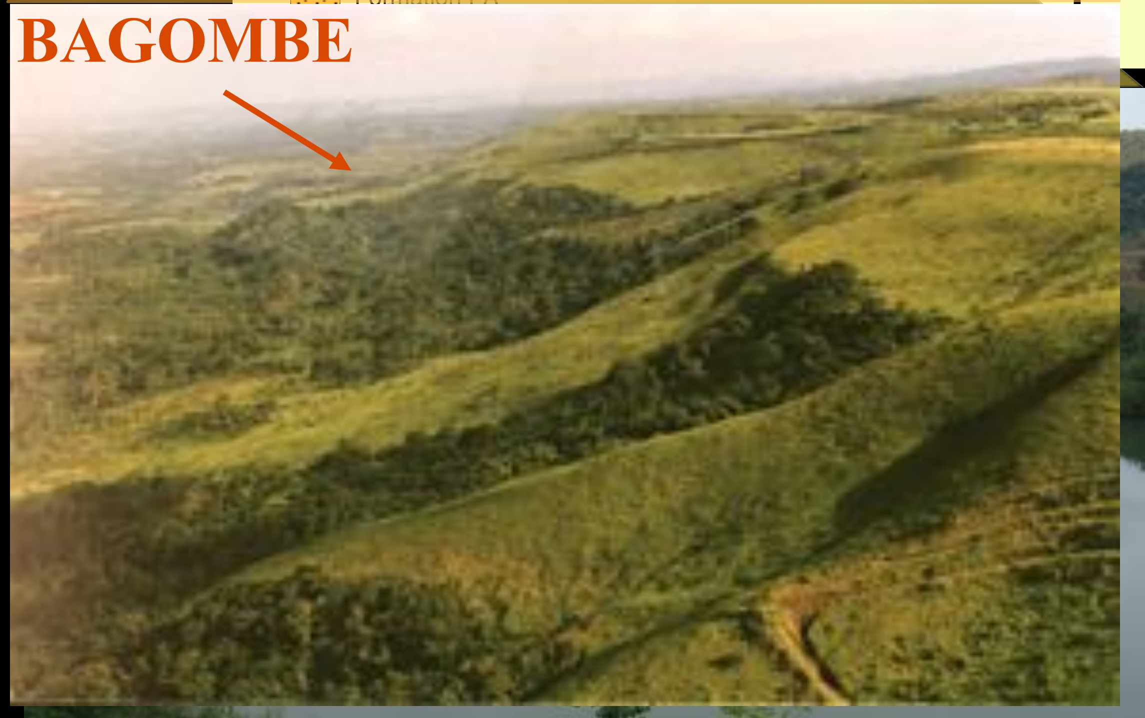
Table 1 | Geometry and physical characteristics as observed in 1975 for some Oklo reaction zones.

Reaction Zone	U content[NAU91]		^{235}U amount		Reaction Zone extension	Estimated power			Burn-up (GW·d/ton)
	Mass[NAU91] (tons)	Mass fraction (% wt.)	Missing ^{235}U (kg)	Burnt ^{235}U (in kg 1.95 Ga ago[NAU91])	Maximum ellipsoidal Width[GAU75,GAU75] X(m) x Y(m)	Released Energy[NAU91] (GW·d)	Operating Duration[GAU96] [BLA98] (10^3 y)	Mean power [NAU91] (kW)	
RZ1	230-240	40	200[NAU91]	2012	12 x 40	1.9×10^3	-		8.1
RZ2	200	50-60	200[NAU91]	2012	12 x 30	2.0×10^3	~800	6.5	9.5
RZ9	44	25-30	26.4[NAU91]	265	7 x 12	2.5×10^2	~220	3.2	2.8
RZ10	340	50-60	90[BLA98]	905	20 x 50[BLA98]	8.6×10^2	~200	11.8	2.5


Mounana
Boyindzi
Mounana
Oklo
Okelobondo
GABON
0°
Bangombé
Mikouloungou
Formation FC-FE
Formation FB
Formation FA
basement
fault
doleritic intrusion
uranium deposit
5 km
N
Mikouloungou







Reactor zones discovered:

- 13 in Oklo (numbered 1 to 16, but 12 & 14 were not reactors & RZ 10 & 11 were one reactor)
- 1 Okelobondo
- 1 in Bangombe

... but there may have been more !!!