Field trip EAGE Toulouse 2025

Exploring Natural hydrogen in the Pyrenean piedmont From source rock to reservoirs

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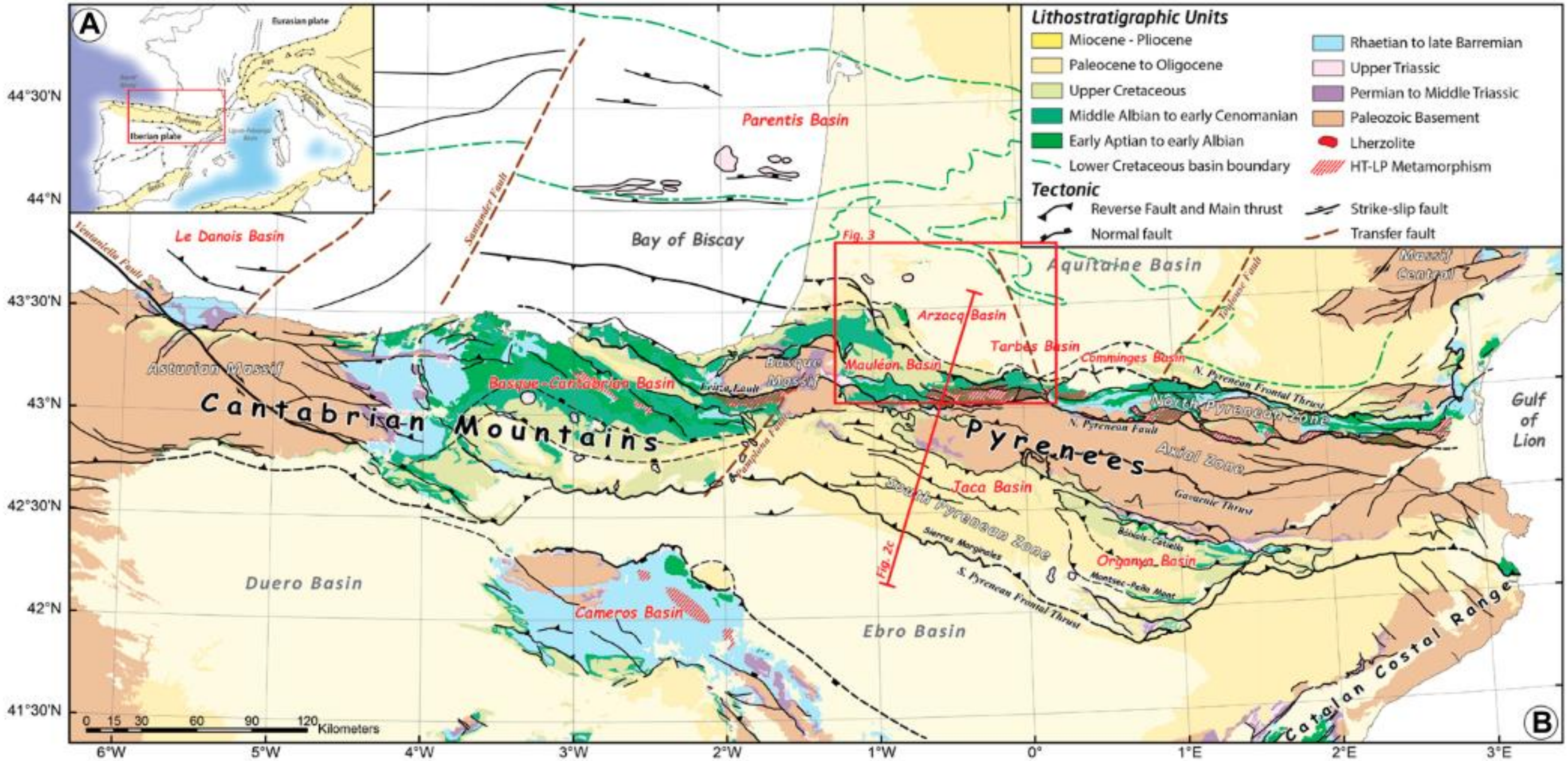
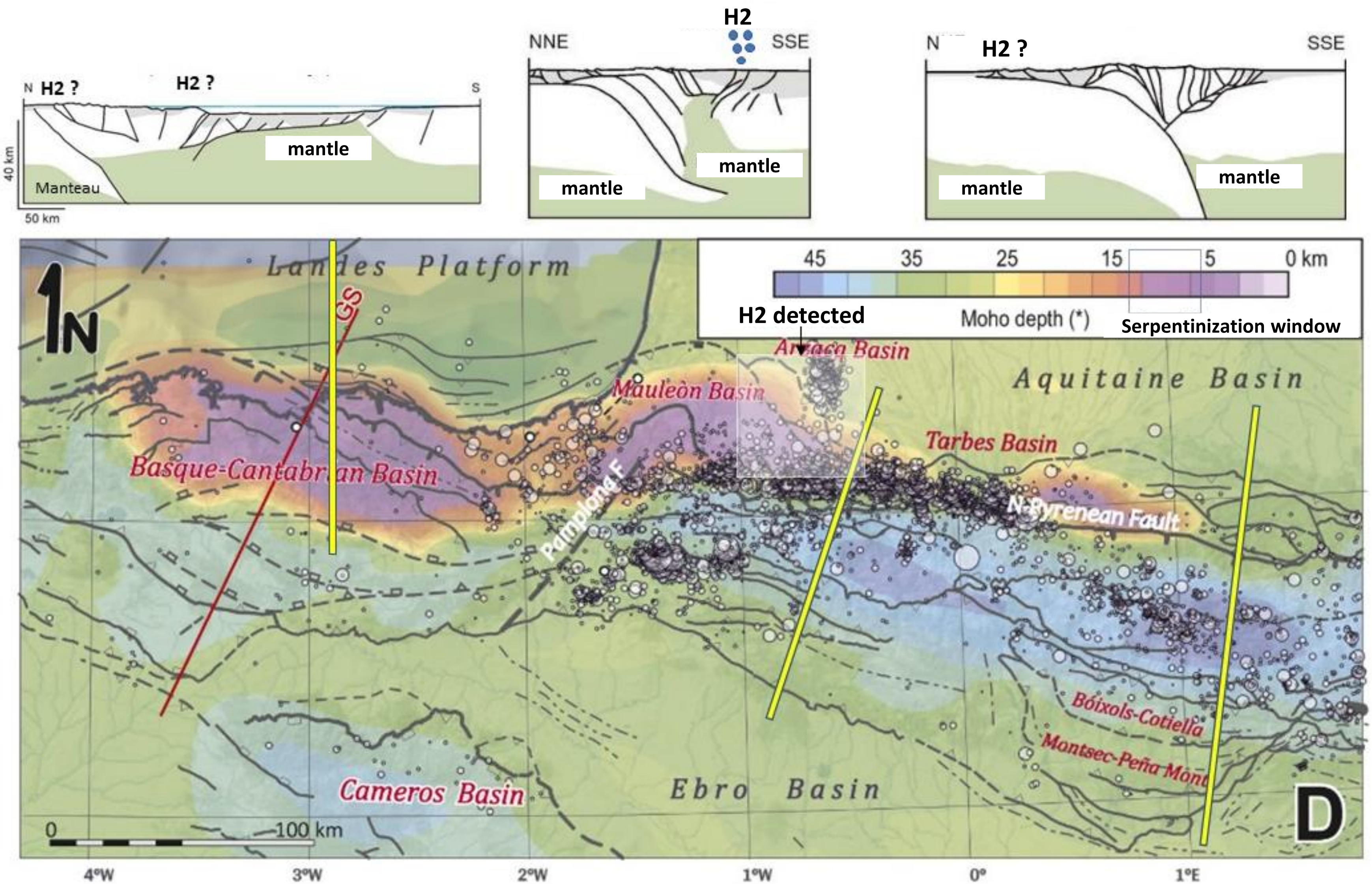
Photo C. Aubourg

Geological setting



Ducoux et al., (GSA, 2021)

Pyrenees Moho depth
a mantle in the serpentinization window

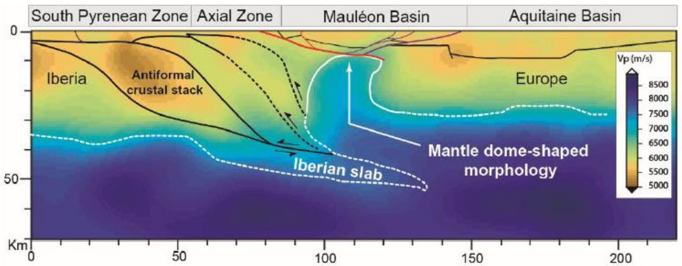


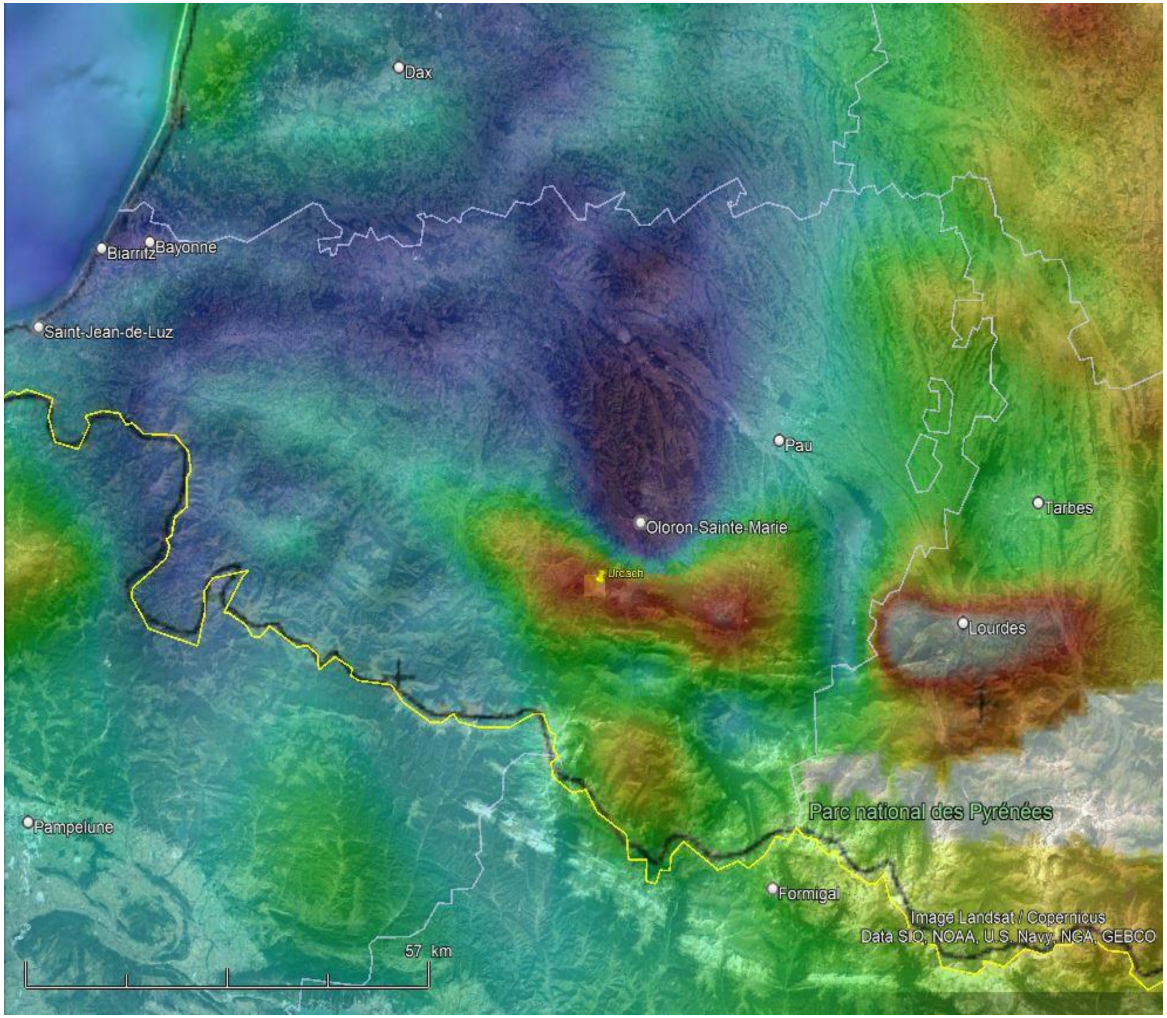
Map from Pedrera et al., (2021)

Magnetic map of western Pyrenees

Two main magnetic positive anomalies : Mauleon and Lourdes? Associated with positive gravimetric anomalies

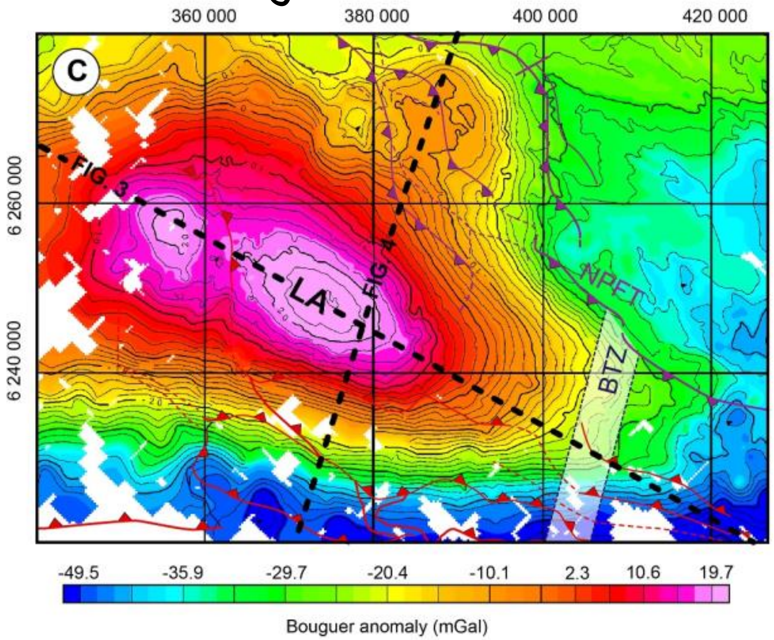
→ Dense magnetic bodies at shallow depths ?



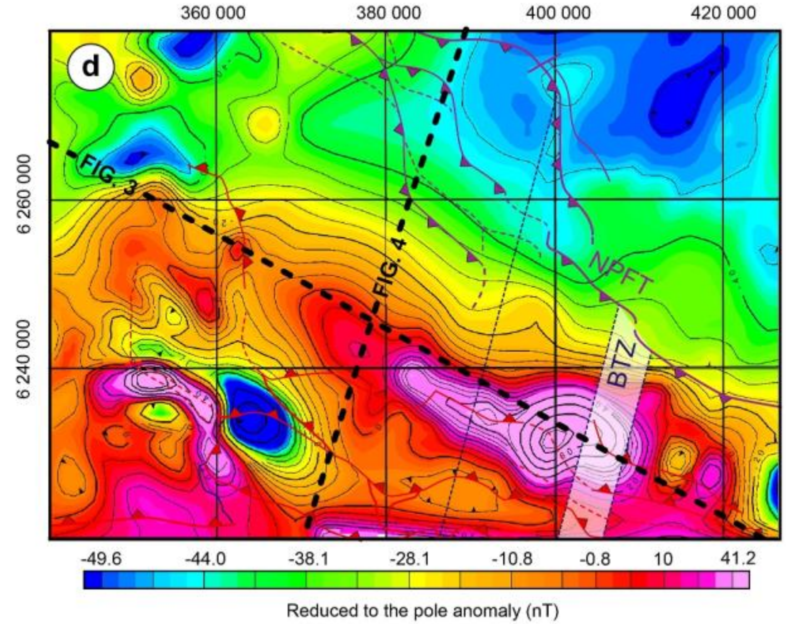


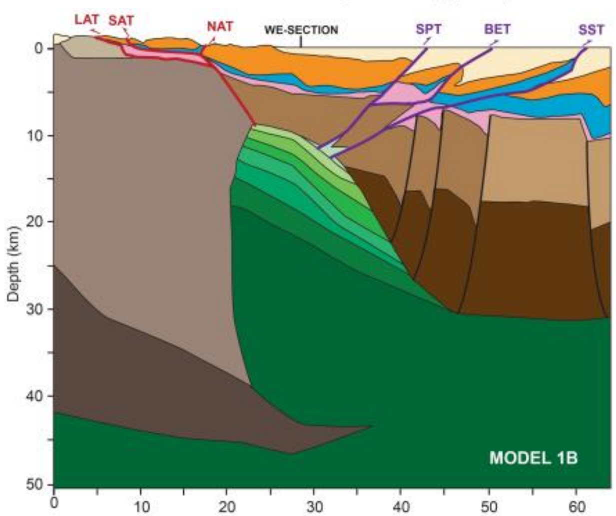
Proximity of mantle : matching geophysical data

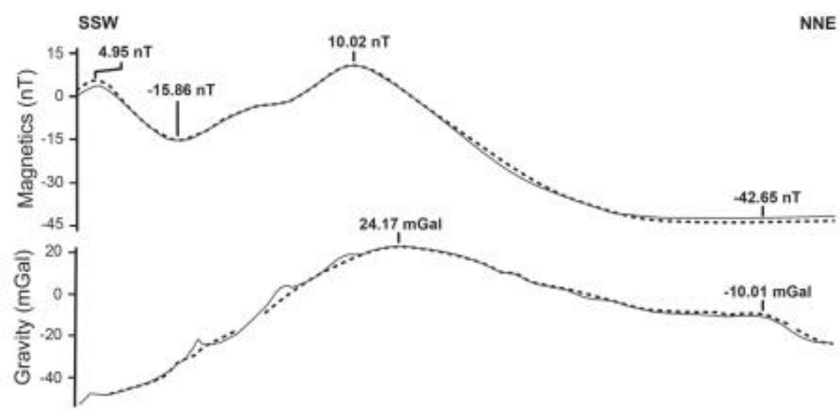
Magnetic data



Gravimetric data







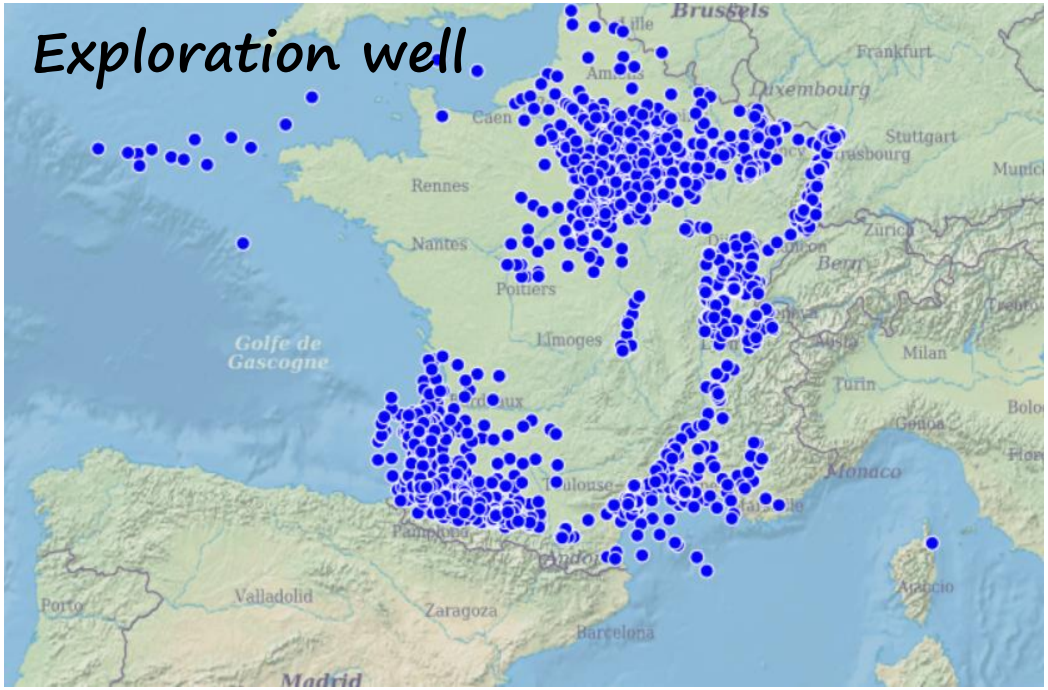
Saspiturry et al., 2024

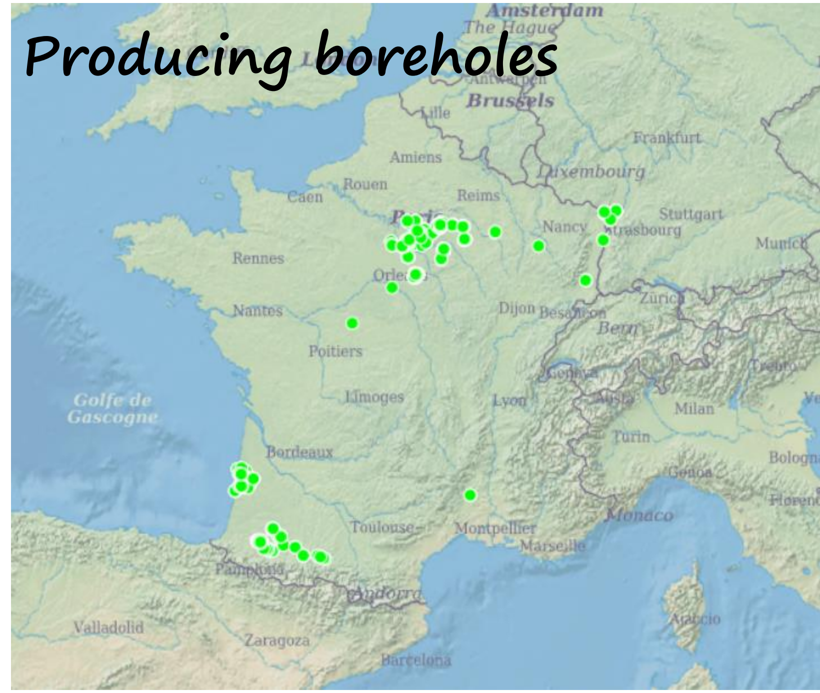
Exploring Natural hydrogen in the Pyrenean piedmont
From source rock (day 1) to reservoirs (day 2)

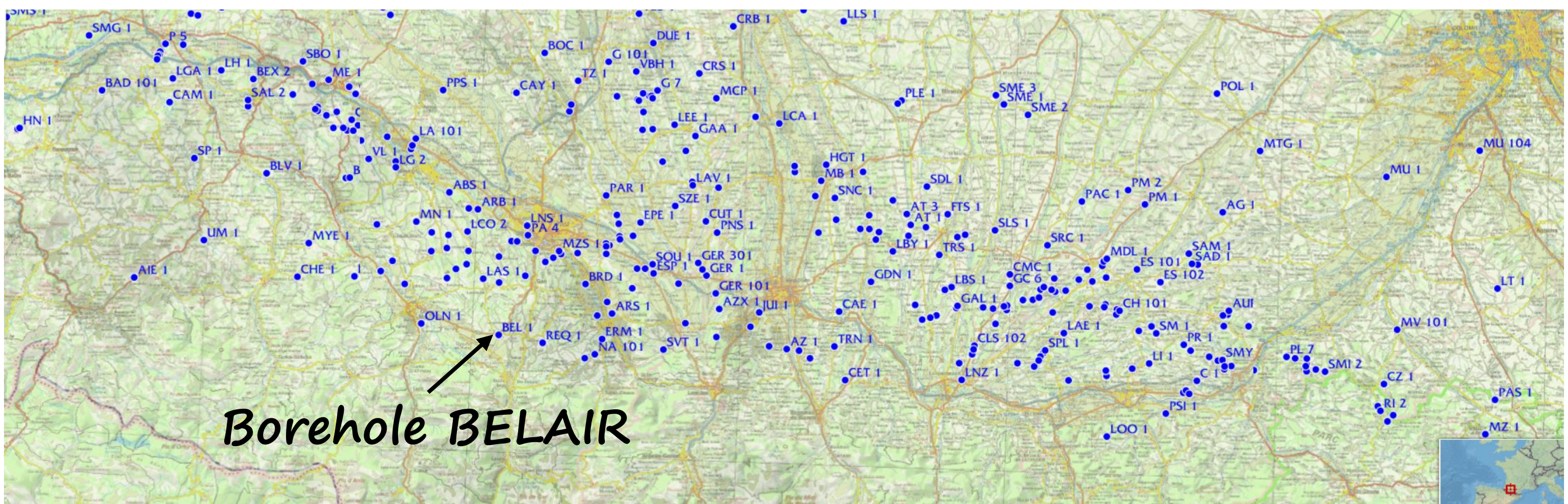
Day 1

Breaking science in North Pyrenees.
A pinch of salt, a little water, mantle rocks, and hydrogen.

Oil&Gas exploration

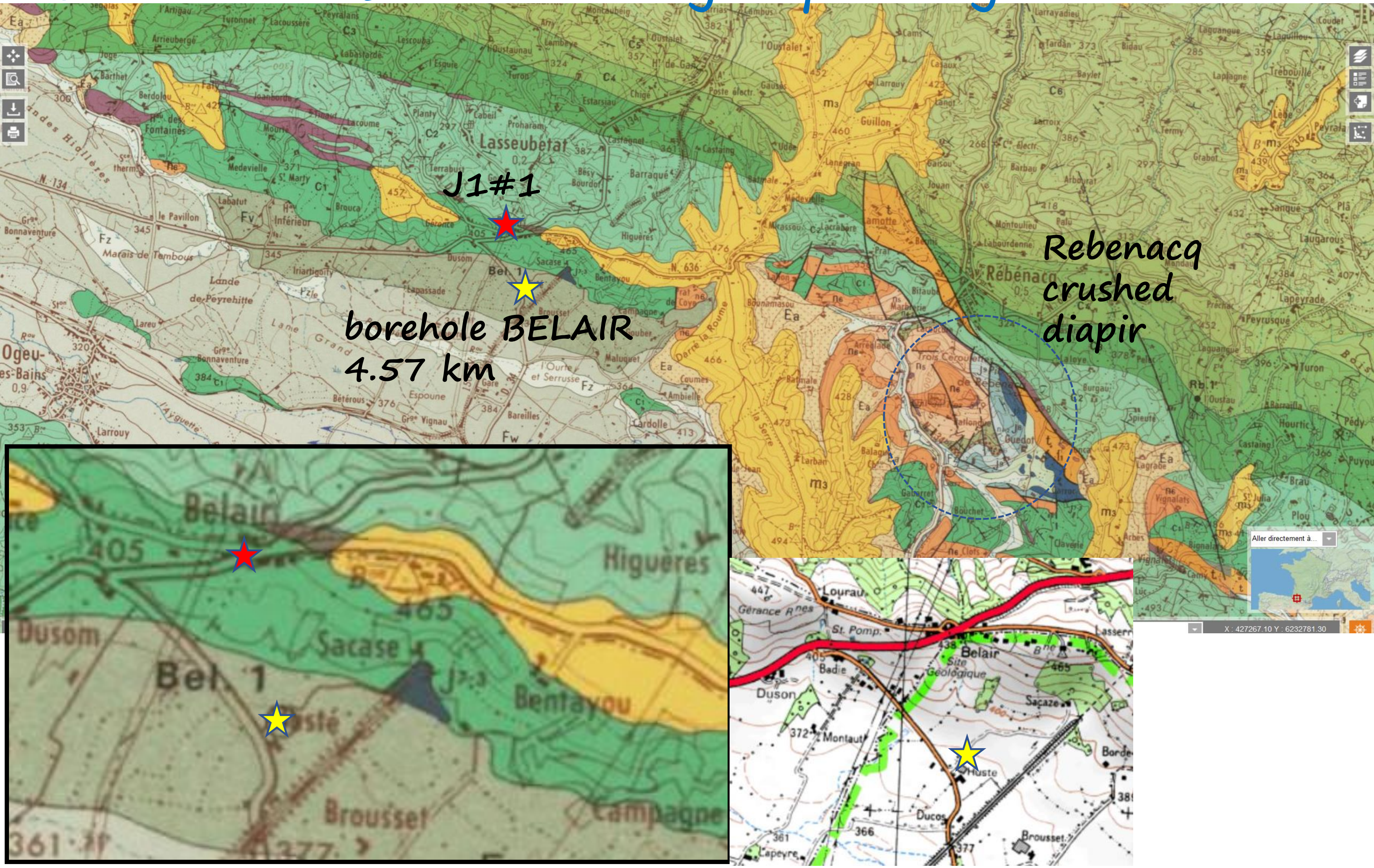






http://www.minergies.fr/fr/cartographie

STOP J1#1 BELAIR: a ridge separating two worlds

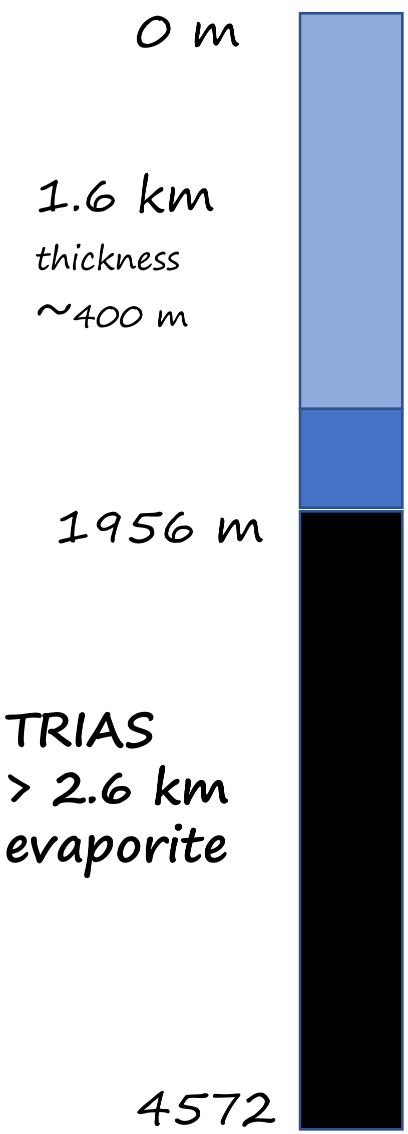


http://www.minergies.fr/fr/cartographie

Borehole Belair 1982

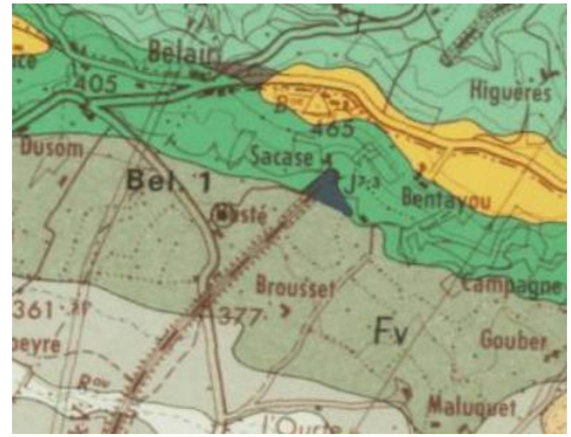
1.2 - But du sondage

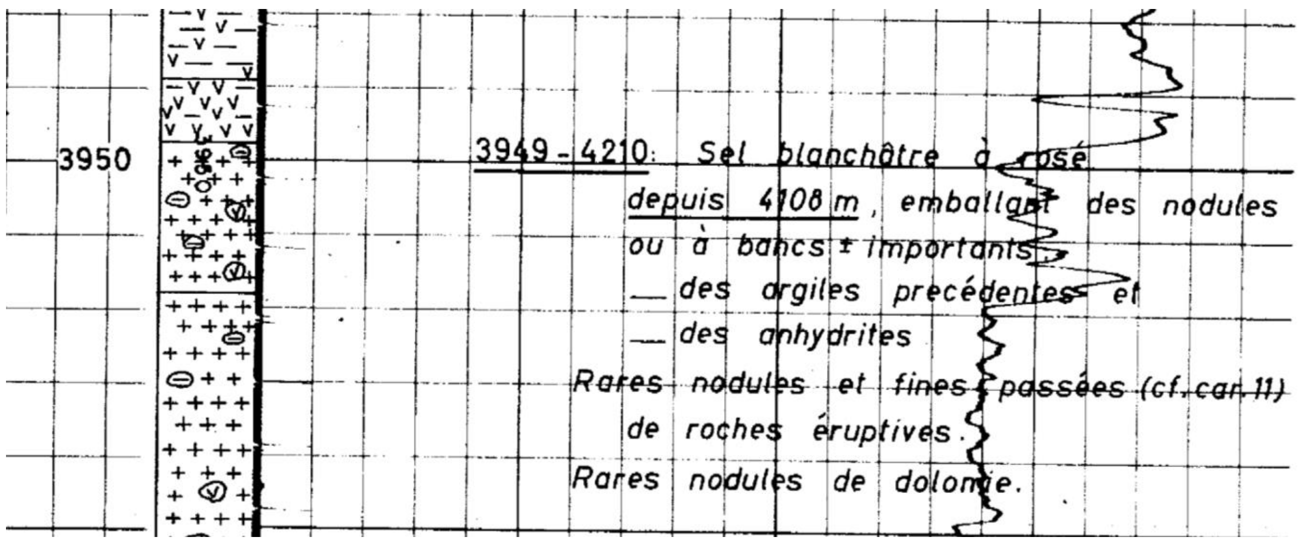
Reconnaissance du potentiel pétrolier, de la stratigraphie et lithologie des séries allochtones du prospect de Guiche n° 1. L'objectif principal était situé entre 900 m (base présumée du Cénozoïque) et le décollement principal (contact allochtone-autochtone).



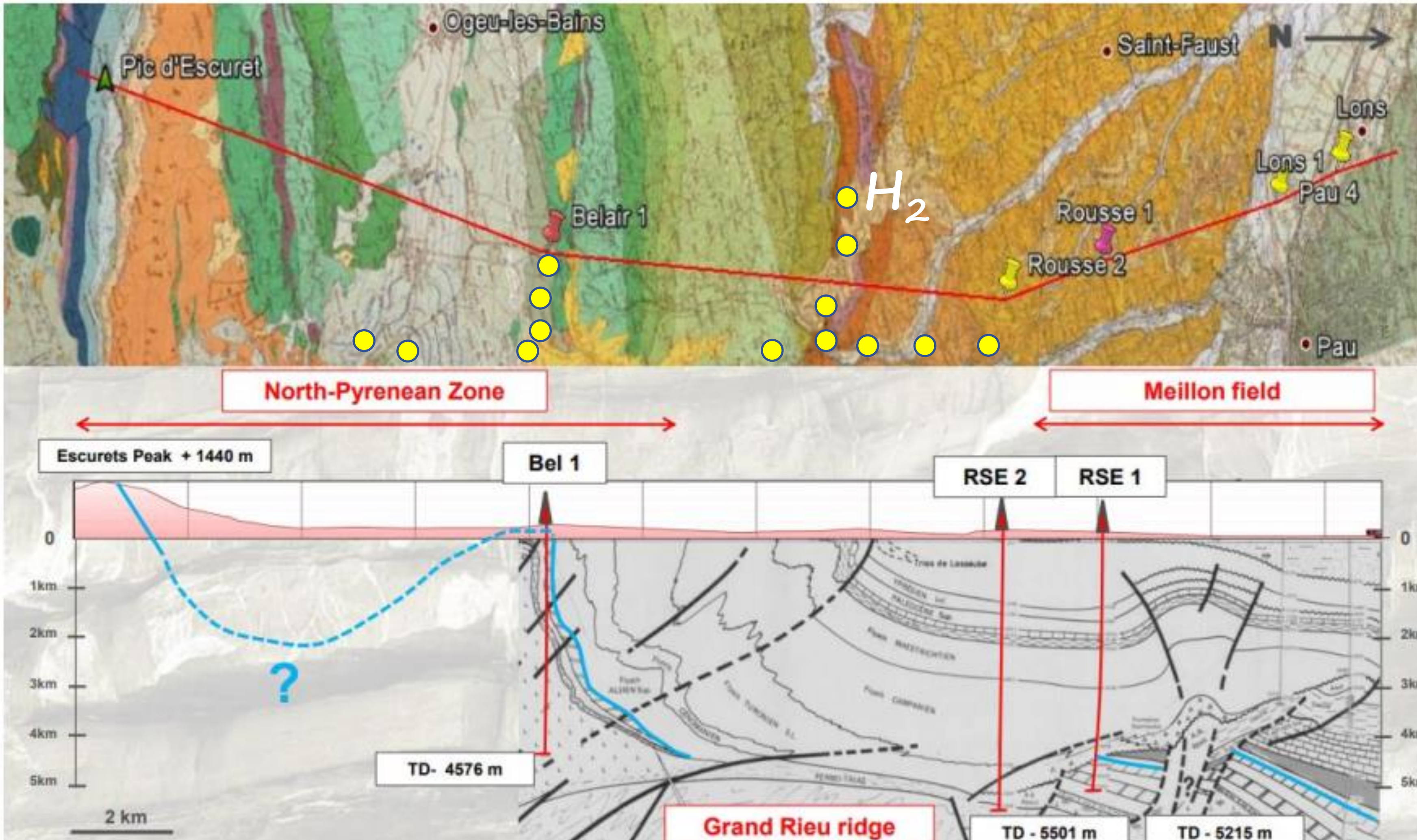
Callovo Oxfordian :
Meillon Dolomite (R)
Sub-vertical bedding

Low Jurassic sequence



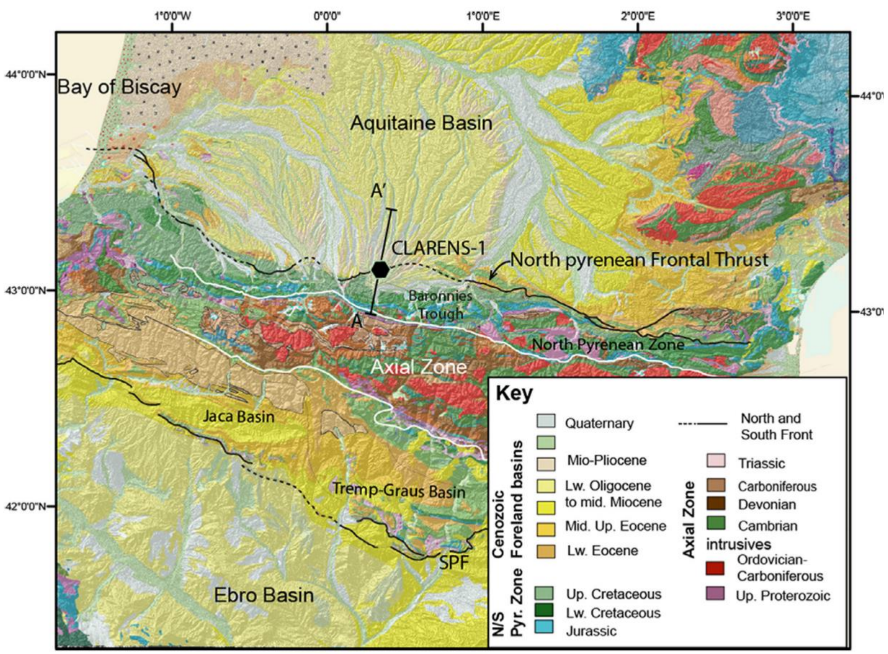


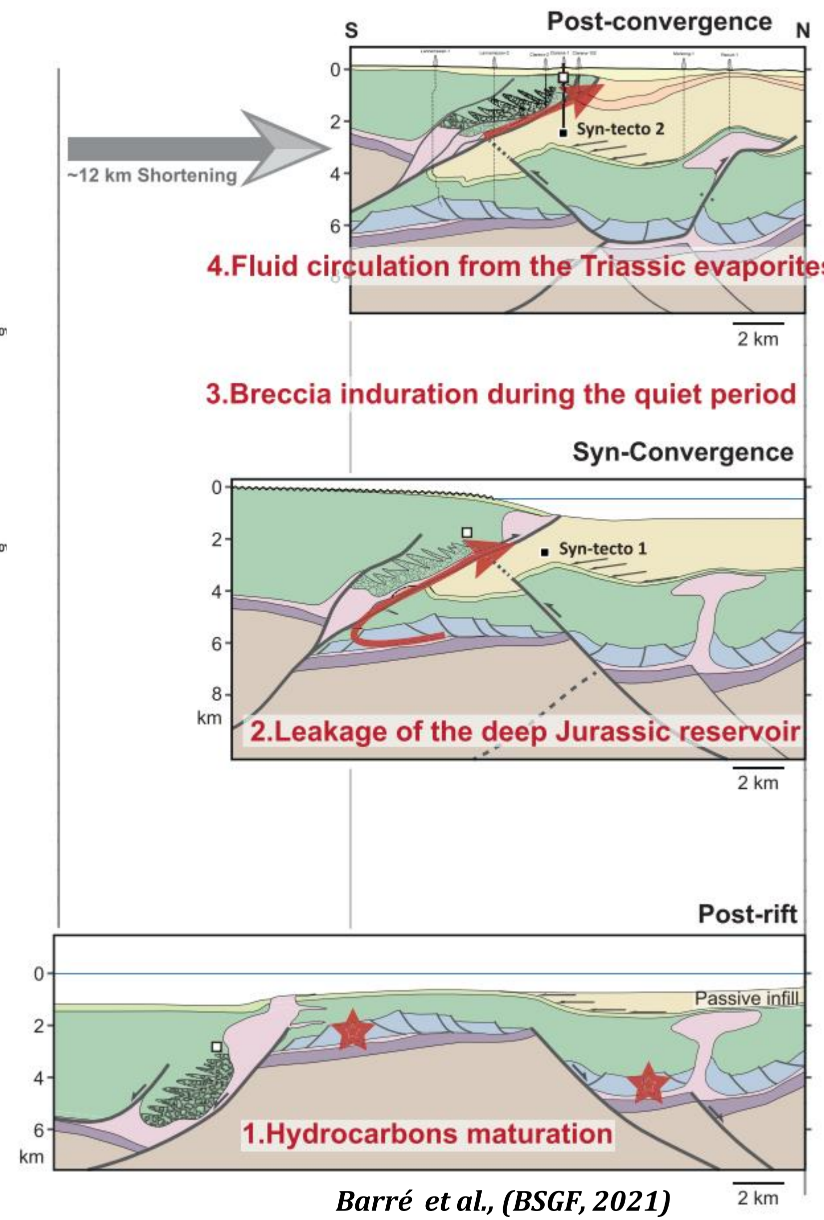
Inverted Normal fault → welded structure



Document from Geolval

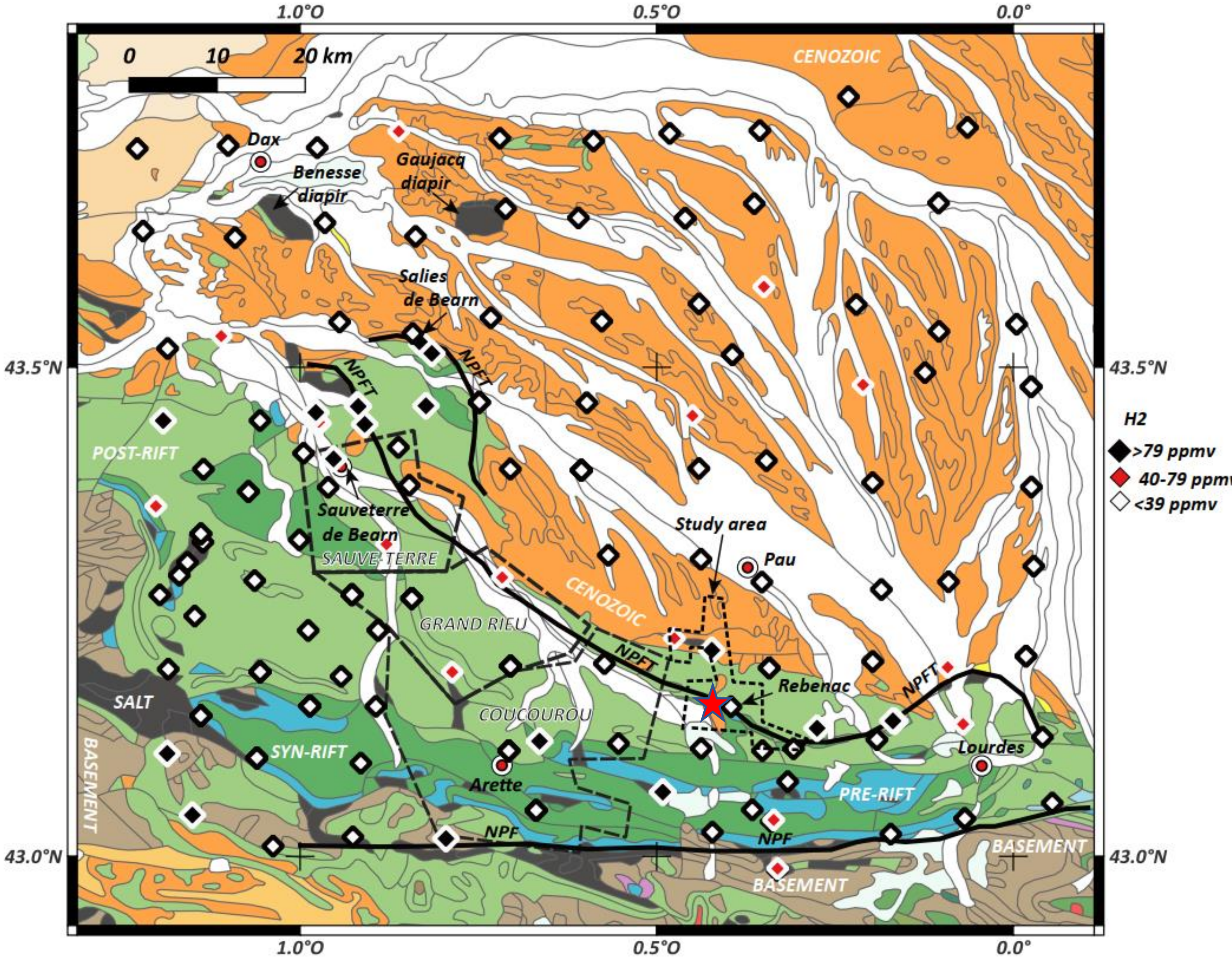
The North Pyrenean frontal thrust





Barré et al., (BSGF, 2021)

Exclusive Search Permits H2 along NPFT



Data from Lefeuvre et al. (2021, 2022) map from Aubourg et al., (submitted)

H2 source rock ?

Oxydation	Radiolyse	Pyrolyse
		
Iron rich rock Fe^{2+}	granite	Shales
Temperature 👍	❎	👍
100°C–350°C		200°C–300°C
water 👍	👍	❎

olivine + water → serpentine + brucite + magnetite + H2

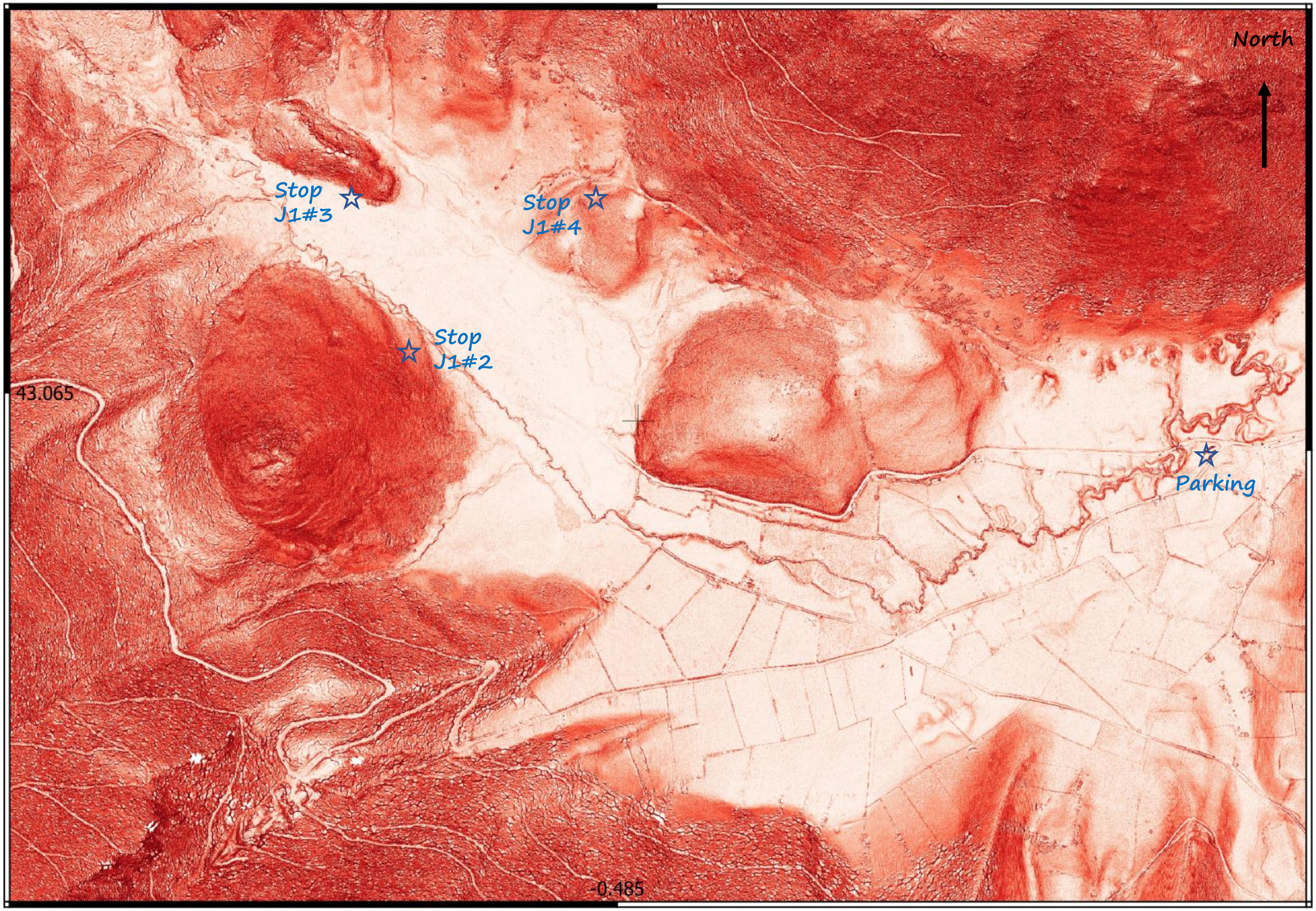
$$30(Mg,Fe^{2+})_2SiO_4 + 41H_2O \rightarrow 15(Mg,Fe^{2+},Fe^{3+})_3Si_2O_5(OH)_4 + 9(Mg,Fe^{2+})(OH)_2 + 2Fe^{3+}{}_2Fe^{2+}O_4 + 2H_2$$

key observation points for stop J1#1

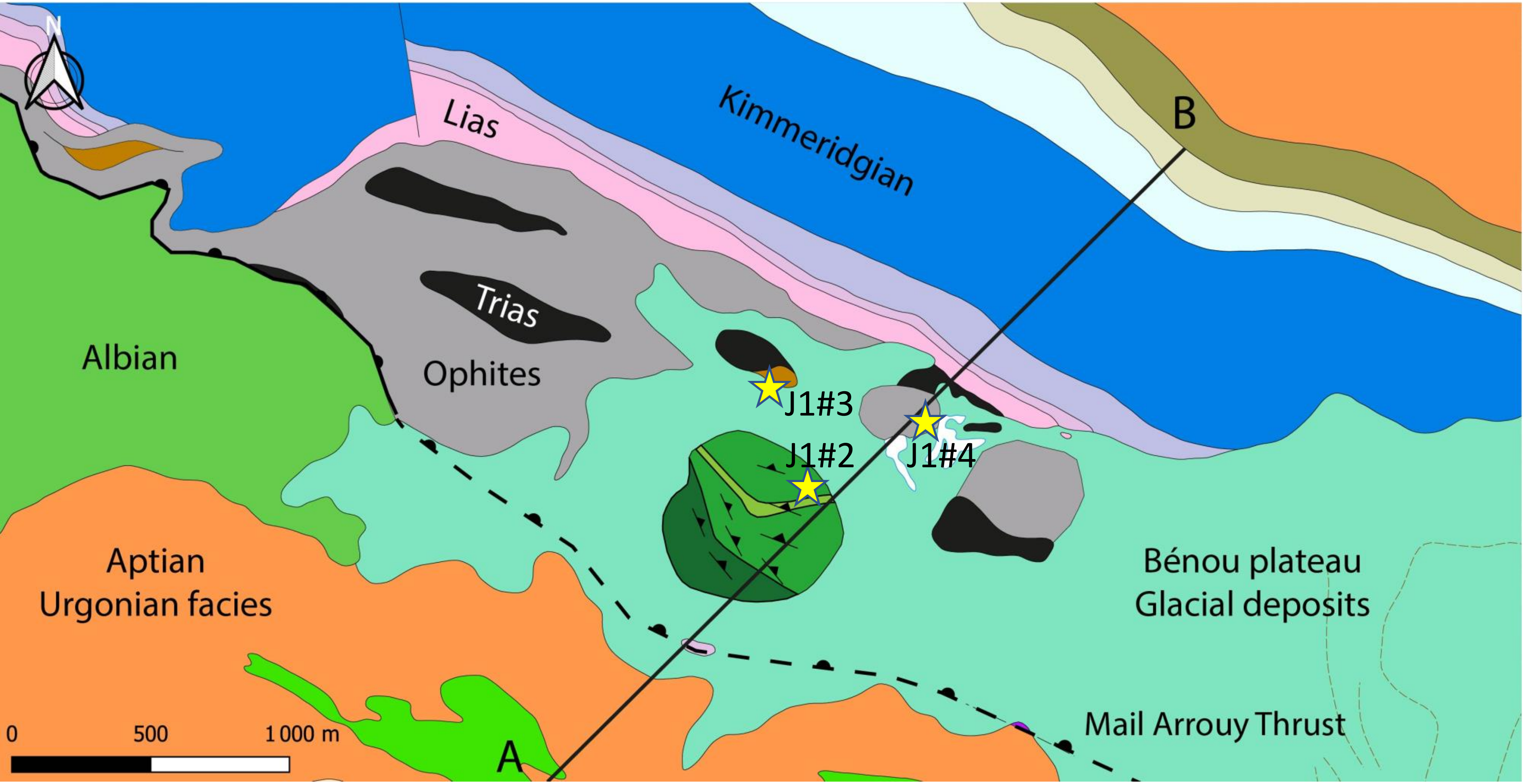
- ✓ Bélair is located above the blind **North Pyrenean Frontal Thrust**,
- ✓ 4.6 km. Borehole Bel.1 revealed the preservation of a diapir, which grew in a normal fault during the Late Cretaceous.
- ✓ This diapir marks the boundary between rift-like metamorphism to the south and unmetamorphosed rocks to the north.
- ✓ Furthermore, this fault also functions as a major drainage system, including H2.

Your synthesis

Stop J1#2 to #4 Benou Plateau ; a collection of H2 source rocks…

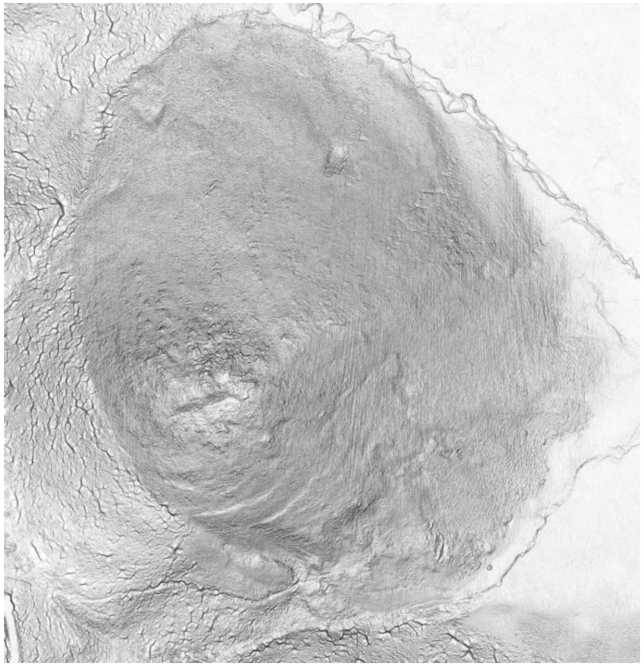


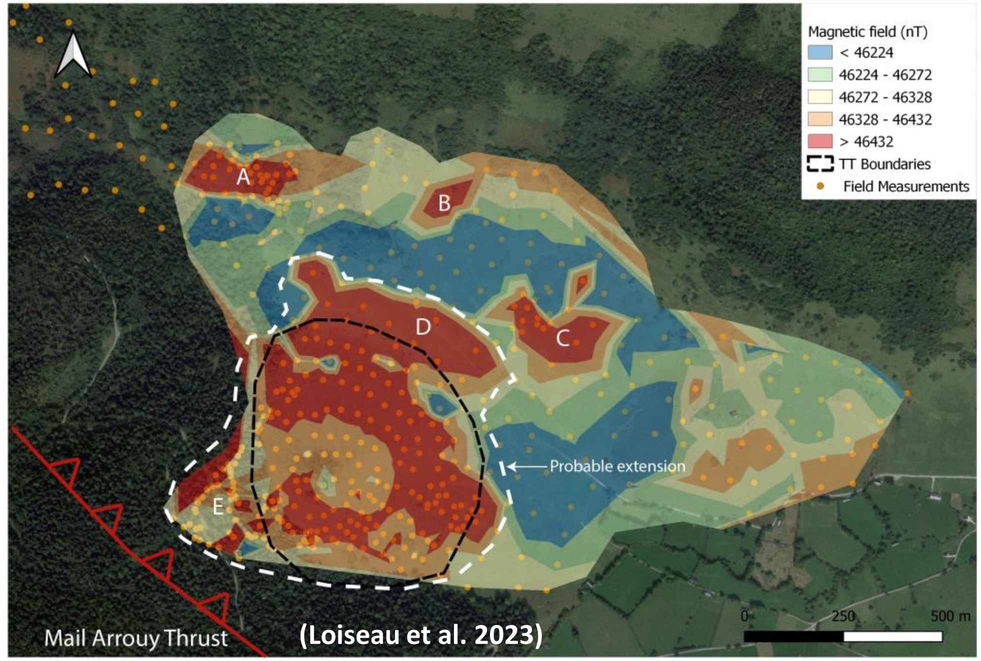
Simplified geological maps

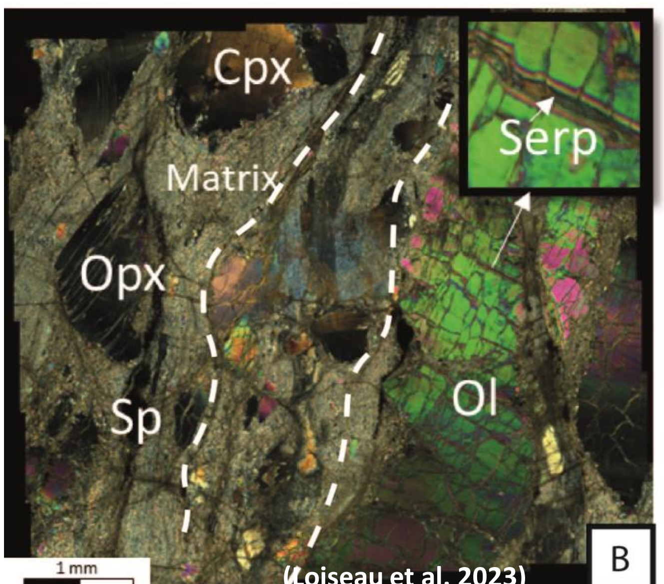


(Loiseau et al. 2023)

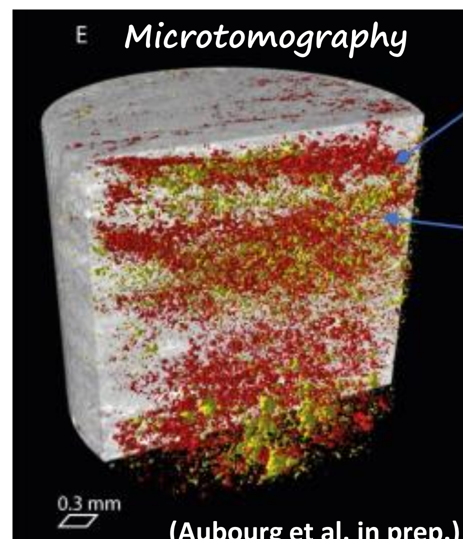
Stop J1#2 Turon de la Técouère







Olivine : 35-55%
Opx : 20-23%
Cpx : 8-14%
Spinel : 3-5%
Plg : 2-3%
Serpentine 5-30%
Magnetite 0-3%



Magnetite ~3.1%

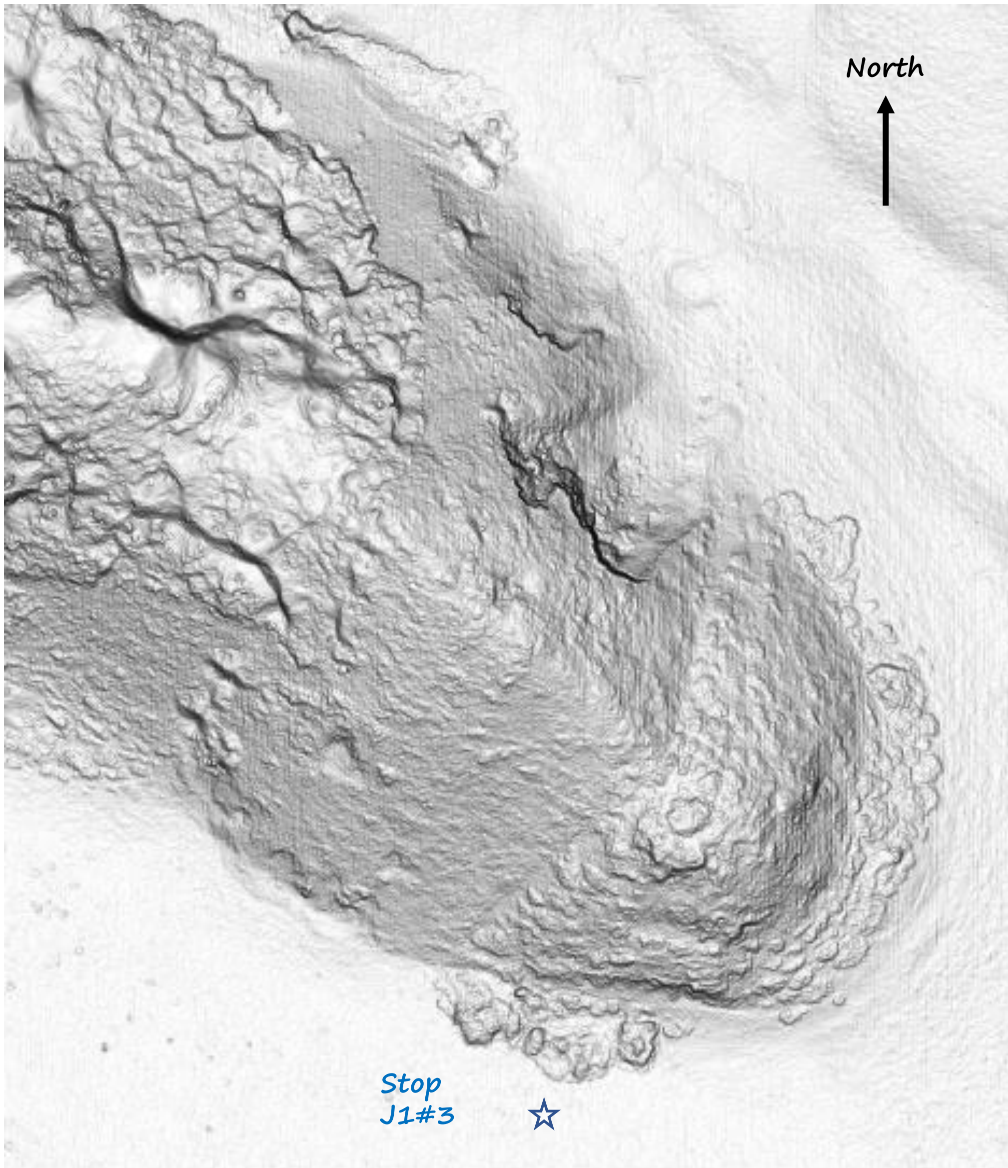
Pore ~2.3%

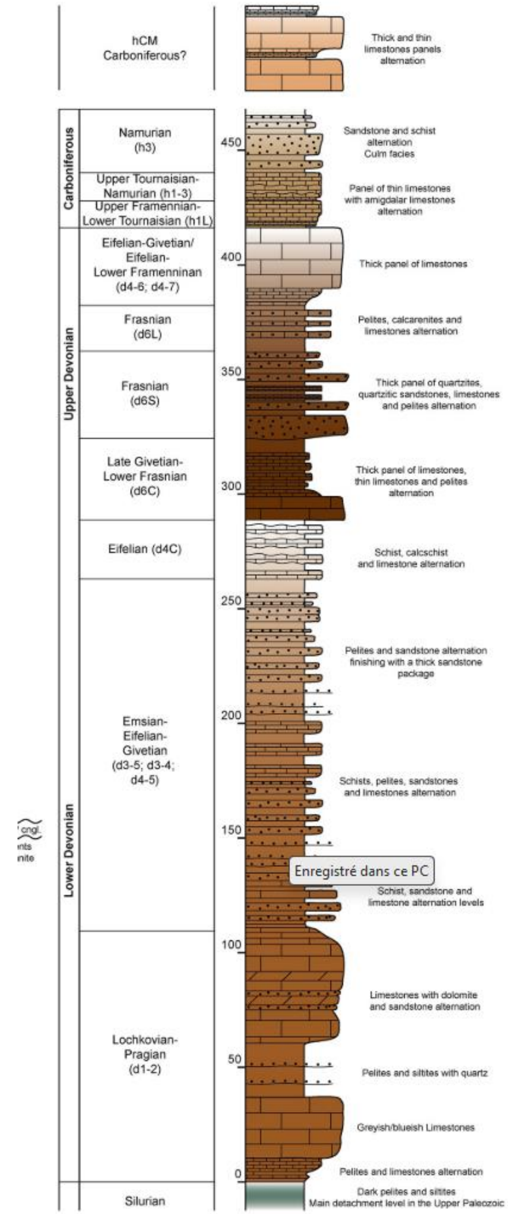
key observation points for stop J1#2

- ✓ The Turon de la Técouère is a mylonitized continental lherzolite with remnants of garnet facies, placing it at an initial depth of ~70 km.
- ✓ The uplift process is linked to late Cretaceous (110-100 Ma) hyperextension.
- ✓ This lherzolite is variably serpentinized, in late exhumation processes.
- ✓ H2 emanations are detected, which do not reflect surface alteration processes, but migration along the Mail Arrouy weld.

Your synthesis

Stop J1#3 Mapping





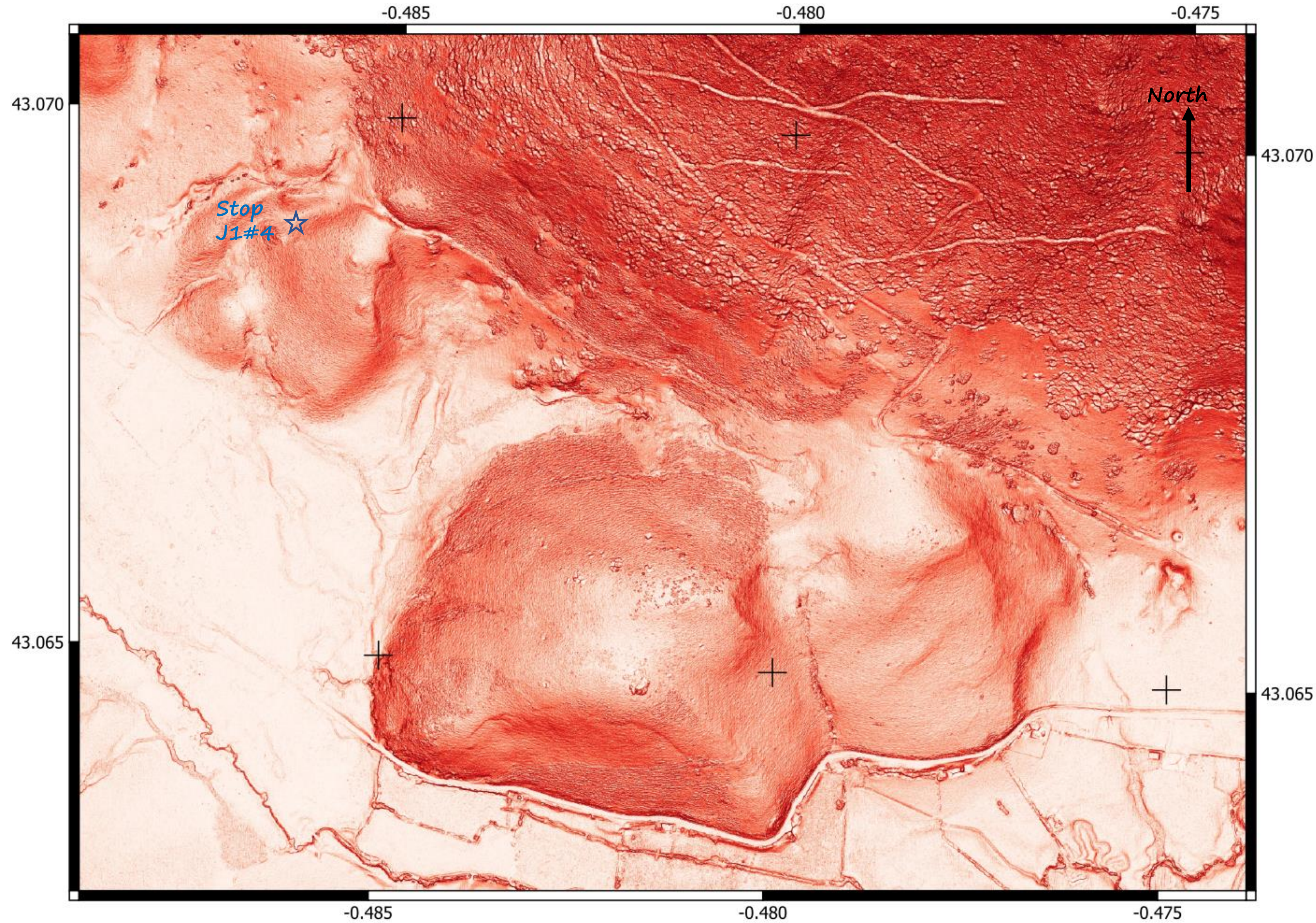
(Caldera et al. 2023)

key observation points for stop J1#3

- ✓ Metamorphic Silurian rock (~350°C to 400°C) is stuck to a piece of Triassic carbonate.
- ✓ This Silurian rock was torn away by a diapiric process and then brought back to the surface (stinger, raft).
- ✓ Rich in organic matter (TOC 1-10%), it is a potential source rock for the Pyrenean H_2 system.

Your synthesis

Stop J1#4 Ophite (gabbros)

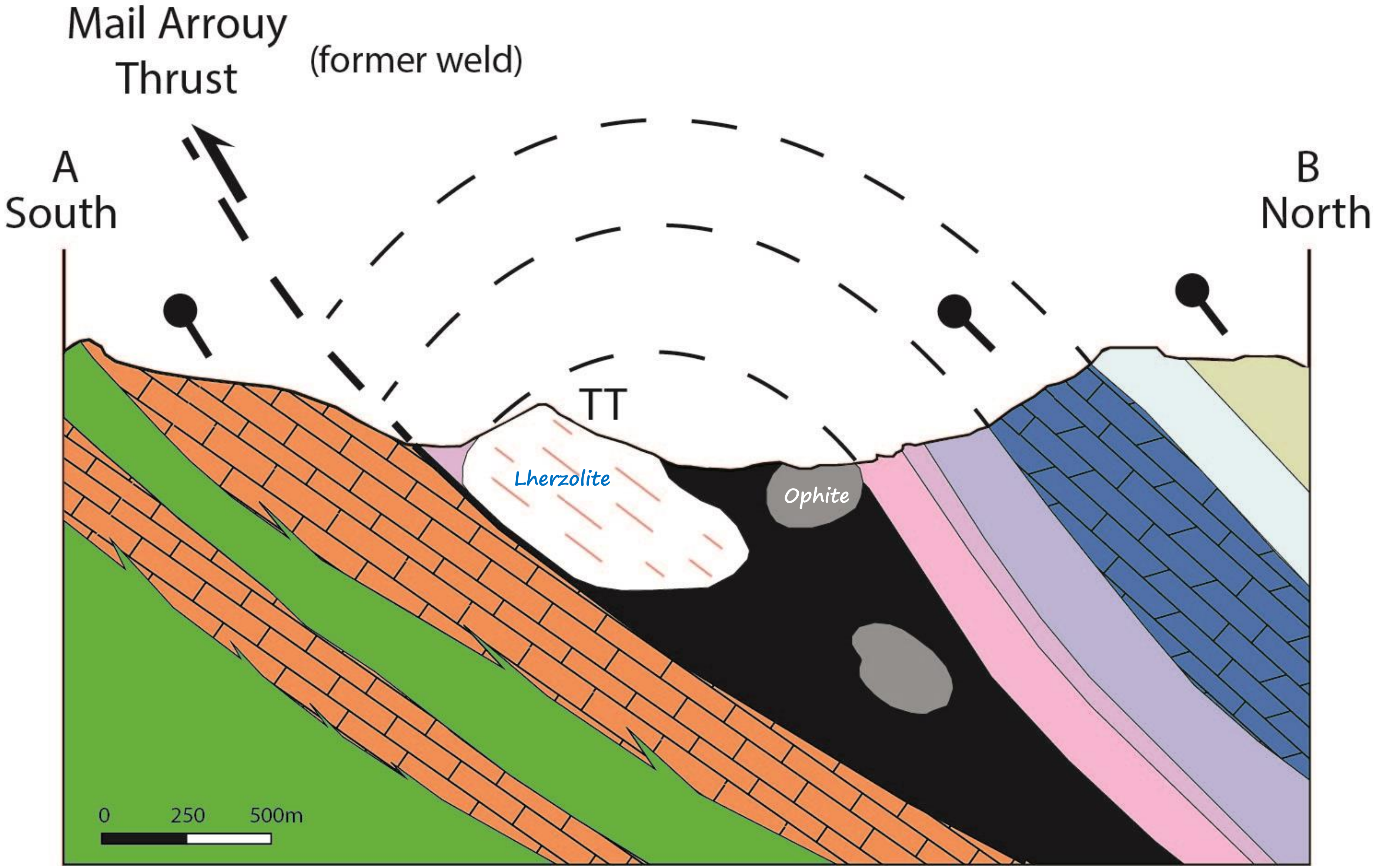


key observation points for stop J1#4

- ✓ Ophites are gabbros that formed around 200 million years ago.
- ✓ The magma chambers trapped in the evaporite layers of the Triassic period can be several kilometers in size.
- ✓ They rose up into diapiric systems, along with other rafts, including Paleozoic and lherzolites, to name just a few examples.
- ✓ With several percent magnetite and olivines, it is a rock rich in Fe2+, which can generate hydrogen during redox processes.
- ✓ However, its potential has never really been evaluated.

Your synthesis

Cross section



(Loiseau et al. 2023)

Summary of the day's observations.

- ✓ A substantial H_2 drainage zone has been identified along the Northern Pyrenean Frontal Thrust (J1#1), with **three exclusive exploration** permits having been granted or are currently under review.
- ✓ The NPFT is initially a normal fault, active at the end of the Cretaceous period, and likely situated at depth, where diapirism initiated.
- ✓ The reactivation of this fault during the Alpine contraction (~83 Ma to ~20 Ma) is sometimes limited.
- ✓ The process of diapirism resulted in the emplacement of bedrock (Silurian J1#3), gabbros (Ophite J1#4), and lherzolites (Turon de la Técouère J1#2) at the surface.
- ✓ These rocks were found to be within an H_2 production window. The Silurian experienced a peak burial temperature of ~350°C and released a maximum amount of H_2 between 200°C and 300°C, probably during the Late Cretaceous. The lherzolites underwent heterogeneous serpentinization during the final stages of their exhumation in the Late Cretaceous.
- ✓ Numerical models (Zwaan et al., 2025) suggest that the current generation of H_2, linked to active serpentinization of the mantle at ~10 km, generates 600,000 tons per year. This is equivalent to the needs of a city with a population of half a million. Should the estimated production cost (if reservoirs are found) be approximately $1 per kg, then this could be considered as a potentially viable energy resource.

Exploring Natural hydrogen in the Pyrenean piedmont
From source rock (day 1) to reservoirs (day 2)

Day 2

The regional geological context from outcrops observations

Presentation outline day 2

J2#0- Herrere stop. Albo-Cenomanian Pillow-lavas. A key for opening Gulf of Biscay and hyper extension.
J2#1- Bearn Foothills : Location and context of the Iberian Margin
J2#2- Mail Arrouy stop : Tectonic and stratigraphic setting
J2#3- Escot Canyon stop 1 : Structuration
J2#4- Escot Canyon stop 2 : Stratigraphy and
J2#5- Escot Fountains : a mature petroleum system
J2#6- Accous stop : Geodynamics and salt tectonics
J2#7- Some characteristics of this Iberian margin : gravity, magnetics, magmatism, thermal gradients, lherzolithes , abiotic CH4,

Field trip conclusions : a frontier white hydrogen system and associated incipient exploration

North Iberian Margin Map and context

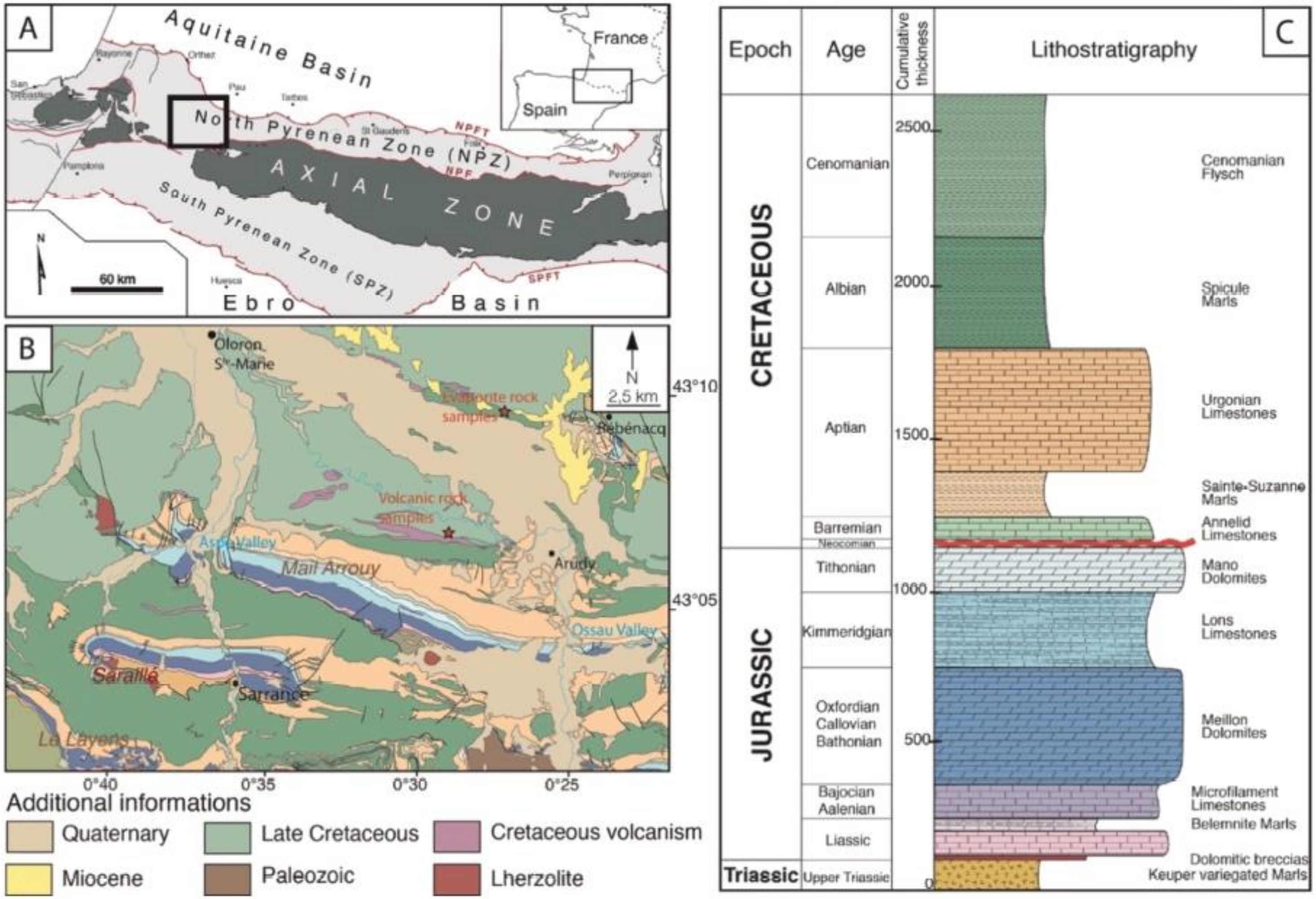
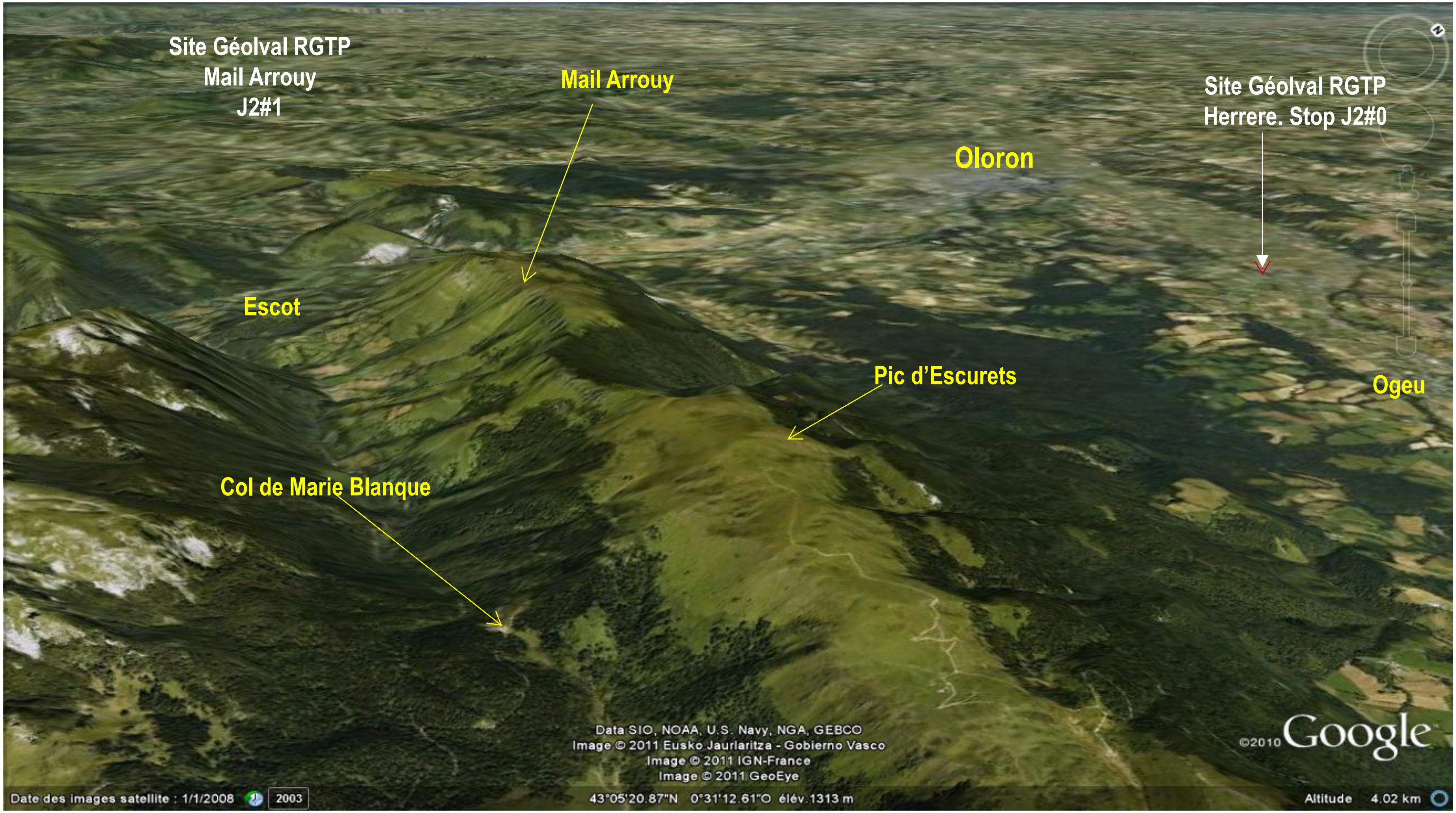
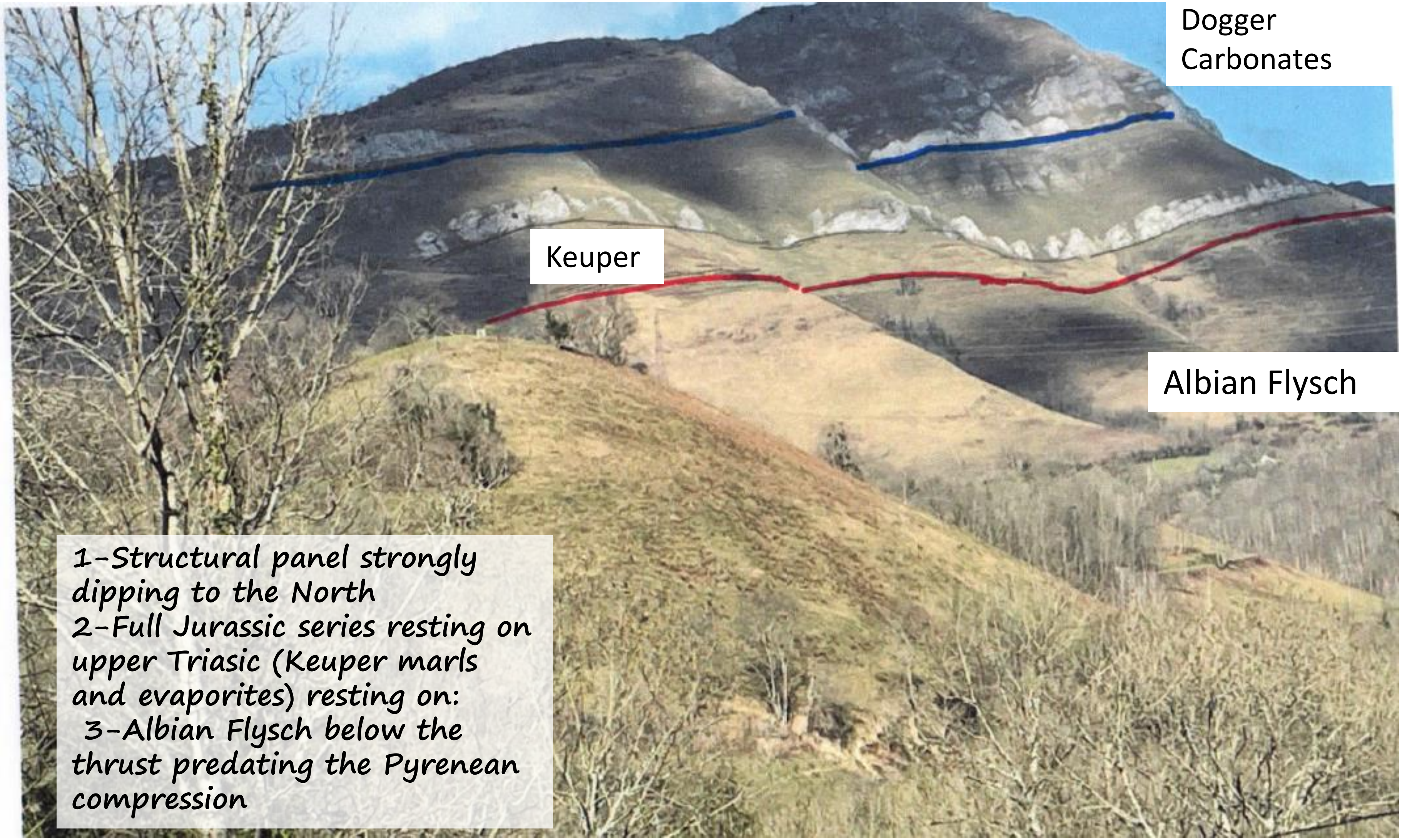


Fig. 34 A) Main structural domains of the Pyrenees with location of the Chaînons Béarnais (after Clerc et al. (2016b)); B) Geological map of the Chaînons Béarnais (modified after Castéras (1970)). The colors correspond to the lithostratigraphic log; C) Simplified lithostratigraphic log showing the different stratigraphic formation present in the Mail Arrouy.

J2#1 Entering the Bearn Foothills: 3D view of the Mail Arrouy Range From Ossay Valley (WNW direction)



J2#2 Mail Arrouy 'fault' from South-West (RGTP site)



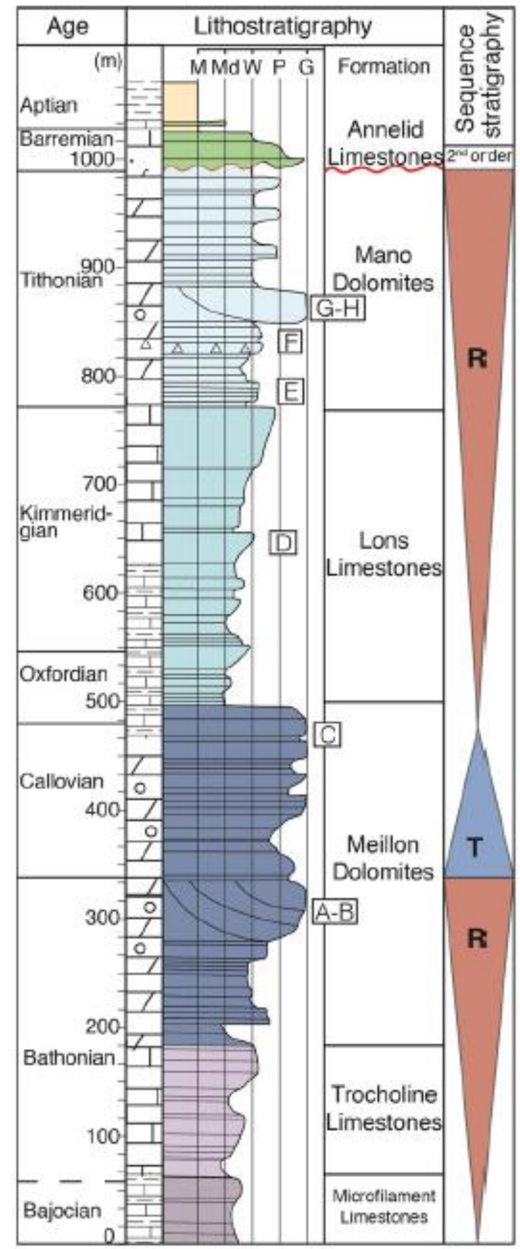
J2#2 Mail Arrouy stratigraphy (From James, 1998)

The Mail Arrouy series is characterized by two massive (~200 m) dolomites bodies : the Meillon Dolomites (Bathonian/Callovian)) and the Mano dolomites (Tithonian) separated by the Kimmeridgian marly limestones.

The two dolomites are major carbonate reservoirs of the Meillon and giant Lacq fields, whereas the Kimmeridgian rich in organic matter is the source-rock.

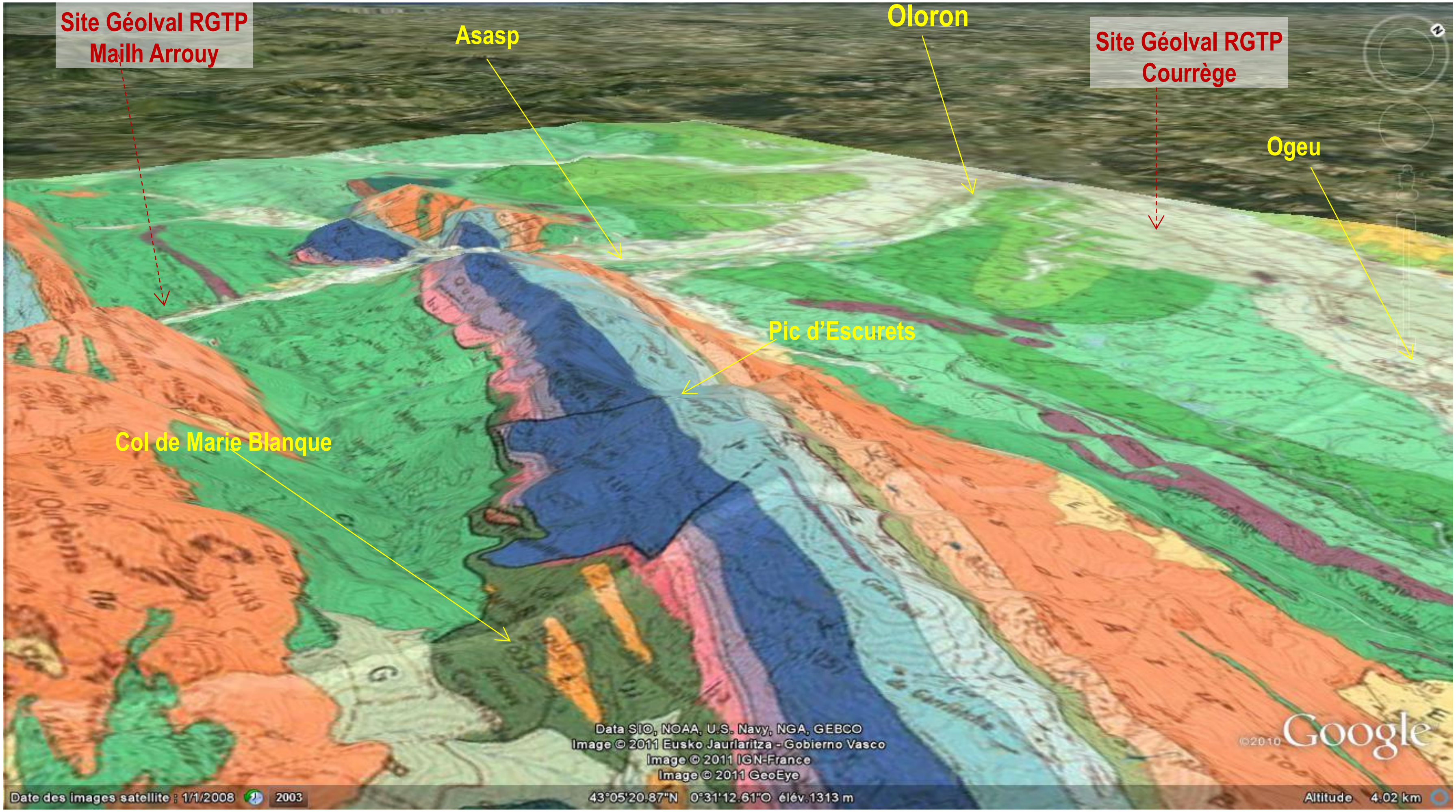
The Meillon dolomites are often linked to high energy oo or bioclastic facies ; the Mano dolomites are often vacuolar , stromatolitic and brechified, witnessing to a probable emersive episodes, associated with karsts,

This emersion is well documented at the top with a 15 My gap at the base of Lower Cretaceous, associated with bauxites.

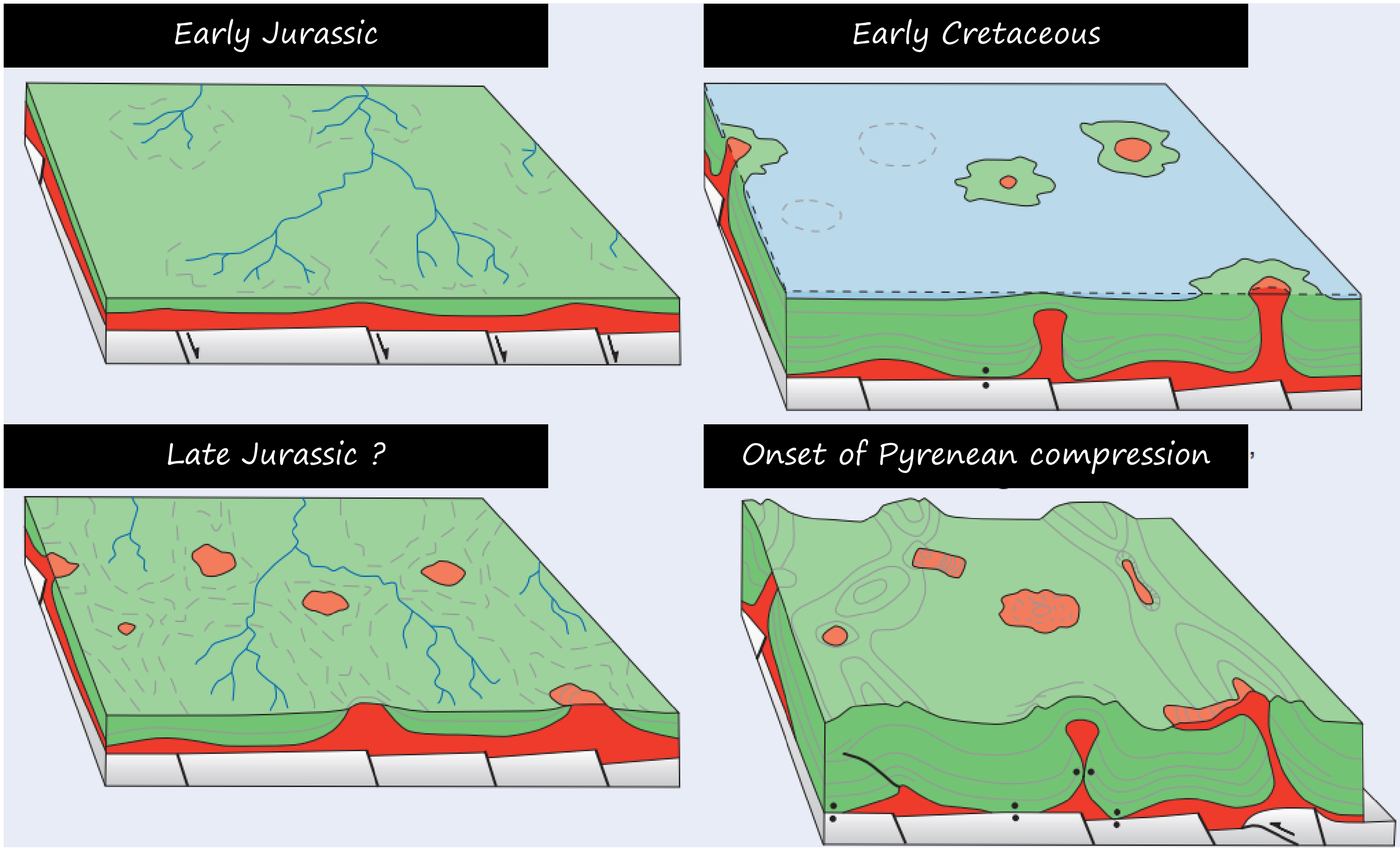


Geological understanding of the Mail Arrouy thrust

Main highlight : A thrust (reverse fault) at the base of the fold with a ductile layer in the Triasic (Keuper)



Chainons Béarnais: an ancient salt province



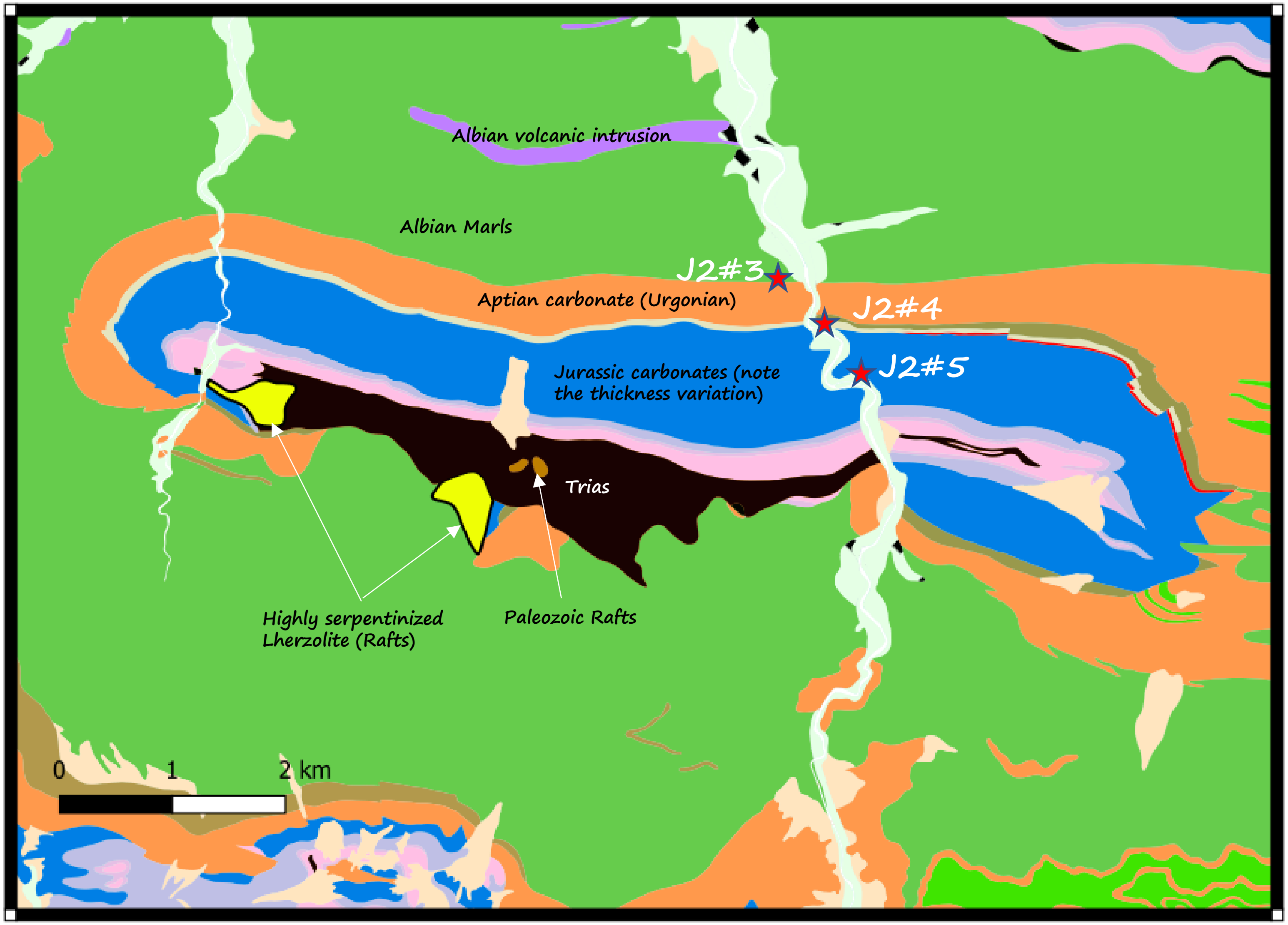
Adapted from Callot et al., (2012)

key observation points for stop J2#2

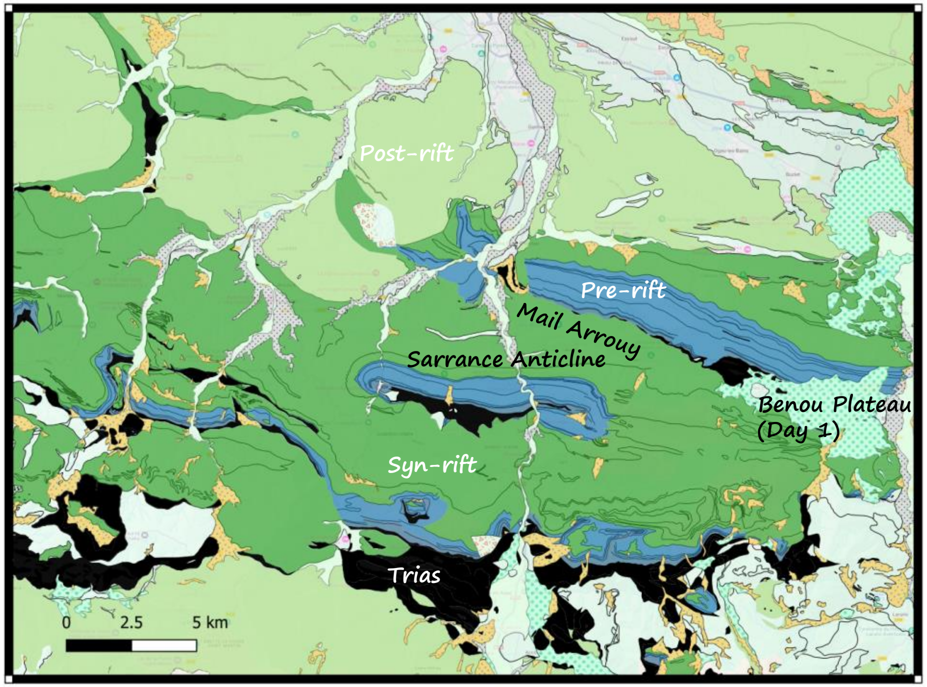
- ✓ The Mail Arrouy overlap has a southward vergence, which is unusual in a chain that is supposed to have a double vergence.
- ✓ It is an active fault, at the foot of which Quaternary terrace deformations are observed (~cm/year).
- ✓ This fault extends eastward into the anticline of the Bénou plateau (Day 1).
- ✓ In the case of a diapiric system, this fault is probably a weld.
- ✓ Observations of the contact show very little deformation in the Albian marls, which is not expected in the footwall of a major reverse fault.

Your synthesis

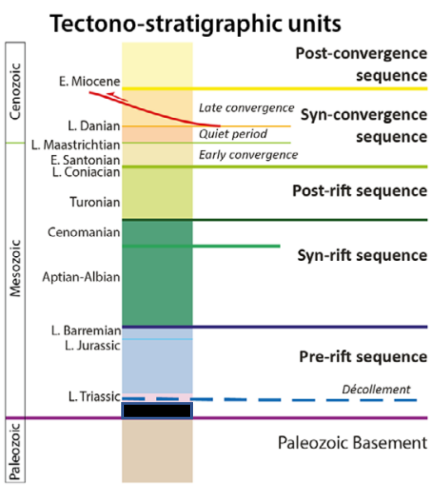
The Sarrance anticline : 3 stops location



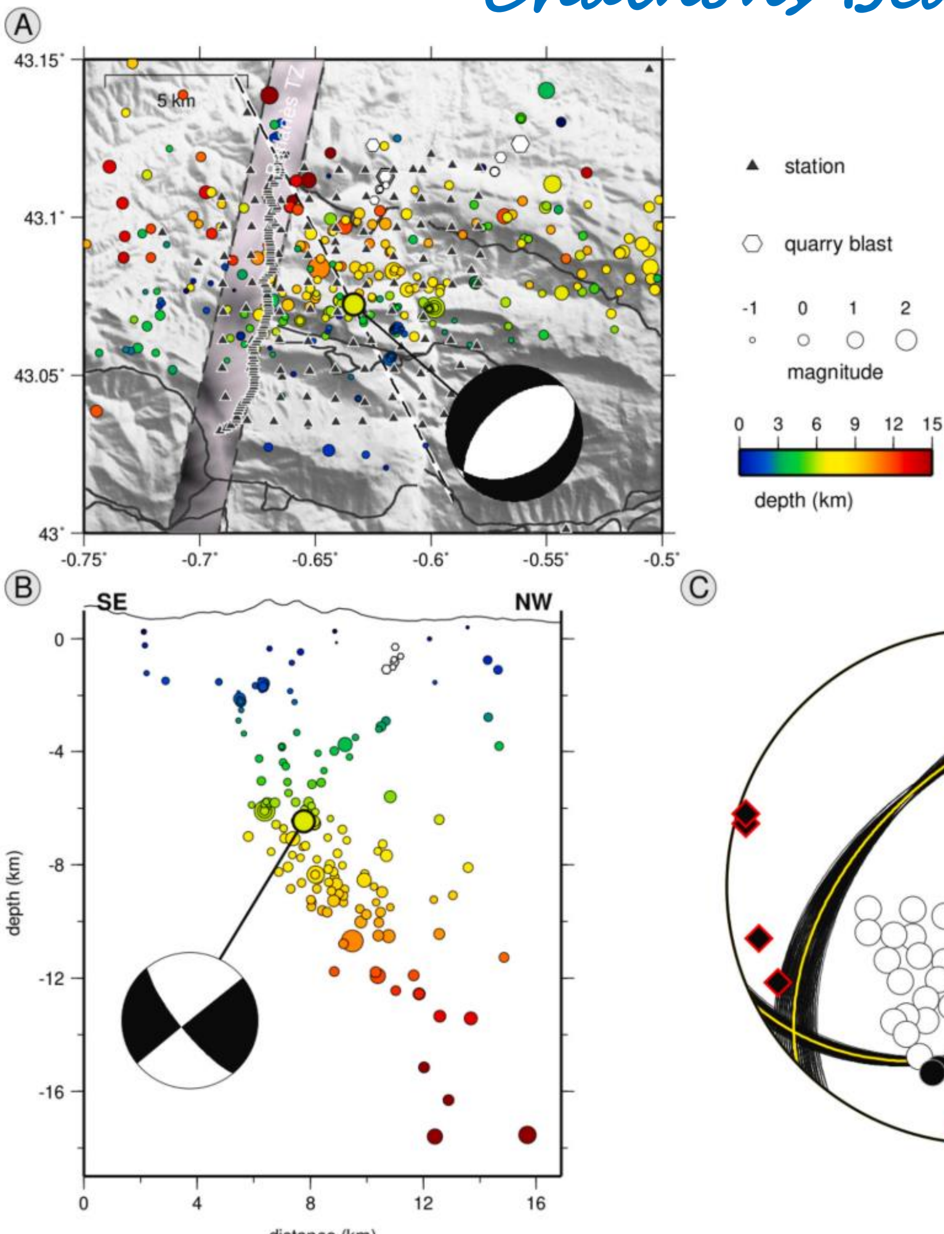
A former salt province

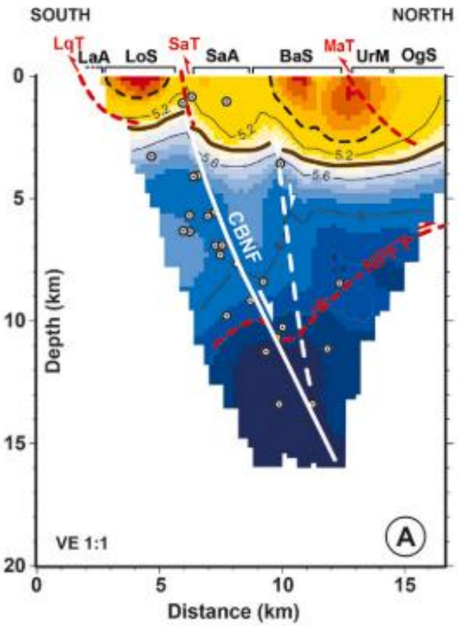


The 'Butterfly' fold (Zagros, Iran)



Deep active normal fault of Chainons Béarnais





Chevrot et al., (2024)

J2#3 Escot. Lower Cretaceous Facies. Urgonian Aptian Reservoir.

Reef limestones showing the so-called « urgonian » facies with a very large geographical extension (Alps).

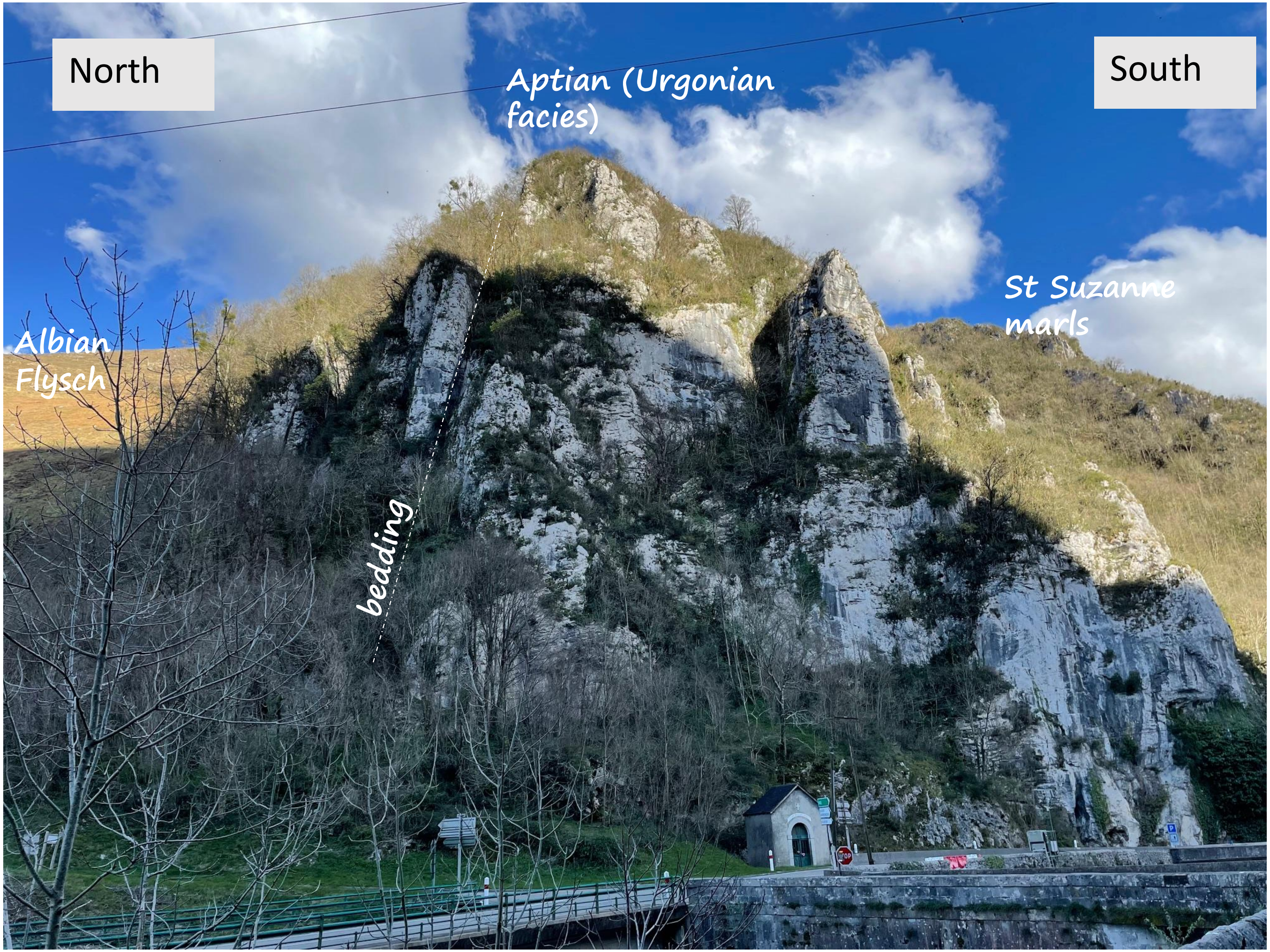
They correspond to Carbonate plateform of a marine shallow depositionnal environment but with important isopach and lateral facies variations (probable salt tectonics context).

Many fragments of shells, belonging to the rudist family, forming clear topographic highs in the landscape (northern flank of Mail Arrouy).

These limestones, abusively called « Arudy marbles » have been extracted in several quarries in the region and have been used for building lot local of towns and villages.

Most of these « reefal structures » have been drilled for oil and gas in the Aquitaine basin, but with little commercial success.

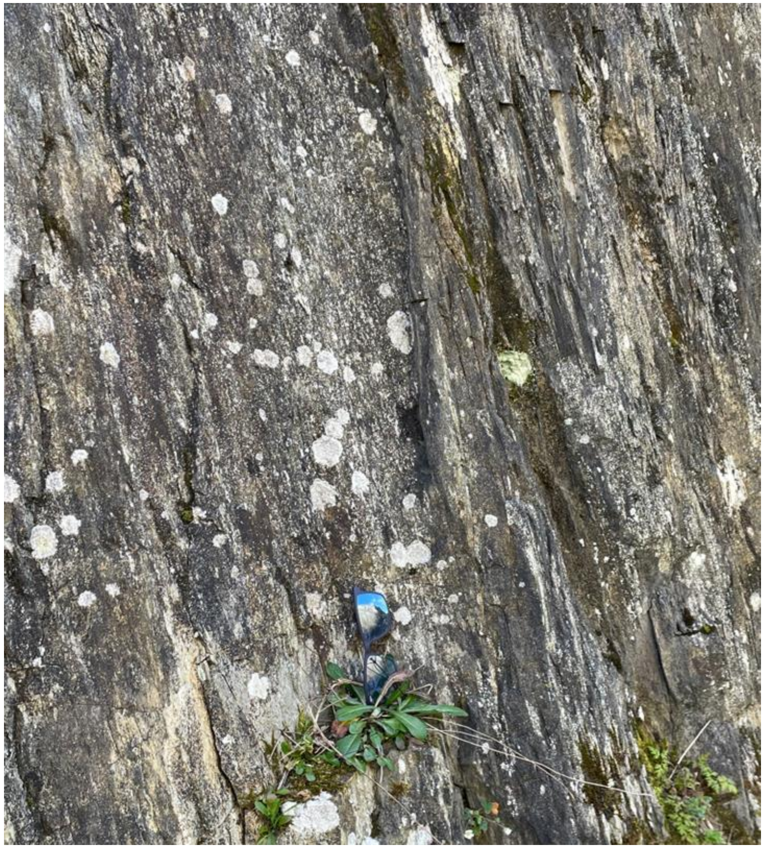
J2#4 The Escot canyon North stop .



J2#5 The Escot canyon. The Lacq giant gas field system. Jurassic Mano dolomite covered by St Suzanne marls.

Jurassic Mano dolomite

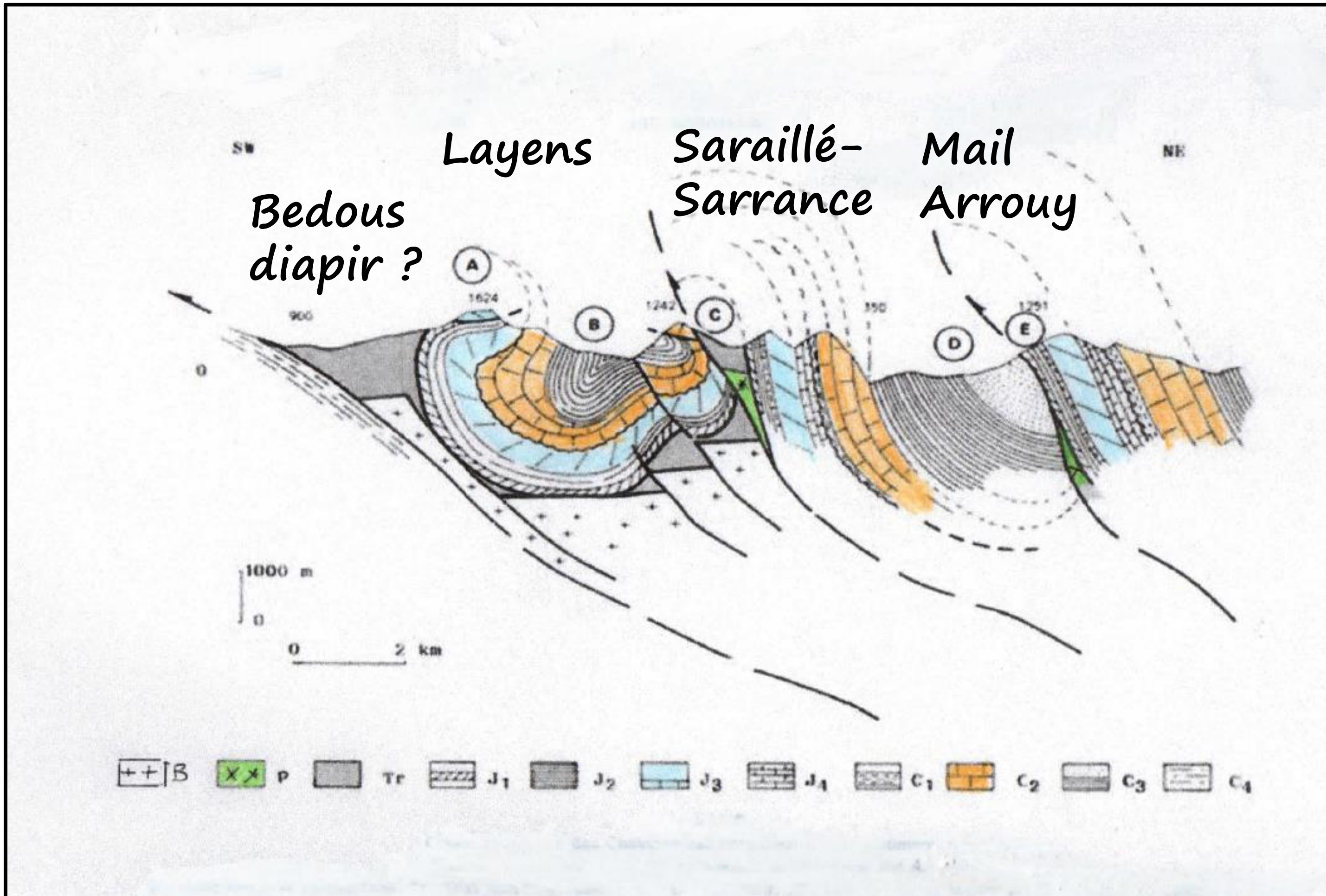
St Suzanne marls.



Bearn Foothills : a NNE-SSW cross-section modified from J. Canerot (1989) : BCREP-Elf Aquitaine 13-1,87-99

3 successive structural units :

- faulted folds with thrusts to the SSW with Triasic evaporites resting onto Upper Cretaceous
- Thrusts injected with ophites (gabbros) and even peridotites (lherzolites): initial salt welds?
- 2 different Jurassic series from South (reduced section in Layens: no Malm and less dolomites) to North (full section in Mail Arrouy): inner to external platform evolution or incipient diapirism in the Bedous-Layens area ?



The different dolomitization processes

(from Motte, G. Phd 2020)

Three main dolomite configurations :

- 1-Massive thick dolomite (mainly stratified)
- 2-Limited dolomite (mainly fault related)
- 3-Dolomite cementation (primary or fracture porosity: mainly in extensive tectonic context)

Needs strong fluids-rocks interactions
Often polyphased dolomites

	Dolomitization	Massive Tot	Massive %	Limited Tot	Limited %	Cementation Tot	Cementation %
Burial	Near surface to shallow	47	78	22	27	8	11
	Shallow to intermediate	7	12	13	16	14	19
	Intermediate to deep	6	10	48	58	53	71
Fluids	Seawater	5	8	3	4	4	5
	Evaporated seawater	40	67	15	18	1	1
	Modified seawater	7	12	14	17	7	9
	Basinal brines	8	13	45	54	54	72
	Magmatic - metamorphic	0	0	3	4	3	4
	Meteoric	0	0	1	1	1	1
	?	0	0	2	2	5	7
Mg source	Seawater	52	87	38	46	19	25
	Evaporite dissolution	5	8	8.5	10	12	16
	Clays	1	2	5	6	8	11
	Dolomite in situ	0	0	5	6	4	5
	Mantle serpentinization	0	0	1	1	1	1
	Magmatic	0	0	3.5	4	3	4
	?	2	3	22	27	28	37
Mechanism	Reflux	41	68	15	18	4	5
	Fault-related	10	17	41	49	45	60
	Squeegee fluid expulsion	1	2	5	6	7	9
	Thermal convection	1	2	9	11	7	9
	Mixing zone	5	8	4	5	3	4
	Burial	0	0	8	10	6	8
	Diapir-related	0	0	0	0	1	1
	?	2	3	1	1	2	3
	Hydrothermal regime	7	12	37	45	41	55
Global control	Depositional environment and climatic conditions	48	80	20	24	9	12
	Extensional structures	8	13	32	39	34	45
	Compressive structures	3	5	14	17	19	25
	Volcanic activity	1	2	5	6	3	4
	Diapirism	0	0	0	0	1	1
	Burial	0	0	12	14	9	12
	Tot	60	100	83	100	75	100

Based on 100 case studies worldwide for the last 20 years

The dolomitization in Mano and Meillon Fm from Mail Arrouy outcrops.

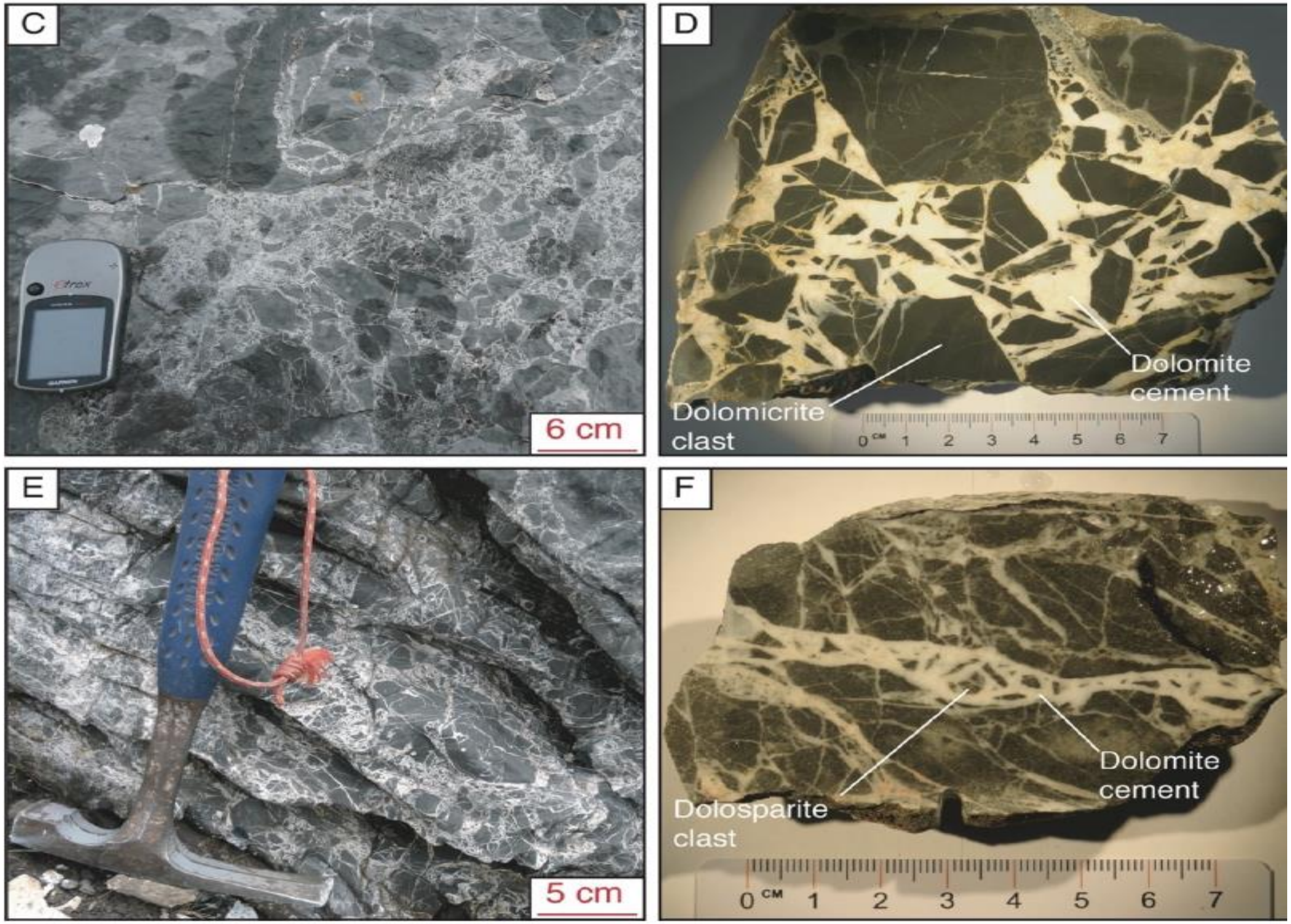
(From Motte, G., Phd 2020)

Mano Dolomite (Portlandian)

Example of almost complete replacement of the initial carbonate mud by white dolomitic cement, forming a mosaic breccia texture

Meillon Dolomite (Oxfordian Kimmeridgian)

Breccia with angular clasts supported by a white dolomitic cement. This Breccia differs from the D by the abundance of diffuse fracturing.



The multiple stages dolomitization processes : the case of the Mail Arrouy foothills (dating from U-Pb isotopy) : Main dolomitizations in Albian

1-Both Meillon and Mano were first massively dolomitized in near-surface to shallow burial conditions during Berriasian-Valanginian,

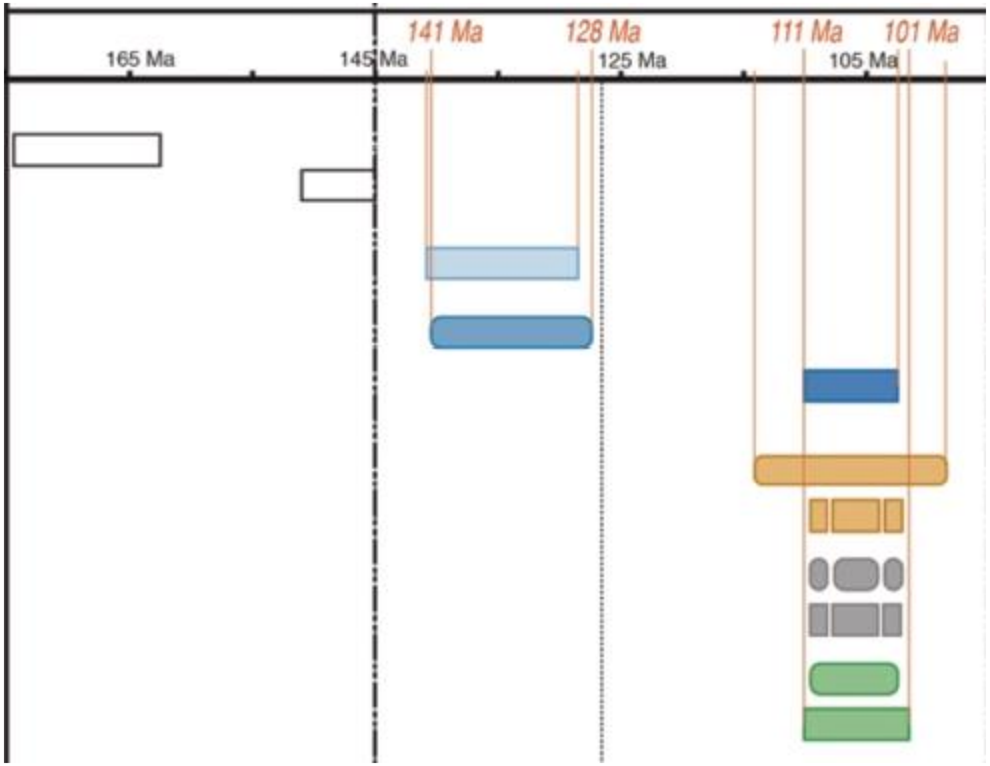
2- Between the Barremian and the Albian, influx of hot fluids, associated with partial to complete recrystallization of the initial dolomites.

3-Subsequent dolomites precipitated in both formations during the Albian, as high temperature
(T > 160°C), vein- and pore-filling cements but whereas the Meillon dolomite cements record the influx of the evaporite brines, the Mano unit precipitation is related with clay-derived water.

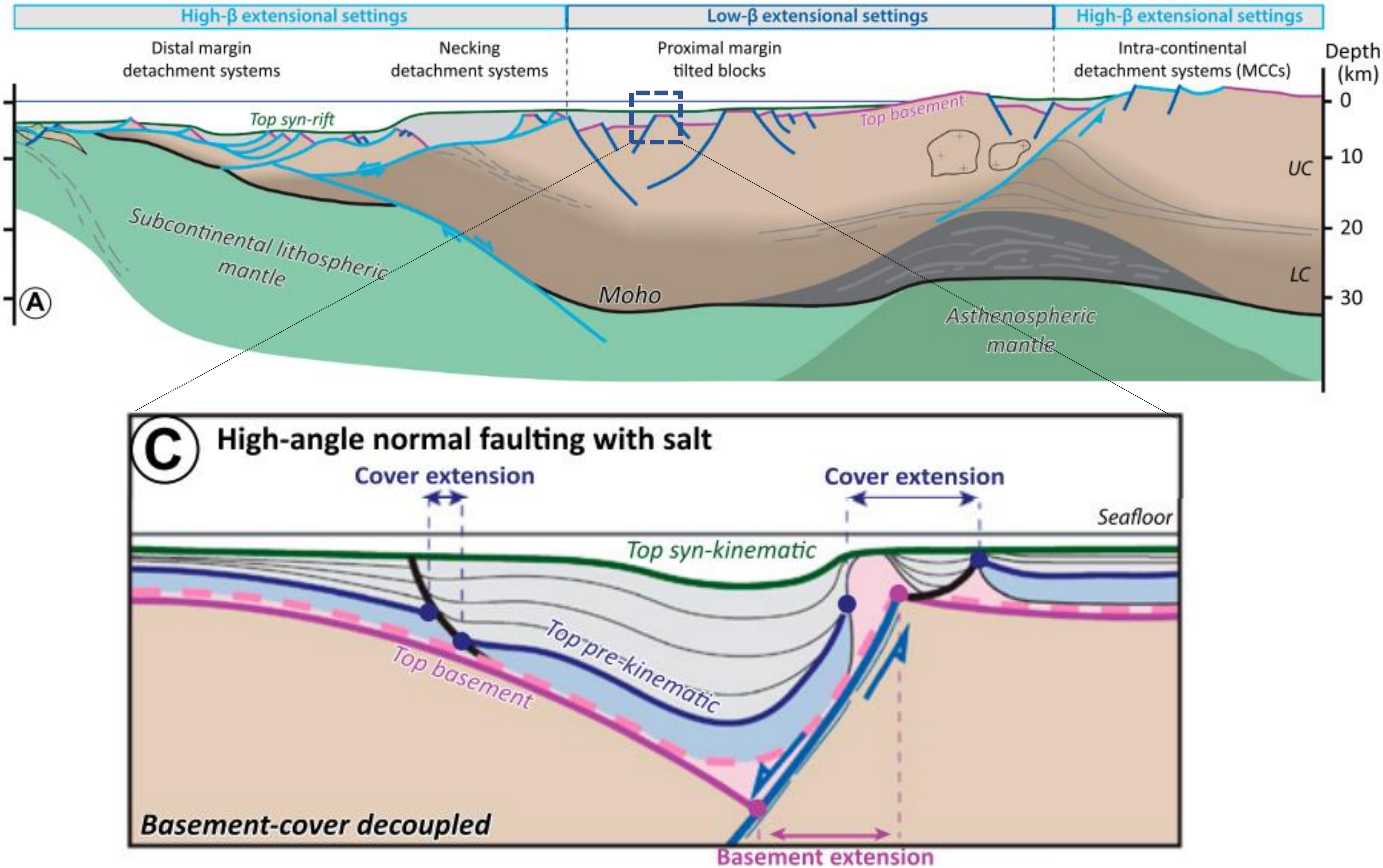
4-Finally, a last episode of dolomite cementation
occurred only in the vicinity of faults and volcanic intrusions during the Albian, recording the highest
fluid-inclusion temperatures (T > 250°C) in both.

Carbonate sedimentation

2,3 and 4

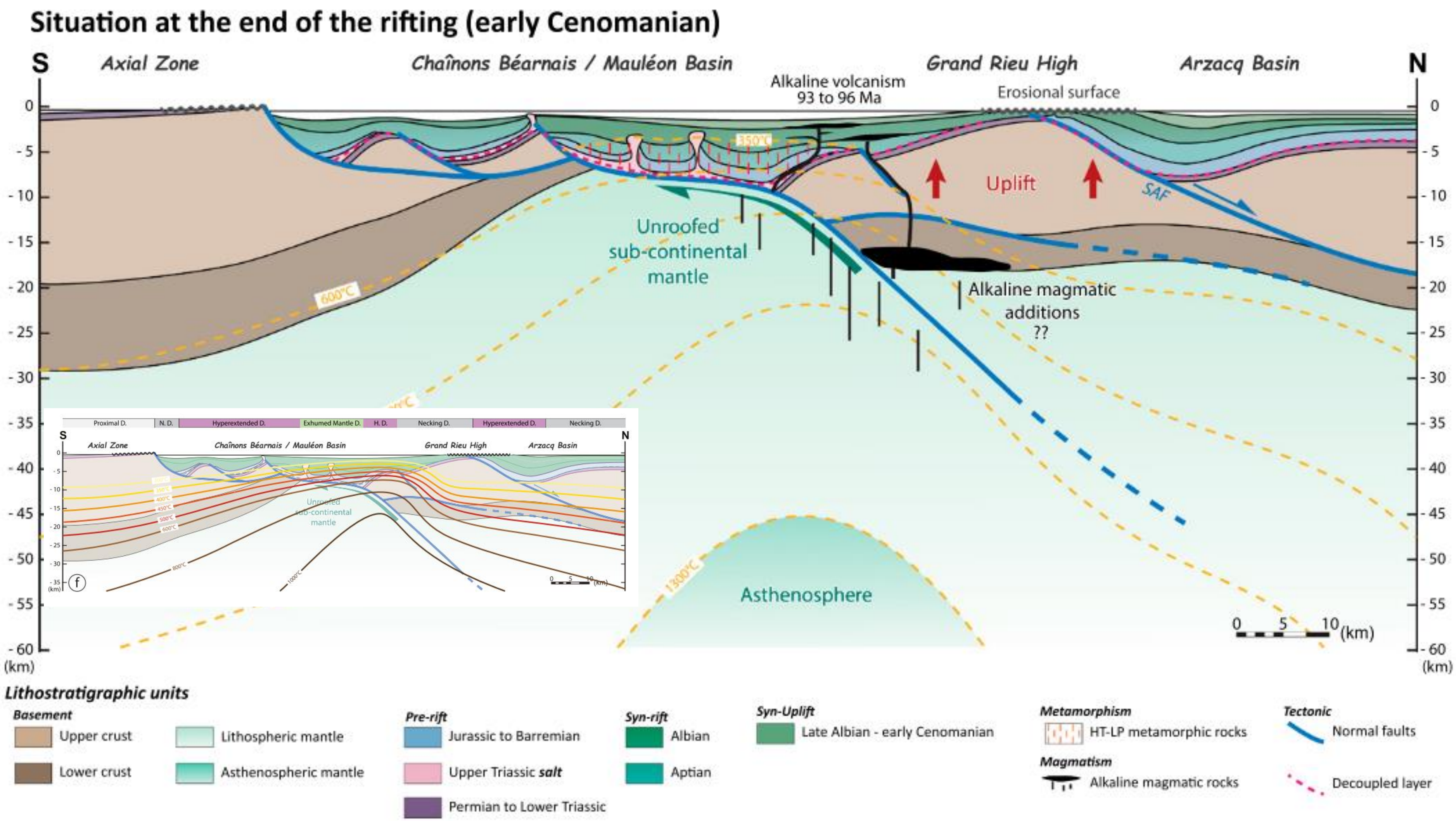


Hyper extension and necking zone



Ducoux et al., (GSA, 2021)

A view at the end of late Cretaceous Rifting



Ducoux et al., (GSA, 2021)

ZIM : a HT-LP rift-derived metamorphism

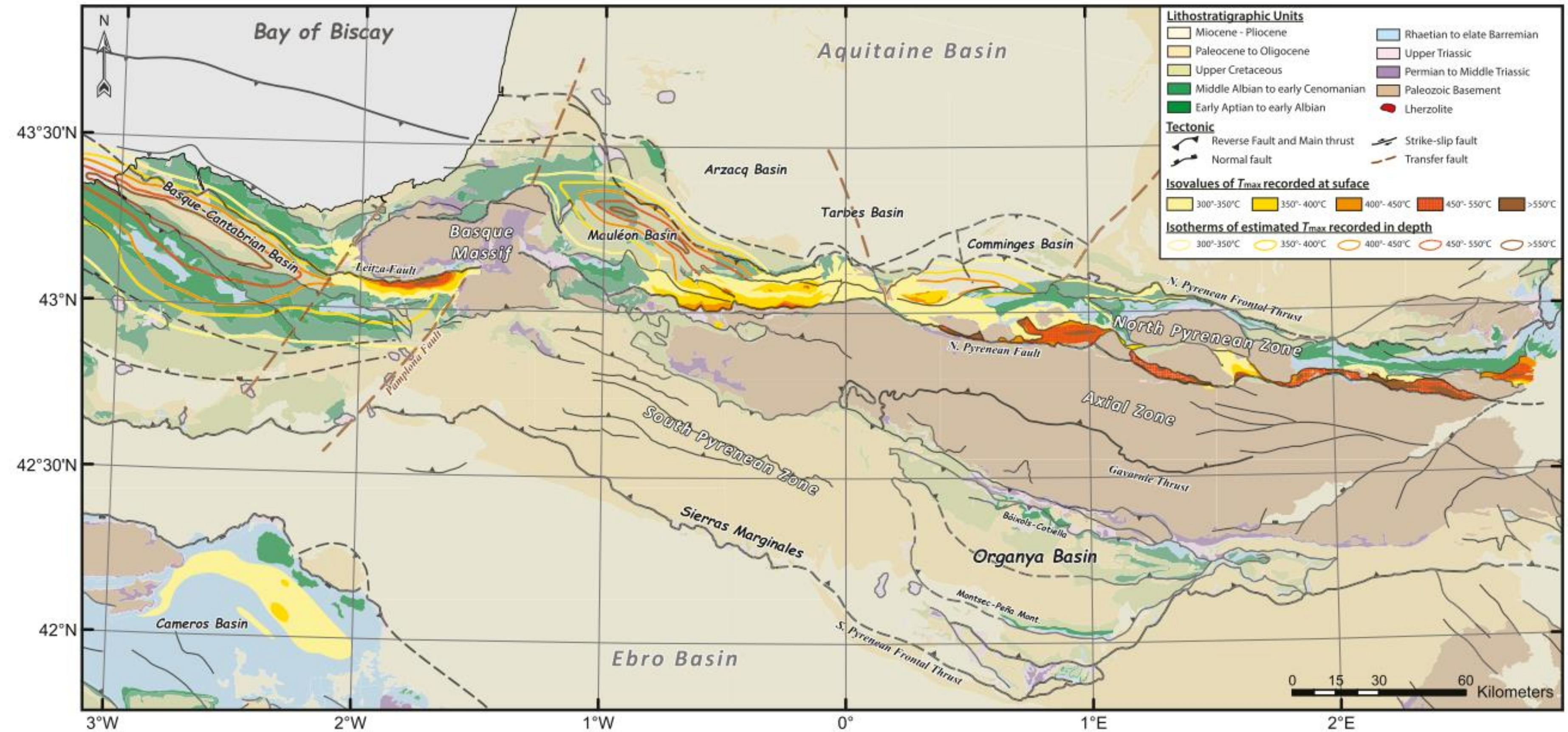


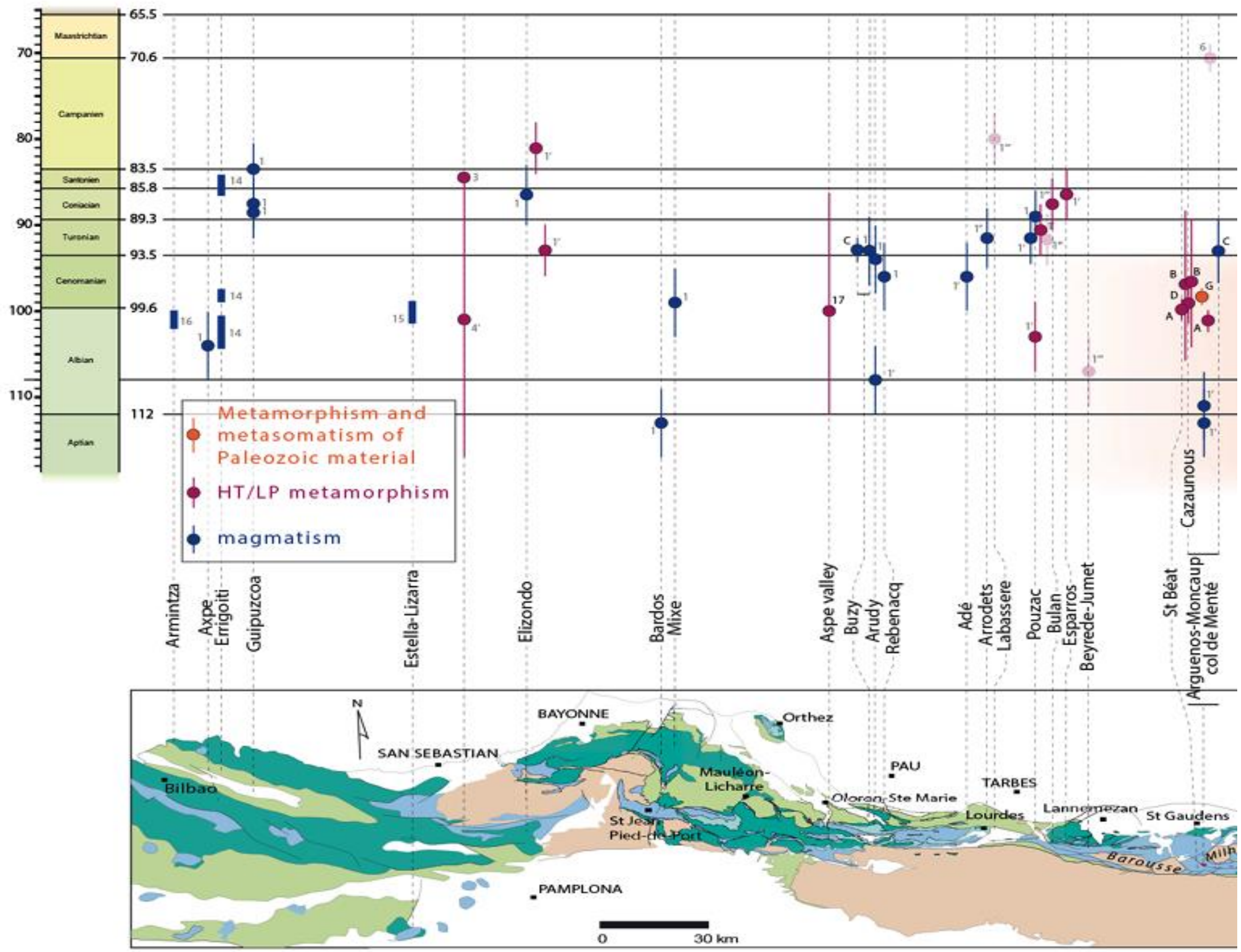
Fig. 11. Interpretative map of the HT/LP metamorphism in the overall Pyrenean-Cantabrian belt and Cameros Basin, combining measured T_{max} data at surface and estimated T_{max} data at the base of former rift basins. Estimated T_{max} were calculated from R_o values measured in boreholes. The HT/LP metamorphism mapping of the Cameros Basin is from Rat *et al.* (2019).

Ducoux et al., (BSGF, 2021)

HT-LP rift-related metamorphism

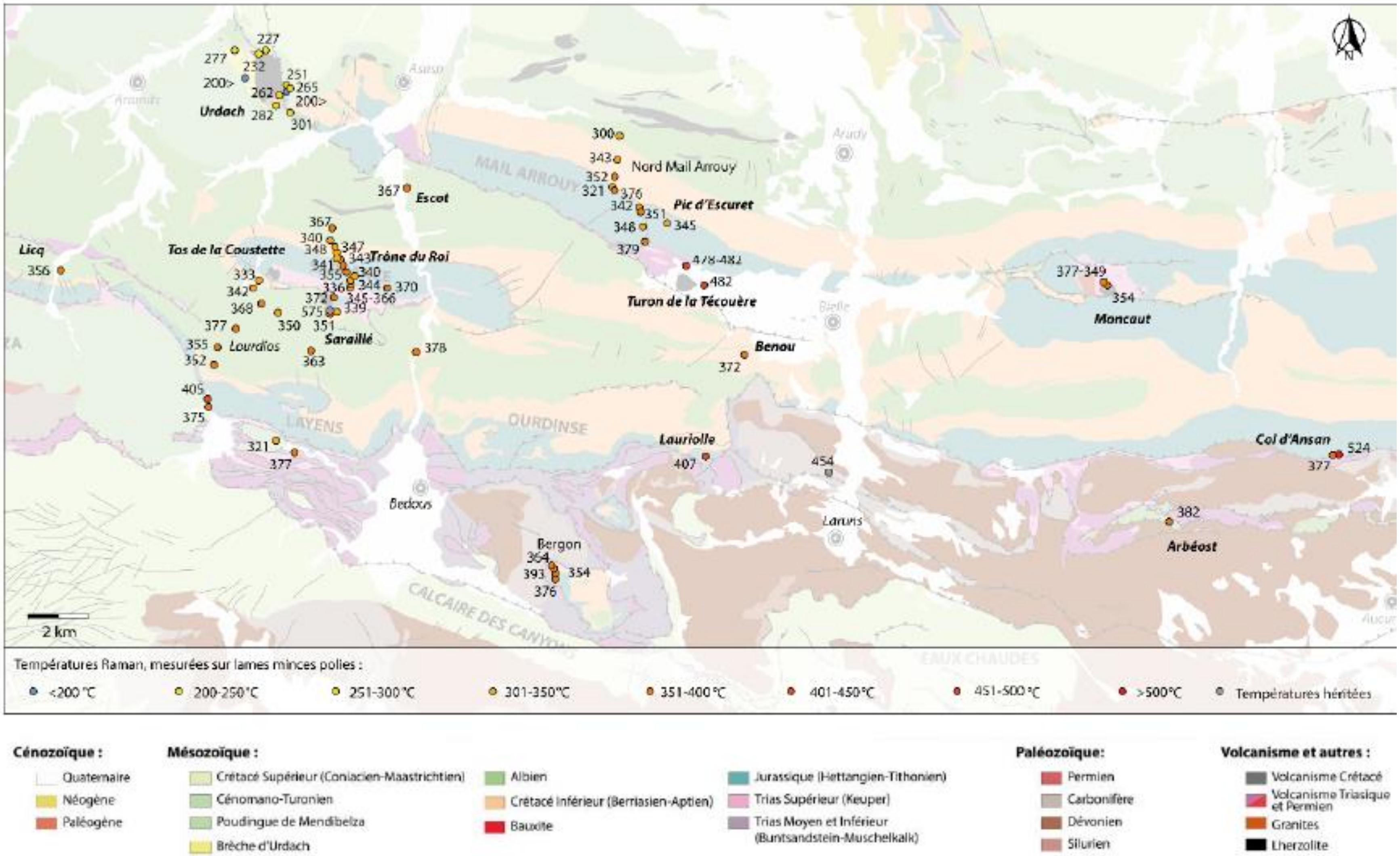
Locations and ages of HT-LP metamorphism and magmatic bodies in the Western Pyrenees Foothills

Upper Albian-Cenomanian-Turonian hyperextension



(Clerc et al. 2015)

Peak burial temperature in the Bearn Foothills



(Corre, Phd, 2016)

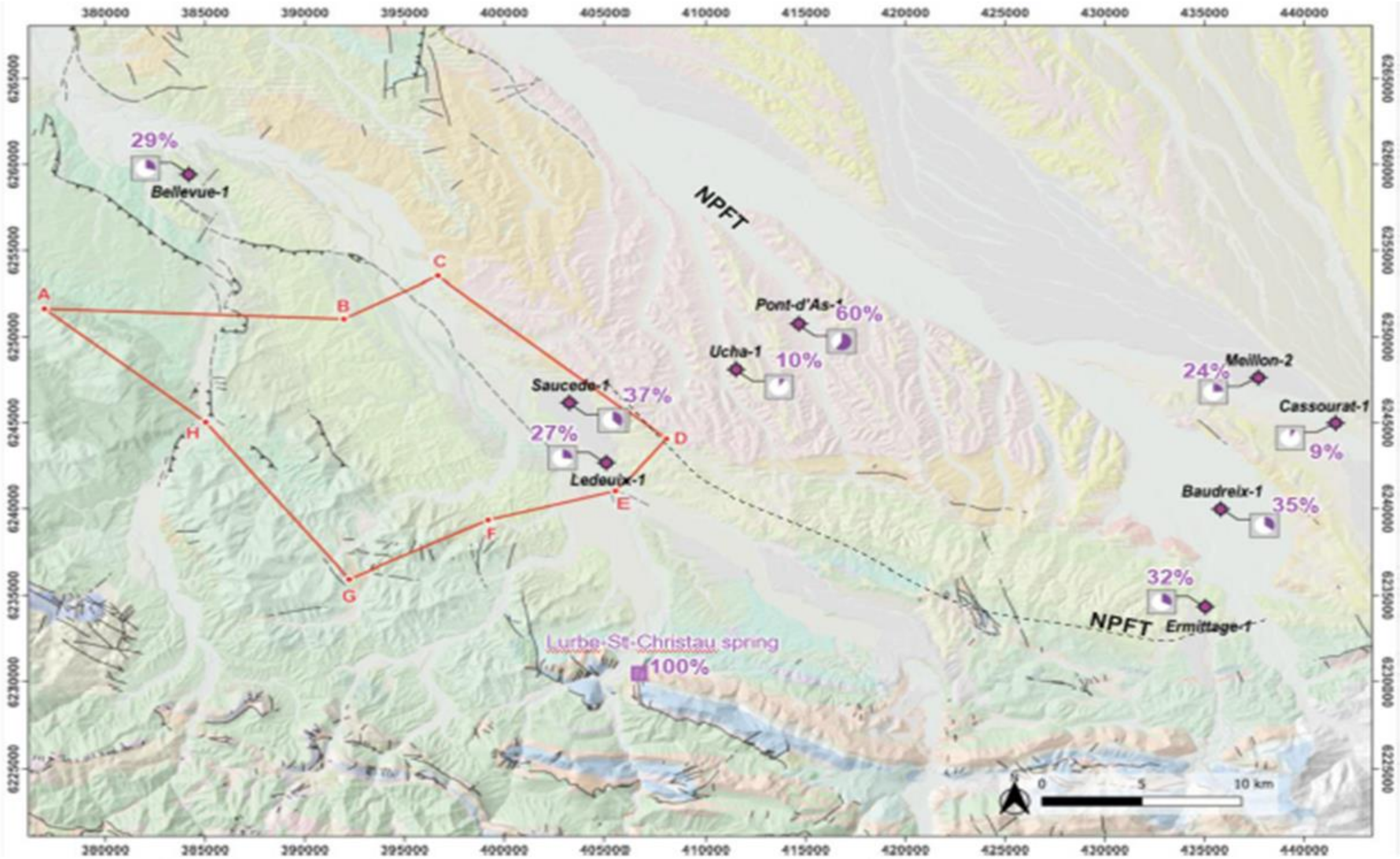
Abiotic methane in the Bearn foothills vicinity

Several gas fields in the southern Aquitaine basin have shown presence of abiotic methane revealed by isotopic data.

Source for the CH4 are not only the classical Jurassic marls but possibly a CH4 coming from the combination of

$CO_2+4H_2 = CH_4+ 2H_2O$

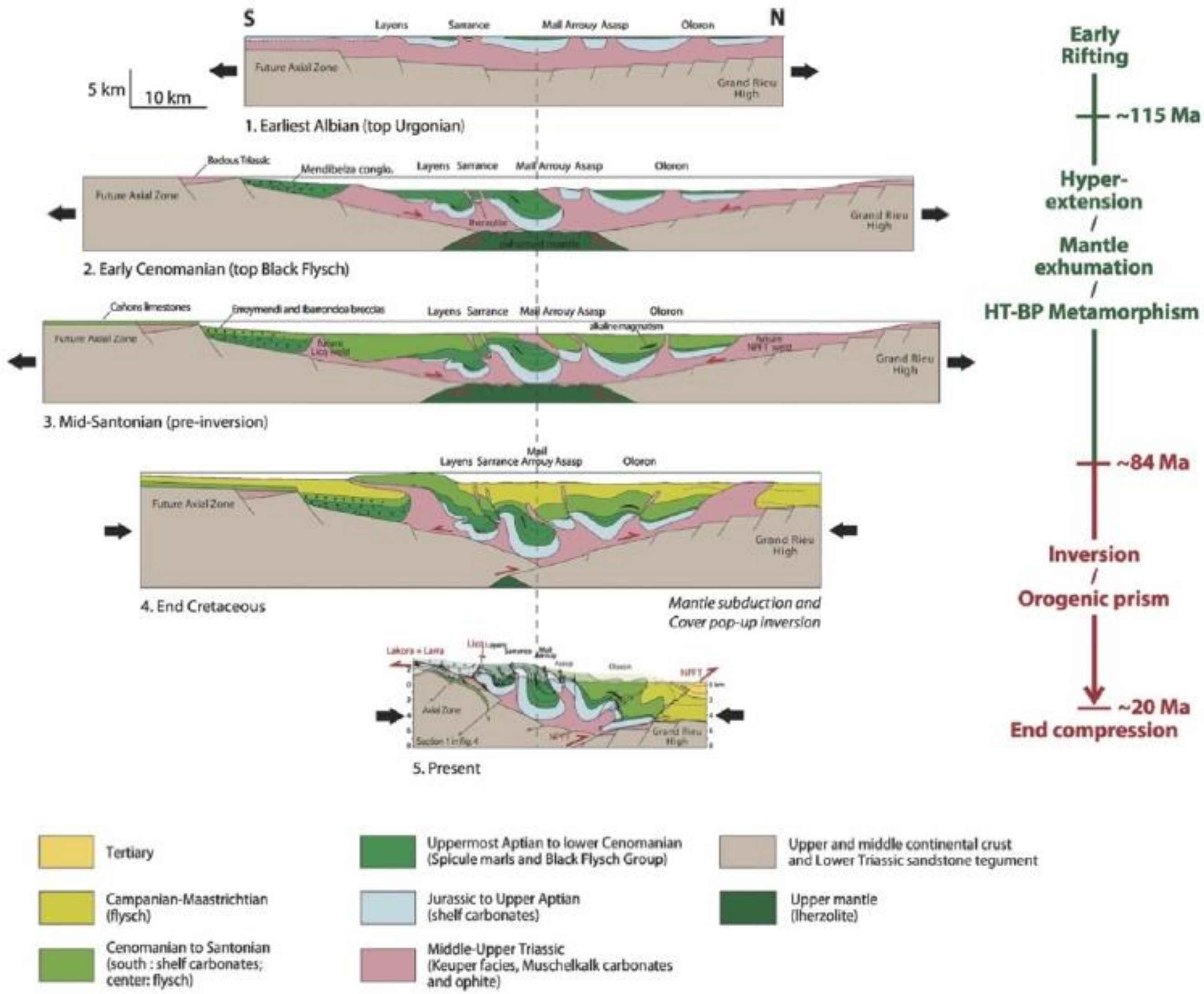
Location of boreholes reporting methane of abiotic origin.



Conclusion : Tectonic evolution of the Bearn foothills

How to reconciliate all these field data :

- Thick evaporite sequence in Triasic
- Carbonate platform in Jurassic
- Salt tectonic in Lower Cretaceous with tilted blocks/rafting
- Dolomitization /Magmatic/Metamorphism asssociated to hyper-extension in Albo-Cenomanian
- Thick deposition of Upper Cretaceous flyshs
- Inversion and compression in Paleogene times



(Labaume and Teixell, 2020)

The target : subsalt paleozoic ?