



CHANGEMENT D'ECHELLE EN GEOSCIENCES :
DE L'ATOME A LA TERRE

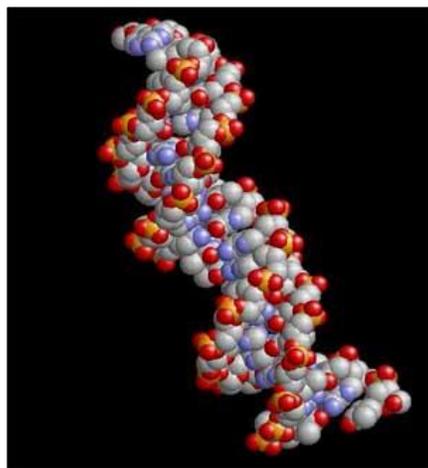
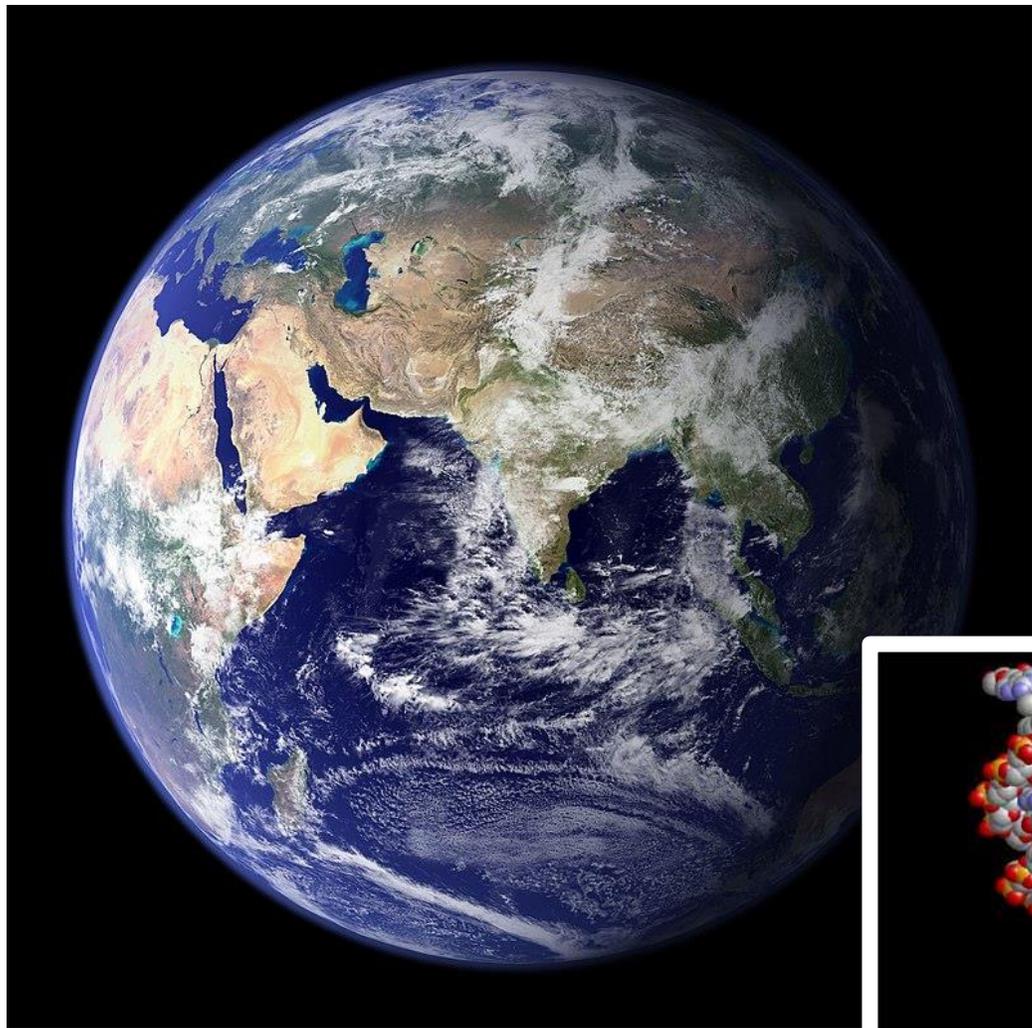
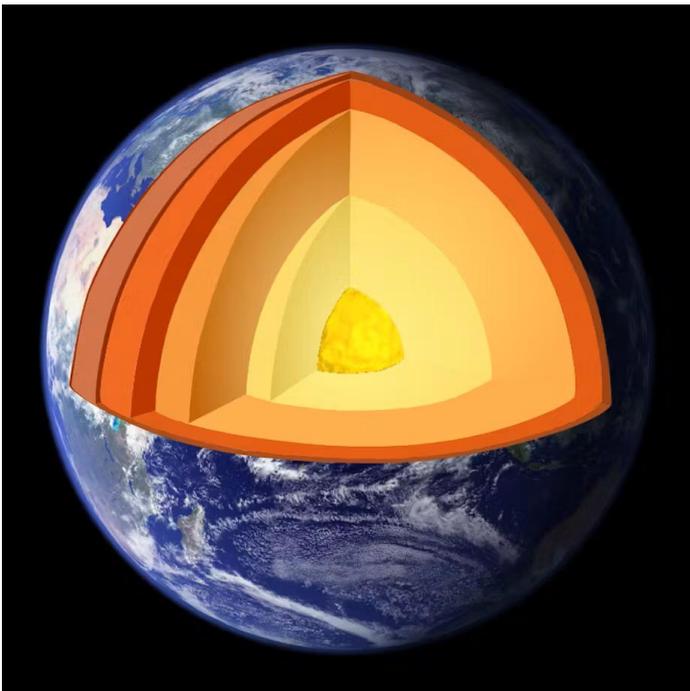
2 nm

Pr Franck Bourdelle
Enseignant-Chercheur en Géosciences

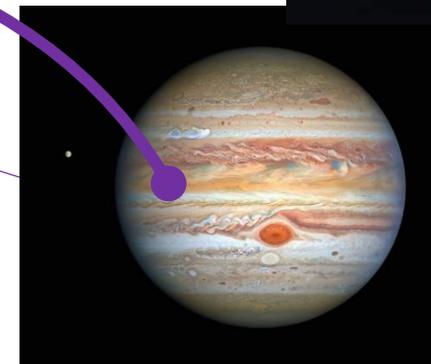
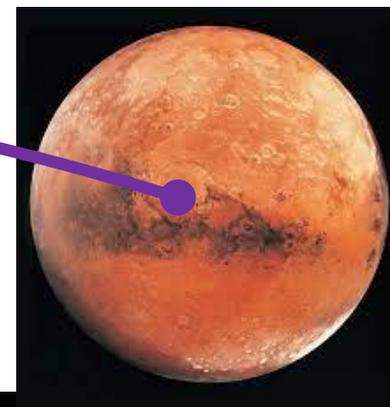
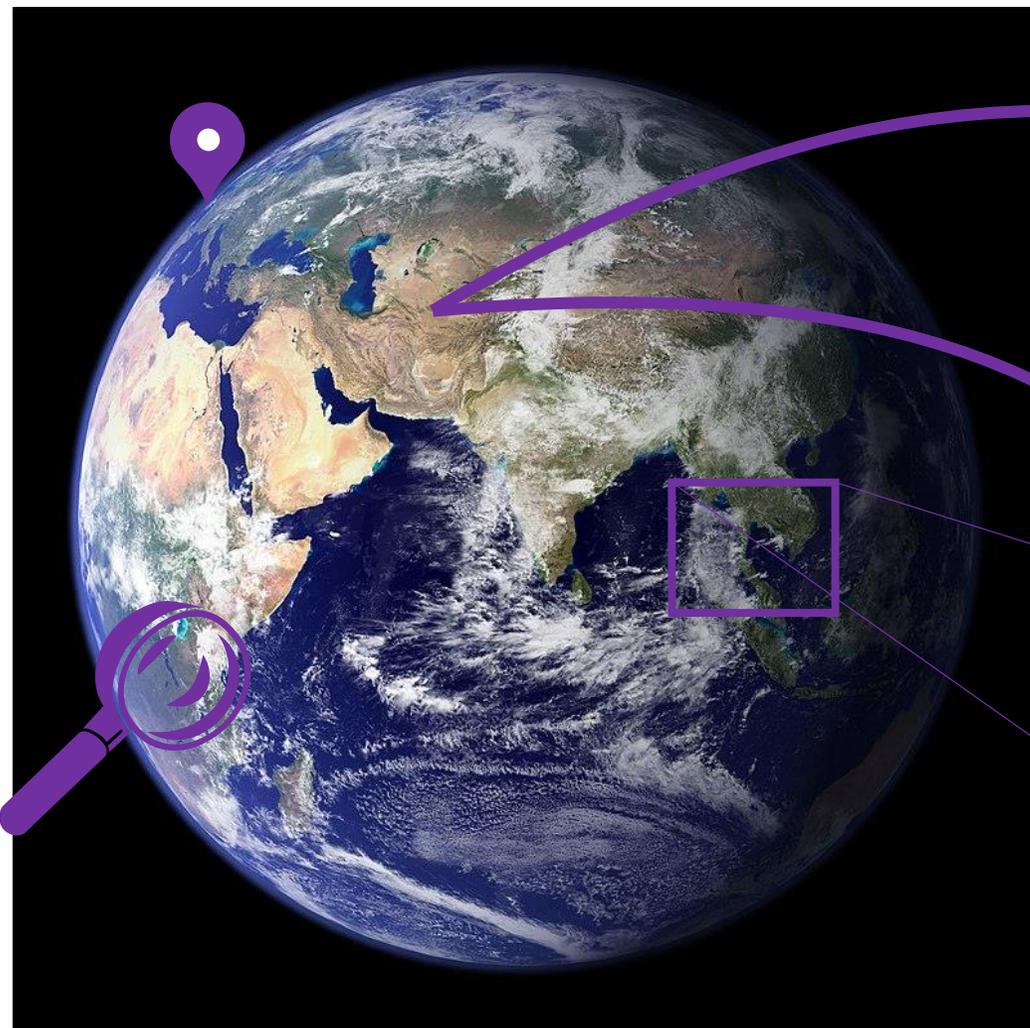
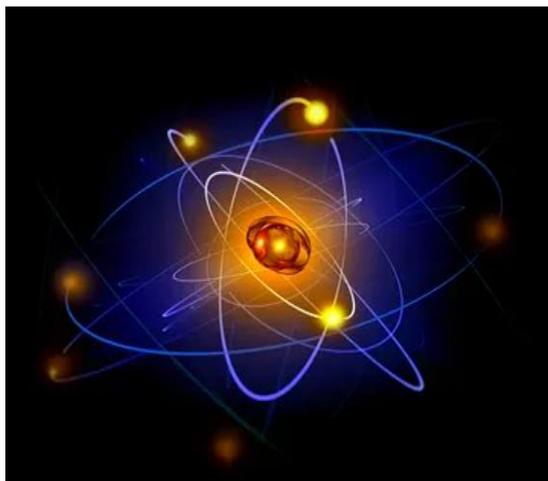
Olympiades Académiques des Géosciences 2022-2023
17 Avril 2023



COMPRENDRE LA TERRE : SON FONCTIONNEMENT, SON EVOLUTION, SON ORIGINE... ET NOS ORIGINES !

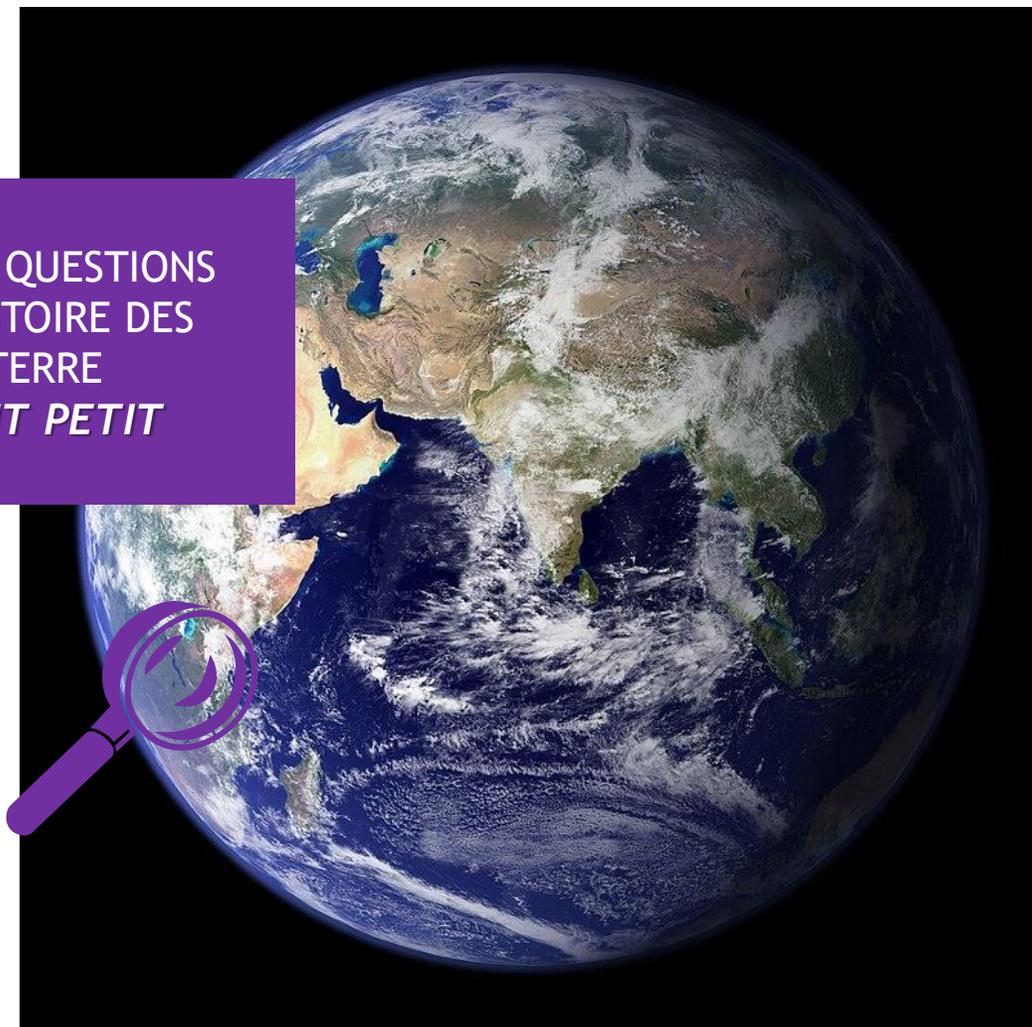
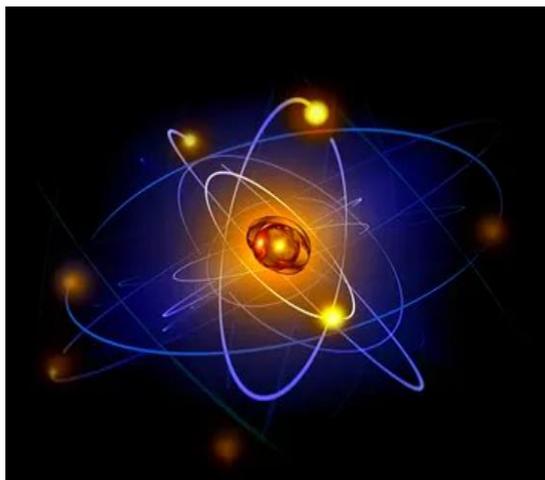


COMPRENDRE LA TERRE : SON FONCTIONNEMENT, SON EVOLUTION, SON ORIGINE... ET NOS ORIGINES !

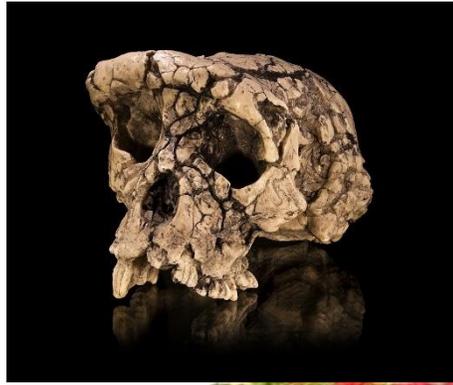


COMPRENDRE LA TERRE : SON FONCTIONNEMENT, SON EVOLUTION, SON ORIGINE... ET NOS ORIGINES !

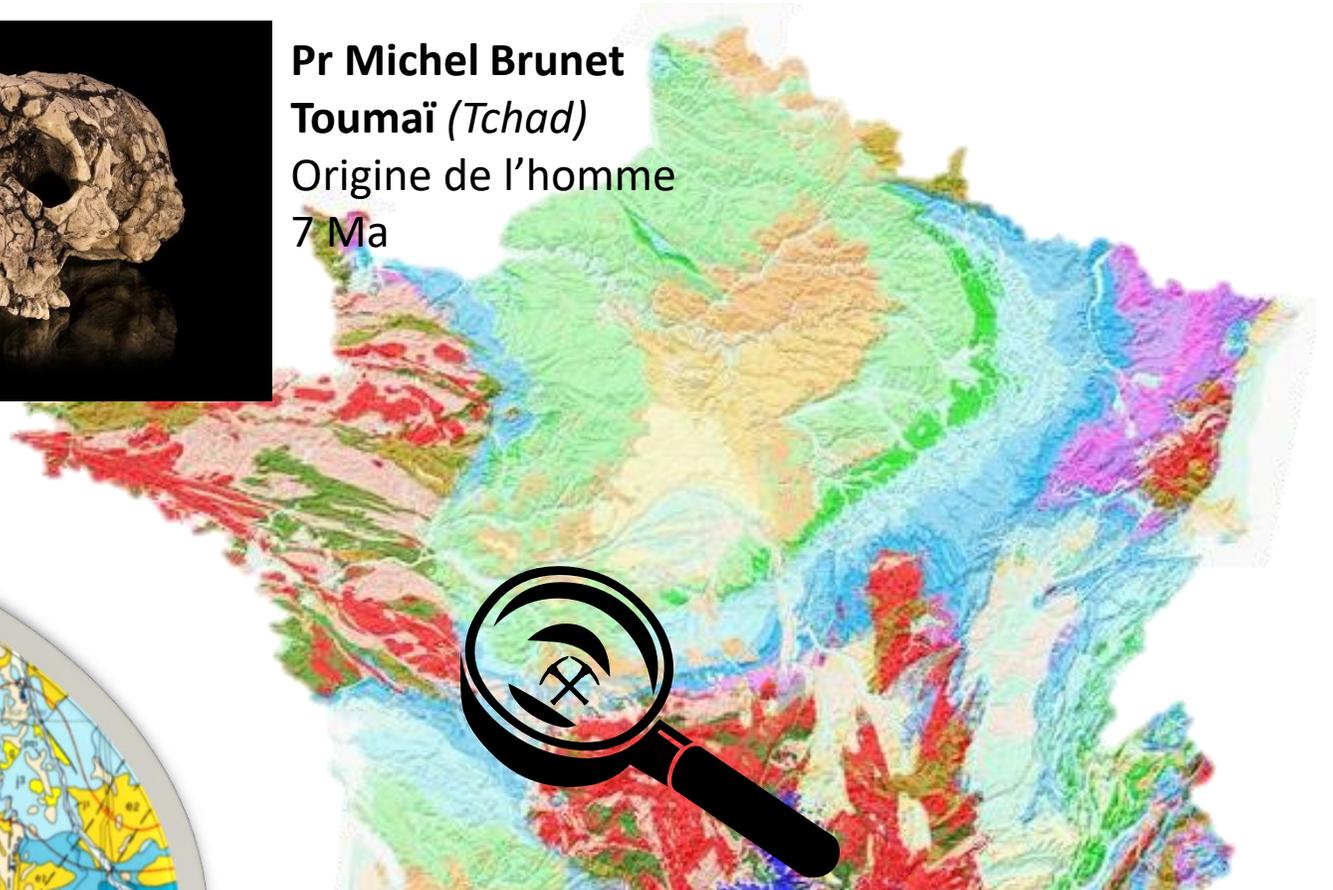
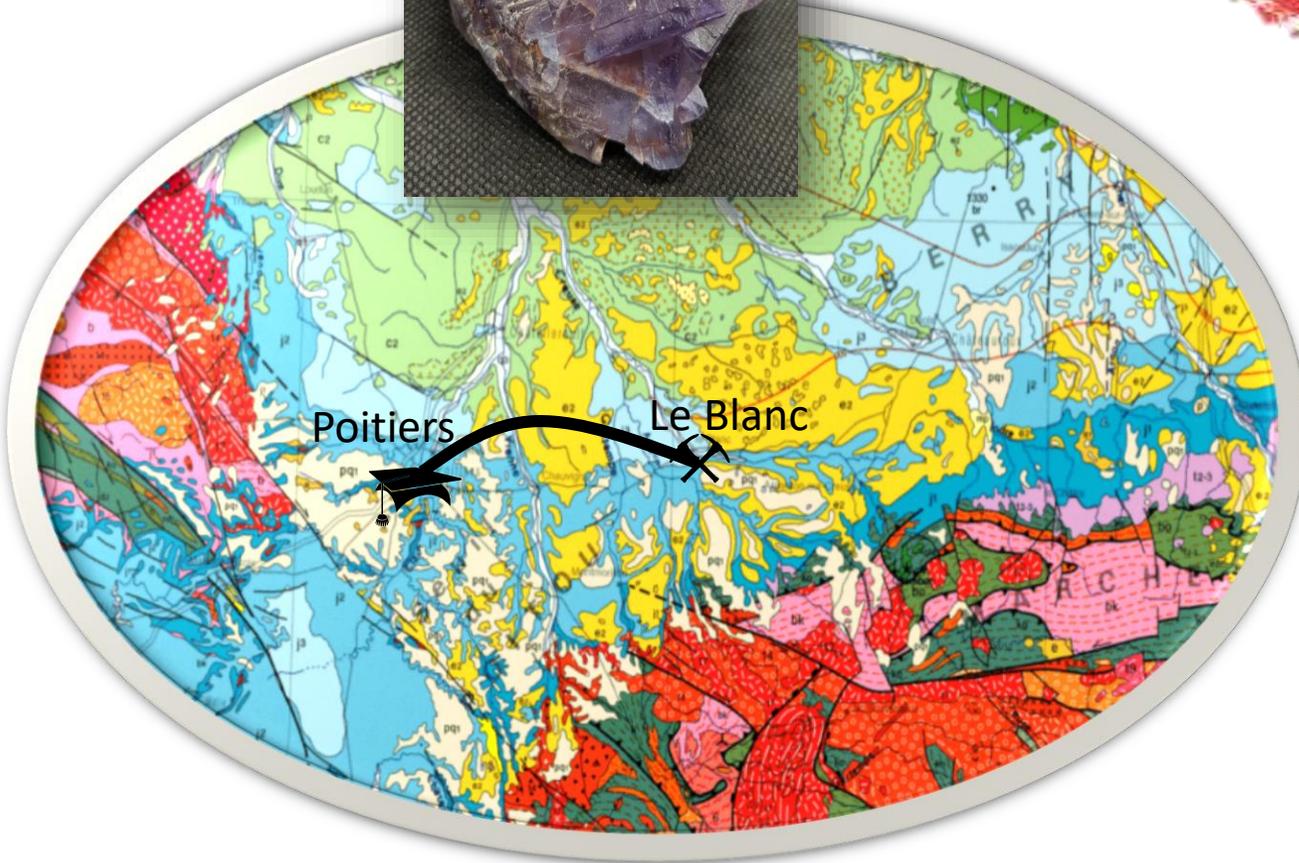
- ▶ DONNER DES REPONSES AUX QUESTIONS SUR NOS ORIGINES ET L'HISTOIRE DES GEOSYSTEMES/DE LA TERRE *EN ETUDIANT L'INFINIMENT PETIT*



LES ORIGINES D'UN CHERCHEUR



Pr Michel Brunet
Toumaï (*Tchad*)
Origine de l'homme
7 Ma

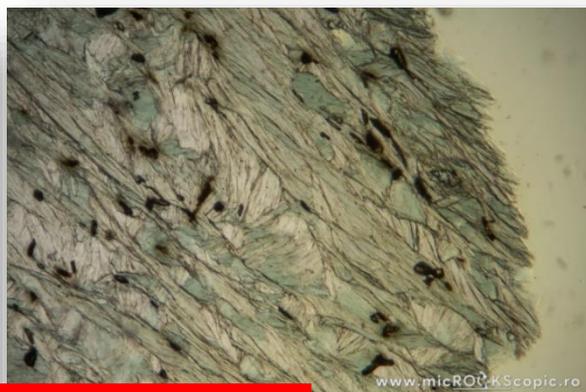


Pr Abderrazak El albani
Orga. pluricellulaires (*Gabon*)
Aux origines de la vie
2,1 Ga

LES ORIGINES D'UN CHERCHEUR

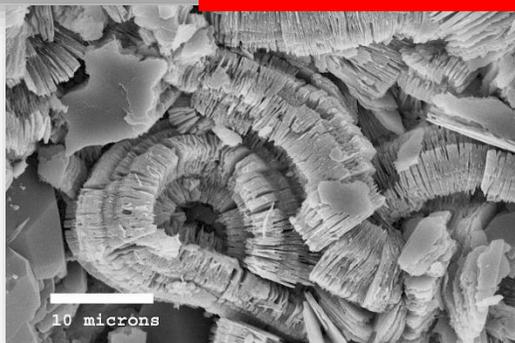


@ James St John



www.micROSCOPIE.ro

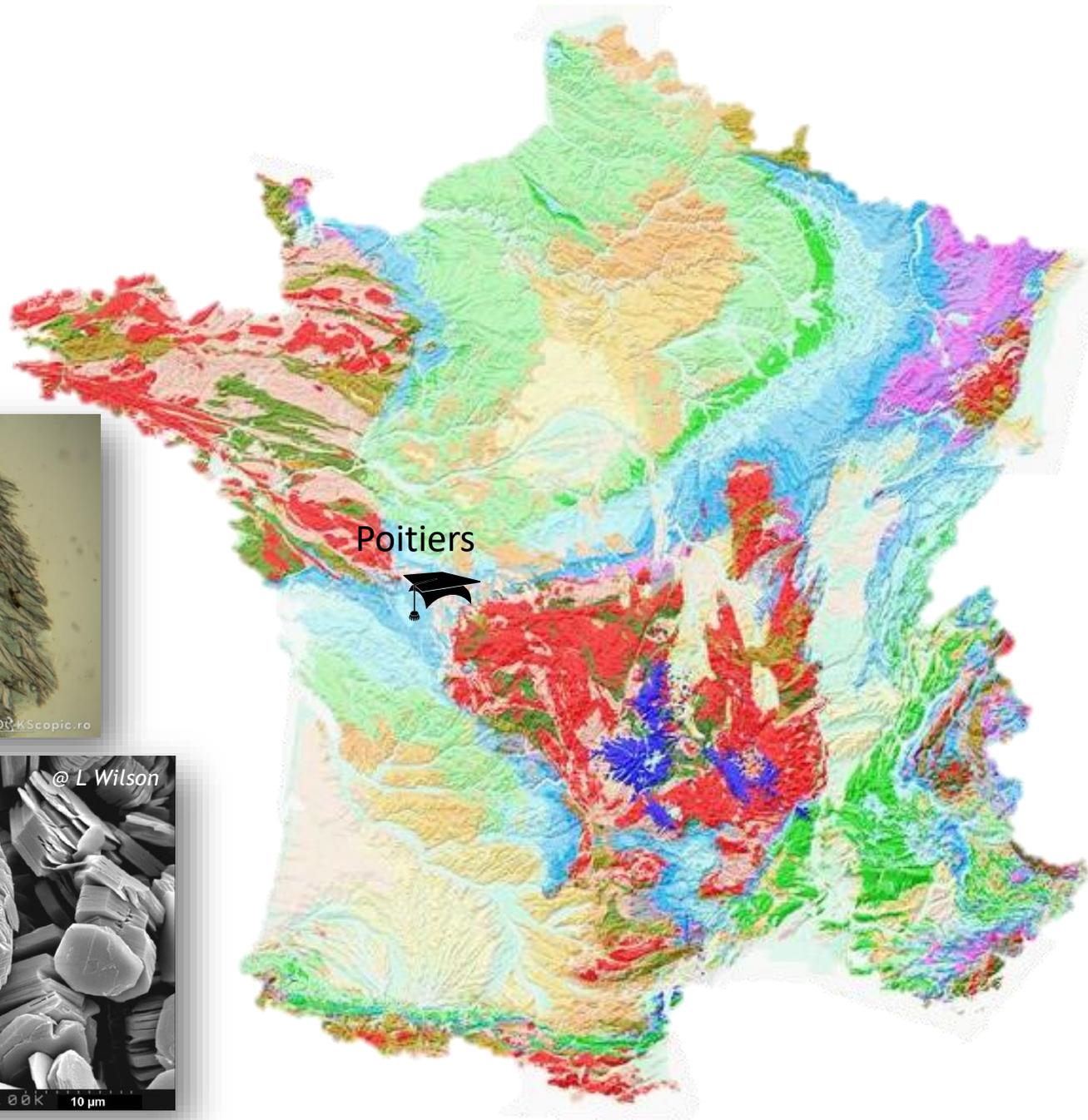
Phyllosilicates
« Minéraux argileux »



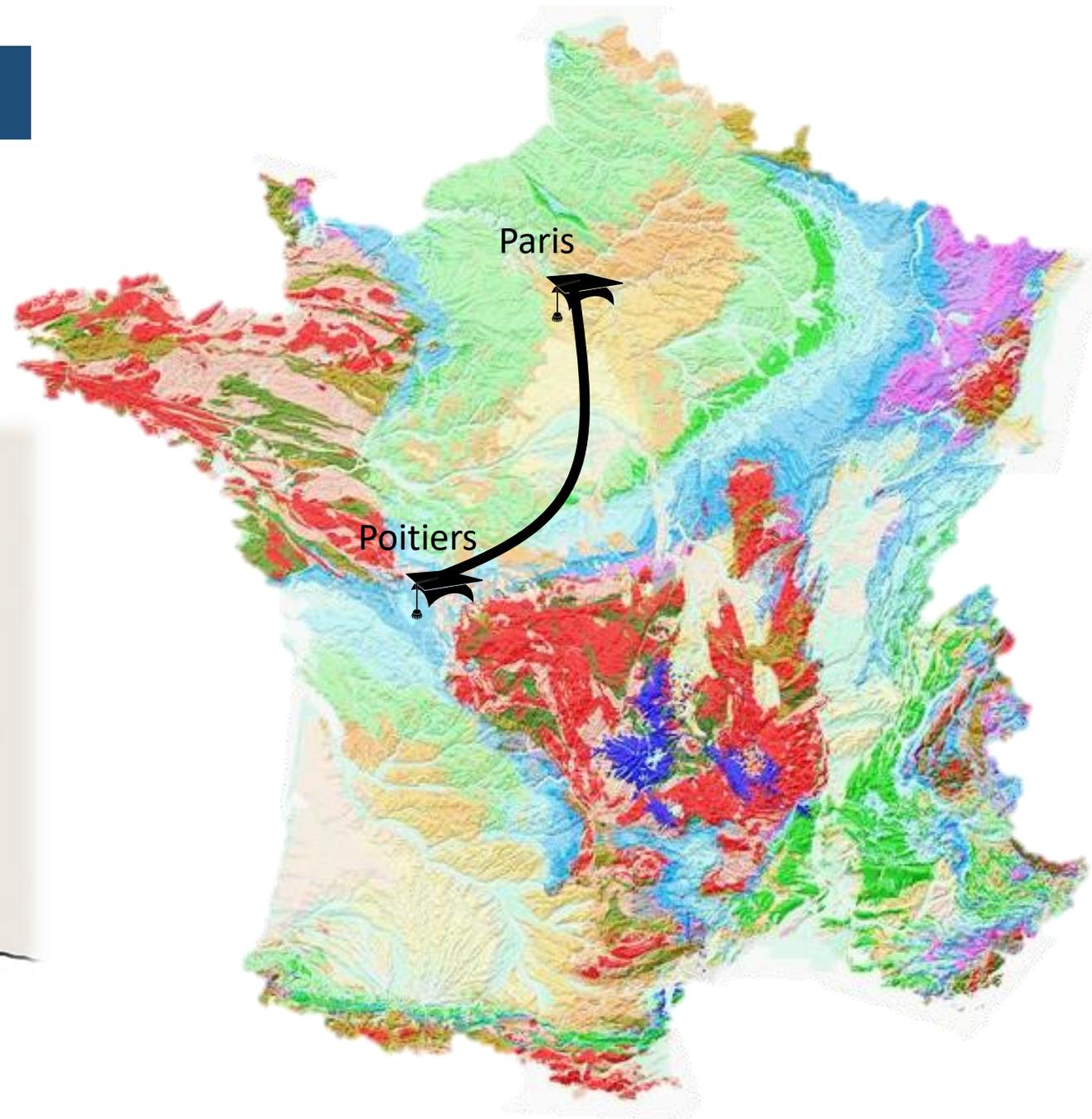
10 microns



@ L Wilson



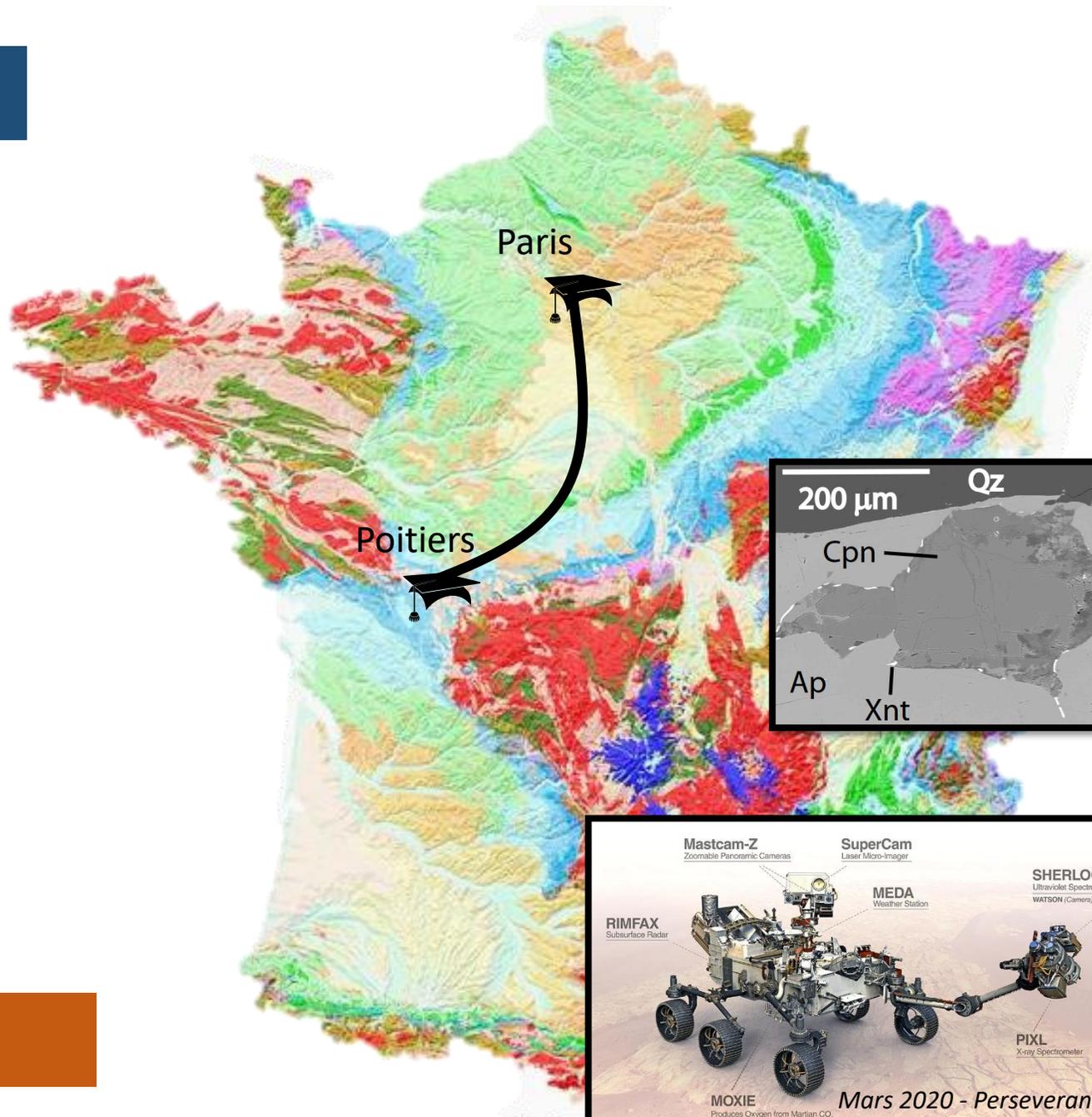
LE CHANGEMENT D'ECHELLE D'UN CHERCHEUR



LE CHANGEMENT D'ECHELLE D'UN CHERCHEUR



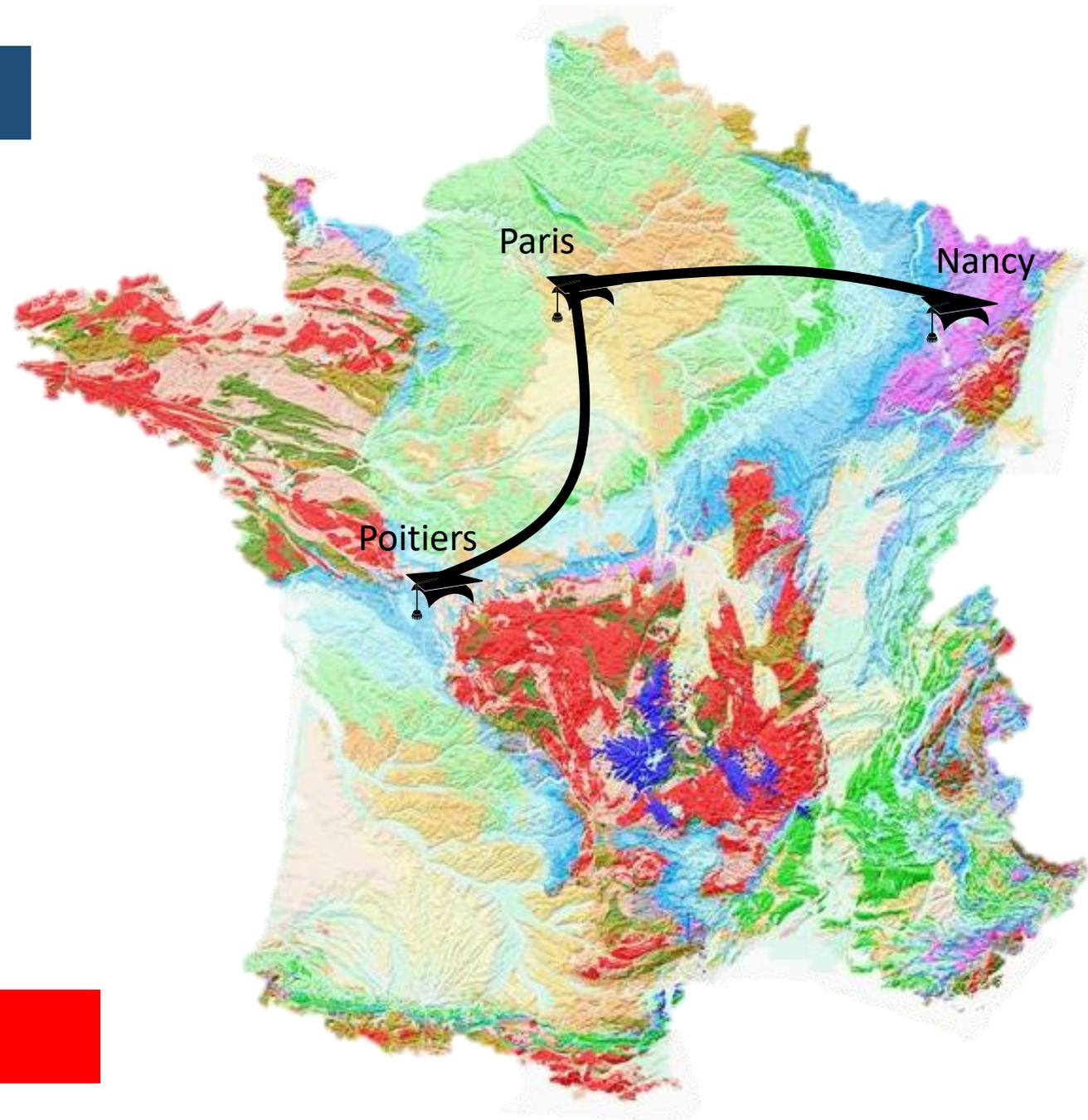
▶ LE CHANGEMENT D'ECHELLE SPATIALE



LE CHANGEMENT D'ECHELLE D'UN CHERCHEUR



UNIVERSITÉ
DE LORRAINE

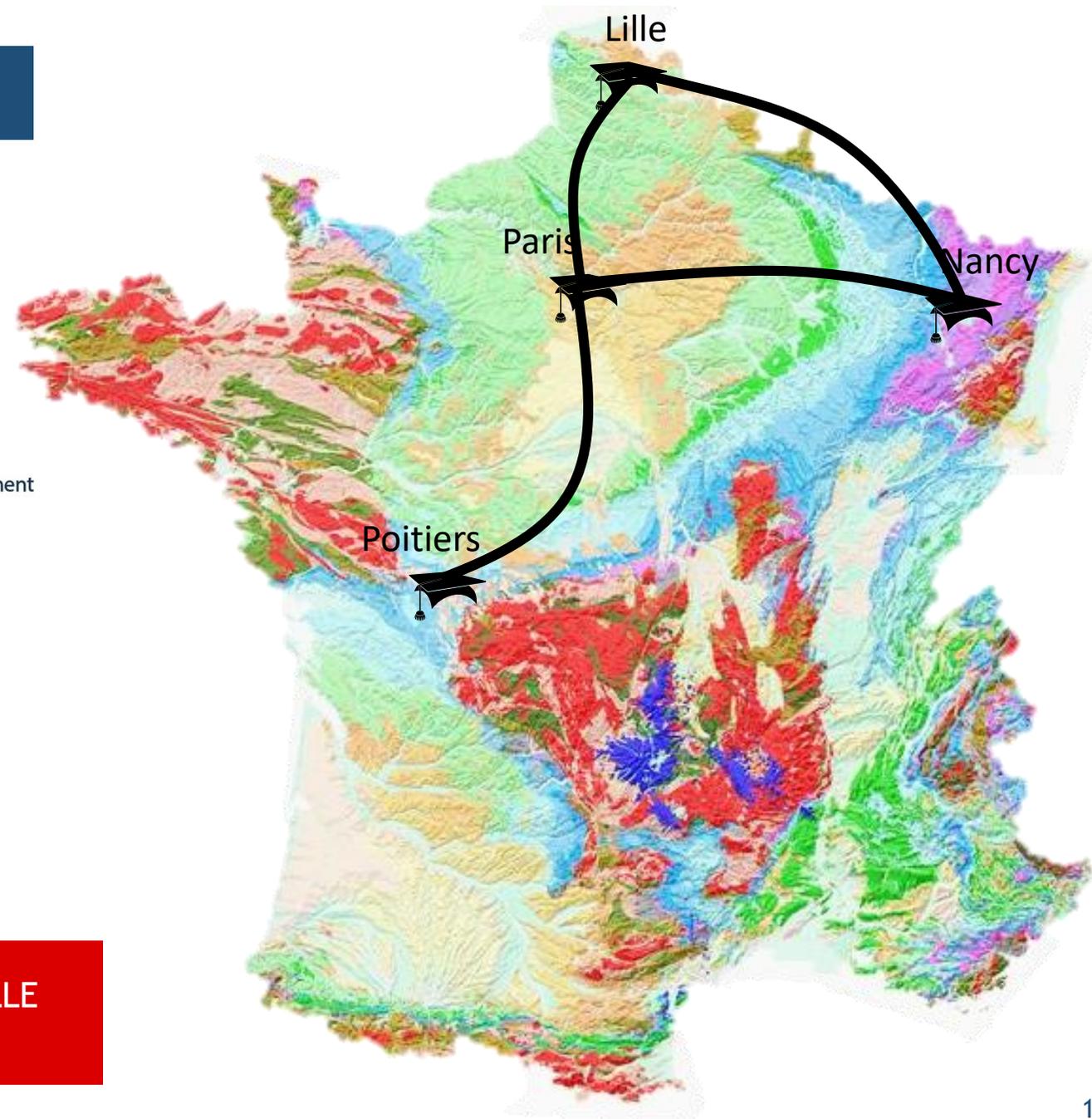


► LE CHANGEMENT D'ECHELLE TEMPORELLE

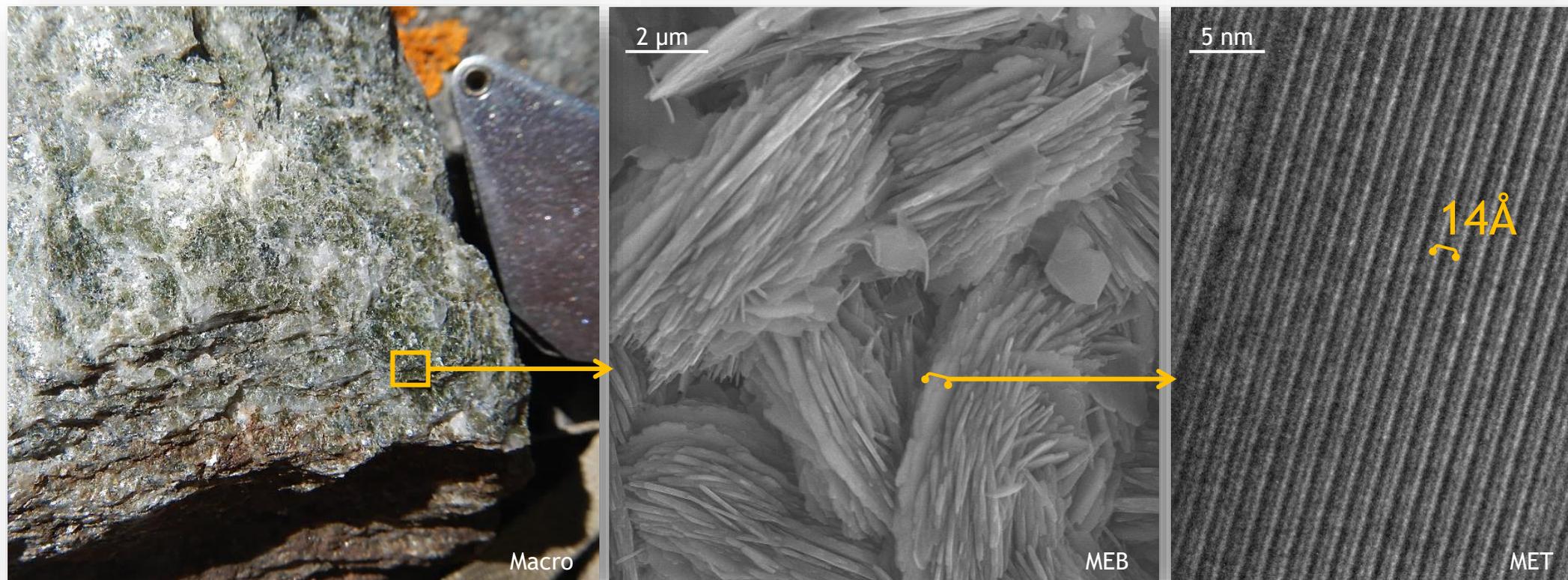
LE CHANGEMENT D'ECHELLE D'UN CHERCHEUR



Laboratoire
de Génie Civil
et géo-Environnement



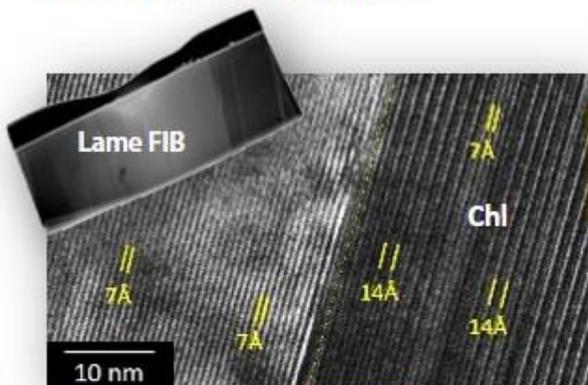
► COUPLAGE DU CHANGEMENT D'ECHELLE TEMPORELLE
ET DU CHANGEMENT D'ECHELLE SPATIALE



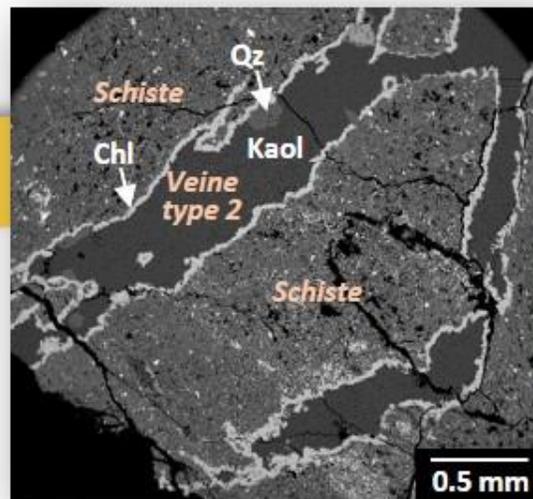
« MINERAUX ARGILEUX » PHYLLOSILICATES ▶ STRUCTURE EN FEUILLETS + COMPOSITION VARIABLE

CHANGEMENT D'ECHELLE SPATIALE EN GEOSCIENCES ?

De l'échelle nano...



FIB/MET-EDS
STXM-XANES
Thermométrie



... micro ...

MEB
Incl. Fluides
Raman MO RSCM
Thermométrie



Terril d'Haillincourt



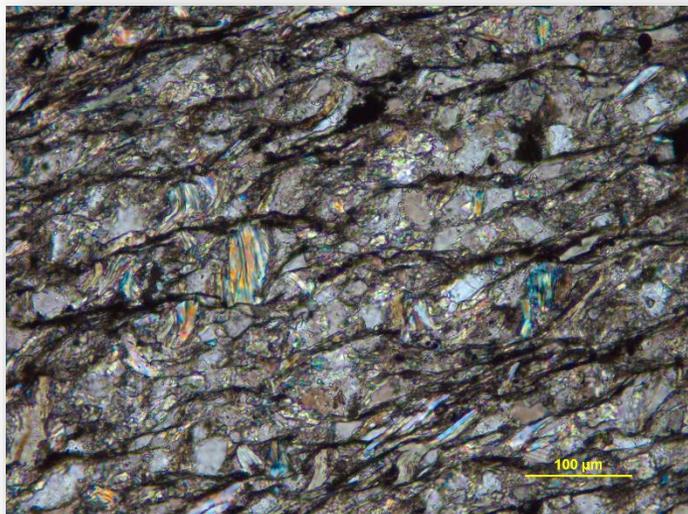
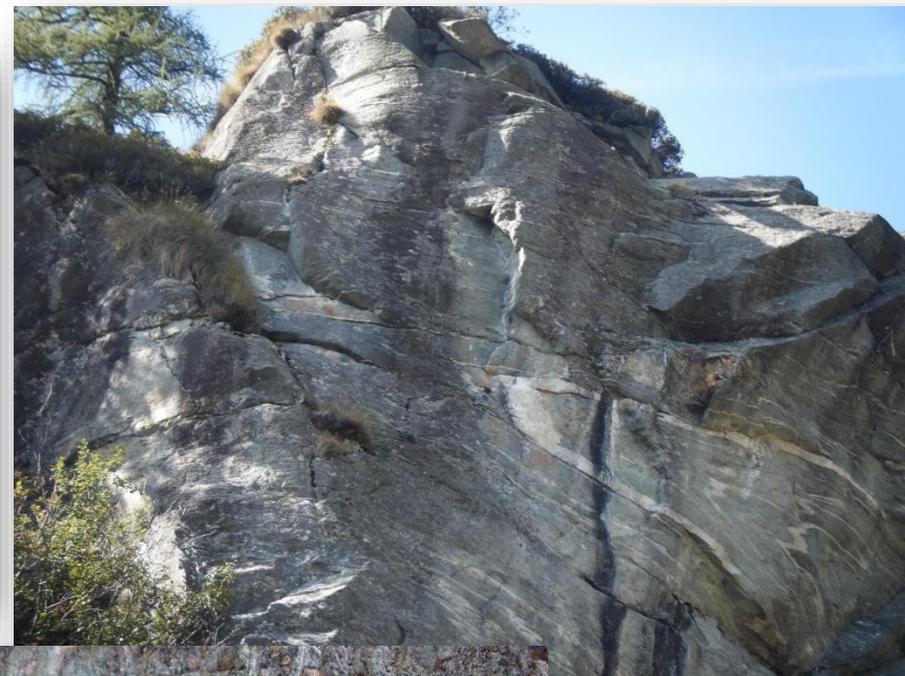
Histoire P-T-X bassin houiller

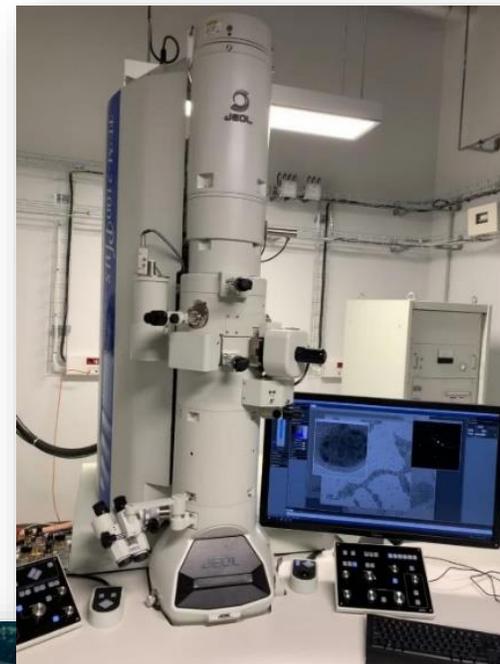
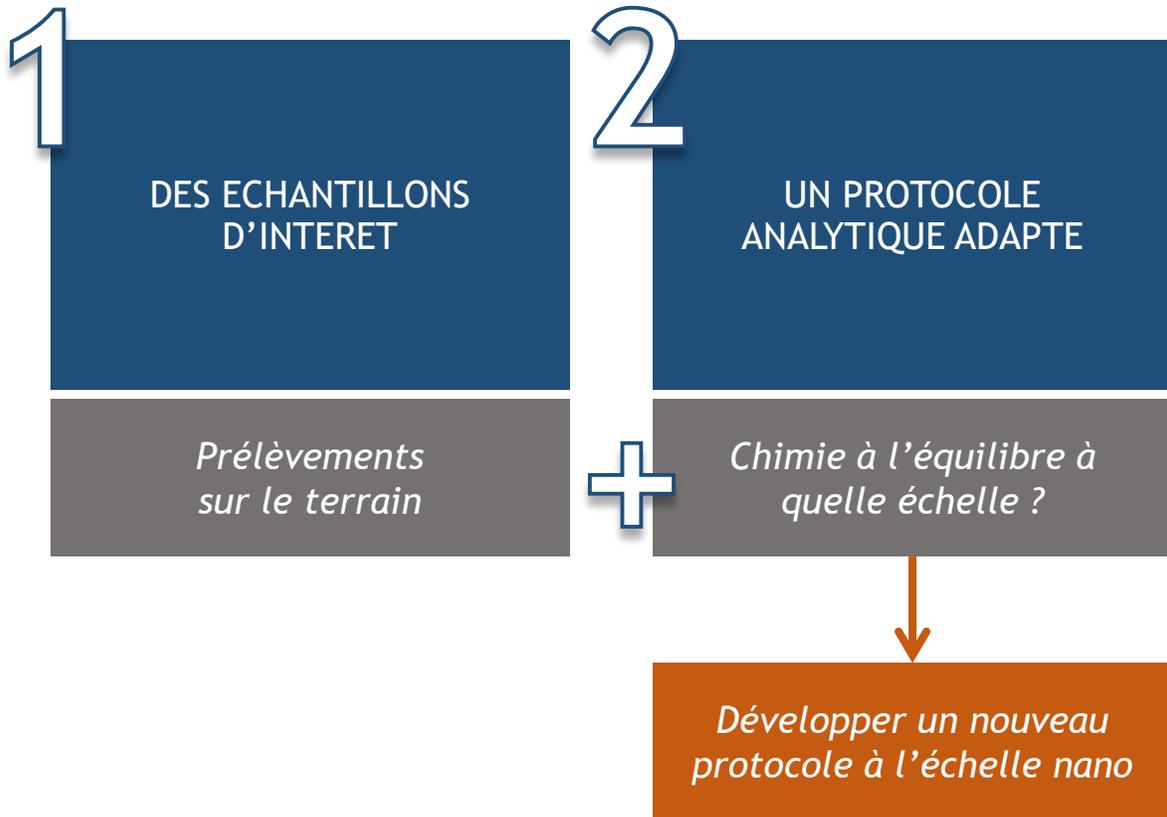
... à l'échelle Régionale

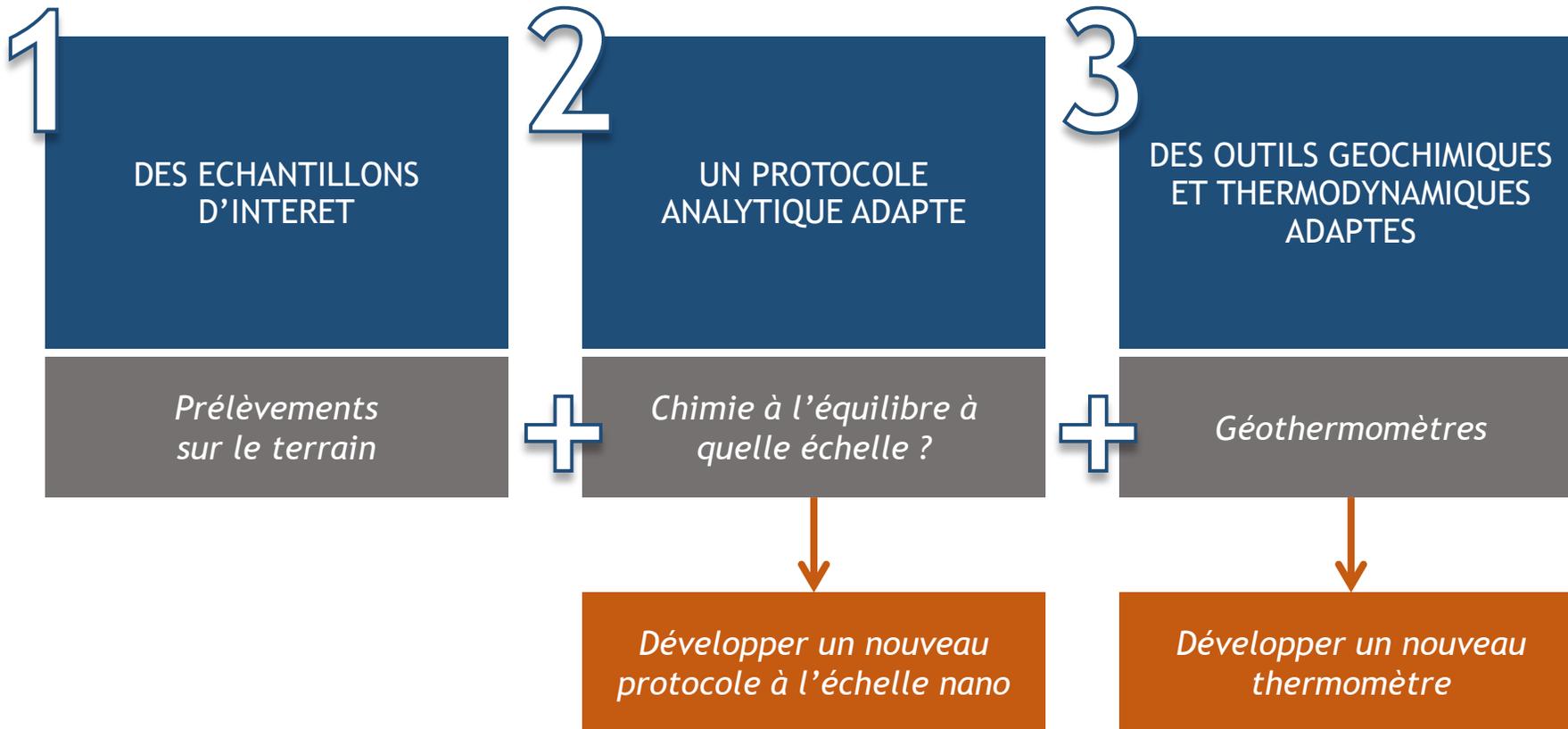
1

DES ECHANTILLONS
D'INTERET

*Prélèvements
sur le terrain*







$$\Delta G_r^0 + R.T.\ln K = 0$$

$$K = \prod_j (a_{ideal})_j^{v_j}$$

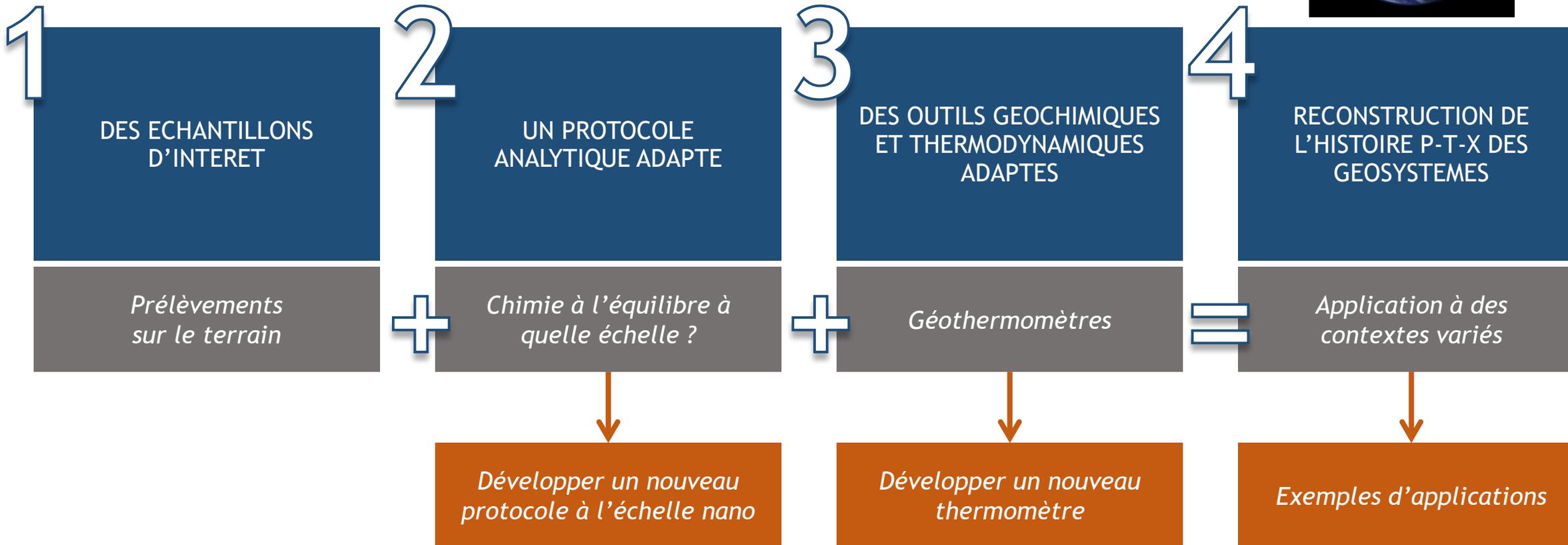
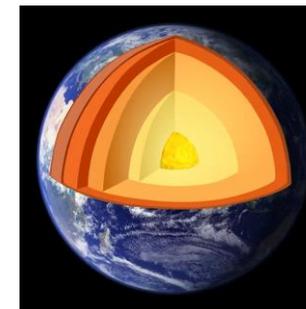
$$\log K = \frac{-\Delta G_r^0}{2.303(R.T)} = \frac{A}{T} + B$$

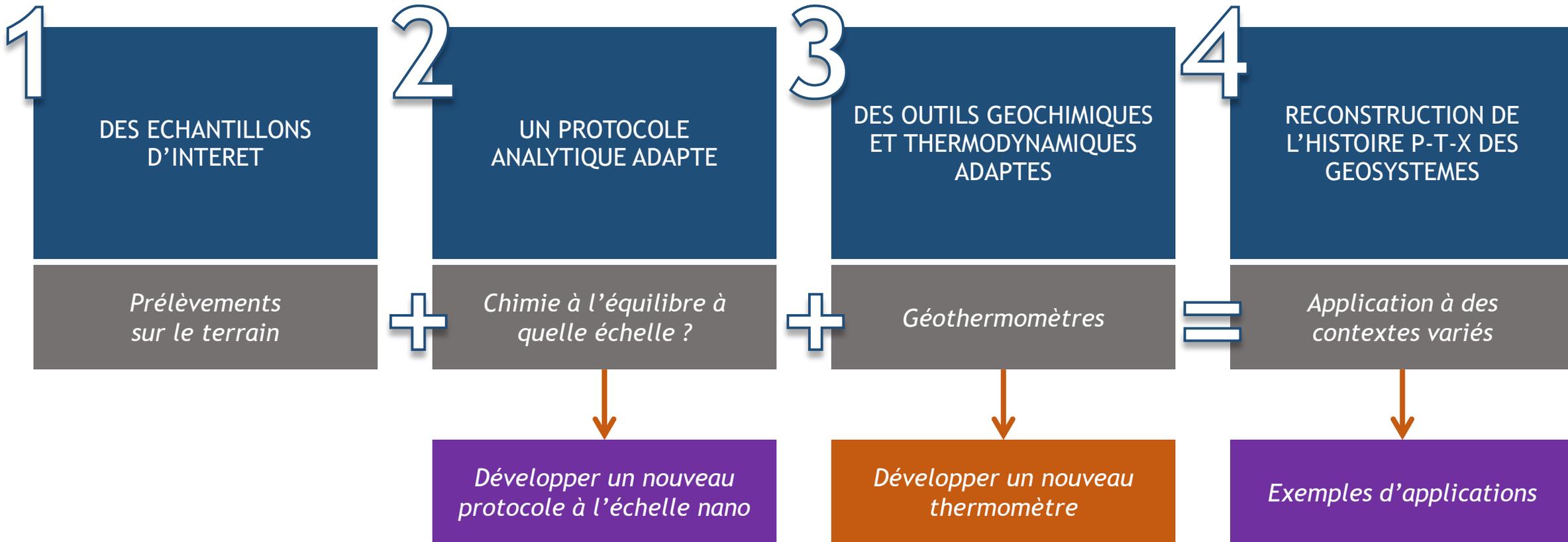
$$\dots = \log \left(\frac{a_{Mg-Am}^3 \cdot a_{SiO_2}^7 \cdot a_{H_2O}^4}{a_{Mg-ChlS} \cdot a_{Mg-Sud}^3} \right)$$

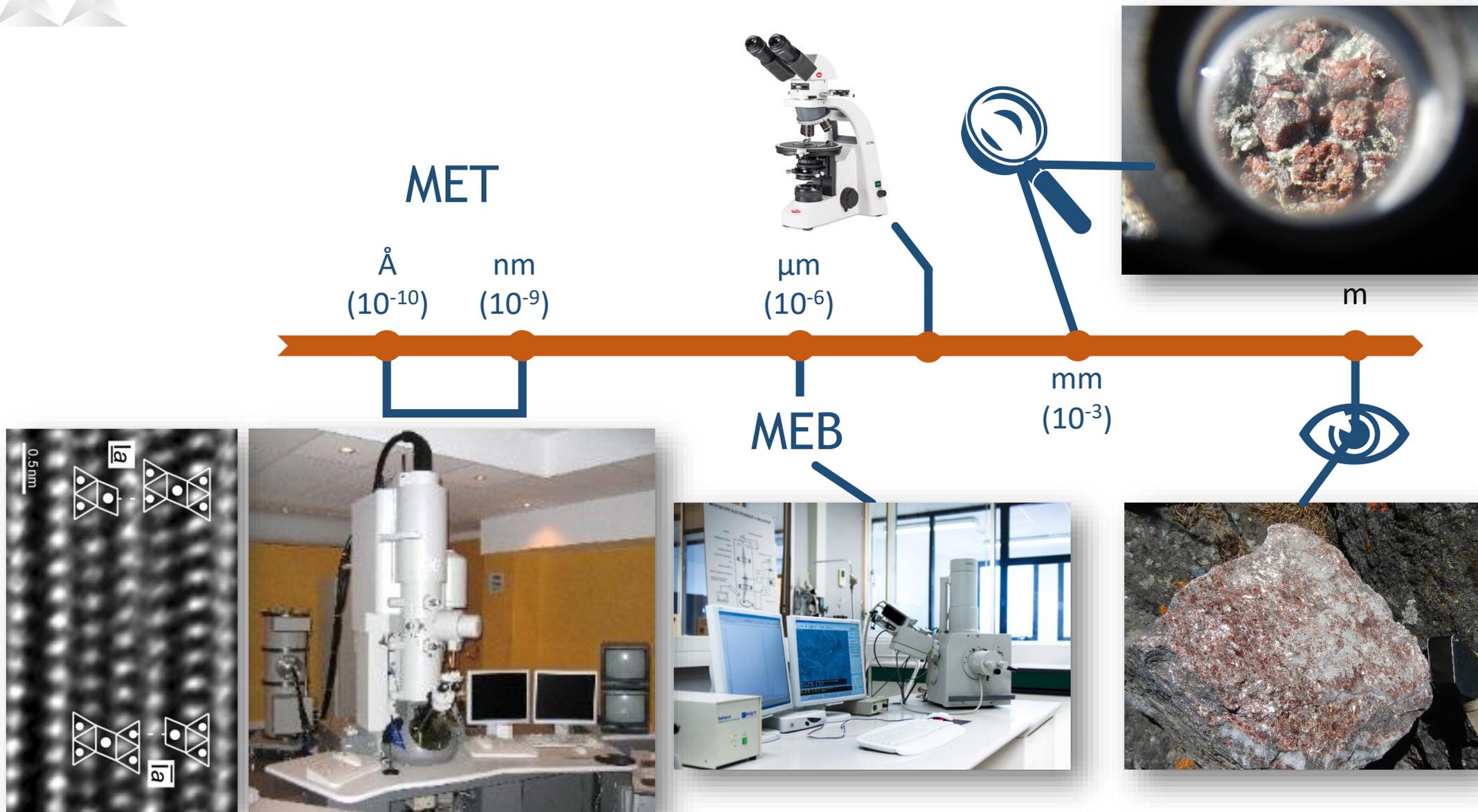
$$= 3 \log a_{Mg-Am} - \log a_{Mg-ChlS}$$

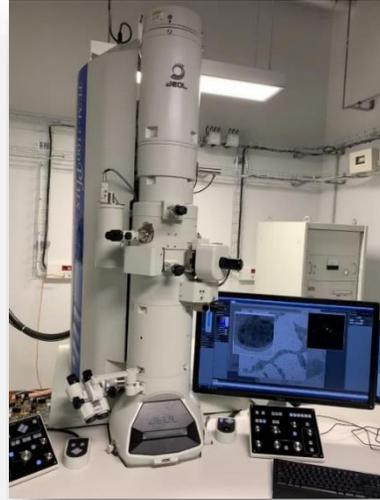
$$- 3 \log a_{Mg-Sud} + 7 \log a_{SiO_2} + 4 \log a_{H_2O}$$

$$\log K = \frac{11185729}{T(K)^2} - \frac{56598}{T(K)} + 72.3$$



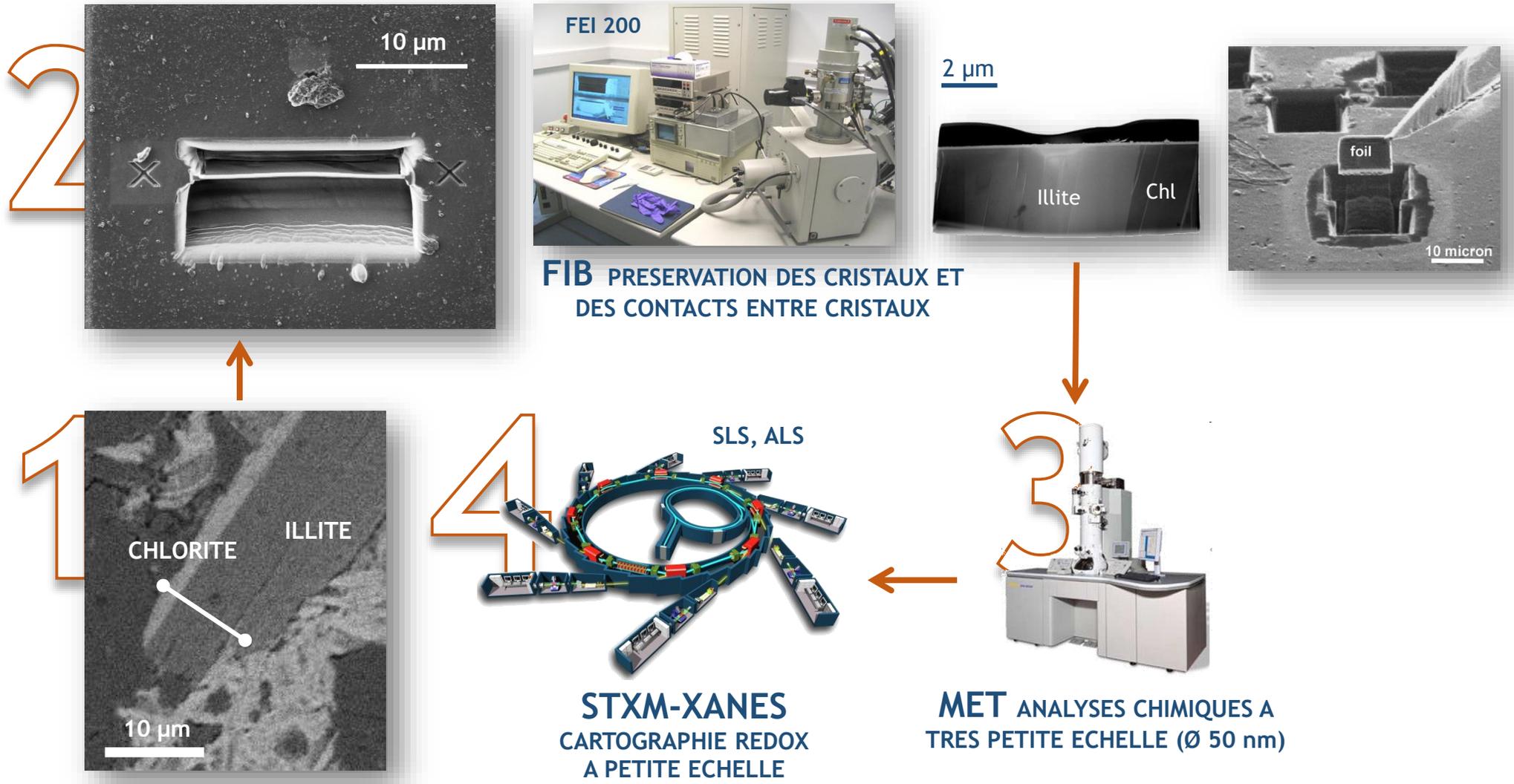




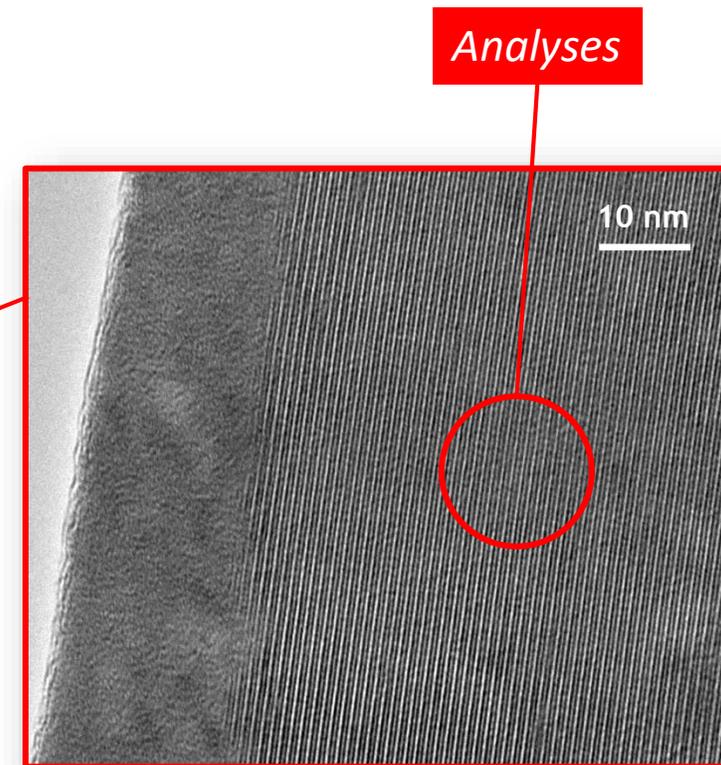
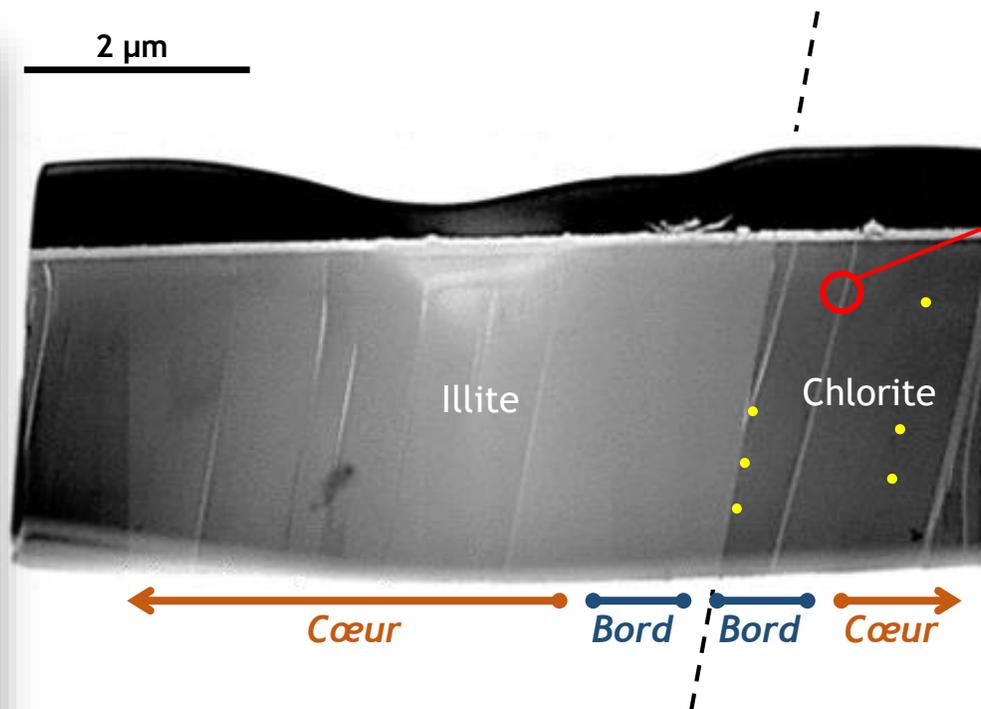


*Plus on veut voir
le petit ou le
lointain, plus le
microscope est
grand !*





LA CHIMIE BRUTE



Analyses

Hypothèse : zonation chimique intracristalline en équilibre avec les conditions P-T

LA CHIMIE BRUTE

Selection of TEM-EDX analyses of Glarus chlorite. For each sample, a crystal core and crystal rim analysis are given. Max T°C refers to maximum temperature (peak metamorphism) obtained from independent conventional thermometers (Ebert et al., 2007). Cathelineau T°C: temperatures estimated with the Cathelineau (1988) thermometer (Eq. (1)). Bourdelle T°C: temperatures estimated with the Bourdelle et al. (2013a) thermometer (Eq. (3)).

Sampling profile	N														S	
Sample	GL07 13		GL07 15		GL07 16		GL07 17		GL07 23/24		GL07 21		GL07 20		GL07 19	
Rim/core analysis	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
Analysis code	A2chl1	A1chl8	B3chl4	B2chl7	A5chl30	A5chl8	B1chl21	B1chl18	C3chl1	B2chl21	B1chl2	B1chl6	A2chl10	A4chl8	A2chl7	A3chl20
TEM-EDX analyses																
SiO ₂	33.57	30.15	31.72	29.21	31.88	31.52	31.27	30.19	30.10	30.15	30.28	29.28	31.38	30.44	29.94	28.96
TiO ₂	0.06	0.00	0.00	0.08	0.13	0.00	0.00	0.00	0.00	0.00	0.05	0.08	0.09	0.01	0.01	0.00
Al ₂ O ₃	26.38	27.50	26.40	29.02	26.71	24.69	26.63	27.57	27.55	26.42	28.45	27.98	25.02	25.61	26.32	26.17
FeO	26.52	29.54	23.70	28.34	22.70	26.68	24.85	25.51	29.53	28.84	28.68	30.46	29.80	26.36	30.47	31.31
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	13.27	12.63	18.07	12.57	17.98	16.19	16.77	16.70	12.64	14.56	12.54	12.20	13.26	17.42	13.04	13.51
CaO	0.11	0.16	0.00	0.26	0.55	0.67	0.03	0.02	0.03	0.00	0.00	0.00	0.00	0.05	0.00	0.06
Na ₂ O	0.00	0.00	0.00	0.20	0.00	0.25	0.08	0.00	0.03	0.00	0.00	0.00	0.04	0.00	0.00	0.00
K ₂ O	0.10	0.02	0.10	0.33	0.04	0.00	0.36	0.00	0.06	0.04	0.00	0.00	0.40	0.11	0.22	0.00
Struct. form. (apfu)																
Si	3.01	2.77	2.83	2.67	2.83	2.86	2.81	2.72	2.76	2.76	2.76	2.70	2.89	2.76	2.77	2.69
Ti	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
Al(IV)	0.99	1.23	1.17	1.33	1.17	1.14	1.19	1.28	1.24	1.24	1.24	1.30	1.11	1.24	1.23	1.31
Al(VI)	1.80	1.74	1.61	1.80	1.63	1.51	1.63	1.65	1.74	1.61	1.82	1.74	1.60	1.50	1.63	1.56
Fe ²⁺	1.99	2.27	1.77	2.17	1.69	2.03	1.87	1.92	2.27	2.21	2.19	2.35	2.29	2.00	2.35	2.43
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.78	1.73	2.40	1.72	2.38	2.19	2.25	2.24	1.73	1.99	1.70	1.68	1.82	2.36	1.80	1.87
Ca	0.01	0.02	0.00	0.03	0.05	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Na	0.00	0.00	0.00	0.03	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
K	0.01	0.00	0.01	0.04	0.00	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.05	0.01	0.03	0.00

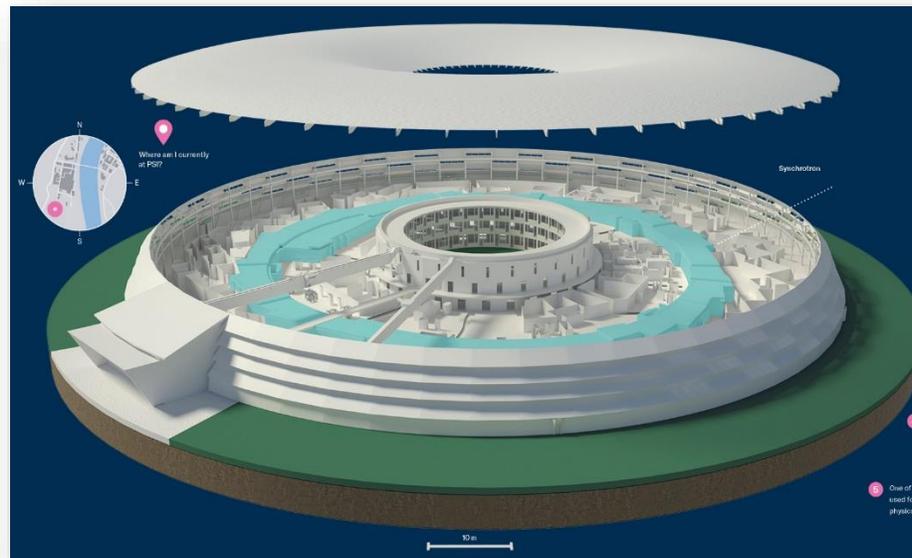
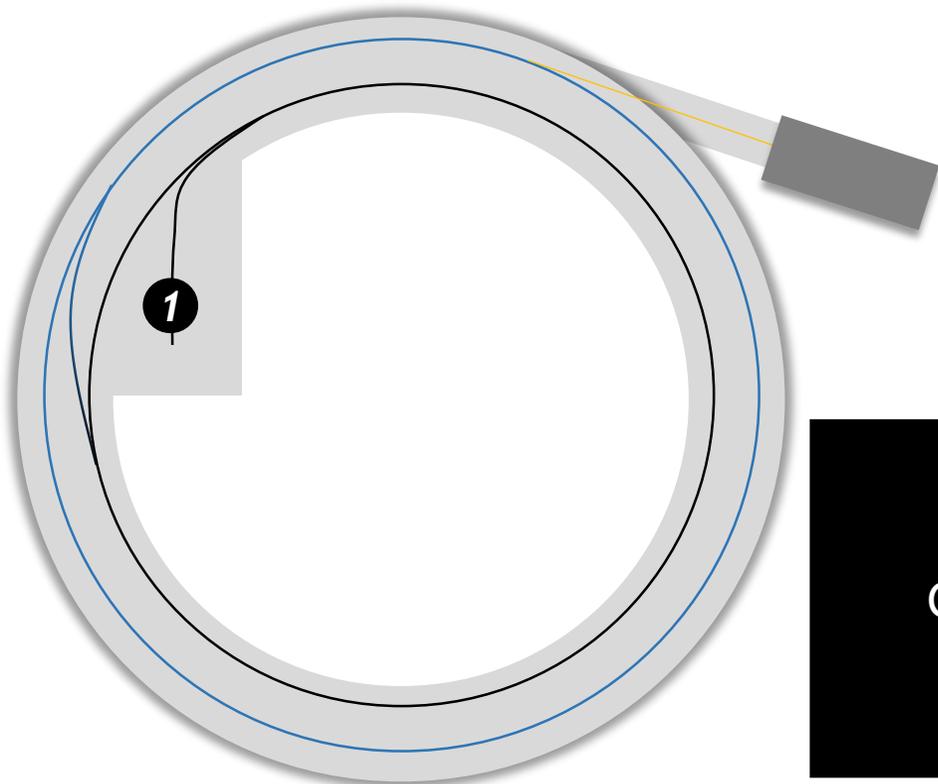
ET LA VALENCE ?

Fer : Fe^{2+} ou Fe^{3+} ?

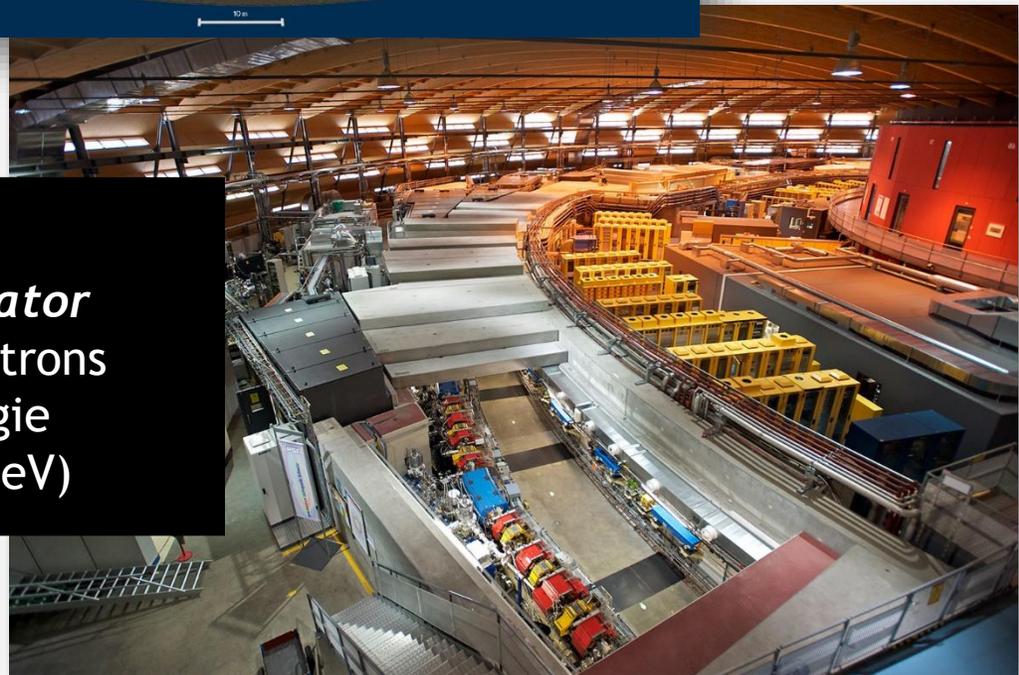
Manganèse : Mn^{2+} , Mn^{3+} , Mn^{4+} ?



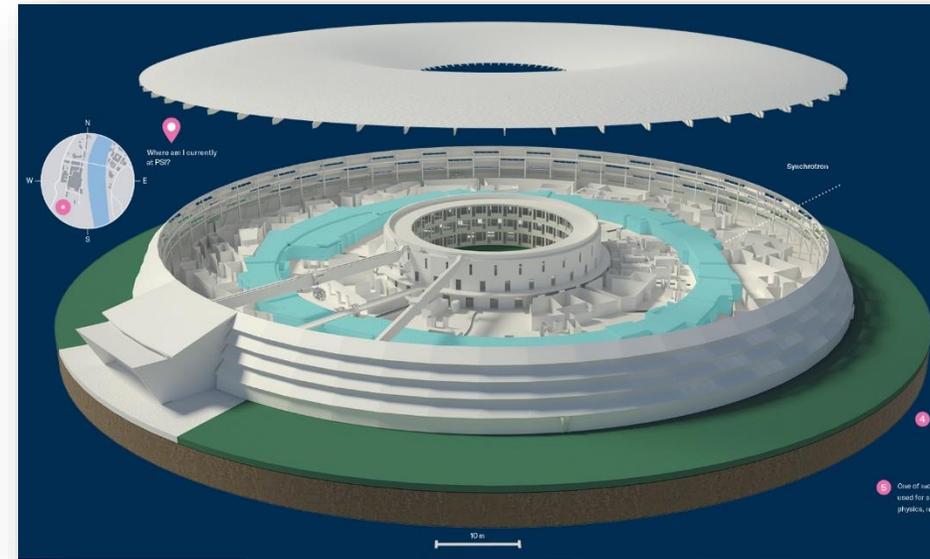
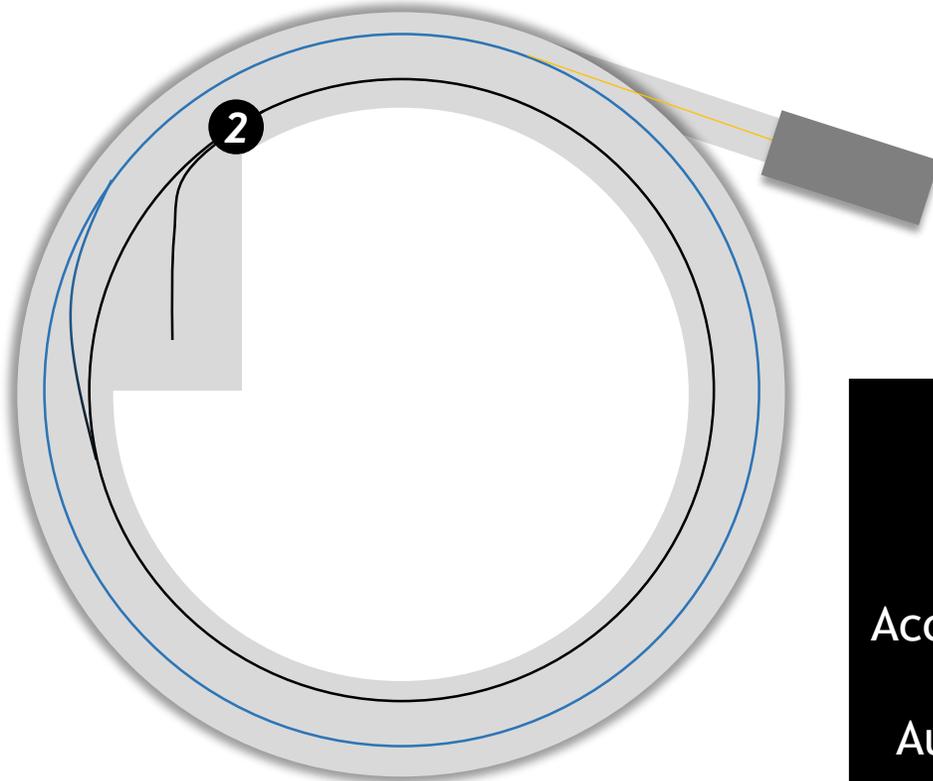
ET LA VALENCE ?



1
Linear Accelerator
Génère des électrons
à haute-énergie
(100 million d'eV)



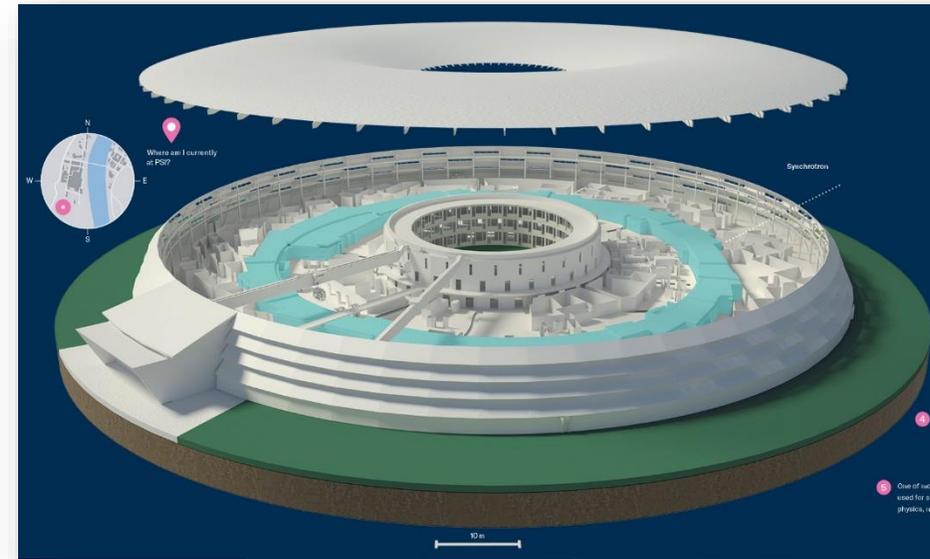
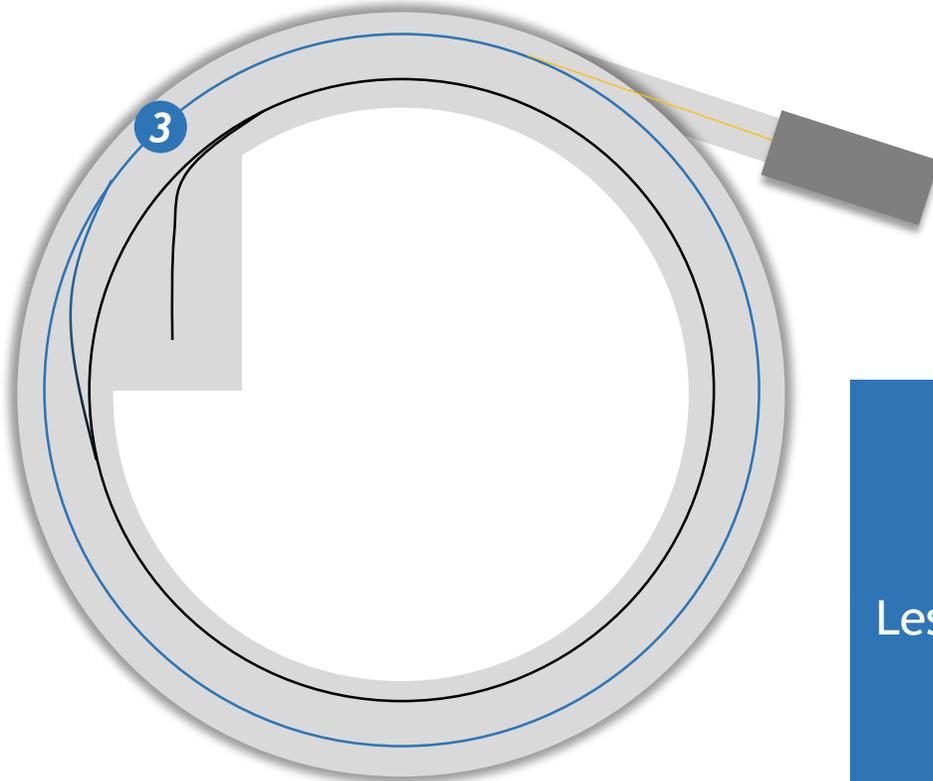
ET LA VALENCE ?



2
Booster Ring
Anneau « de vitesse »
Accélère les électrons jusqu'à
la vitesse de la lumière
Augmente l'énergie jusqu'à
2,4 Milliards d'eV



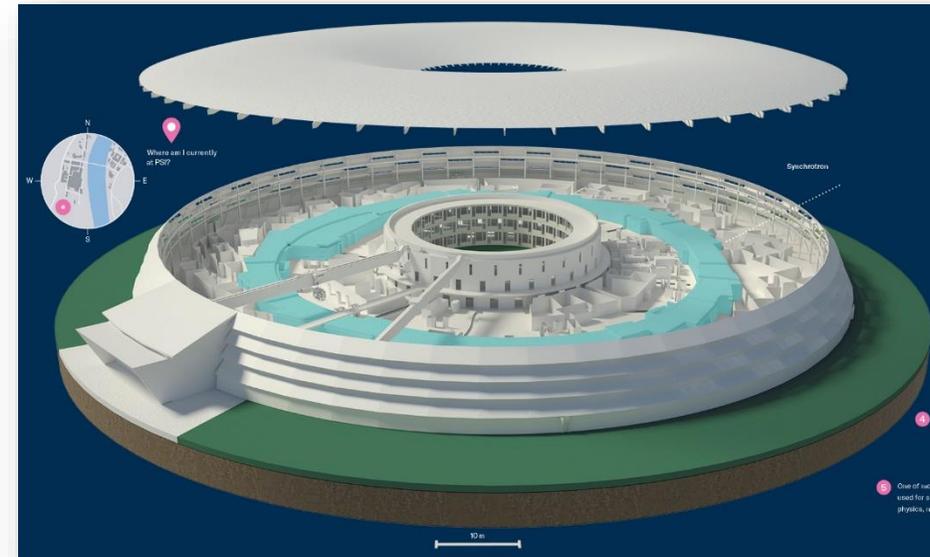
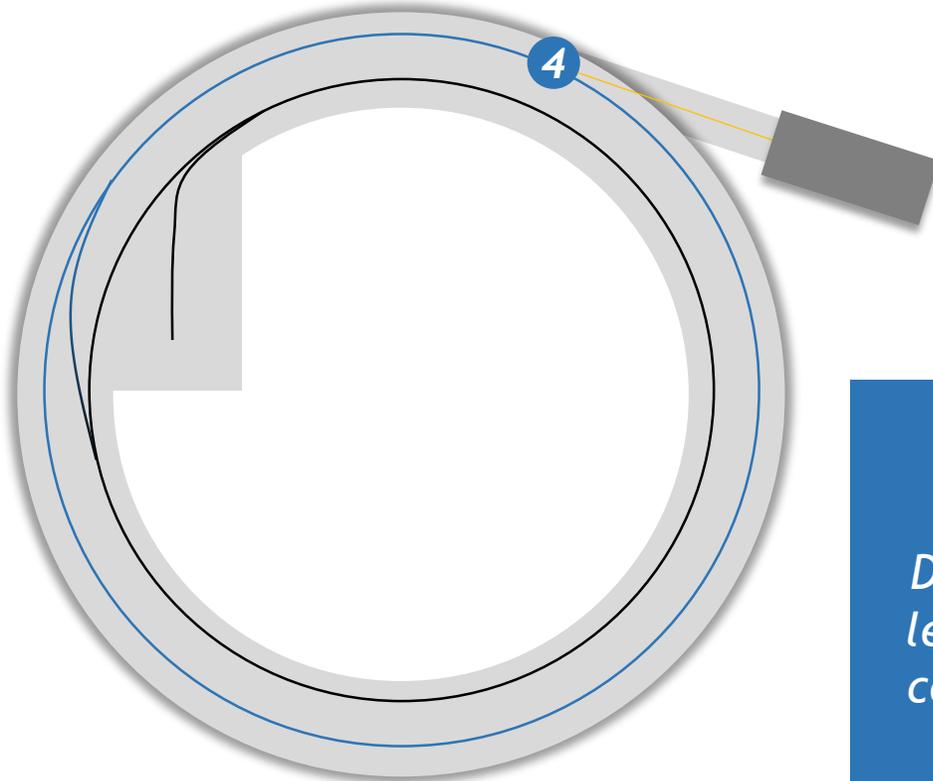
ET LA VALENCE ?



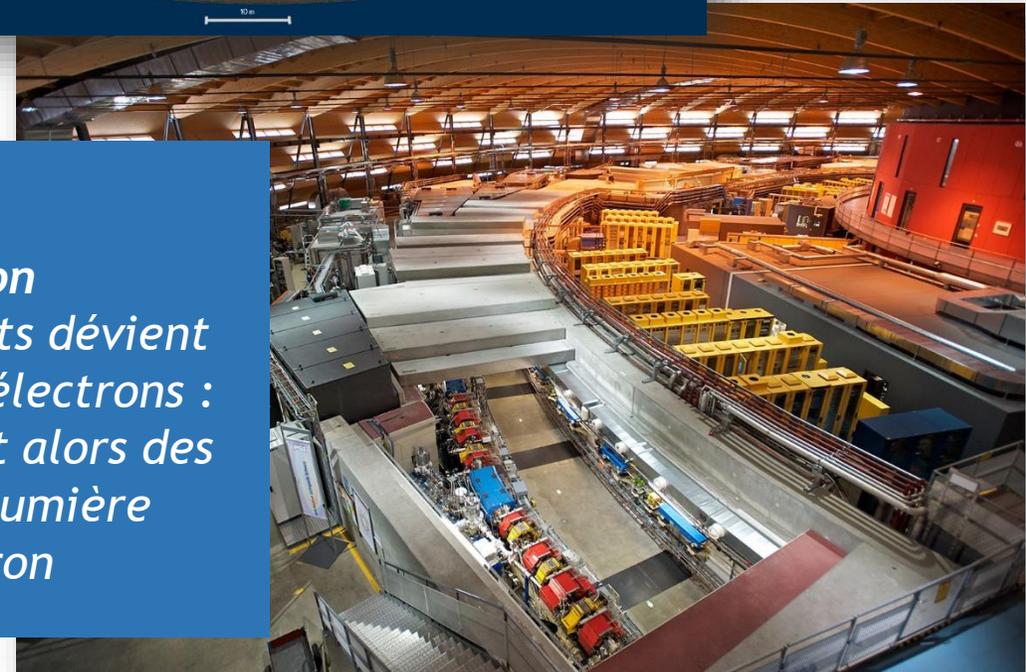
3
Storage Ring
Anneau « de stockage »
Les électrons sont stabilisés à
haute vitesse
et haute énergie



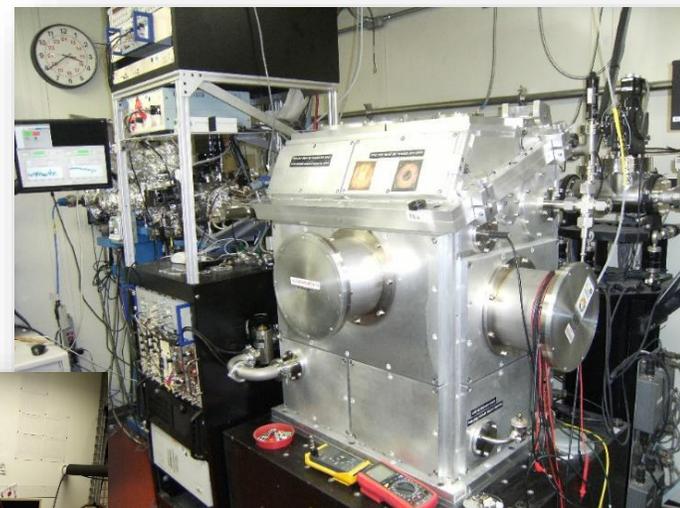
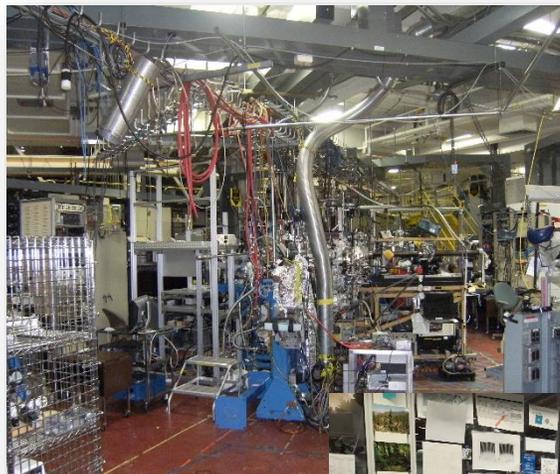
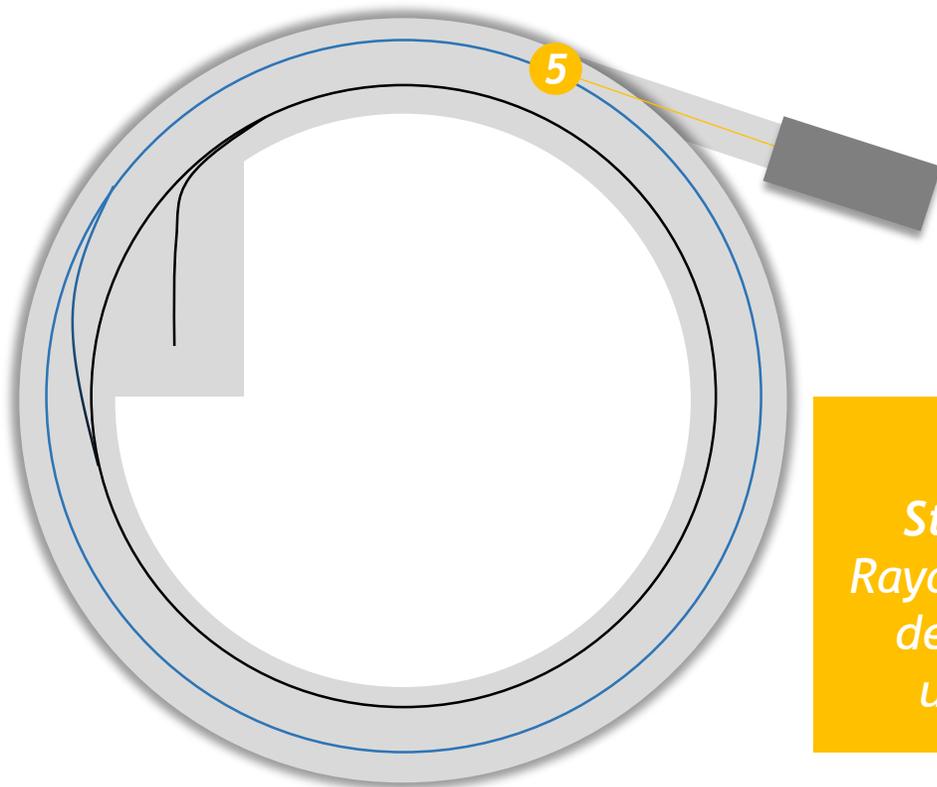
ET LA VALENCE ?



4
Déviation
Des super aimants dévient légèrement des électrons : ceux-ci émettent alors des rayons X - la lumière synchrotron



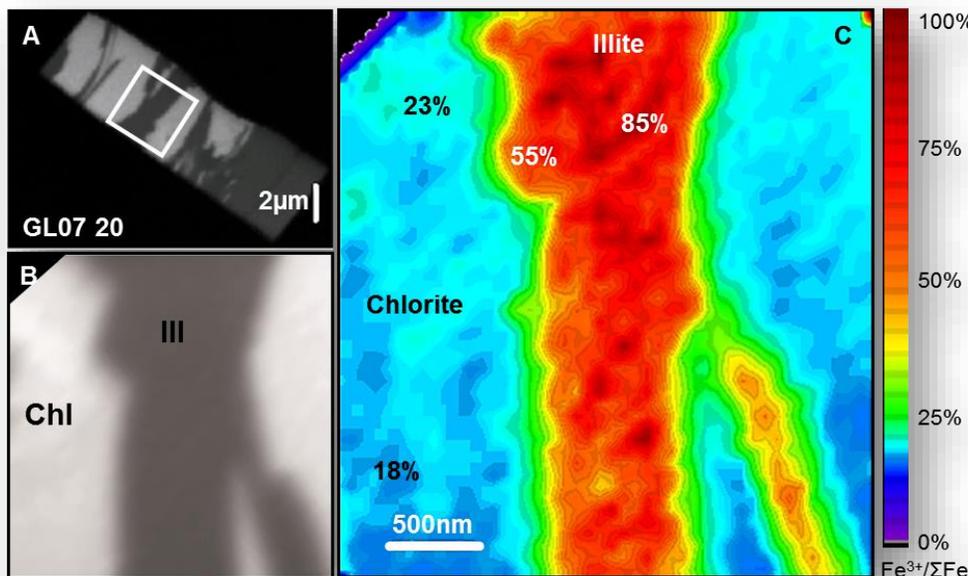
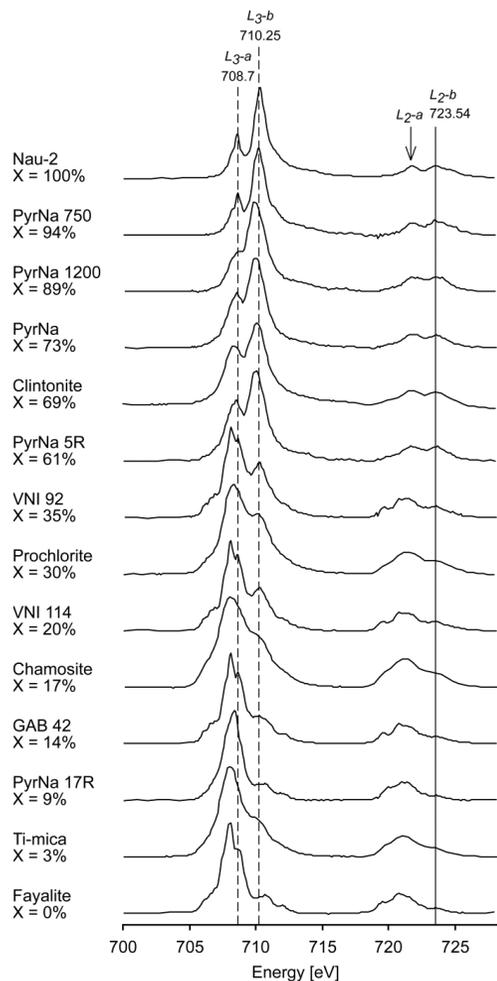
ET LA VALENCE ?



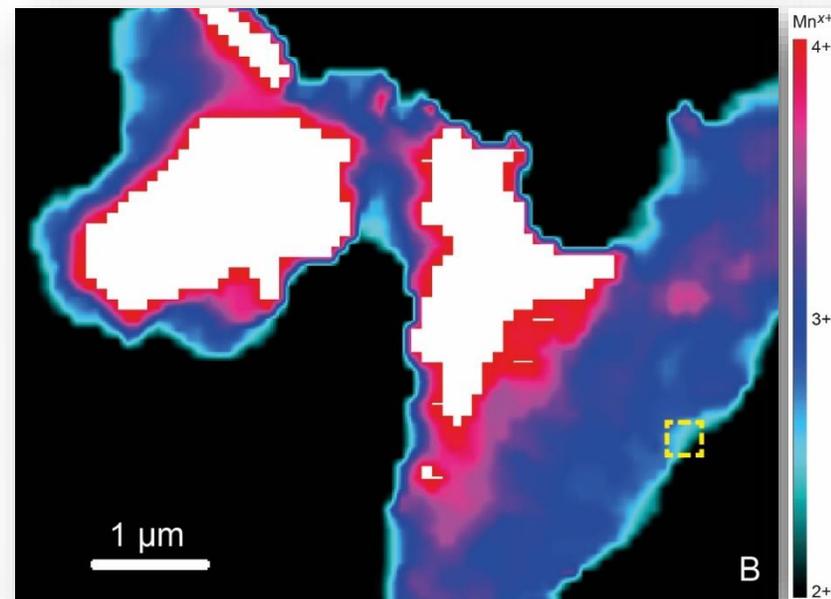
5
*Stations / Microscopes
Rayons X arrivent dans l'une
des stations, afin d'être
utilisés pour l'analyse*



ET LA VALENCE ?



$$\frac{Fe^{3+}}{Fe^{3+} + Fe^{2+}}$$

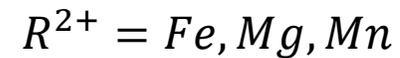
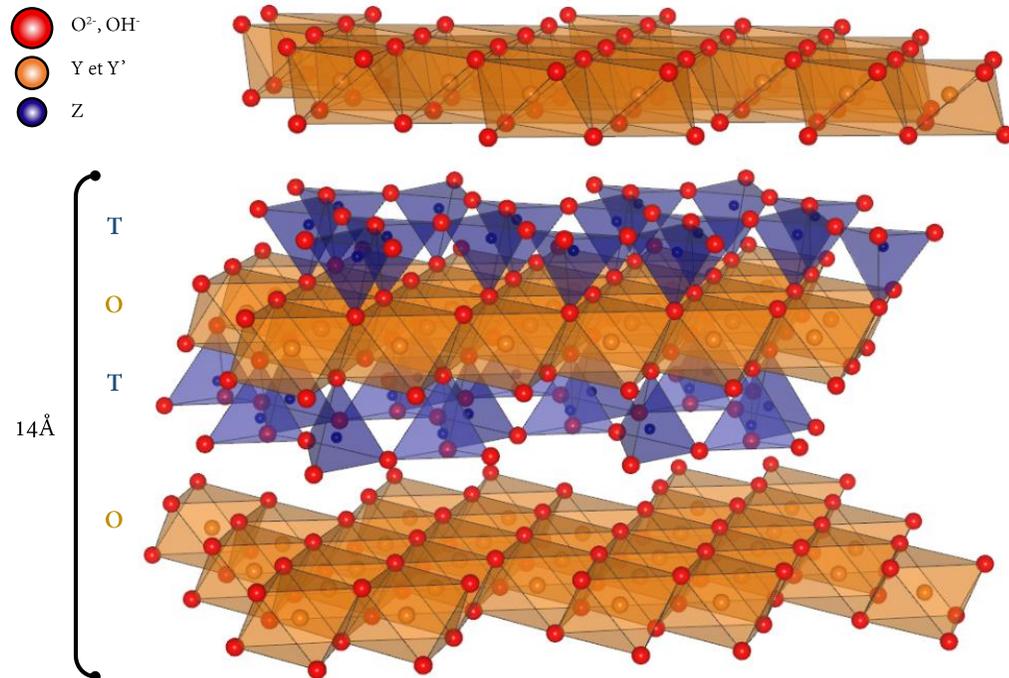


$$\frac{aMn^{2+} + bMn^{3+} + cMn^{4+}}{a + b + c}$$

L'INFINIMENT PETIT : LES ORIGINES



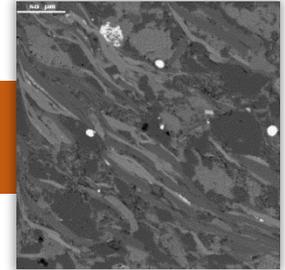
Grand Collisionneur de Hadrons LHC - 27km de circonférence
 Accélération de protons à 7 TeV / 9500 électroaimants / 9 milliards €
 Découverte du Boson de Higgs ainsi que de 3 autres particules fondamentales
 Objectif : reproduire certaines réactions s'étant produites juste après le Big Bang



- ▶ APPLICATION DES THERMOMETRES
- ▶ RECONSTRUCTION DE L'HISTOIRE DES GEOSYSTEMES

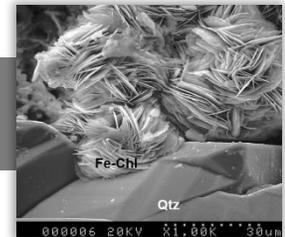
1

METAMORPHISME BAS DEGRE - CHLORITES SUPPORTANT UN CHEMIN RETROGRADE
SYSTÈME DE GLARUS (SUISSE)



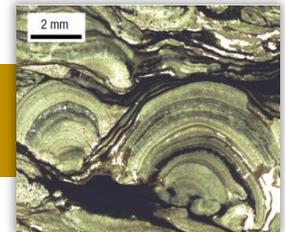
2

BASSIN FRACTURE AVEC CIRCULATION DE FLUIDES - CHLORITES NEOFORMEES
BASSIN DE TIM MERSOI (NIGER)



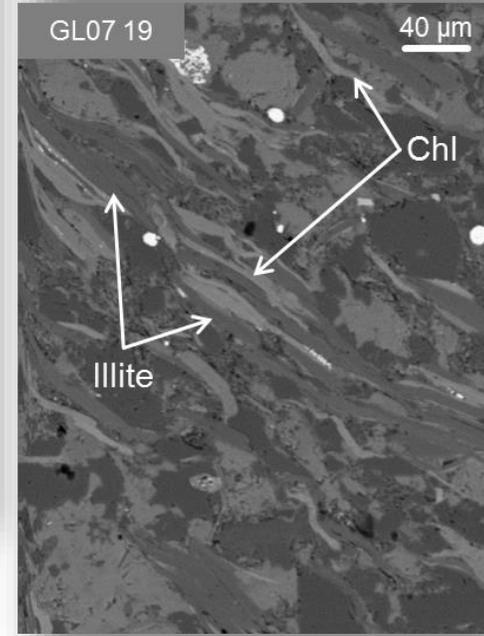
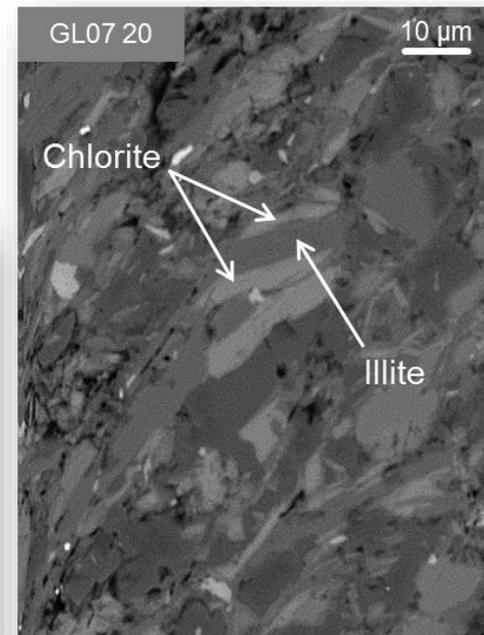
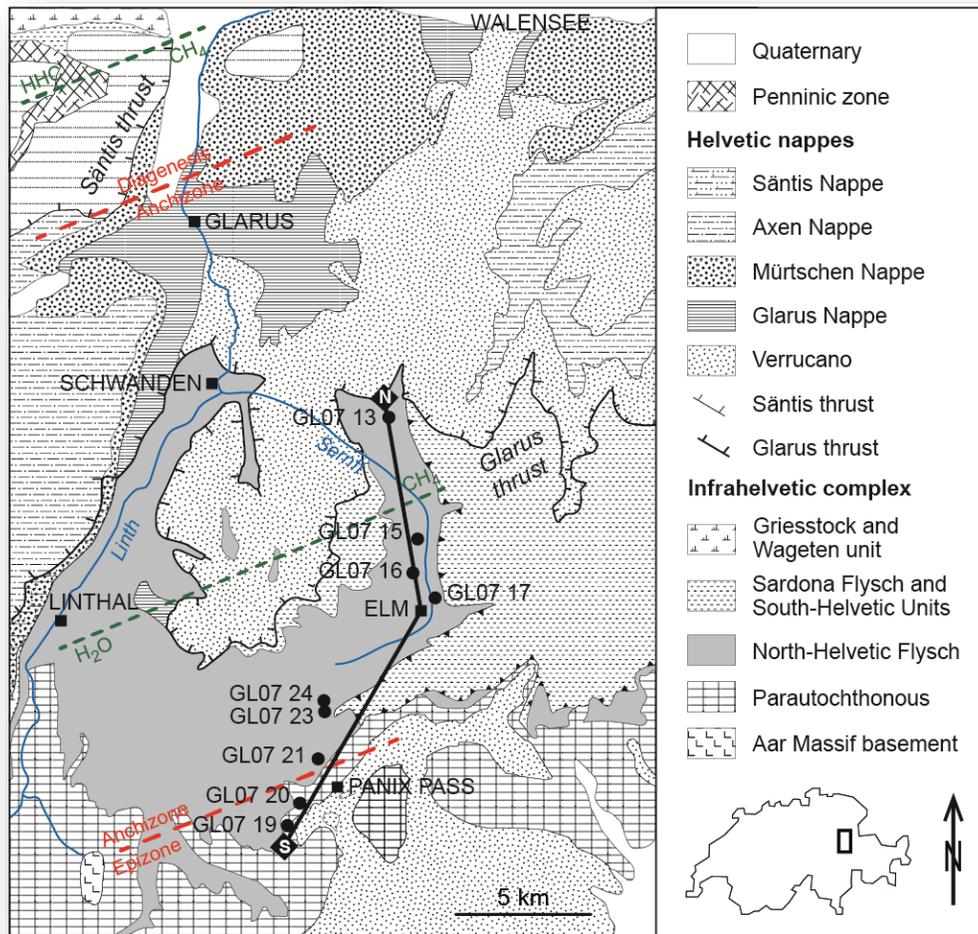
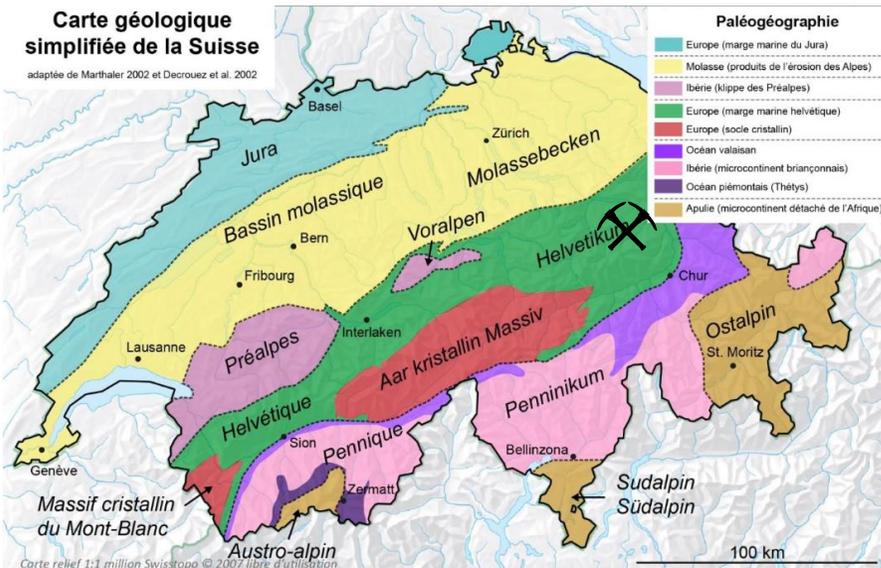
3

SYSTEMES ANCIENS PEU METAMORPHISES - ORIGINES DE LA VIE
STROMATOLITES TUMBIANA (AUSTRALIE)

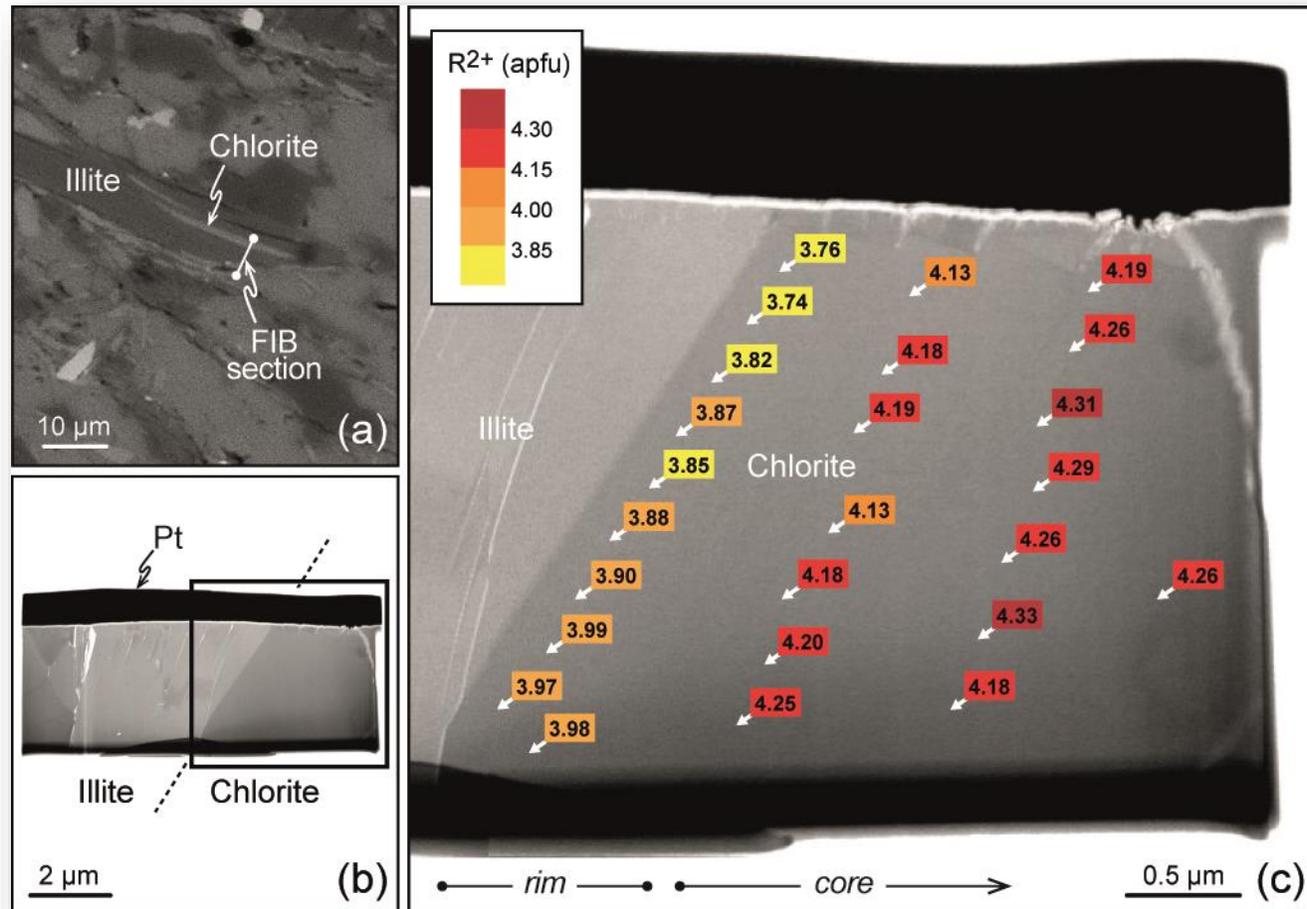


APPLICATION DES NOUVEAUX OUTILS

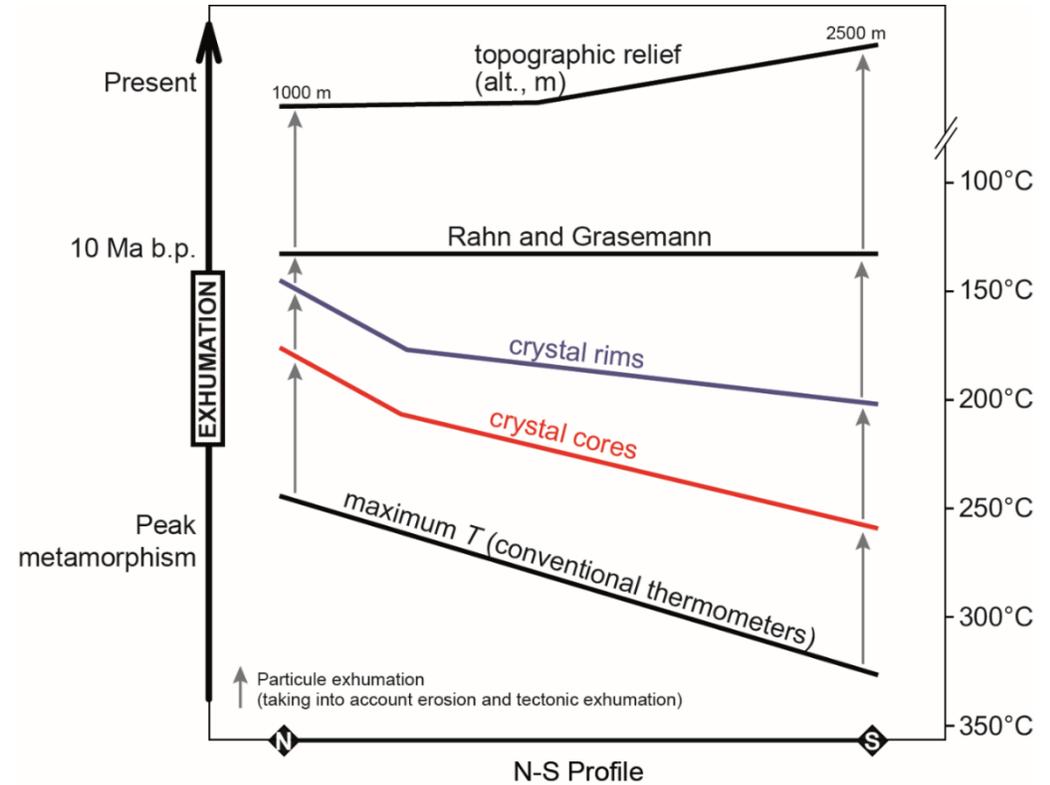
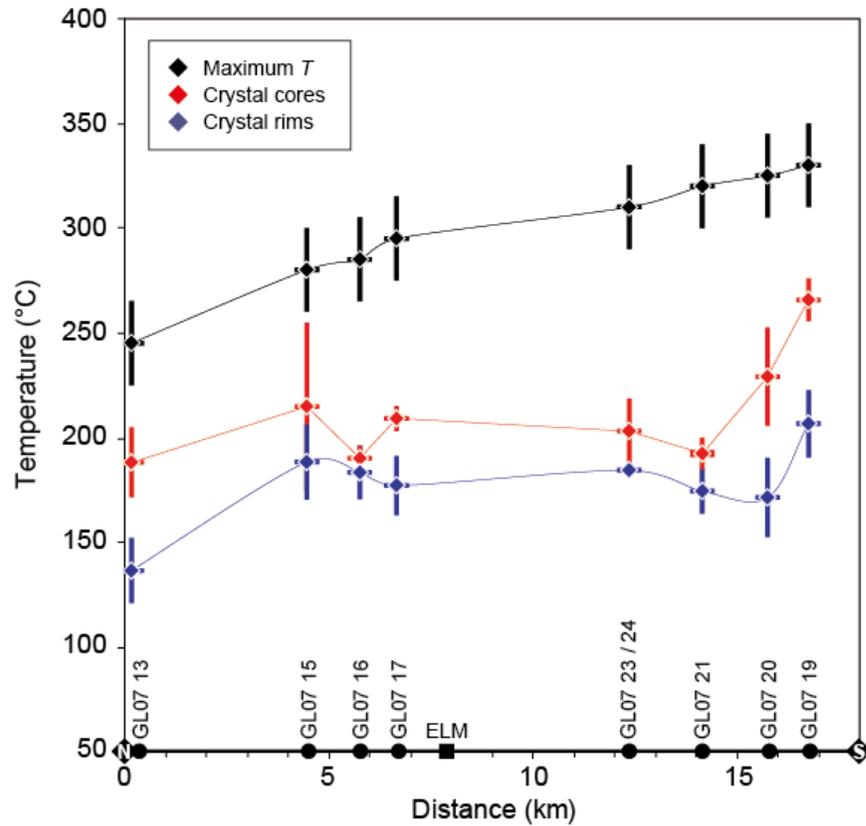
METAMORPHISME BAS DEGRE



Bourdelle et al. (2018)

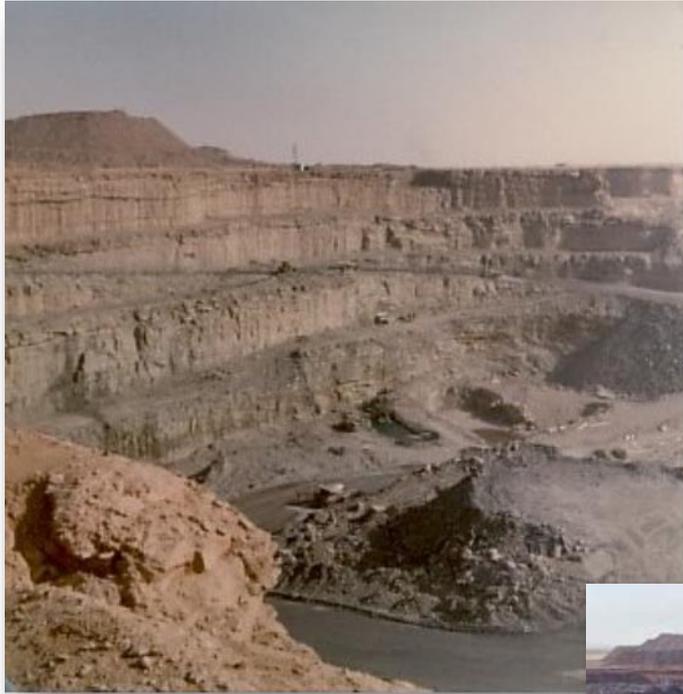


GL07 19 (sud)

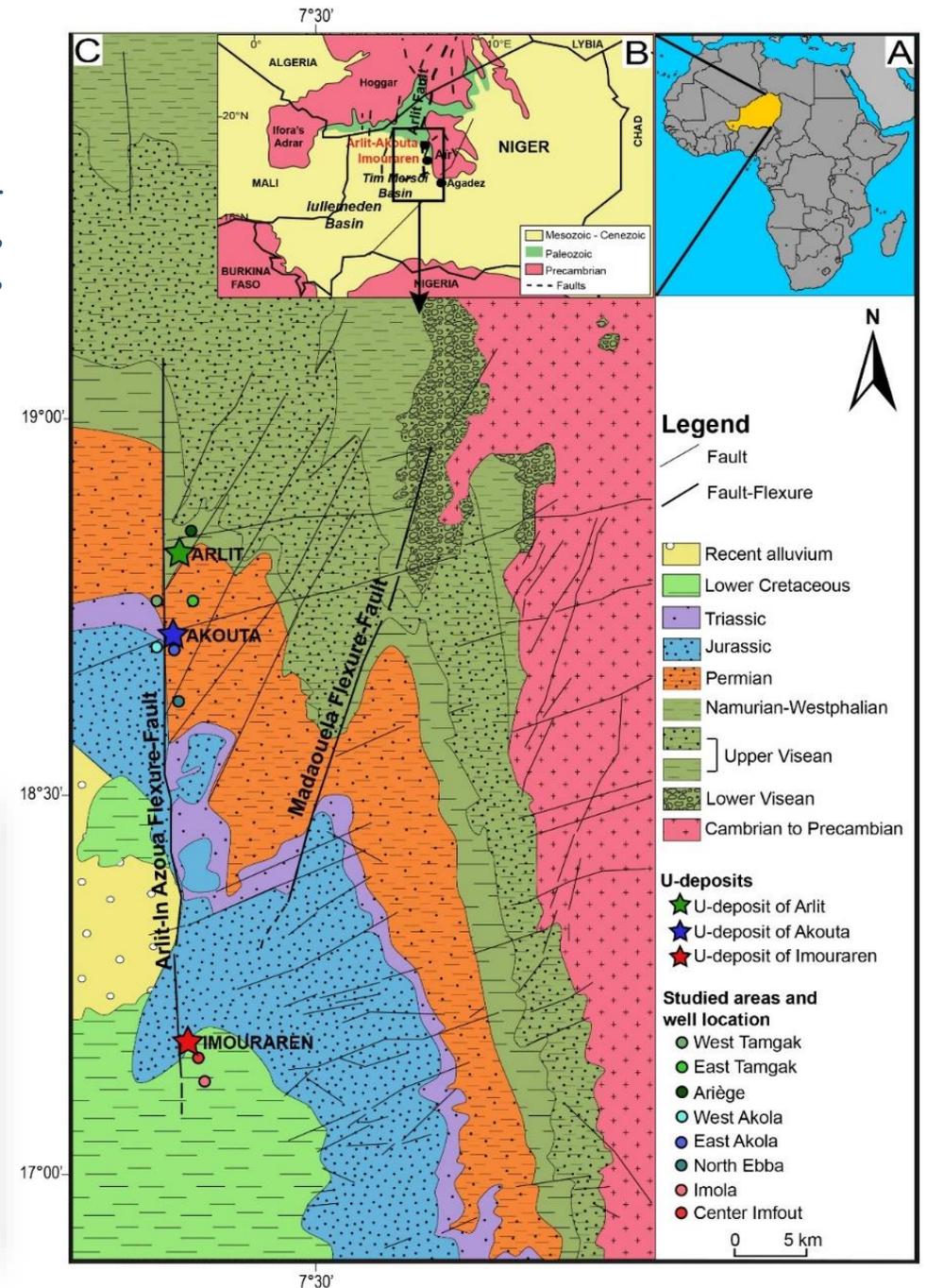


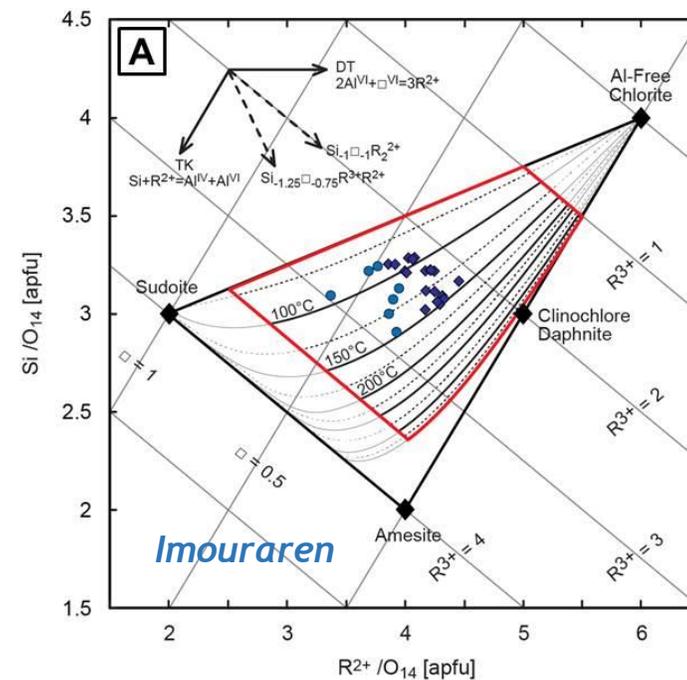
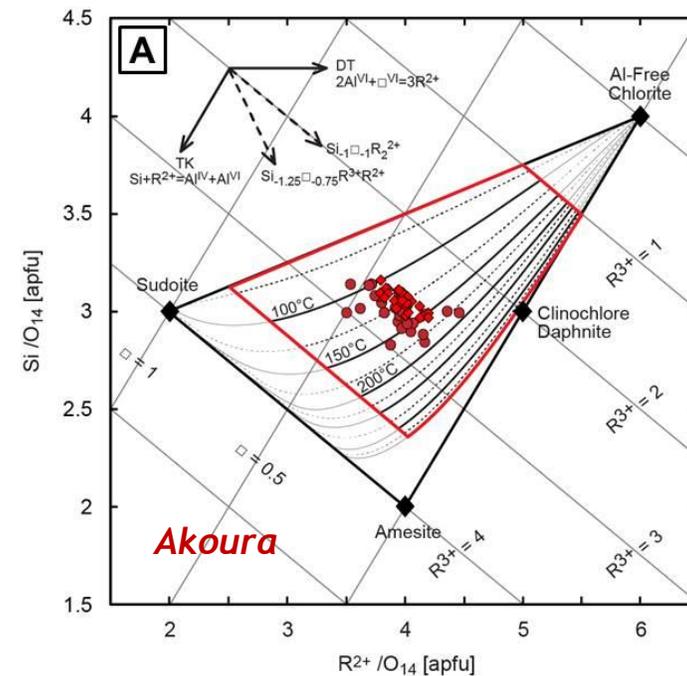
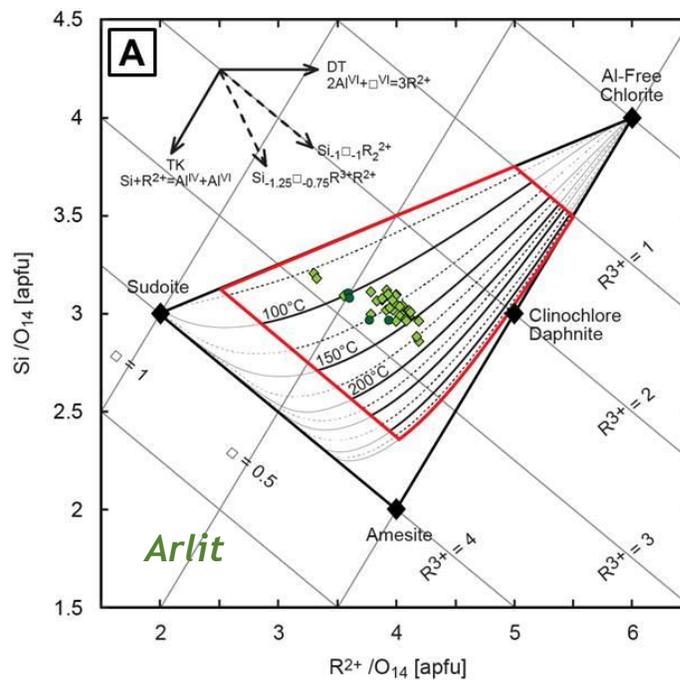
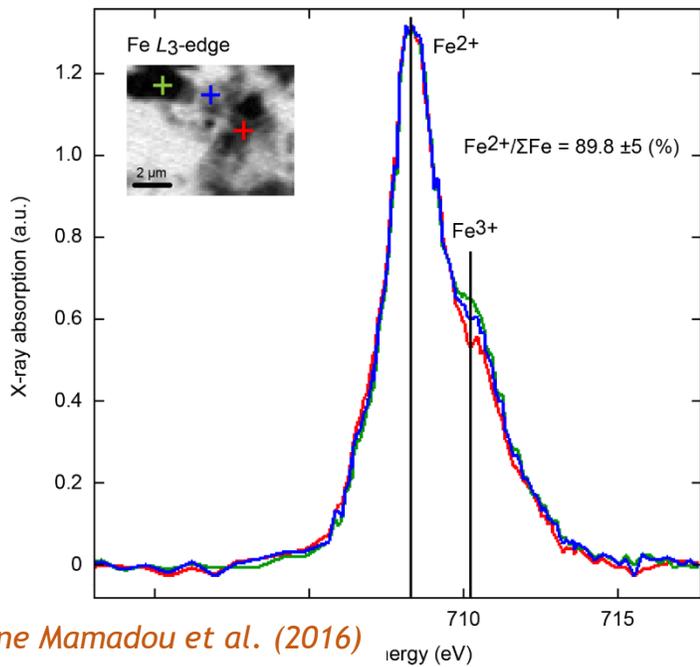
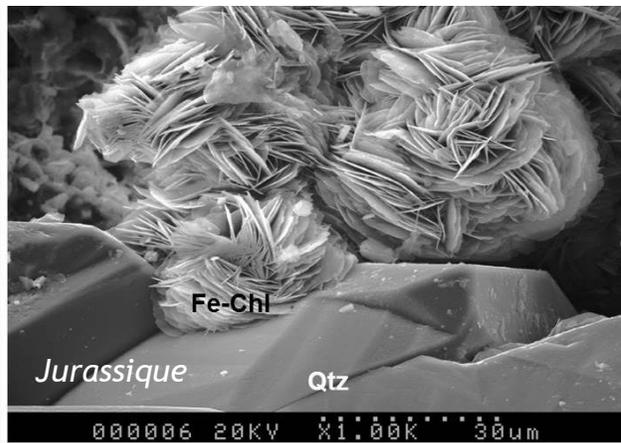
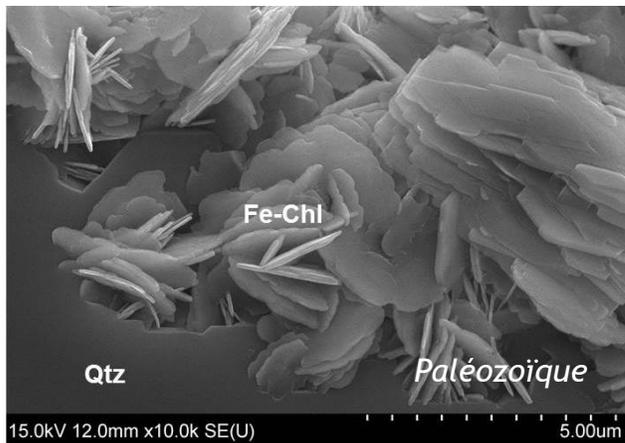
► De l'analyse nano à l'histoire régionale !

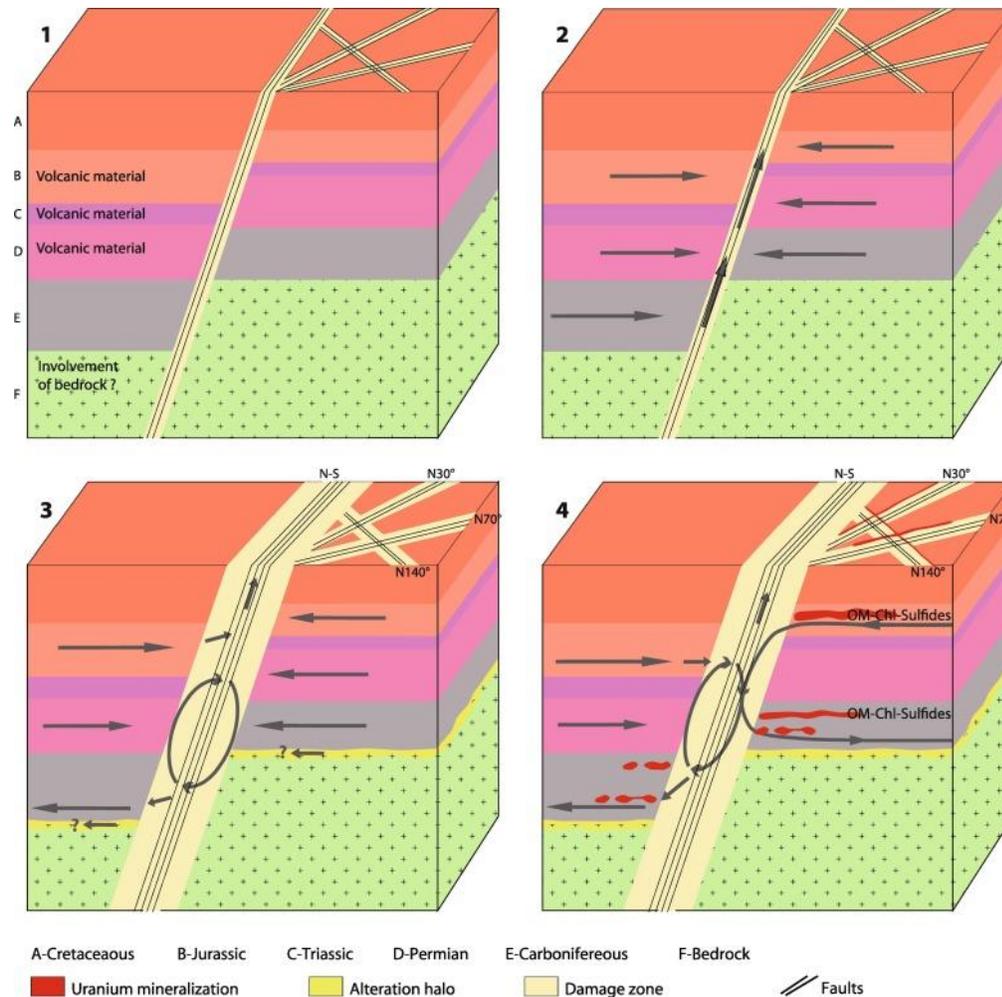
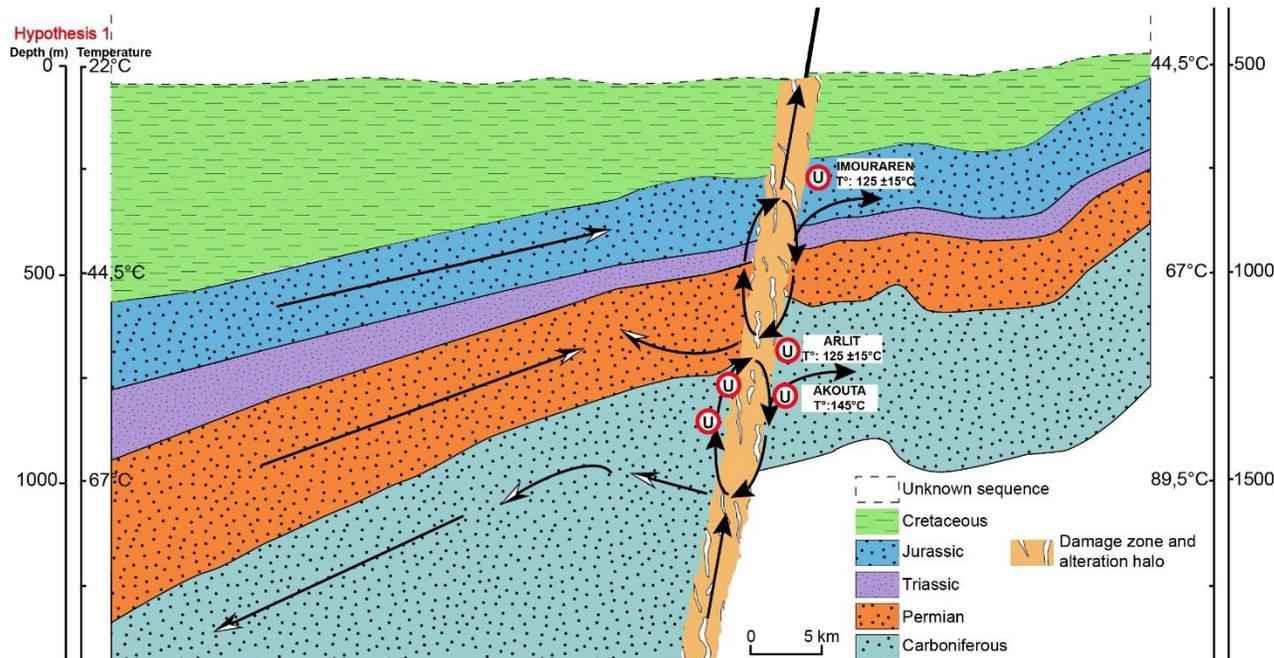
Tim Mersoi
 Akoura et Arlit : Paléozoïque
 Imouraren : Jurassique



Mamane Mamadou et al. (2016)

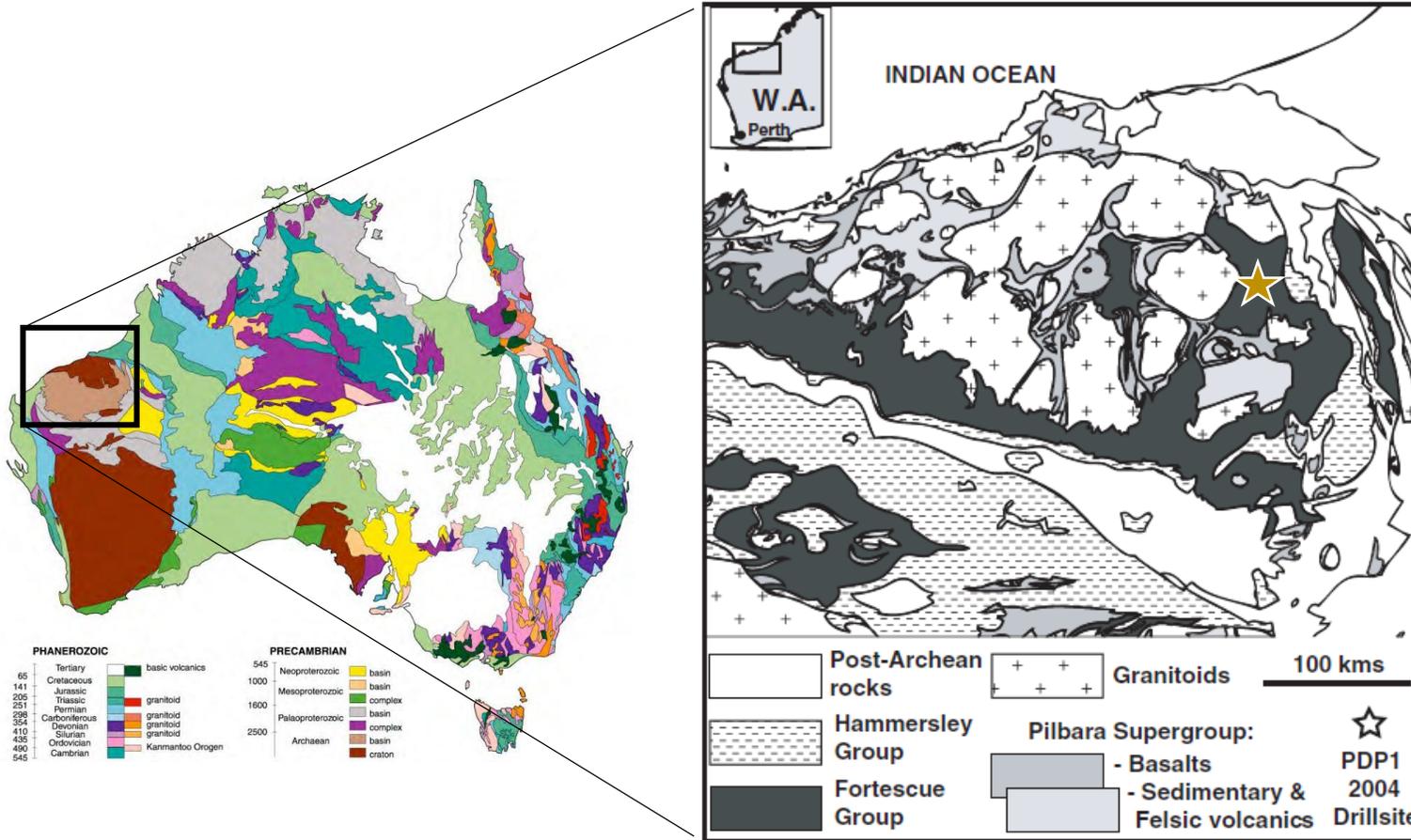






- Fe élevés et Fe³⁺ bas → conditions réductrices, favorable à U_{VI} → U_{IV} dépôt
- T identiques pour les formations Paléozoïque (Arlit et Akouta) et Jurassique (Imouraren)
- Différence de T de 60-80°C entre l'encaissant et le fluide (thermométrie Chl) indiquant des fluides chauds d'origine profonde, expulsés puis drainés par la faille

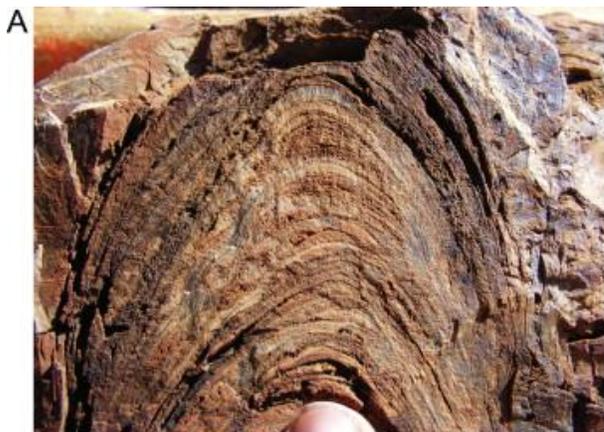
► De l'analyse nano à l'histoire régionale !



Formation de Tumbiana
Groupe de Fortescue
West Australia

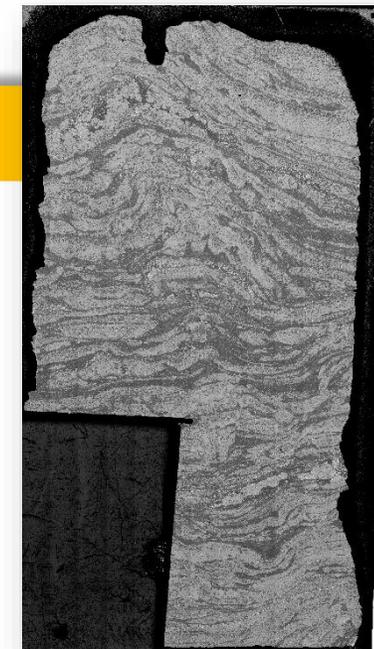
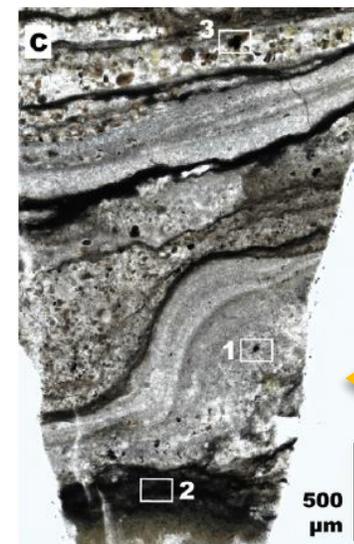
Niveau à verre
volcanique chloritisé
Lepot et al. (2009, 2019)

Des traces de vies de 2,7 Ga ?

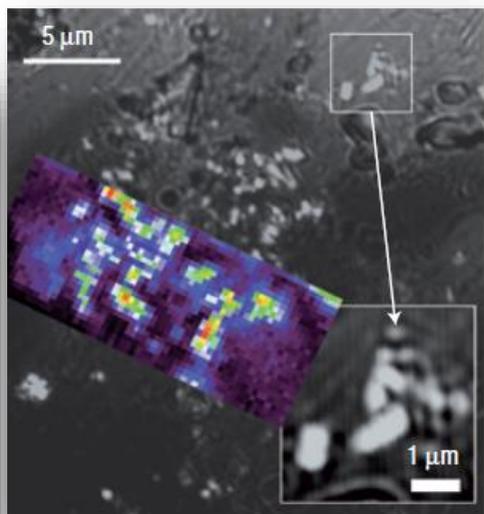
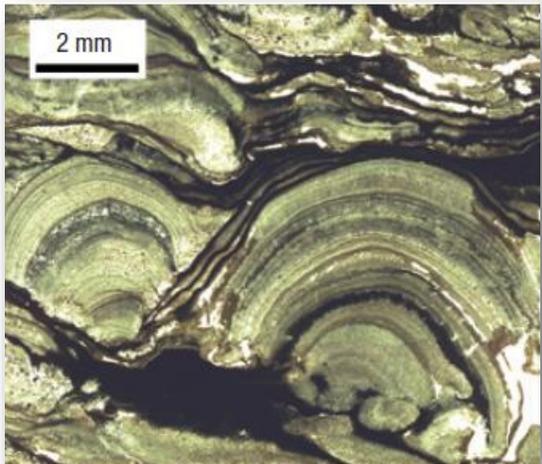


Coffey et al. (2013) / Lepot et al. (2009, 2019)

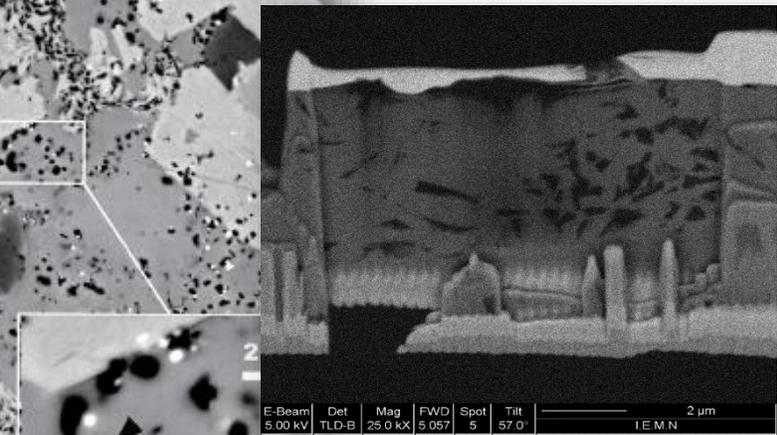
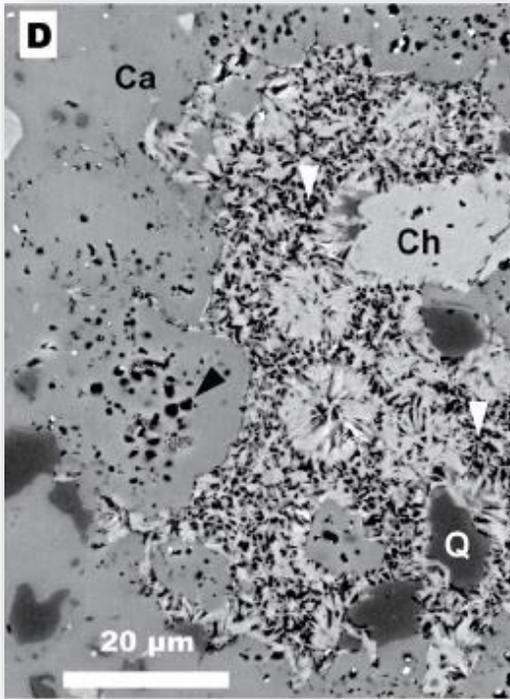
*Stromatolites de l'Archéen
Biogénique ?*



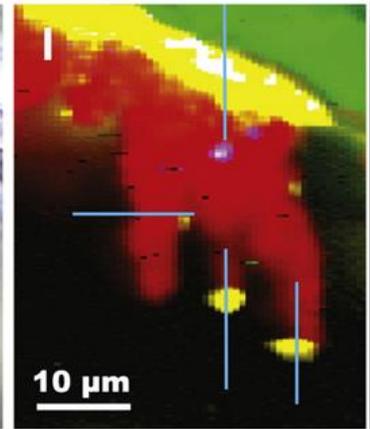
Nanoéchelle ▶ conditions de « préservation » des traces de vies
T = 280 °C



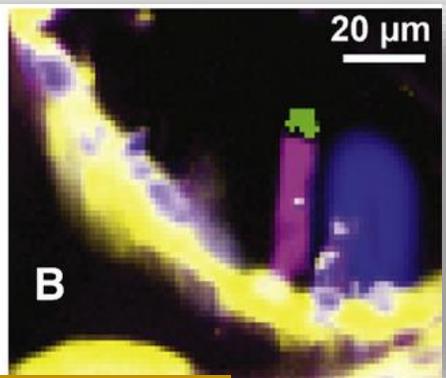
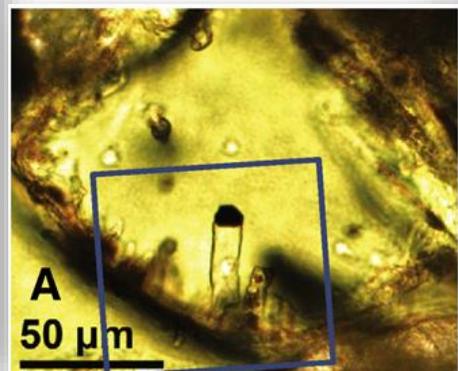
Globules de MO ▶ Biogénique



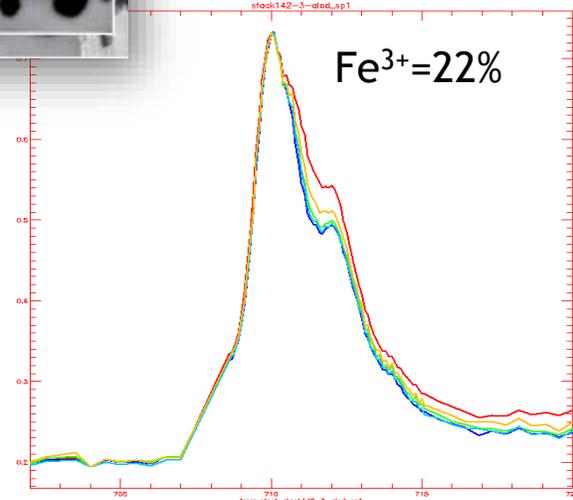
Bourdelle & Lepot (in prep.)



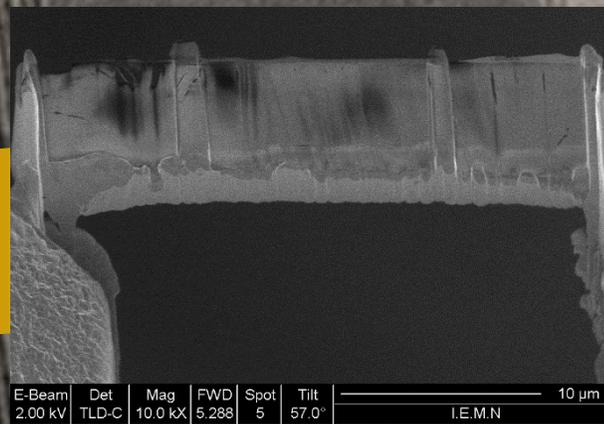
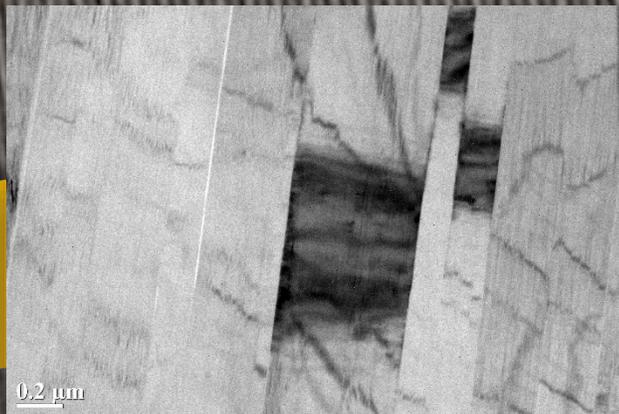
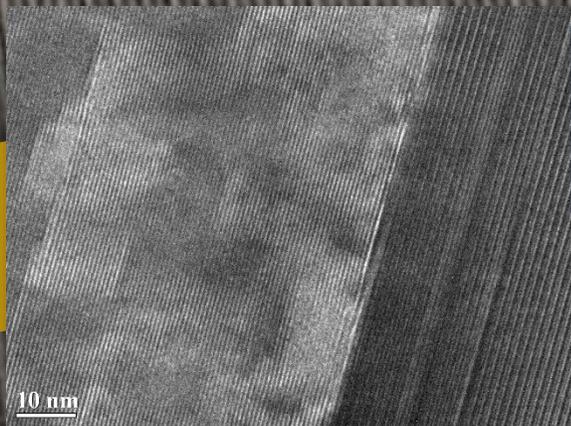
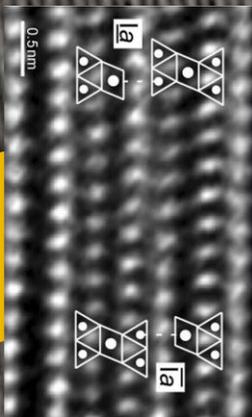
Lepot et al. (2008, 2019)



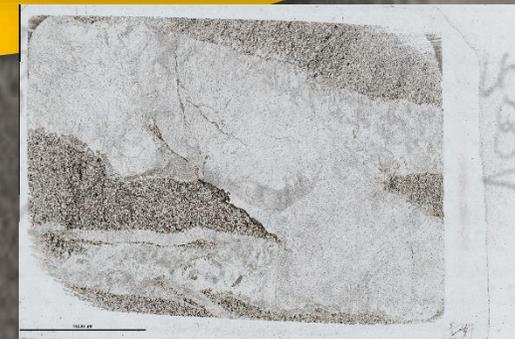
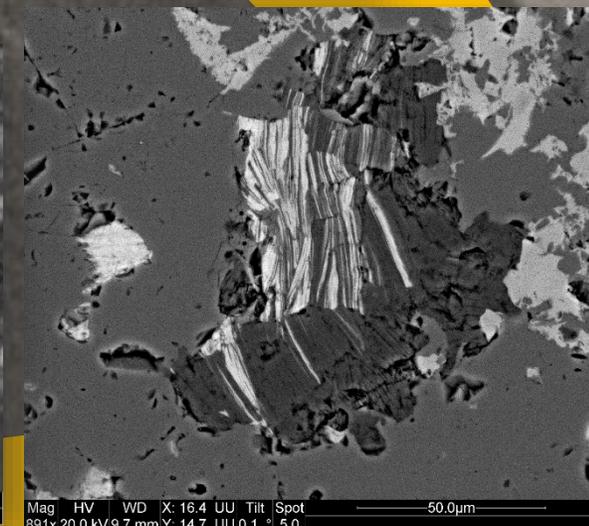
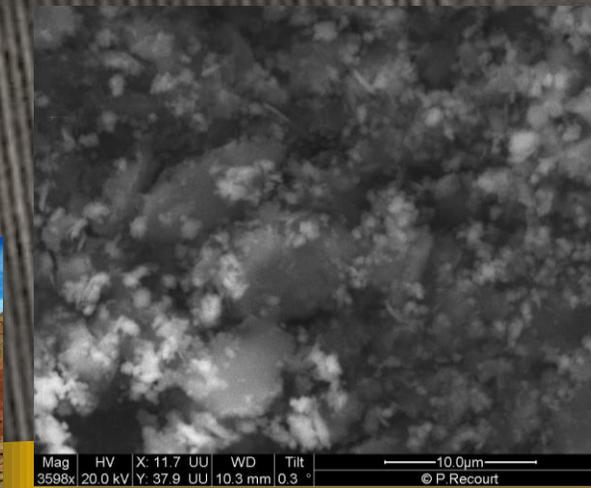
Nanoéchelle ▶ identifier ce qui n'est pas des traces de vies !



MERCI POUR VOTRE ATTENTION !



10 nm



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