Préparation agrégation, SU, 2020

PYRENEES-PROVENCE

Olivier LACOMBE

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

cnrs

ISTeP Institut des Sciences de la Terre de Paris
UMR 7193 - SU - CNRS

INTERNATIONAL STRATIGRAPHIC CHART

International Commission on Stratigraphy

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
Phanerozoic	Cenozoic	Quaternary	Holocene		0.0117	📌
			Pleistocene	Upper	0.126	
				"Ionian"	0.781	
				Calabrian	1.806	📌
				Gelasian	2.588	📌
		Neogene	Pliocene	Piacenzian	3.600	📌
				Zanclean	5.332	📌
			Miocene	Messinian	7.246	📌
				Tortonian	11.608	📌
				Serravallian	13.82	📌
				Langhian	15.97	
				Burdigalian	20.43	
				Aquitanian	23.03	📌
		Paleogene	Oligocene	Chattian	28.4 ±0.1	
				Rupelian	33.9 ±0.1	📌
			Eocene	Priabonian	37.2 ±0.1	
				Bartonian	40.4 ±0.2	
				Lutetian	48.6 ±0.2	
				Ypresian	55.8 ±0.2	📌
			Paleocene	Thanetian	58.7 ±0.2	📌
				Selandian	~ 61.1	📌
				Danian	65.5 ±0.3	📌
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6	📌
				Campanian	83.5 ±0.7	
				Santonian	85.8 ±0.7	
				Coniacian	~ 88.6	
				Turonian	93.6 ±0.8	📌
				Cenomanian	99.6 ±0.9	📌
			Lower	Albian	112.0 ±1.0	
				Aptian	125.0 ±1.0	
				Barremian	130.0 ±1.5	
				Hauterivian	~ 133.9	
				Valanginian	140.2 ±3.0	
				Berriasian	145.5 ±4.0	

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
					145.5 ±4.0	
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	150.8 ±4.0	
				Kimmeridgian	~ 155.6	
				Oxfordian	161.2 ±4.0	
			Middle	Callovian	164.7 ±4.0	
				Bathonian	167.7 ±3.5	📌
				Bajocian	171.6 ±3.0	📌
				Aalenian	175.6 ±2.0	📌
			Lower	Toarcian	183.0 ±1.5	
				Pliensbachian	189.6 ±1.5	📌
				Sinemurian	196.5 ±1.0	📌
				Hettangian	199.6 ±0.6	
		Triassic	Upper	Rhaetian	203.6 ±1.5	
				Norian	216.5 ±2.0	
				Carnian	~ 228.7	📌
			Middle	Ladinian	237.0 ±2.0	📌
				Anisian	~ 245.9	
			Lower	Olenekian	~ 249.5	
				Induan	251.0 ±0.4	📌
	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ±0.7	📌
				Wuchiapingian	260.4 ±0.7	📌
			Guadalupian	Capitanian	265.8 ±0.7	📌
				Wordian	268.0 ±0.7	📌
				Roadian	270.6 ±0.7	📌
			Cisuralian	Kungurian	275.6 ±0.7	
				Artinskian	284.4 ±0.7	
				Sakmarian	294.6 ±0.8	
				Asselian	299.0 ±0.8	📌
		Carboniferous Pennsylvanian	Upper	Gzhelian	303.4 ±0.9	
				Kasimovian	307.2 ±1.0	
			Middle	Moscovian	311.7 ±1.1	
			Lower	Bashkirian	318.1 ±1.3	📌
		Mississippian	Upper	Serpukhovian	328.3 ±1.6	
			Middle	Visean	345.3 ±2.1	📌
			Lower	Tournaisian	359.2 ±2.5	📌

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
					359.2 ±2.5	
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	374.5 ±2.6	📌
				Frasnian	385.3 ±2.6	📌
			Middle	Givetian	391.8 ±2.7	📌
				Eifelian	397.5 ±2.7	📌
			Lower	Emsian	407.0 ±2.8	📌
				Pragian	411.2 ±2.8	📌
				Lochkovian	416.0 ±2.8	📌
		Silurian	Pridoli		418.7 ±2.7	📌
			Ludlow	Ludfordian	421.3 ±2.6	📌
				Gorstian	422.9 ±2.5	📌
			Wenlock	Homerian	426.2 ±2.4	📌
				Sheinwoodian	428.2 ±2.3	📌
			Llandovery	Telychian	436.0 ±1.9	📌
				Aeronian	439.0 ±1.8	📌
				Rhuddanian	443.7 ±1.5	📌
		Ordovician	Upper	Hirnantian	445.6 ±1.5	📌
				Katian	455.8 ±1.6	📌
				Sandbian	460.9 ±1.6	📌
			Middle	Darriwilian	468.1 ±1.6	📌
				Dapingian	471.8 ±1.6	📌
			Lower	Floian	478.6 ±1.7	📌
				Tremadocian	488.3 ±1.7	📌
		Cambrian	Furongian	*Stage 10*	~ 492 *	
				Stage 9	~ 496 *	
				Paibian	~ 499	📌
			Series 3	Guzhangian	~ 503	📌
				Drumian	~ 506.5	📌
				Stage 5	~ 510 *	
			Series 2	*Stage 4*	~ 515 *	
				Stage 3	~ 521 *	
			Terreneuvian	*Stage 2*	~ 528 *	
				Fortunian	542.0 ±1.0	📌

This chart was drafted by Gabi Ogg. Intra Cambrian unit ages with * are informal, and awaiting ratified definitions.

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	Eonothem Eon	Erathem Era	System Period	Age Ma	GSSP GSSA
				542	
Precambrian	Proterozoic	Neo-proterozoic	Ediacaran	~635	📌
			Cryogenian	850	🕓
			Tonian	1000	🕓
		Meso-proterozoic	Stenian	1200	🕓
			Ectasian	1400	🕓
			Calymmian	1600	🕓
		Paleo-proterozoic	Statherian	1800	🕓
			Orosirian	2050	🕓
			Rhyacian	2300	🕓
			Siderian	2500	🕓
	Archean	Neoarchean		2800	🕓
		Mesoarchean		3200	🕓
		Paleoarchean		3600	🕓
		Eoarchean		4000	
	Hadean (informal)			~4600	

Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic (~542 Ma to Present) and the base of Ediacaran are defined by a basal Global Boundary Stratotype Section and Point (GSSP 📌), whereas Precambrian units are formally subdivided by absolute age (Global Standard Stratigraphic Age, GSSA). Details of each GSSP are posted on the ICS website (*www.stratigraphy.org*).

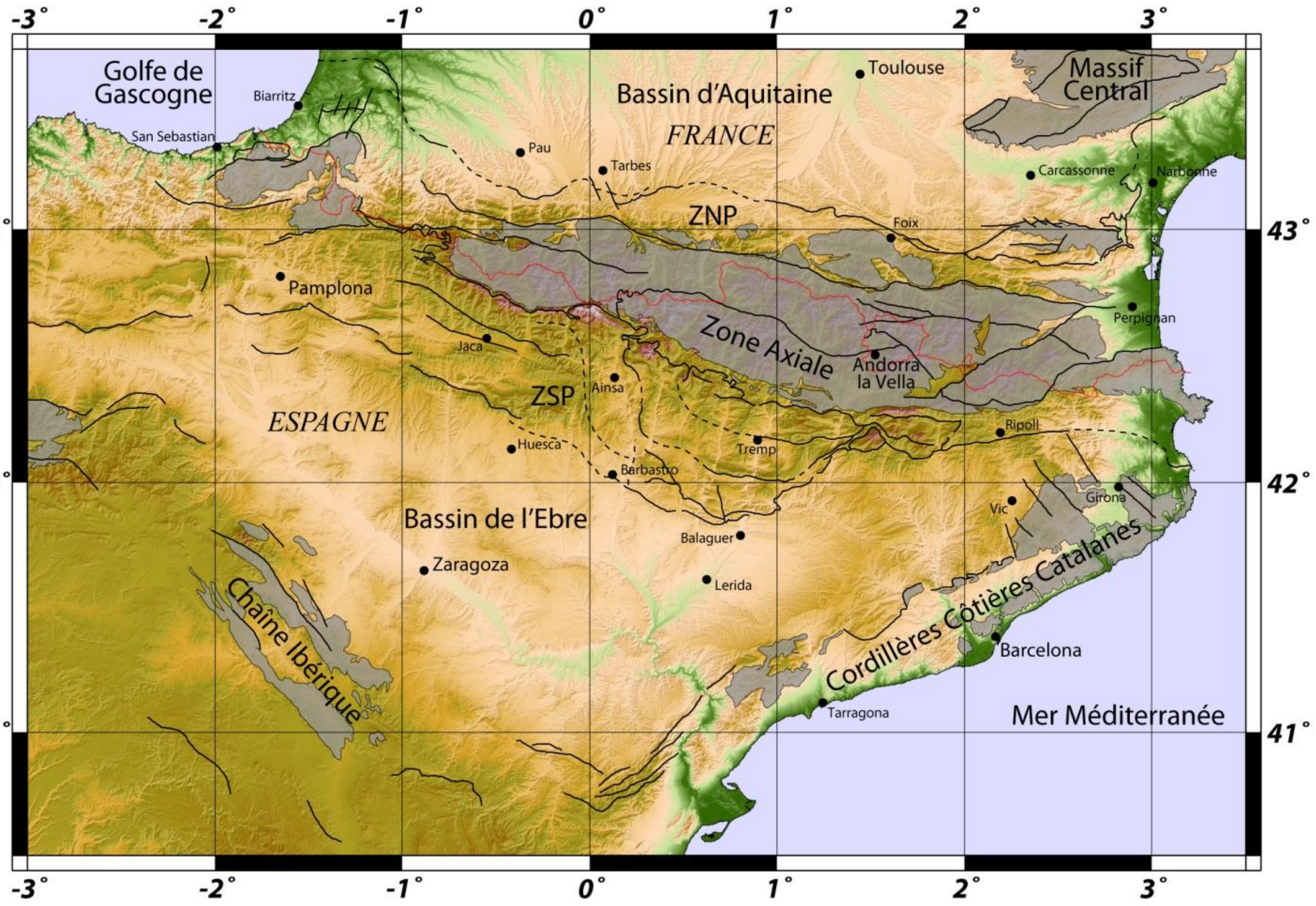
Numerical ages of the unit boundaries in the Phanerozoic are subject to revision. Some stages within the Cambrian will be formally named upon international agreement on their GSSP limits. Most sub-Series boundaries (e.g., Middle and Upper Aptian) are not formally defined.

Colors are according to the Commission for the Geological Map of the World (*www.cgmw.org*).

The listed numerical ages are from 'A Geologic Time Scale 2004', by F.M. Gradstein, J.G. Ogg, A.G. Smith, et al. (2004; Cambridge University Press) and "The Concise Geologic Time Scale" by J.G. Ogg, G. Ogg and F.M. Gradstein (2008).

August 2009

I. La chaîne pyrénéenne : une chaîne intracontinentale


-3°
-2°
-1°
0°
1°
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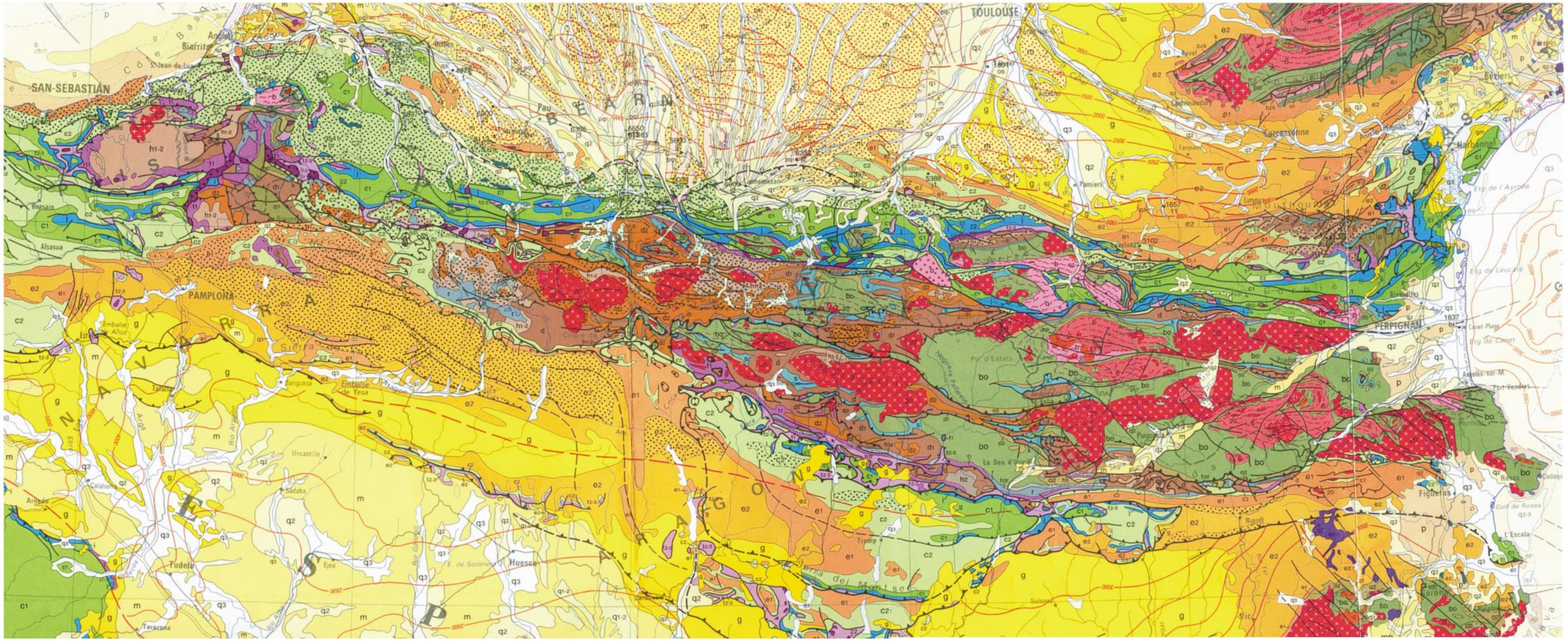
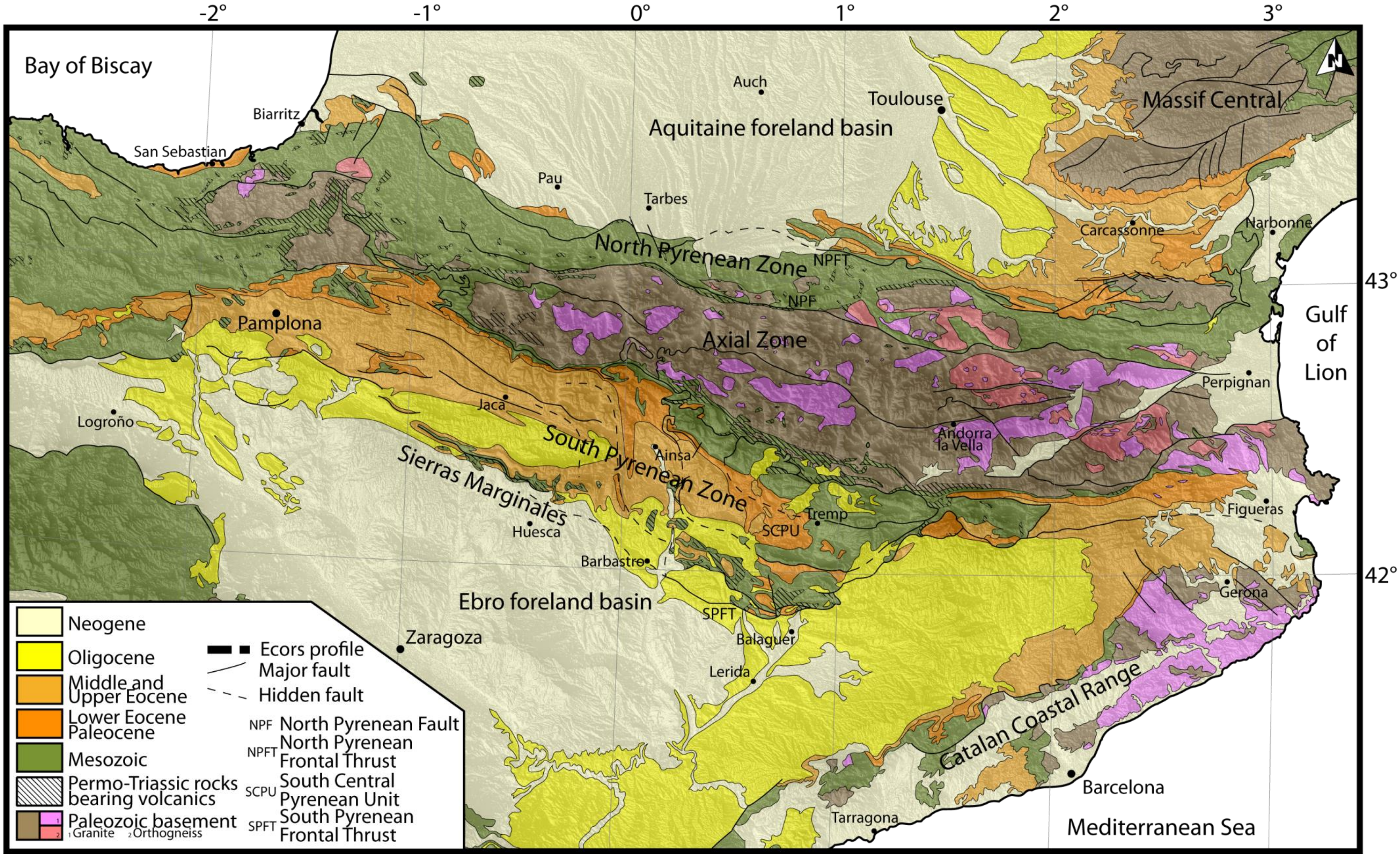
3°
43°
42°
41°
Golfe de Gascogne
Biarritz
San Sebastian
Toulouse
Bassin d'Aquitaine
FRANCE
Massif Central
Pau
Tarbes
Carcassonne
Narbonne
ZNP
Foix
Pamplona
Perpignan
Zone Axiale
Jaca
Andorra la Vella
Ainsa
ZSP
ESPAGNE
Ripoll
Huesca
Tremp
Barbastro
Girona
Vic
Bassin de l'Ebre
Balaguer
Zaragoza
Lerida
Cordillères Côtières Catalanes
Chaîne Ibérique
Barcelona
Tarragona
Mer Méditerranée



SAN-SEBASTIAN
TOULOUSE
PAMPLONA
PERPIGNAN
Biarritz
Pau
BEARN
Carcassonne
Narbonne
Béziers
Pamiers
Alsasua
Huesca
Tudela
Tarazona
Calahorra
Figueras
Roses
L'Escala
Vic
Ripoll
Tremp
La Seu d'Urgell
Pic d'Estats
Argelès-sur-M.
Port-Vendres
Golf de Roses
Embalse de Yesa
NAVARRA
ARAGON

A. Les ensembles structuraux et les séries sédimentaires


-2°
-1°
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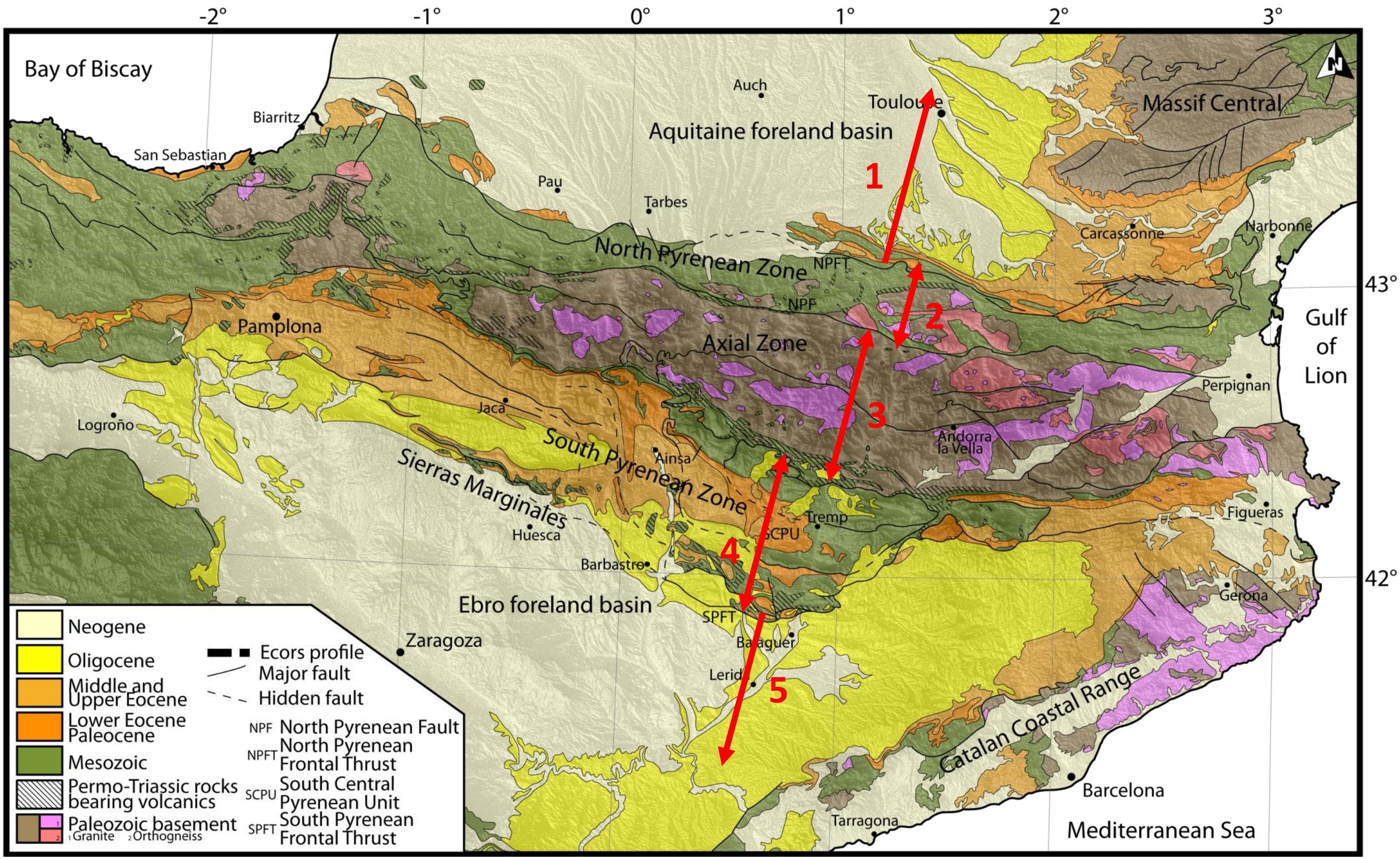
3°
43°
42°
Bay of Biscay
Biarritz
San Sebastian
Pau
Tarbes
Auch
Toulouse
Aquitaine foreland basin
Massif Central
Carcassonne
Narbonne
North Pyrenean Zone
NPFT
NPF
Gulf of Lion
Pamplona
Axial Zone
Perpignan
Jaca
Logroño
Andorra la Vella
Ainsa
South Pyrenean Zone
Sierras Marginales
Figueras
Tremp
SCPU
Huesca
Barbastro
Gerona
Ebro foreland basin
SPFT
Balaguer
Zaragoza
Lerida
Catalan Coastal Range
Barcelona
Tarragona
Mediterranean Sea
Neogene
Oligocene
Middle and Upper Eocene
Lower Eocene Paleocene
Mesozoic
Permo-Triassic rocks bearing volcanics
Paleozoic basement
1 Granite
2 Orthogneiss
Ecors profile
Major fault
Hidden fault
NPF North Pyrenean Fault
NPFT North Pyrenean Frontal Thrust
SCPU South Central Pyrenean Unit
SPFT South Pyrenean Frontal Thrust
N

(Filleaudeau, thèse, 2011)

1 : Zone sous-pyrénéenne et bassin d'avant-pays d'Aquitaine; 2: Zone nord-pyrénéenne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Bay of Biscay
Biarritz
San Sebastian
Pau
Tarbes
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Toulouse
Aquitaine foreland basin
Massif Central
Carcassonne
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Ebro foreland basin
Zaragoza
Figueras
Gerona
Catalan Coastal Range
Barcelona
Tarragona
Mediterranean Sea
1
2
3
4
5
Neogene
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Mesozoic
Permo-Triassic rocks bearing volcanics
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Major fault
Hidden fault
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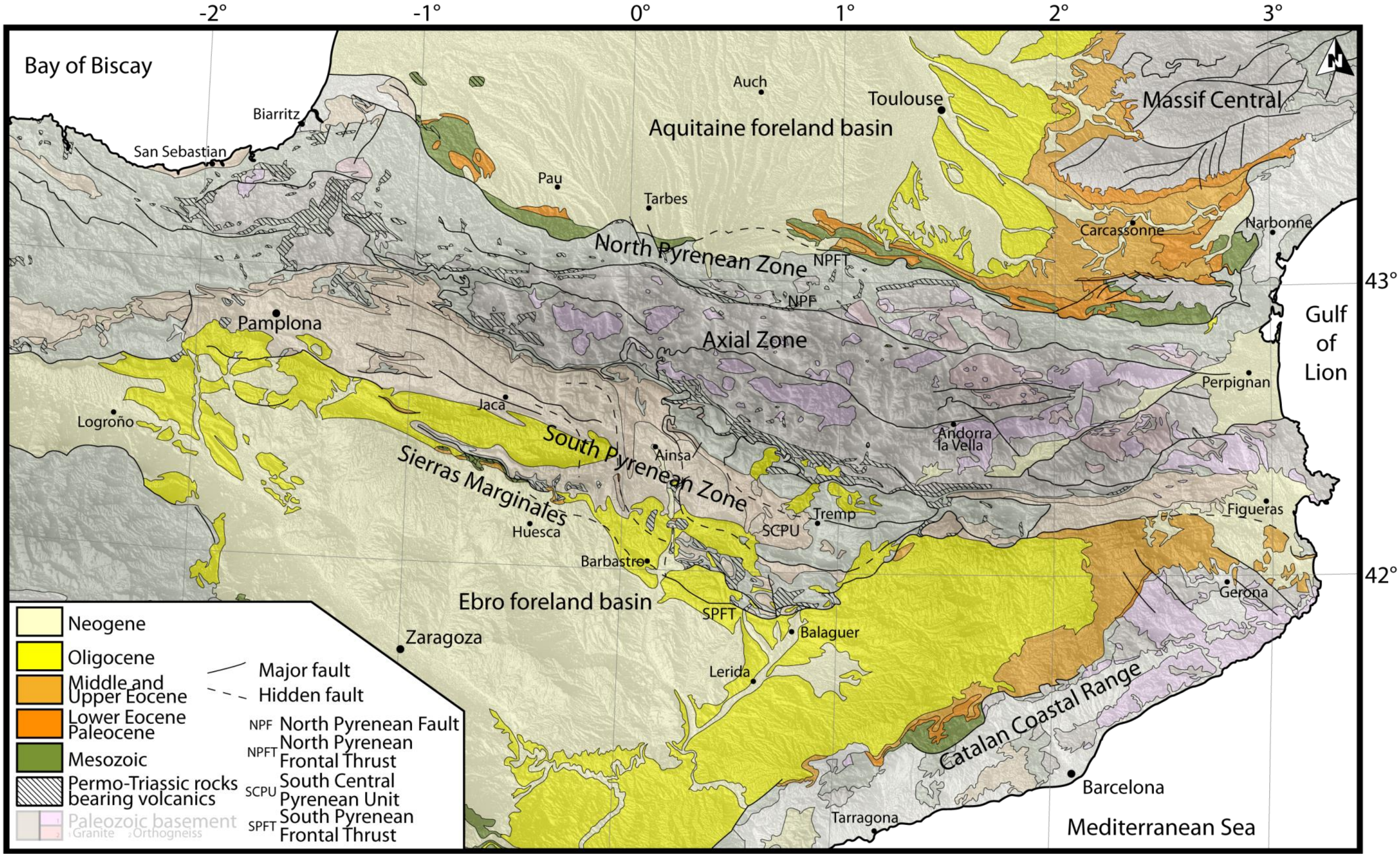
3 : Zone axiale; 4 : Zone sud-pyrénéenne; 5: Bassin d'avant-pays de l'Ebre

Le bassin d'avant-pays aquitain et la Zone Nord-Pyrénéenne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43°
42°
Bay of Biscay
Biarritz
San Sebastian
Pau
Tarbes
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Toulouse
Aquitaine foreland basin
Massif Central
Carcassonne
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Ebro foreland basin
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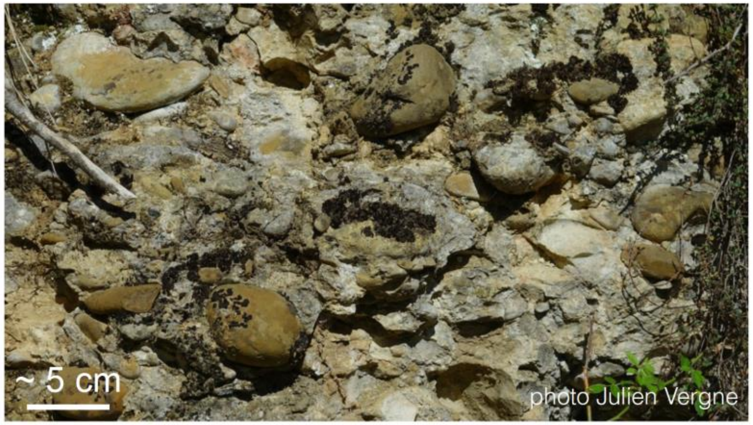
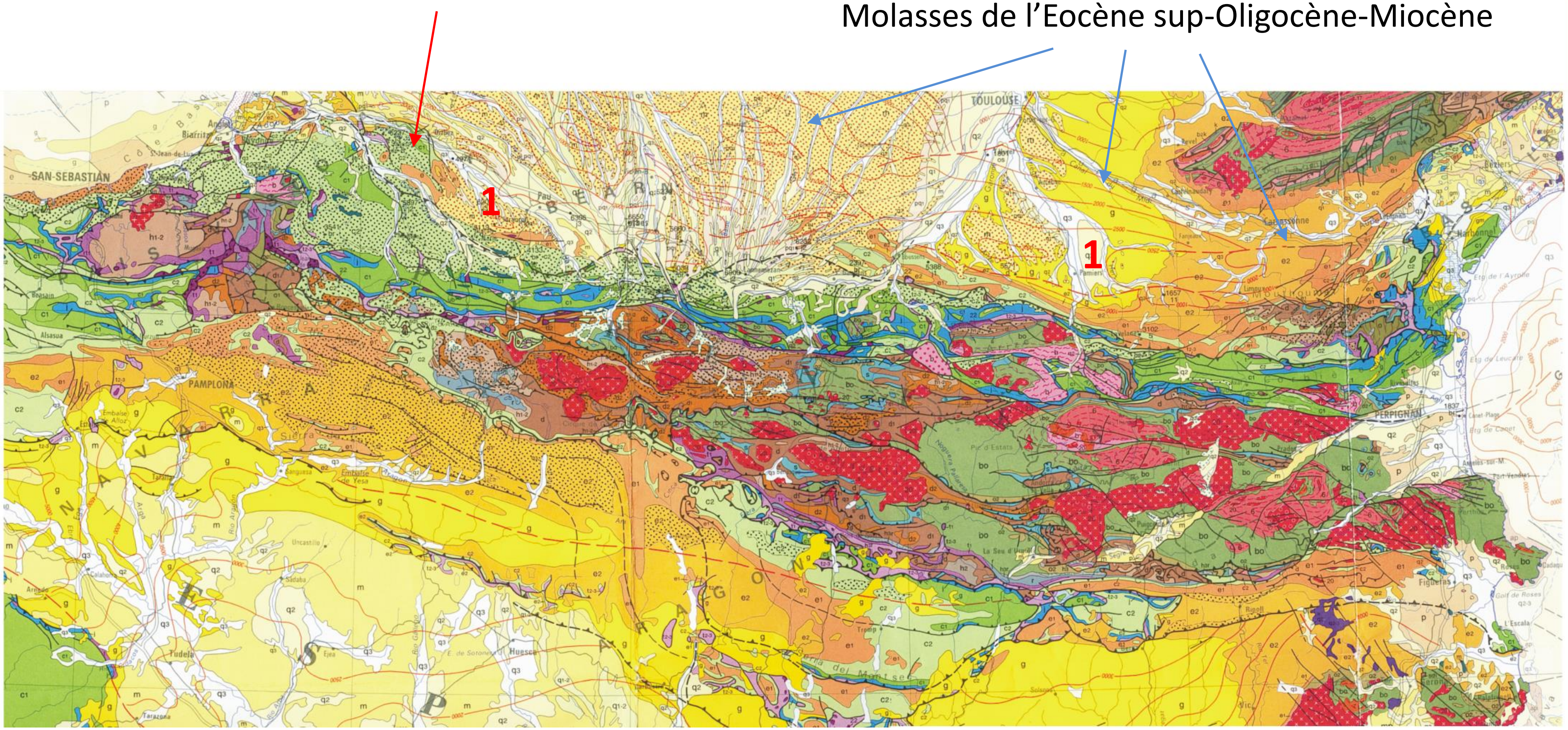
SCPU South Central Pyrenean Unit
SPFT South Pyrenean Frontal Thrust

(Filleaudeau, thèse, 2011)

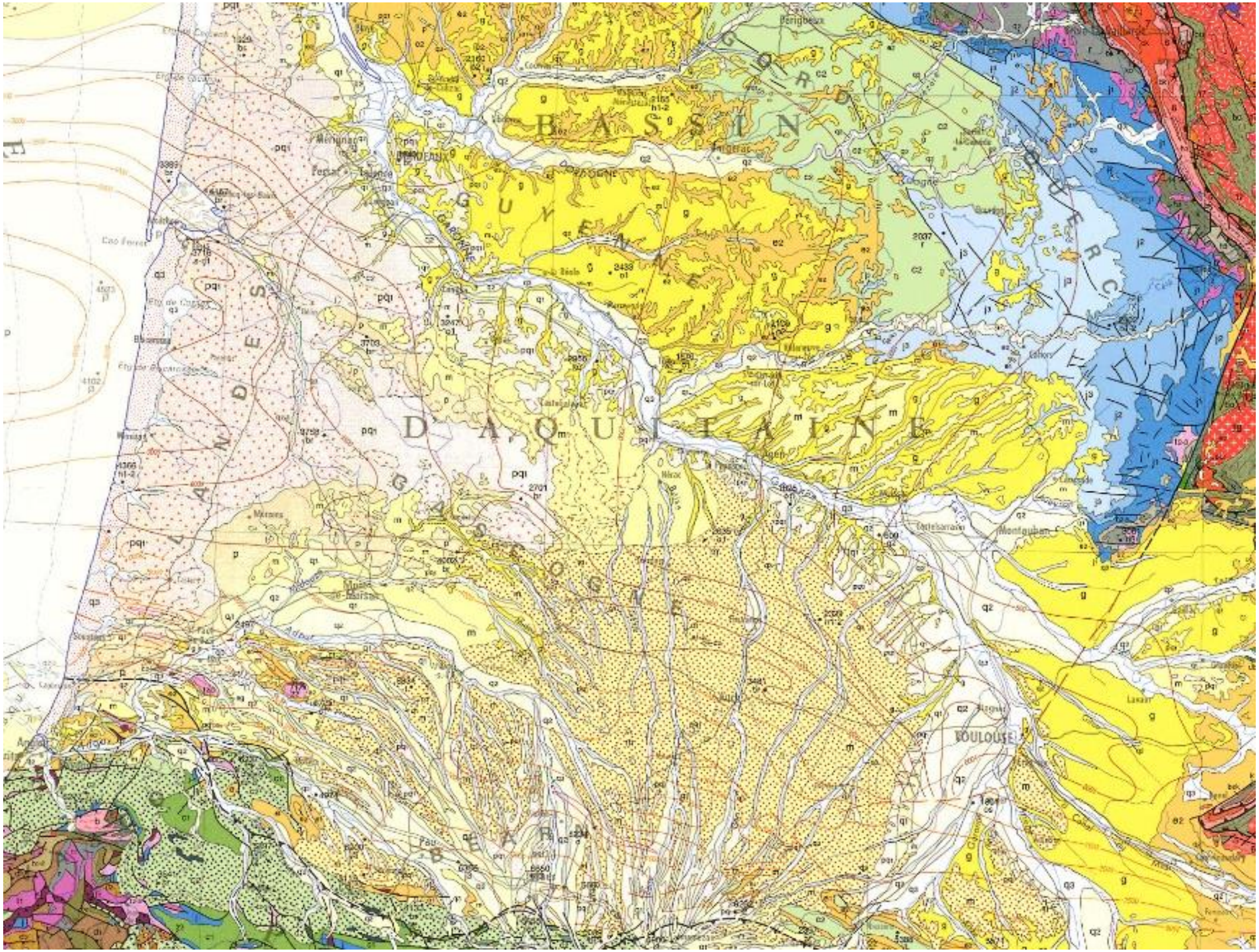
le poudingue de Palassou
(Eocene)

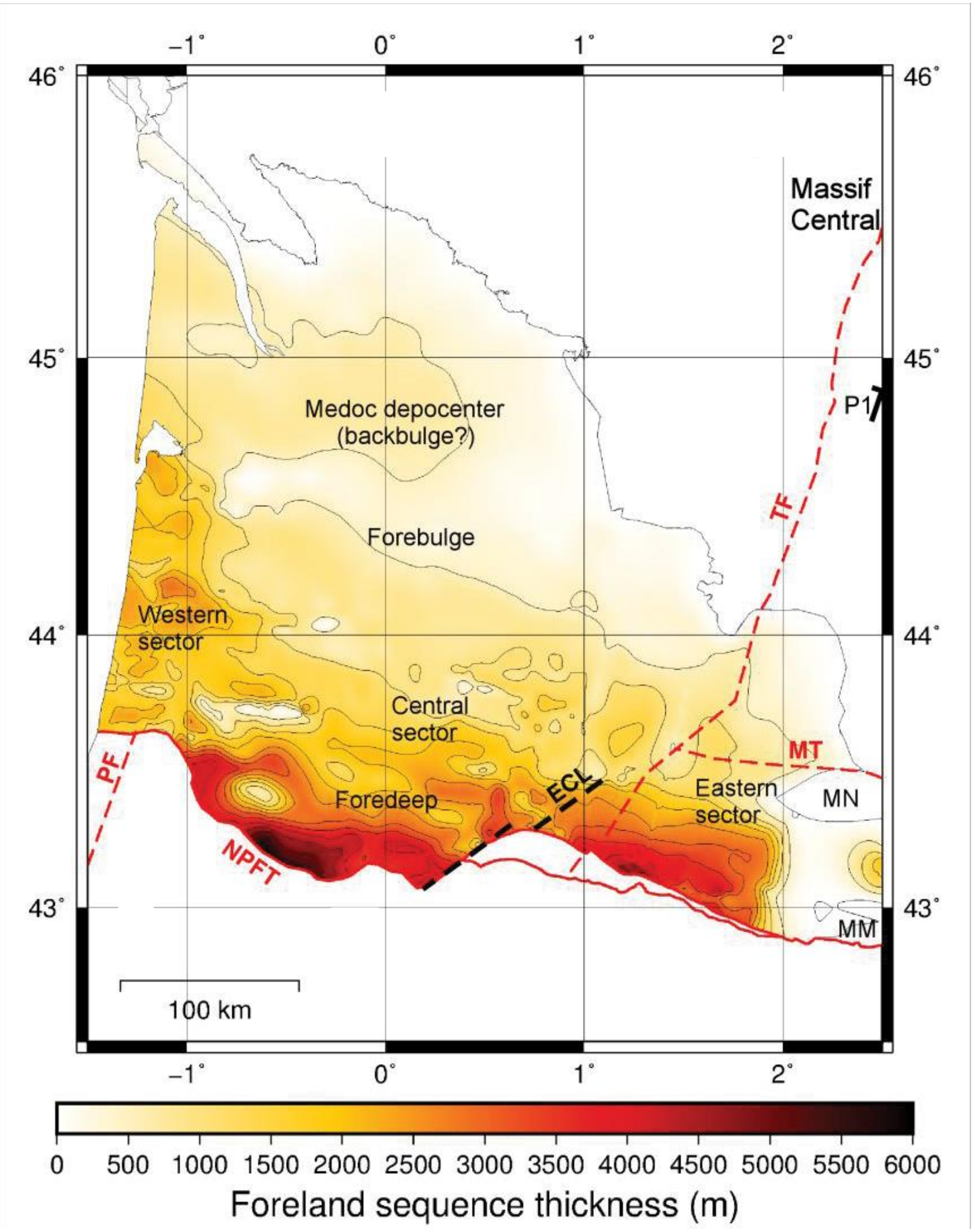

~ 5 cm
photo Julien Vergne


Flysch(**s**) du Crétacé supérieur

Molasses de l'Eocène sup-Oligocène-Miocène

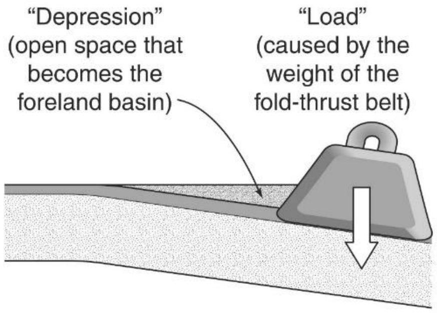
1
1
SAN-SEBASTIAN
PAMPLONA
TOULOUSE
PERPIGNAN
Pau
Biarritz
Huesca
Tudela
Carcassonne
Narbonne
Figueras

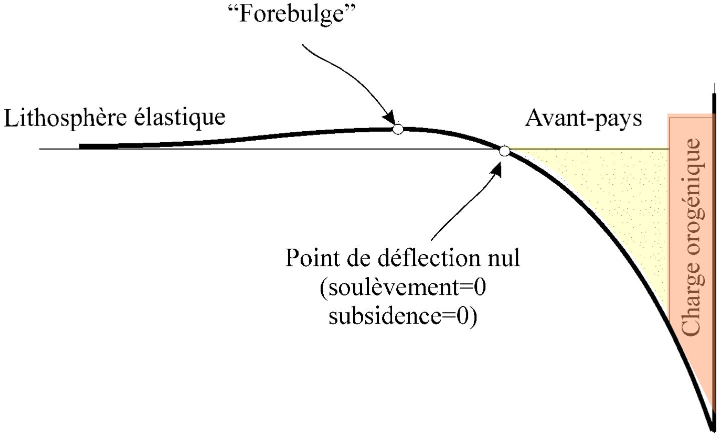

BASSIN
D'AQUITAINE
LANDES
GASCOGNE
GUYENNE
GORD
QUERCY
BEARN
Périgueux
Bergerac
BORDEAUX
Agen
Montauban
TOULOUSE
Castelsarrasin
Auch
Pau
Lavaur
Dordogne
Garonne
Adour


-1°
0°
1°
2°
46°
45°
44°
43°
Massif Central
P1
TF
Medoc depocenter (backbulge?)
Forebulge
Western sector
Central sector
Foredeep
Eastern sector
MT
MN
MM
ECL
NPFT
PF
100 km
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Foreland sequence thickness (m)

(Syn-orogénique : Campanien –Miocène moyen)

(Angrand et al., 2018)


"Depression" (open space that becomes the foreland basin)
"Load" (caused by the weight of the fold-thrust belt)


"Forebulge"
Lithosphère élastique
Avant-pays
Charge orogénique
Point de déflection nul (soulèvement=0 subsidence=0)

subsidence flexurale

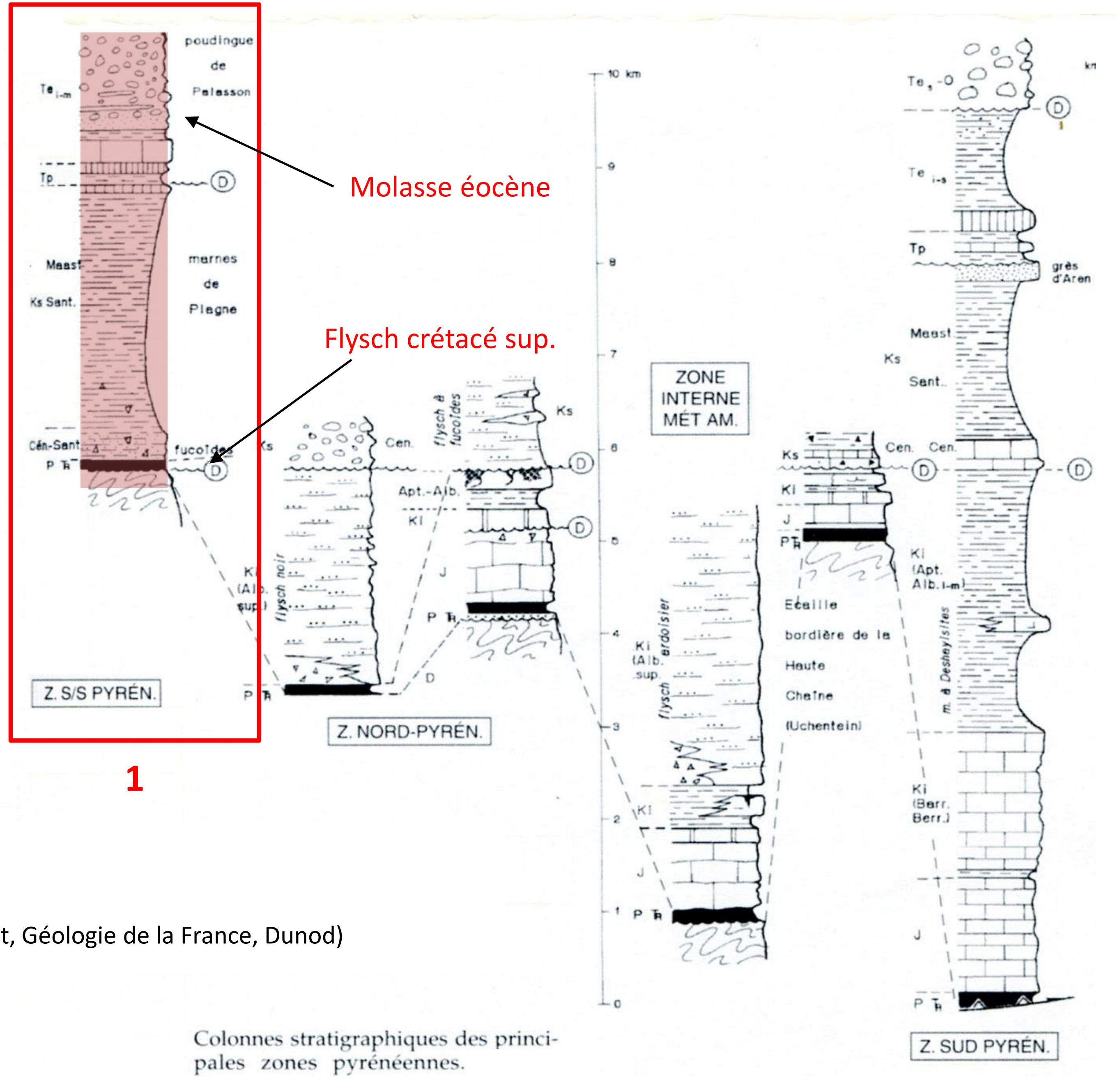
+

subsidence thermique post-rift

Sédim. détritique terrigène >>, Séries sédim. différentes d'une zone à l'autre

Aptien (~110 Ma)

Sédim. carbonatée >>, séries sédim. ~similaires dans toutes les zones


poudingue de Palasson
Te i-m
Tp
D
Maast
Ks Sant.
marnes de Plagne
Cén-Sant
fucoïdes
P Tr
Z. S/S PYRÉN.
Ks
Ki (Alb. sup)
flysch noir
Cen.
Apt.-Alb.
Ki
J
P Tr
flysch à fucoïdes
D
Z. NORD-PYRÉN.
10 km
9
8
7
6
5
4
3
2
1
0
ZONE INTERNE MÉT AM.
Ki (Alb. sup.
flysch ardoisier
Ki
J
P Tr
Ks
Ki
J
P Tr
Cen.
Écaille bordière de la Haute Chaîne (Uchentein)
Te, -O
km
Te i-s
Tp
grès d'Aren
Maast
Ks
Sant.
Cen.
Ki (Apt. Alb. i-m)
m. à Deshayesites
Ki (Barr. Berr.)
J
P Tr
Z. SUD PYRÉN.

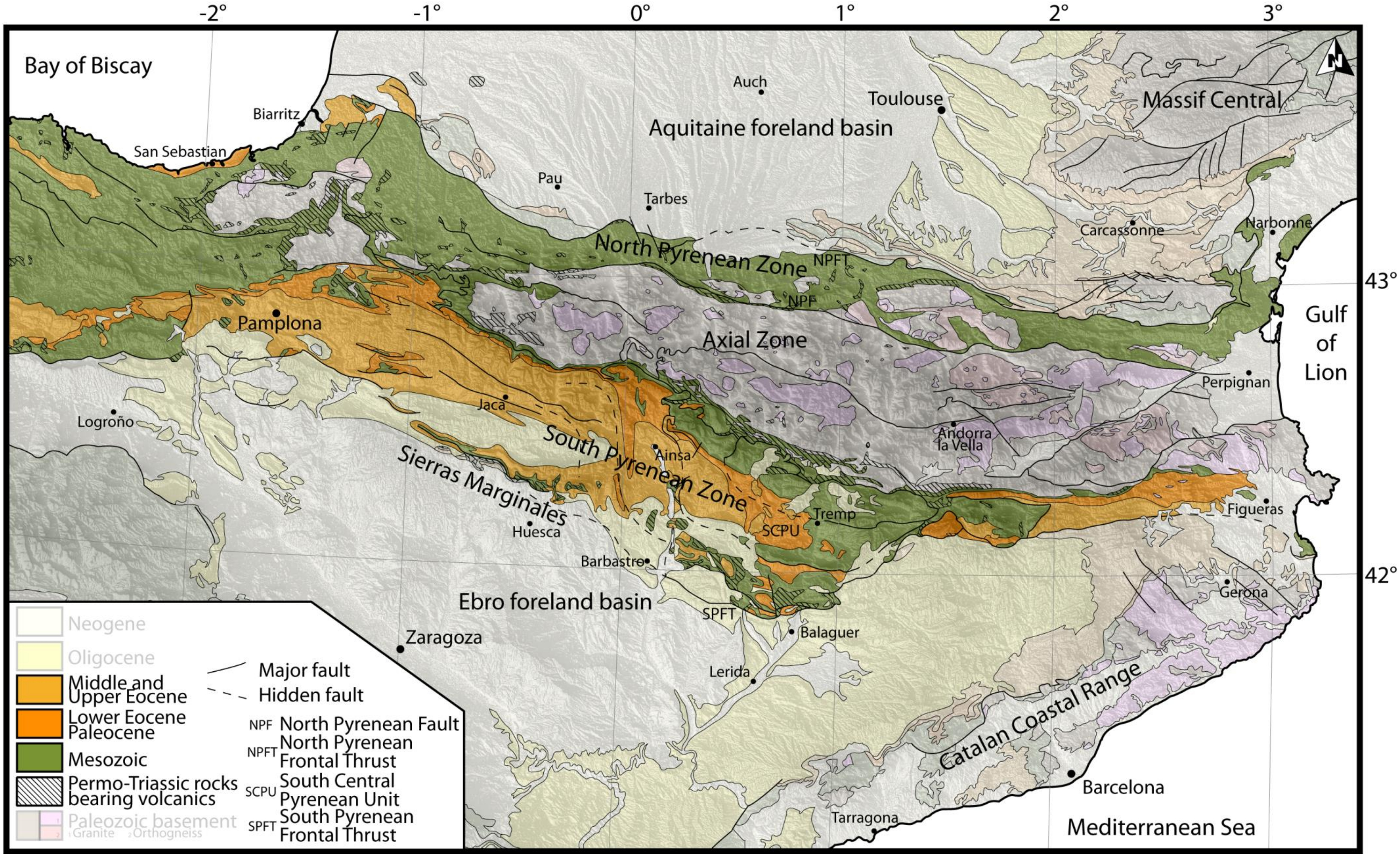
Molasse éocène

Flysch crétacé sup.

1

Colonnes stratigraphiques des principales zones pyrénéennes.

(D'après Dercourt, Géologie de la France, Dunod)


-2°
-1°
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1°
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3°
43°
42°
Bay of Biscay
Biarritz
San Sebastian
Auch
Toulouse
Massif Central
Aquitaine foreland basin
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Ainsa
Sierras Marginales
Tremp
Figueras
SCPU
Huesca
Barbastro
Gerona
Ebro foreland basin
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Balaguer
Zaragoza
Lerida
Catalan Coastal Range
Barcelona
Tarragona
Mediterranean Sea
N
Neogene
Oligocene
Middle and Upper Eocene
Lower Eocene Paleocene
Mesozoic
Permo-Triassic rocks bearing volcanics
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1 Granite
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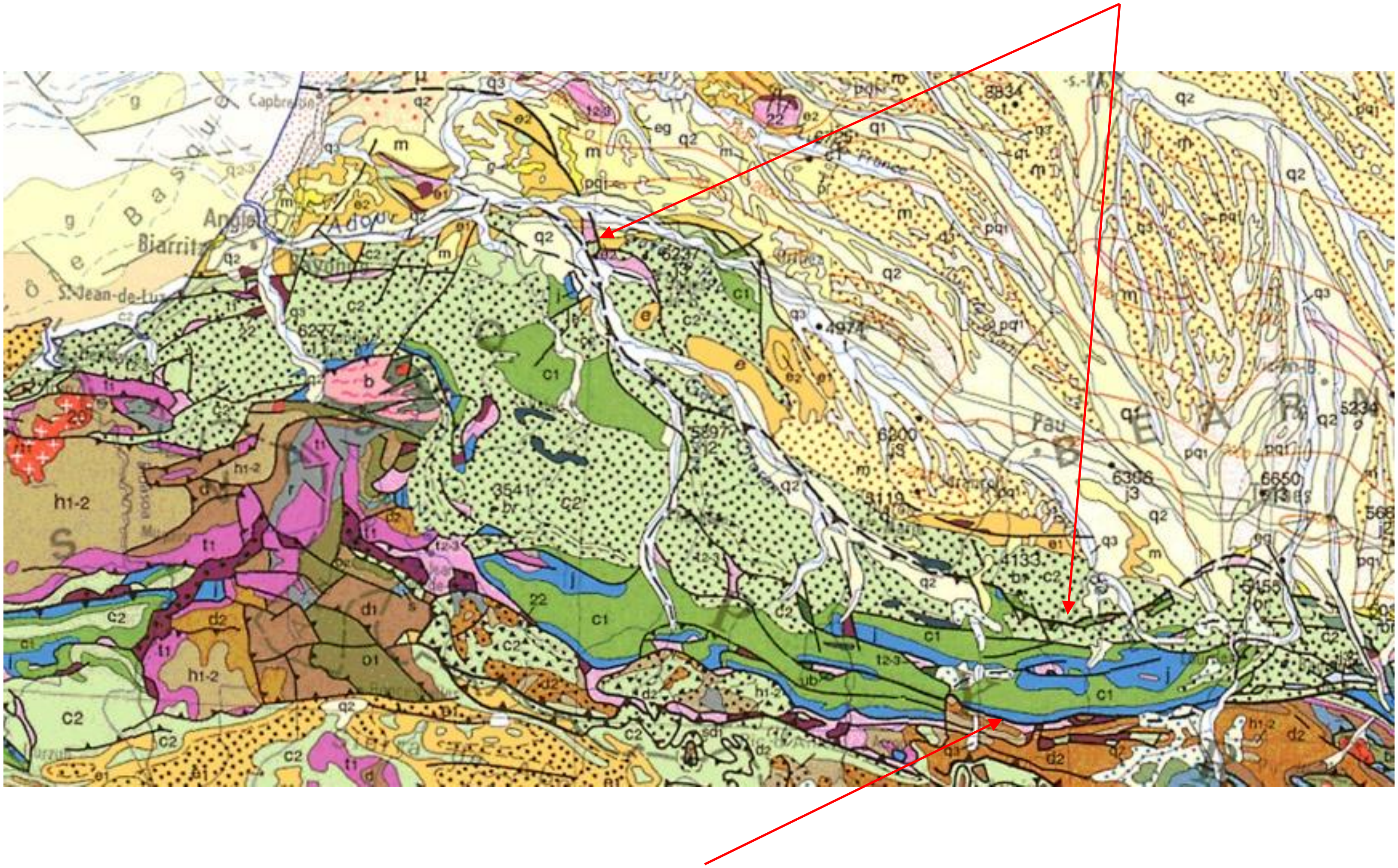
Major fault
Hidden fault
NPF North Pyrenean Fault
NPFT North Pyrenean Frontal Thrust
SCPU South Central Pyrenean Unit
SPFT South Pyrenean Frontal Thrust

(Filleaudeau, thèse, 2011)

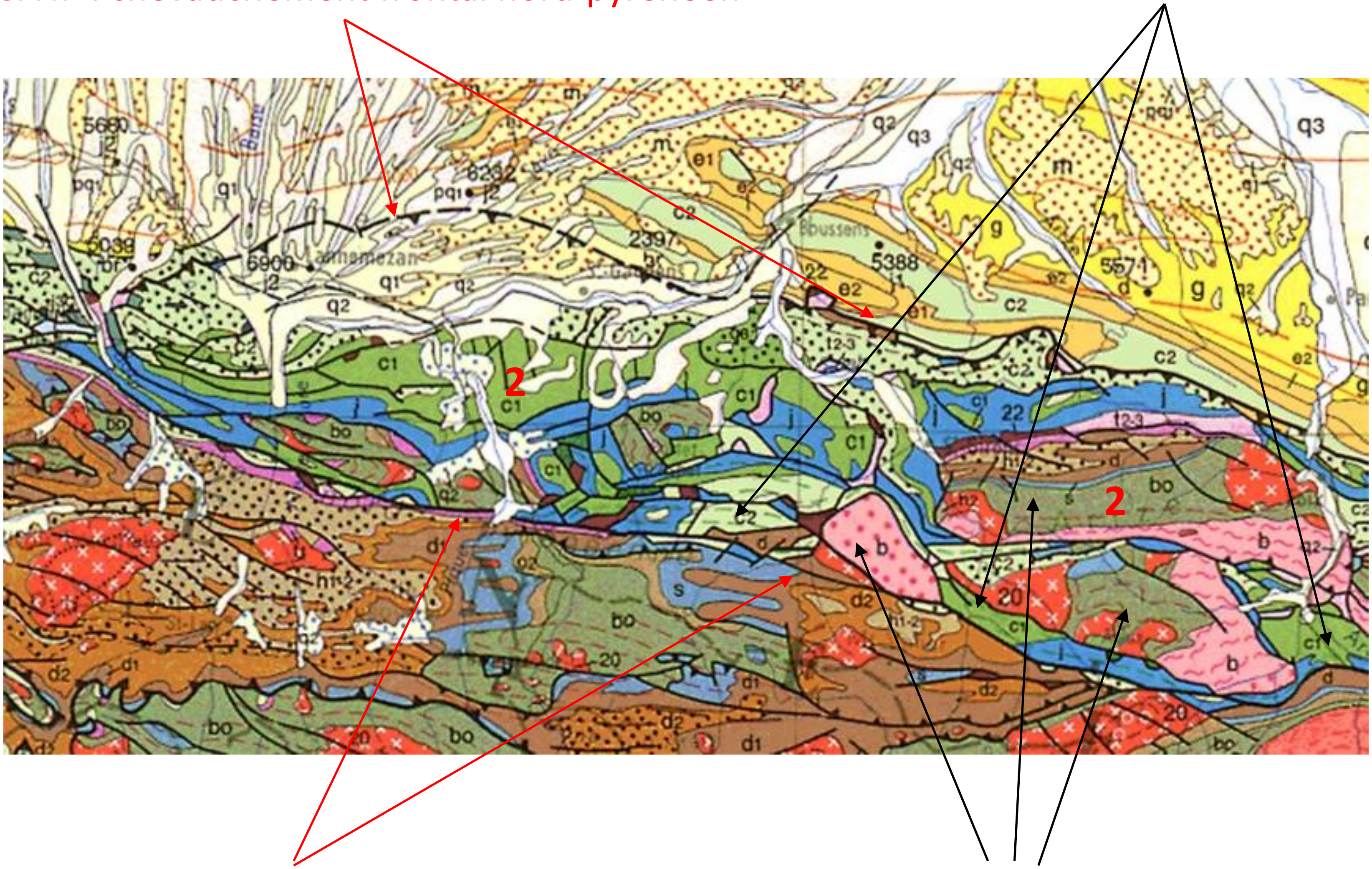

Capbreton
Anglet
Biarritz
St-Jean-de-Luz
Adour
Pau
Basque
h1-2
c1
c2
q2
pq1
m

CFNP : Chevauchement Frontal Nord-Pyrénéen

FNP : Faille Nord-Pyrénéenne

CFNP : chevauchement frontal nord-pyrénéen

Bassins crétacés


2
2
5680
j2
pq1
q1
5039
5900
Lannemezan
j2
q2
8232
2397
St-Gaudens
Boussens
5388
5571
m
e1
e2
c1
c2
q3
g
d
j
22
bo
b
s
d1
d2
h1-2
20

FNP : faille nord-pyrénéenne

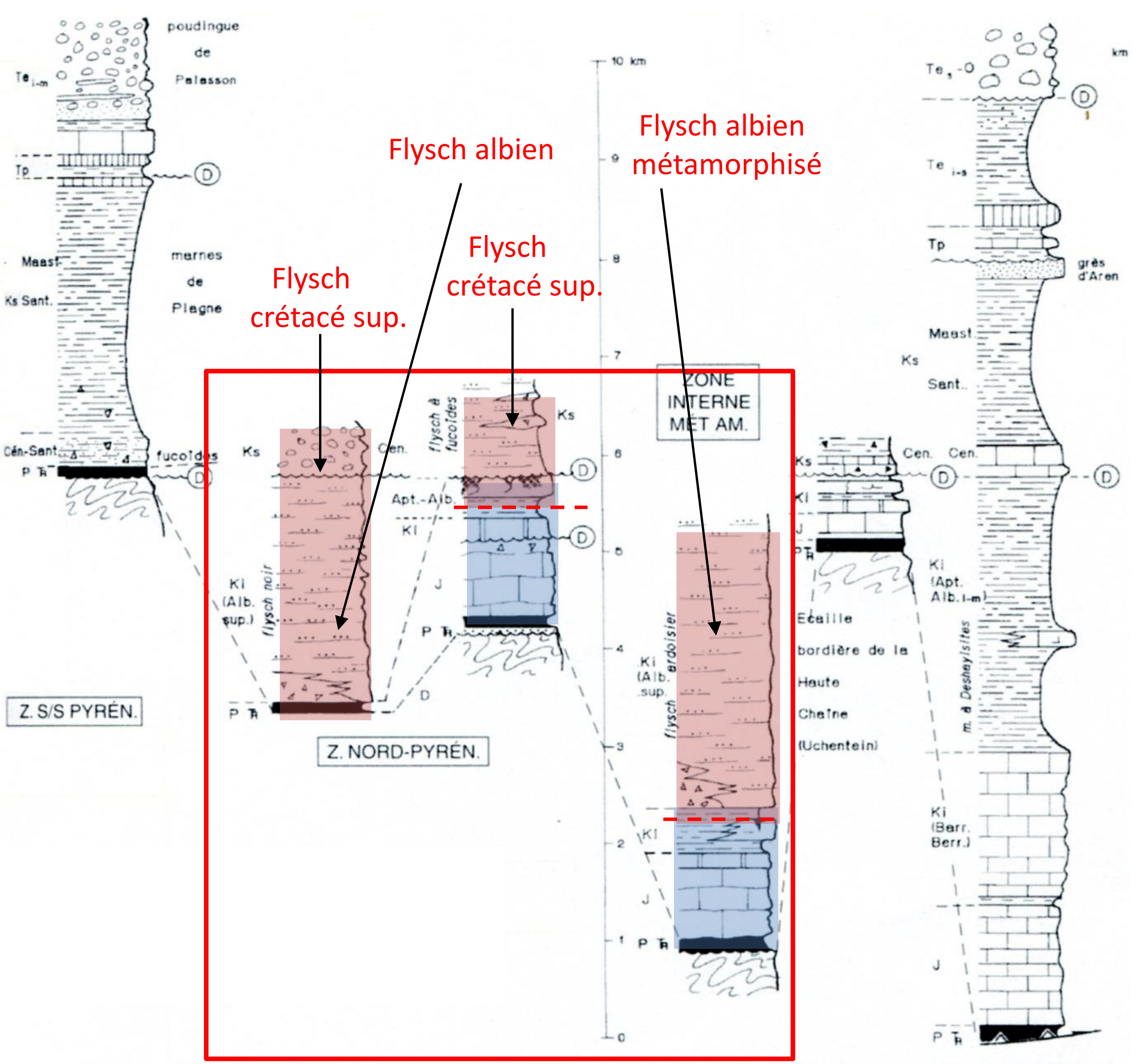
Massifs cristallins nord-pyrénéens

(D’après Dercourt, Géologie de la France, Dunod)

Sédim.
détritique
terrigène
>>,
Séries sédim.
différentes
d’une zone à
l’autre

Aptien
(~110 Ma)

Sédim.
carbonatée
>>, séries
sédim.
~similaires
dans toutes
les zones


poudingue
de
Palasson
Te i-m
Tp
Maest
Ks Sant.
marnes
de
Plagne
Cén-Sant.
P Ŧ
fucoïdes
Ks
Cen.
Ki
(Alb.
sup.)
flysch noir
P Ŧ
D
Z. S/S PYRÉN.
Z. NORD-PYRÉN.
flysch à fucoïdes
Apt.-Alb.
Ki
J
P Ŧ
D
Ks
10 km
9
8
7
6
5
4
3
2
1
0
ZONE
INTERNE
MET AM.
Ki
(Alb.
sup.
flysch ardoisier
Ki
J
P Ŧ
Ks
Ki
J
P Ŧ
Ecaille
bordière de la
Haute
Chaîne
(Uchentein)
Te, -O
km
Te i-s
Tp
grès
d'Aren
Maest
Ks
Sant.
Cen.
Cen.
Ki
(Apt.
Alb. i-m)
m. à Deshayesites
Ki
(Barr.
Berr.)
J
P Ŧ
Z. SUD PYRÉN.

Flysch albien

Flysch albien
métamorphisé

Flysch
crétacé sup.

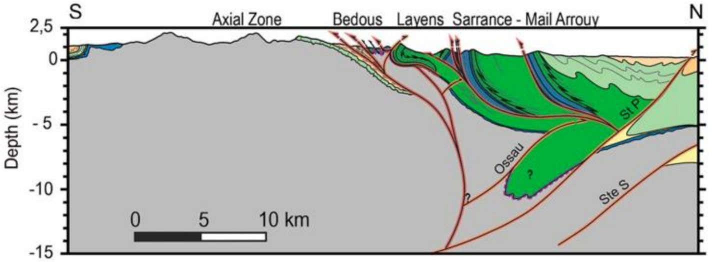
Flysch
crétacé sup.

Colonnes stratigraphiques des principales zones pyrénéennes.

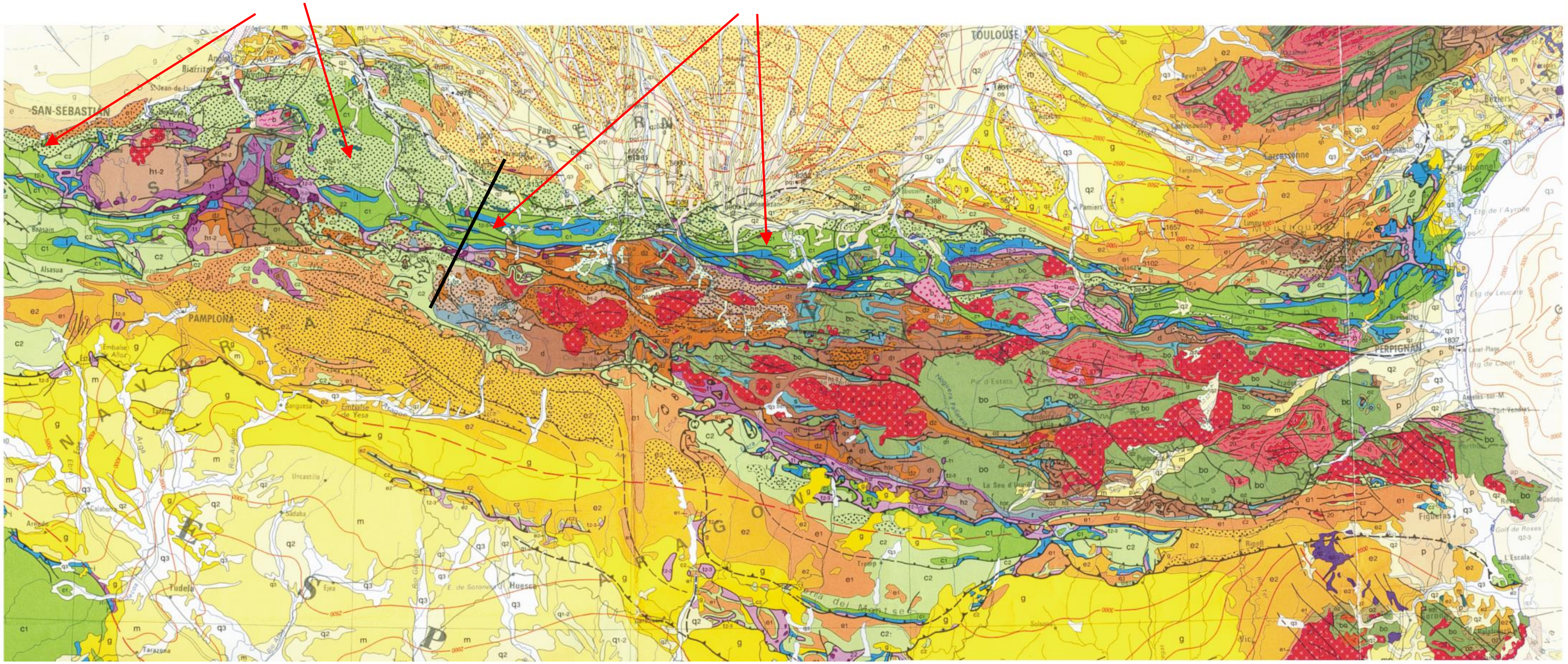
2

FurgoBidaiak

Albian Black flysch


S
N
Axial Zone
Bedous
Layens
Sarrance - Mail Arrouy
2,5
0
-5
-10
-15
Depth (km)
Ossau
St P
Ste S
?
0
5
10 km

Tugend et al. (2014)

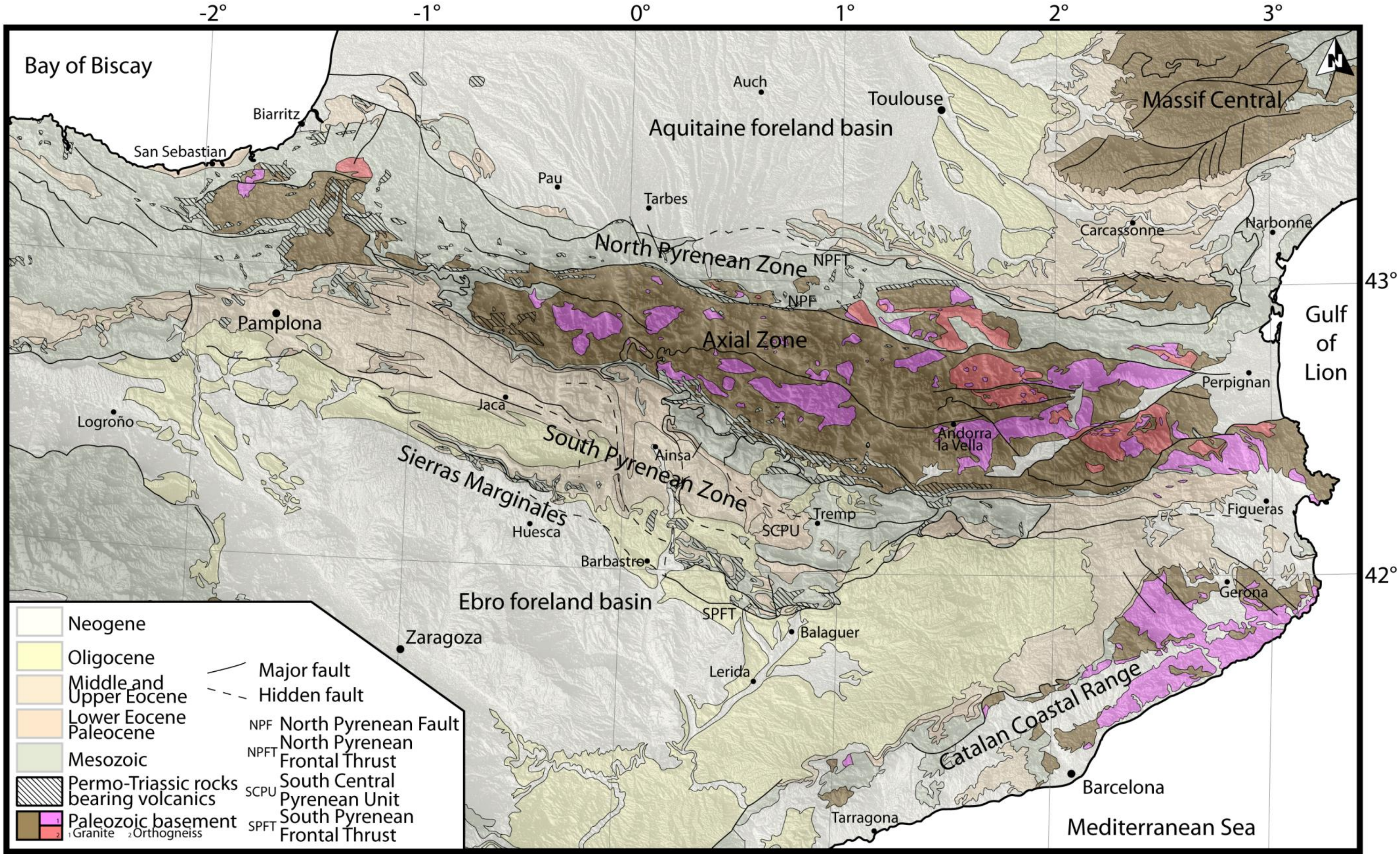


Flysch(**s**) du Crétacé supérieur

Flysch albien

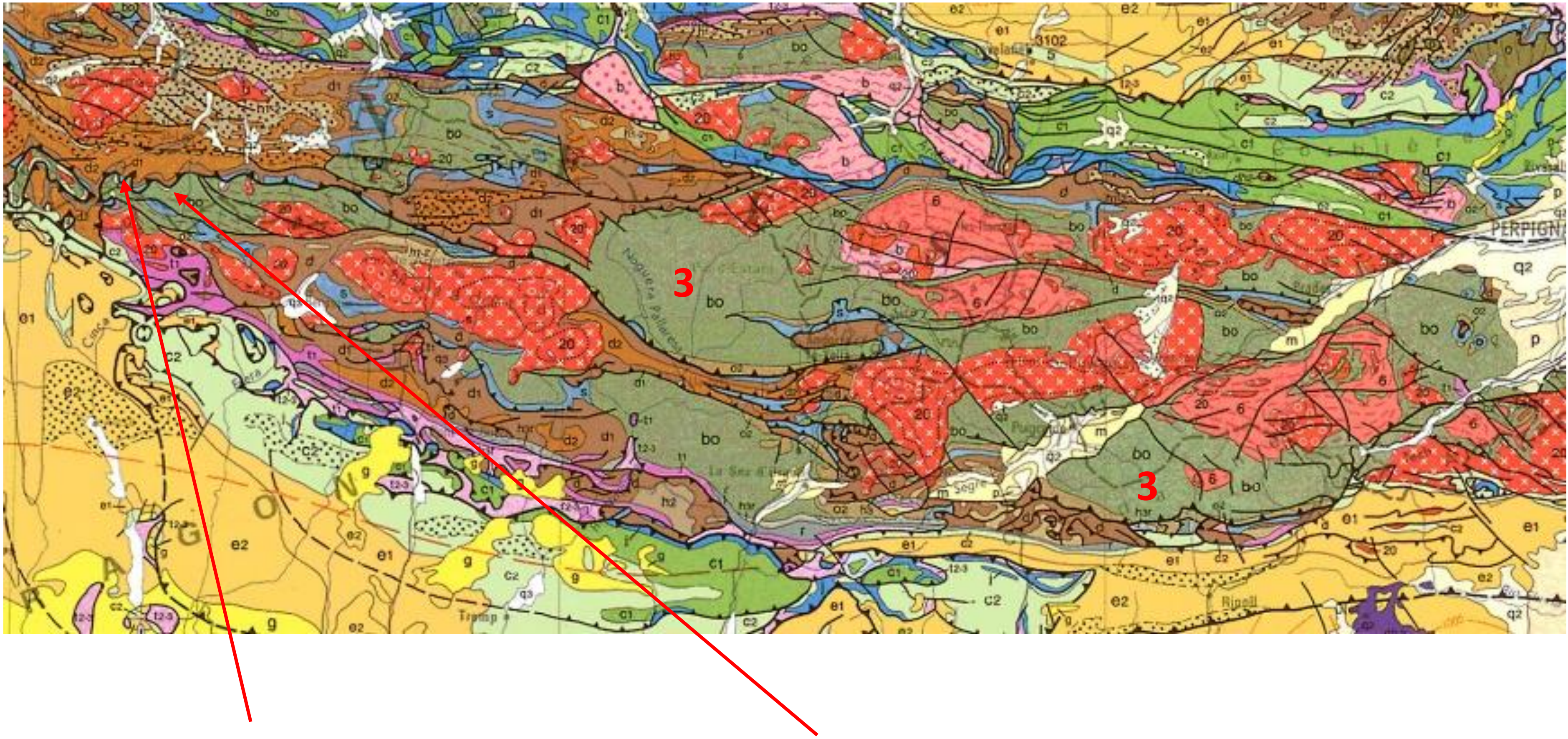
SAN-SEBASTIAN
Biarritz
TOULOUSE
Pau
Carcassonne
Narbonne
PAMPLONA
PERPIGNAN
Huesca
Tudela
Figueras

La Zone Axiale


-2°
-1°
0°
1°
2°
3°
43°
42°
N
Bay of Biscay
Biarritz
San Sebastian
Auch
Toulouse
Aquitaine foreland basin
Massif Central
Pau
Tarbes
Carcassonne
Narbonne
North Pyrenean Zone
NPFT
NPF
Gulf of Lion
Pamplona
Axial Zone
Perpignan
Jaca
Logroño
Andorra la Vella
Ainsa
South Pyrenean Zone
Sierras Marginales
Huesca
Tremp
SCPU
Figueras
Barbastro
Ebro foreland basin
SPFT
Balaguer
Gerona
Zaragoza
Lerida
Catalan Coastal Range
Barcelona
Tarragona
Mediterranean Sea
Neogene
Oligocene
Middle and Upper Eocene
Lower Eocene Paleocene
Mesozoic
Permo-Triassic rocks bearing volcanics
Paleozoic basement
1 Granite
2 Orthogneiss
Major fault
Hidden fault
NPF North Pyrenean Fault
NPFT North Pyrenean Frontal Thrust
SCPU South Central Pyrenean Unit
SPFT South Pyrenean Frontal Thrust

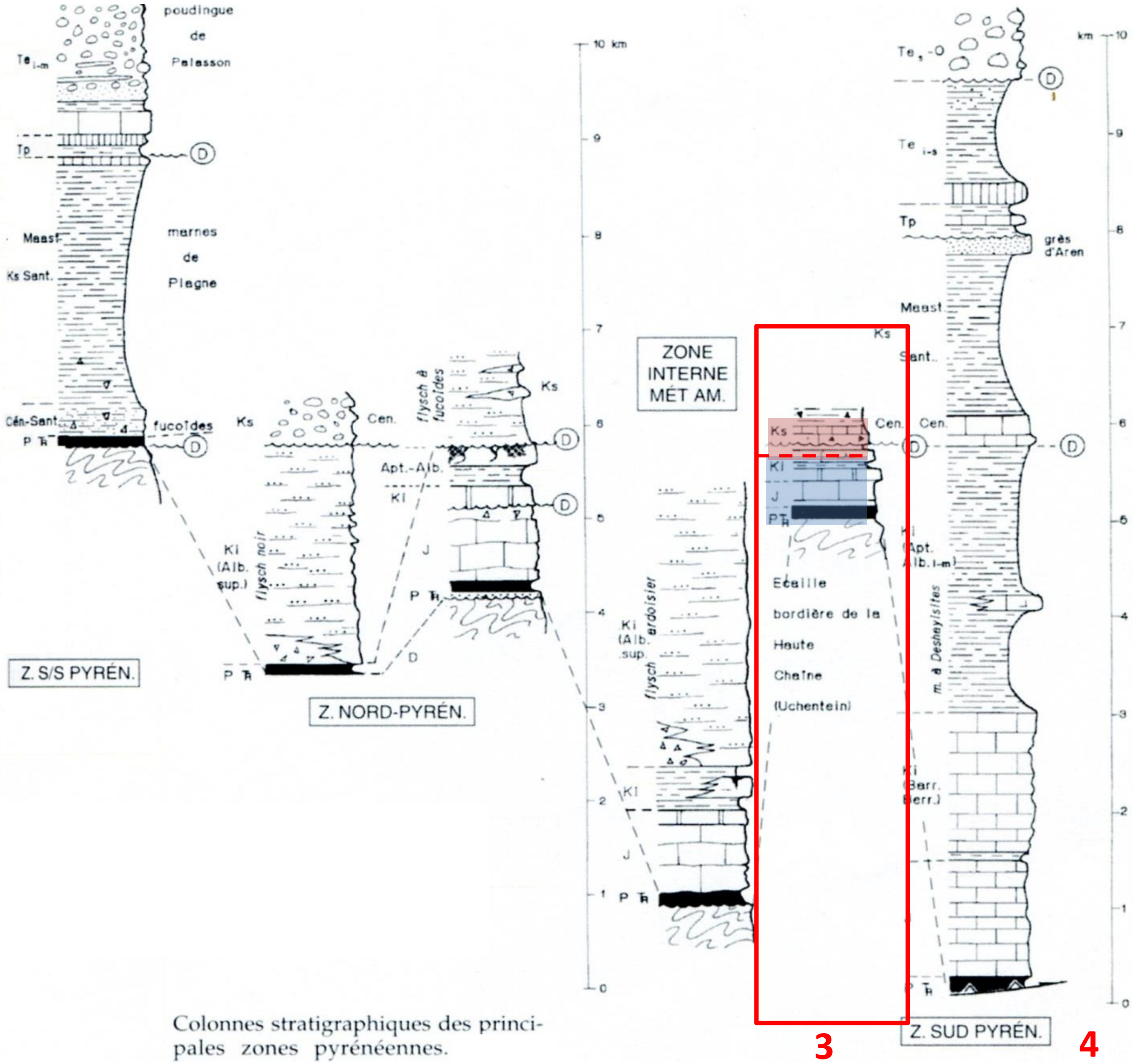
(Filleaudeau, thèse, 2011)

Essentiellement des terrains (méta)sédimentaires et cristallins paléozoïques…


3
3
PERPIGN
Noguera Pallaresa
Segre
bo
20
d1
d2
e1
e2
c1
c2

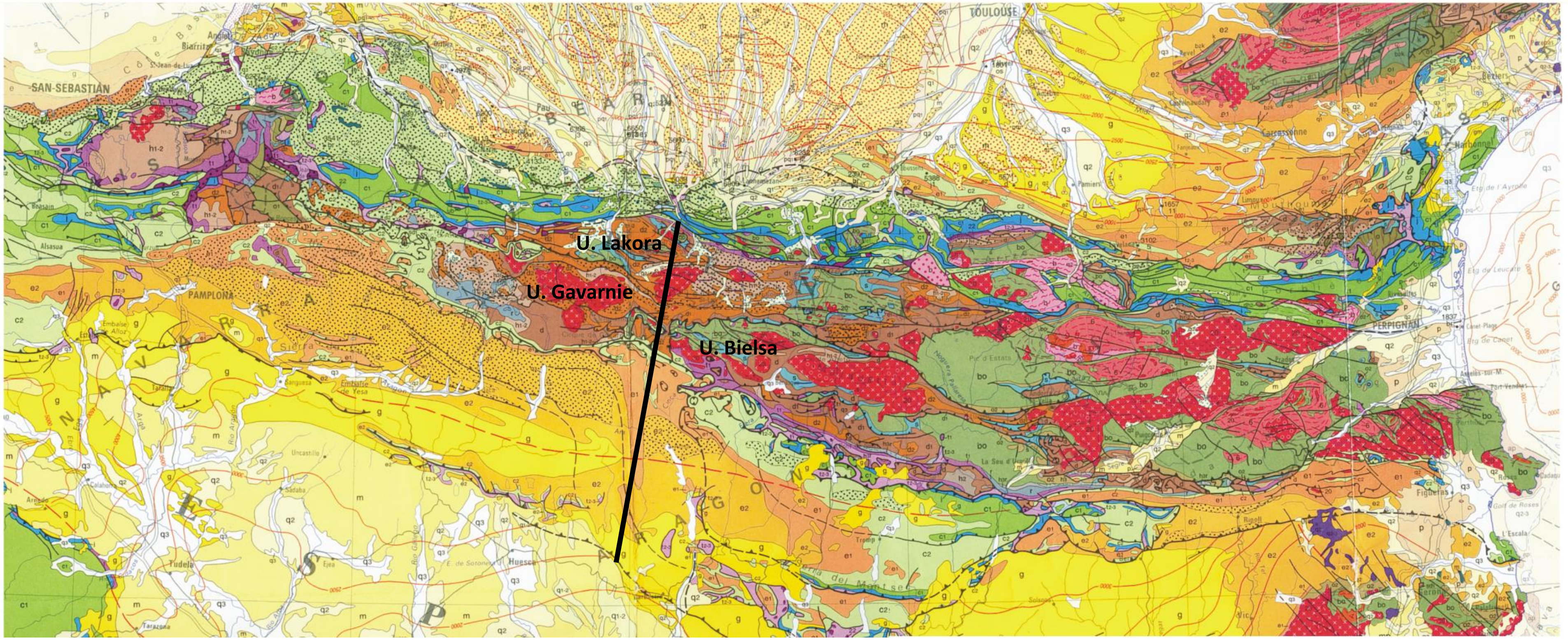
… avec un peu de couverture sédimentaire mésozoïque préservée de l'érosion

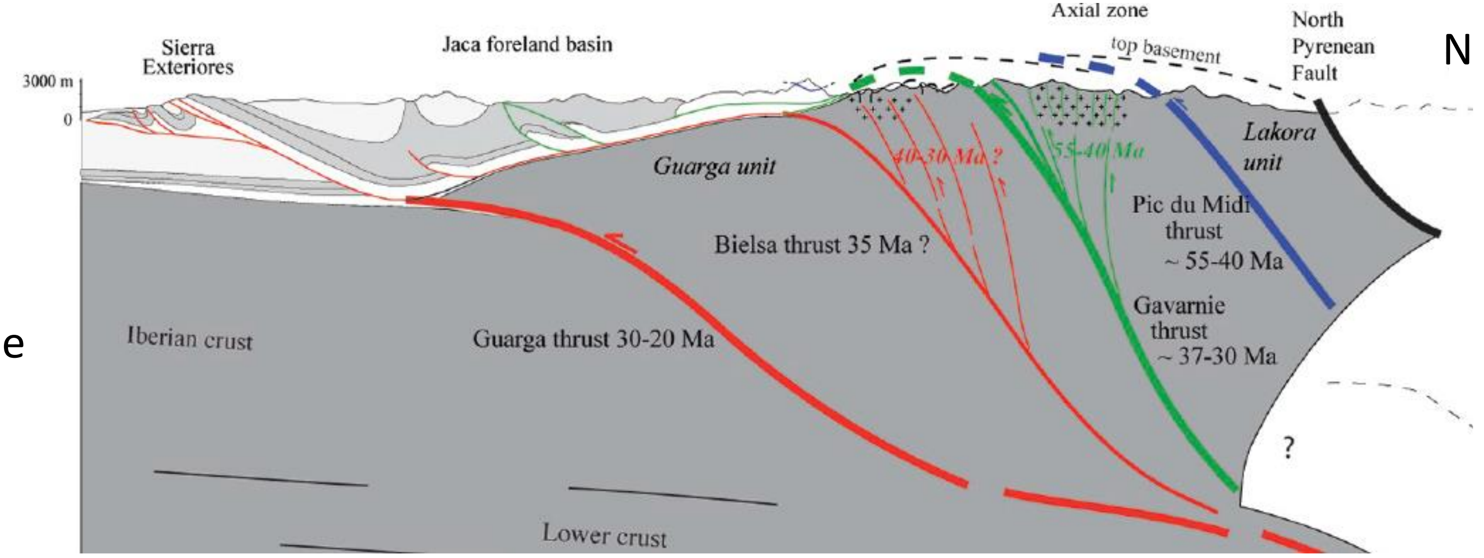
(D’après Dercourt, Géologie de la France, Dunod)

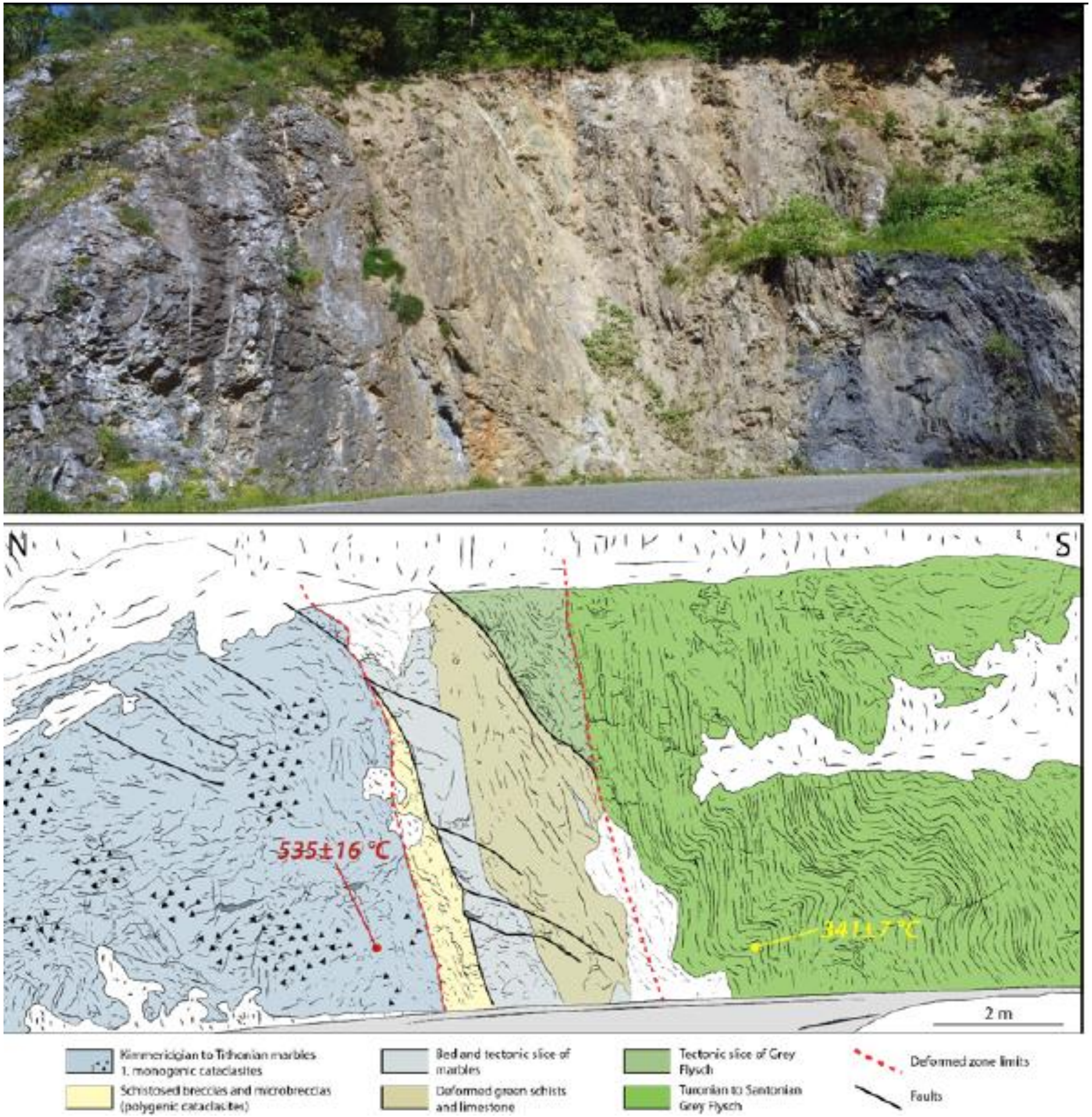

poudingue
de
Palasson
Te i-m
Tp
D
Maast
Ks Sant.
marnes
de
Plagne
Cén-Sant
fucoïdes
P Ŧ
Z. S/S PYRÉN.
Ks
Cen.
Apt.-Alb.
Ki
flysch à fucoïdes
flysch noir
Ki (Alb. sup.)
J
P Ŧ
D
Z. NORD-PYRÉN.
10 km
9
8
7
6
5
4
3
2
1
0
ZONE INTERNE MÉT AM.
flysch ardoisier
Ki (Alb. sup.
Ki
J
P Ŧ
Ks
Cen.
Ki
J
P Ŧ
Ecaille
bordière de la
Haute
Chaîne
(Uchentein)
3
Te 3 -O
Te i-3
Tp
grès
d'Aren
Maast
Sant.
Cen.
Ki
(Apt.
Alb. i-m)
m. à Deshayisites
Ki
(Barr.
Berr.)
P Ŧ
km
Z. SUD PYRÉN.
4

Colonnes stratigraphiques des principales zones pyrénéennes.

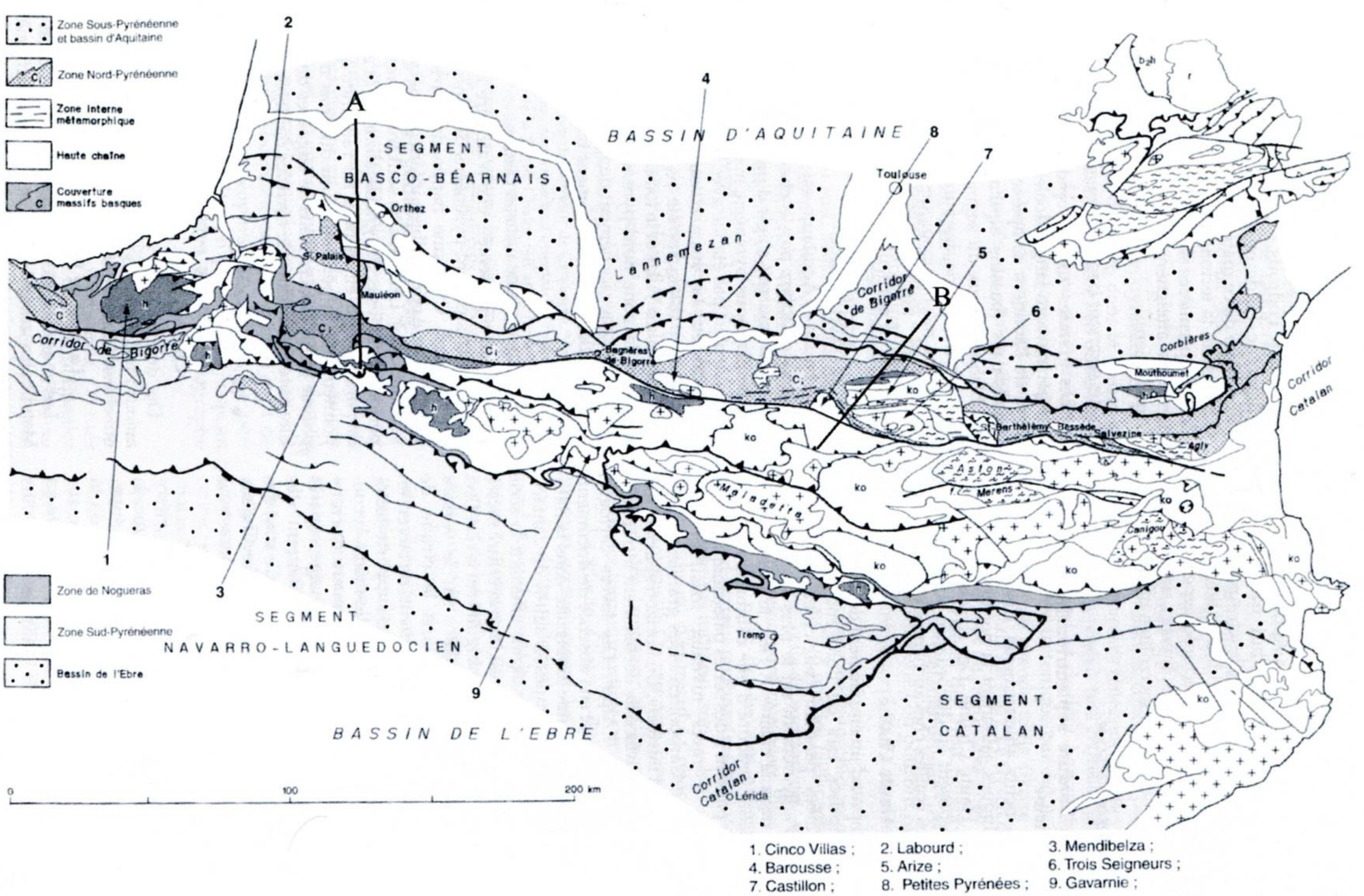
Structure de la Zone Axiale


U. Lakora
U. Gavarnie
U. Bielsa
SAN-SEBASTIAN
TOULOUSE
PAMPLONA
PERPIGNAN
Pau
Tudela
Huesca
Carcassonne
Narbonne
La Seu d'Urgell
Pic d'Estats
Figueras


S
N
Sierra Exteriores
Jaca foreland basin
Axial zone
top basement
North Pyrenean Fault
3000 m
0
Guarga unit
40-30 Ma ?
55-40 Ma
Lakora unit
Pic du Midi thrust ~ 55-40 Ma
Bielsa thrust 35 Ma ?
Gavarnie thrust ~ 37-30 Ma
Iberian crust
Guarga thrust 30-20 Ma
?
Lower crust

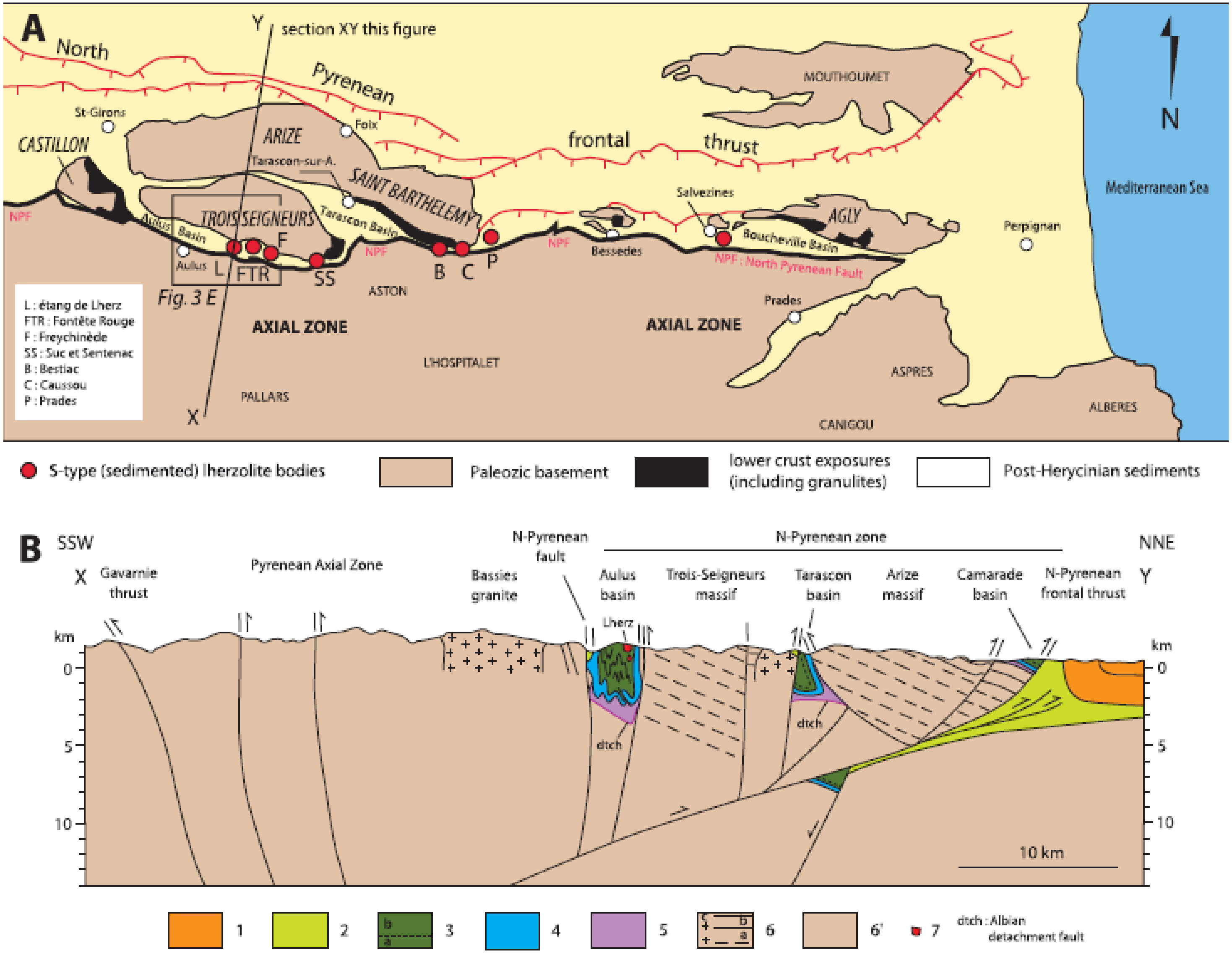

N
S
535±16 °C
341±7 °C
2 m
Kimmericigian to Tithonian marbles 1. monogenic cataclasites
Schistosed breccias and microbreccias (polygenic cataclasites)
Bed and tectonic slice of marbles
Deformed green schists and limestone
Tectonic slice of Grey Flysch
Turonian to Santonian Grey Flysch
Deformed zone limits
Faults

Les structures


Zone Sous-Pyrénéenne et bassin d'Aquitaine
Zone Nord-Pyrénéenne
Zone interne métamorphique
Haute chaîne
Couverture massifs basques
Zone de Nogueras
Zone Sud-Pyrénéenne
Bassin de l'Ebre
BASSIN D'AQUITAINE
SEGMENT BASCO-BÉARNAIS
SEGMENT NAVARRO-LANGUEDOCIEN
SEGMENT CATALAN
BASSIN DE L'EBRE
A
B
Orthez
St Palais
Mauléon
Lannemezan
Toulouse
Corridor de Bigorre
Bagnères de Bigorre
Corbières
Mouthoumet
Corridor Catalan
St Barthélémy
Bessède
Salvezine
Agly
Aston
Merens
Maladetta
Canigou
Tremp
Lérida
ko
h
C
C₁
0
100
200 km
1. Cinco Villas ;
2. Labourd ;
3. Mendibelza ;
4. Barousse ;
5. Arize ;
6. Trois Seigneurs ;
7. Castillon ;
8. Petites Pyrénées ;
9. Gavarnie ;

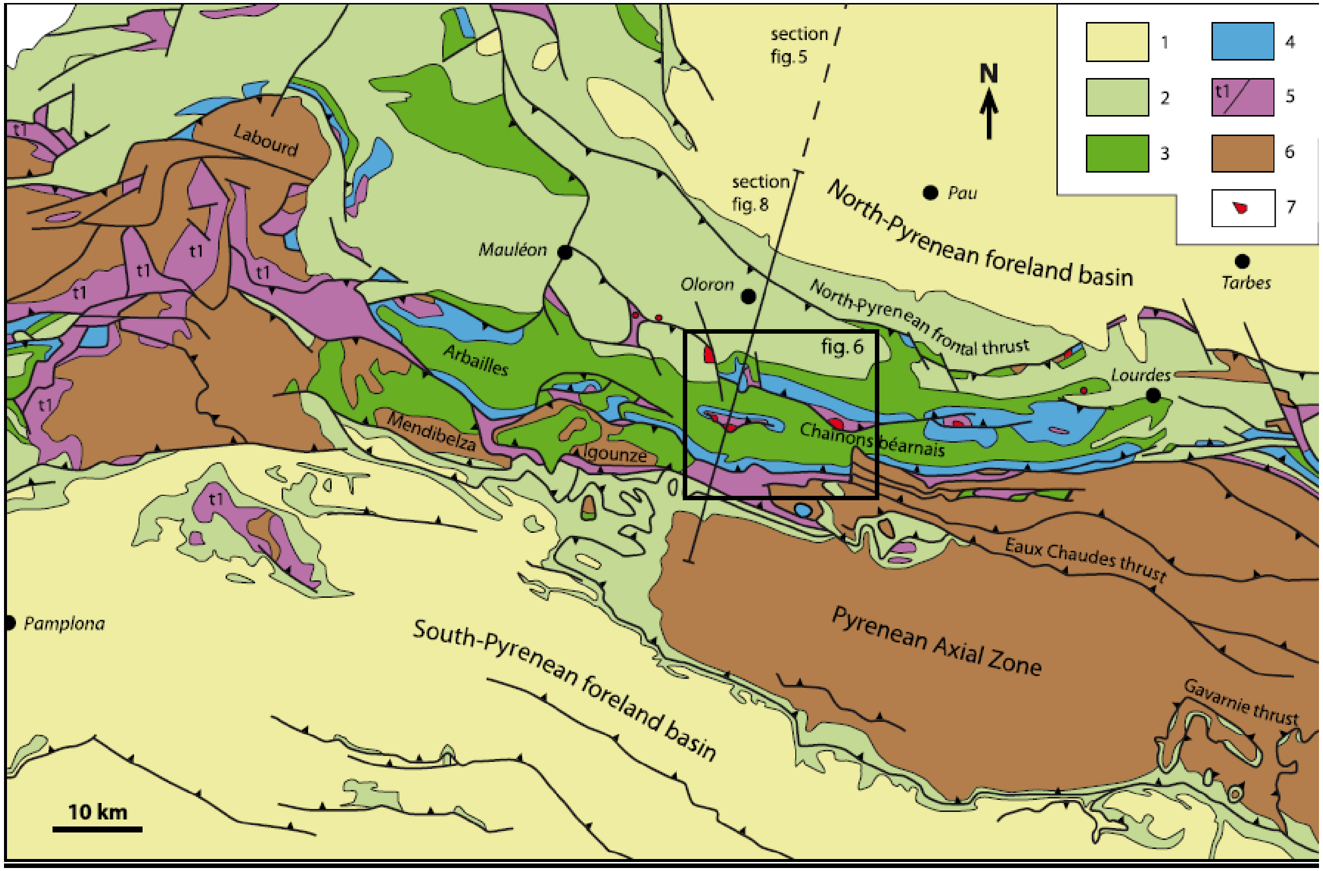
(D'après Dercourt, Géologie de la France, Dunod)

COUPE B

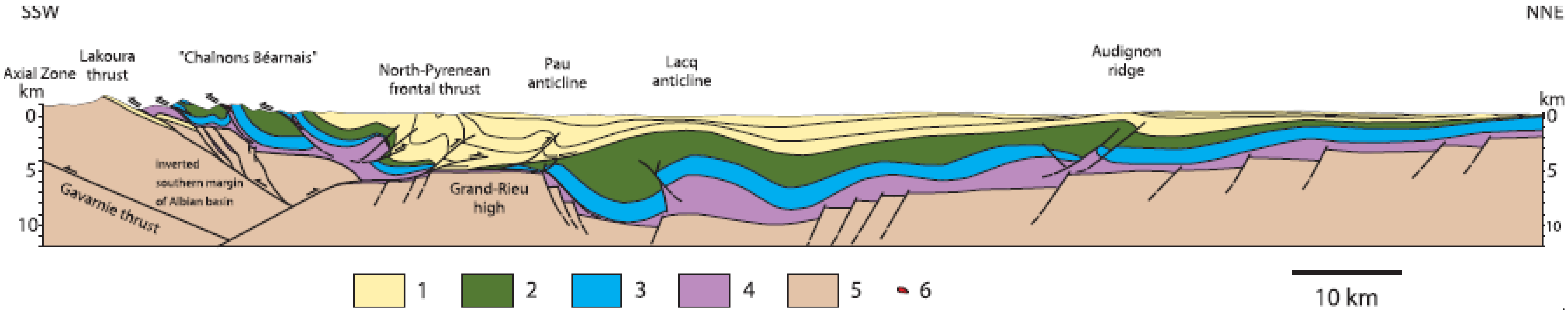

A
North
Pyrenean
frontal
thrust
Y
section XY this figure
St-Girons
CASTILLON
ARIZE
Foix
Tarascon-sur-A.
SAINT BARTHELEMY
TROIS SEIGNEURS
Tarascon Basin
Aulus Basin
Aulus
L
FTR
F
SS
B
C
P
NPF
ASTON
Fig. 3 E
MOUTHOUMET
Salvezines
AGLY
Bessedes
Boucheville Basin
NPF : North Pyrenean Fault
Perpignan
Mediterranean Sea
N
Prades
AXIAL ZONE
AXIAL ZONE
L'HOSPITALET
PALLARS
X
ASPRES
CANIGOU
ALBERES
L : étang de Lherz
FTR : Fontête Rouge
F : Freychinède
SS : Suc et Sentenac
B : Bestiac
C : Caussou
P : Prades
S-type (sedimented) lherzolite bodies
Paleozic basement
lower crust exposures (including granulites)
Post-Herycinian sediments
B
SSW
NNE
X
Gavarnie thrust
Pyrenean Axial Zone
Bassies granite
N-Pyrenean fault
N-Pyrenean zone
Aulus basin
Trois-Seigneurs massif
Tarascon basin
Arize massif
Camarade basin
N-Pyrenean frontal thrust
Y
Lherz
km
0
5
10
km
0
5
10
dtch
dtch
10 km
1
2
b
a
3
4
5
b
a
6
6'
7
dtch : Albian detachment fault

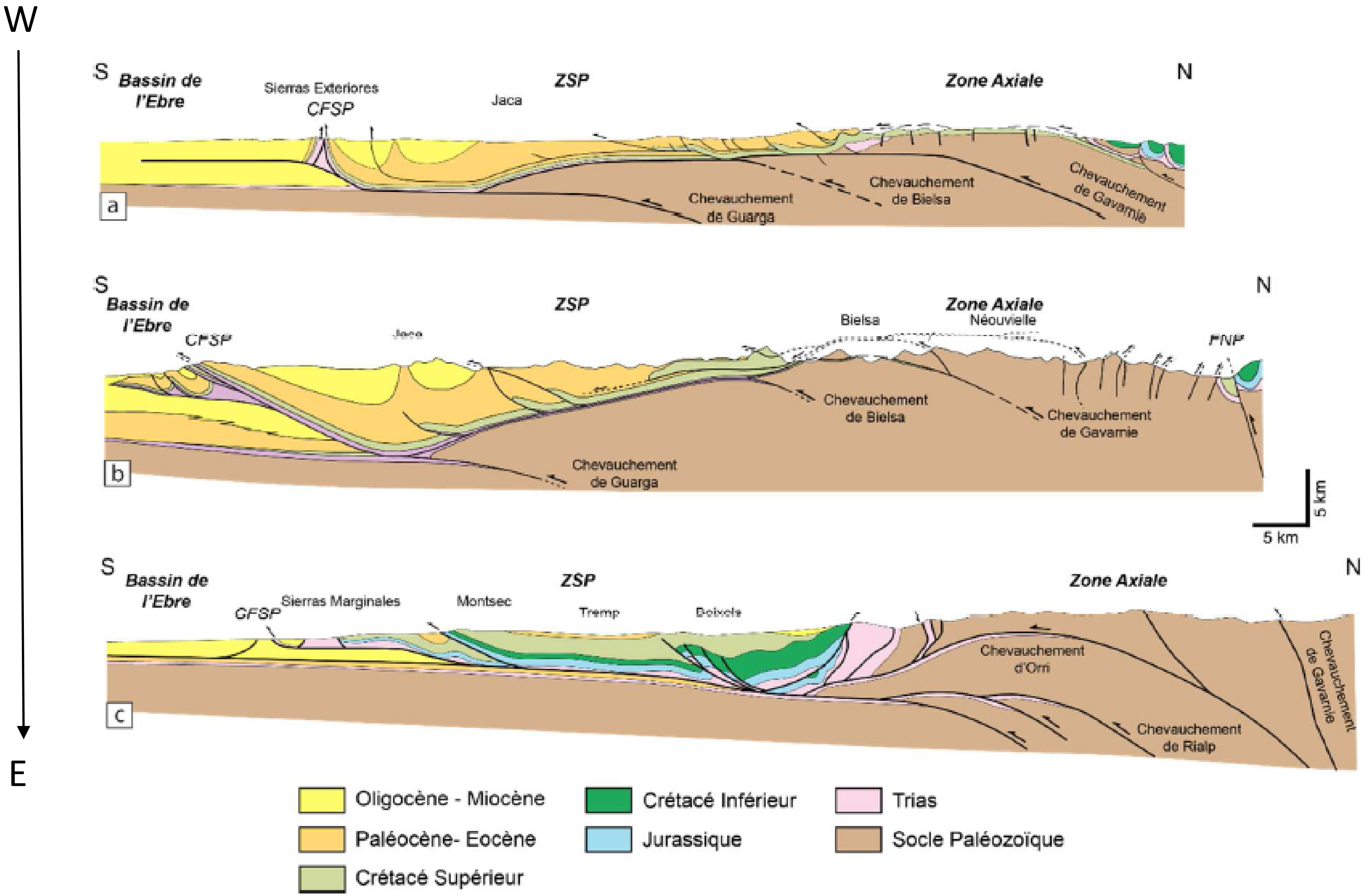
(Lagabrielle et al., 2010)

(Lagabrielle et al., 2010)

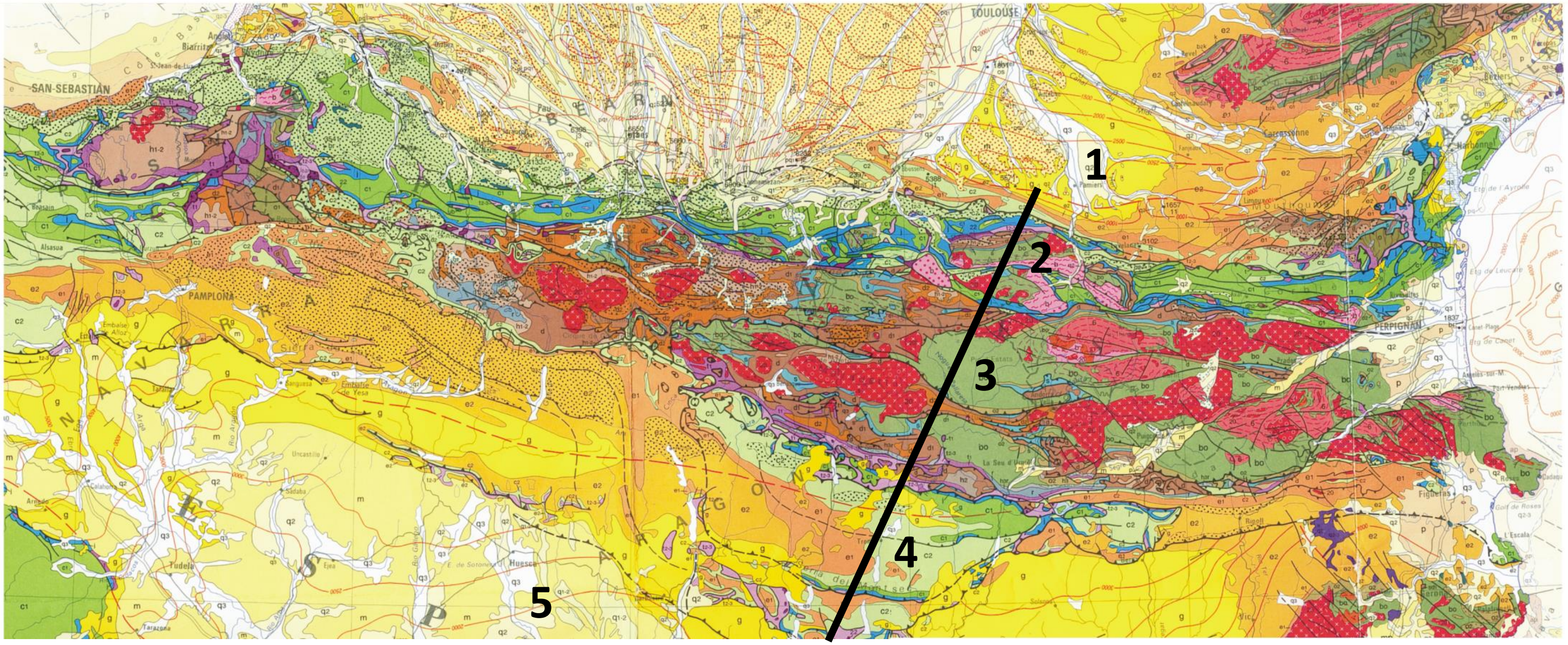

section fig. 5
N
1
2
3
4
t1
5
6
7
Pau
section fig. 8
North-Pyrenean foreland basin
Tarbes
Labourd
Mauléon
Oloron
North-Pyrenean frontal thrust
fig. 6
Lourdes
Arbailles
Mendibelza
Igounze
Chaînons béarnais
t1
Eaux Chaudes thrust
Pyrenean Axial Zone
Pamplona
South-Pyrenean foreland basin
Gavarnie thrust
10 km

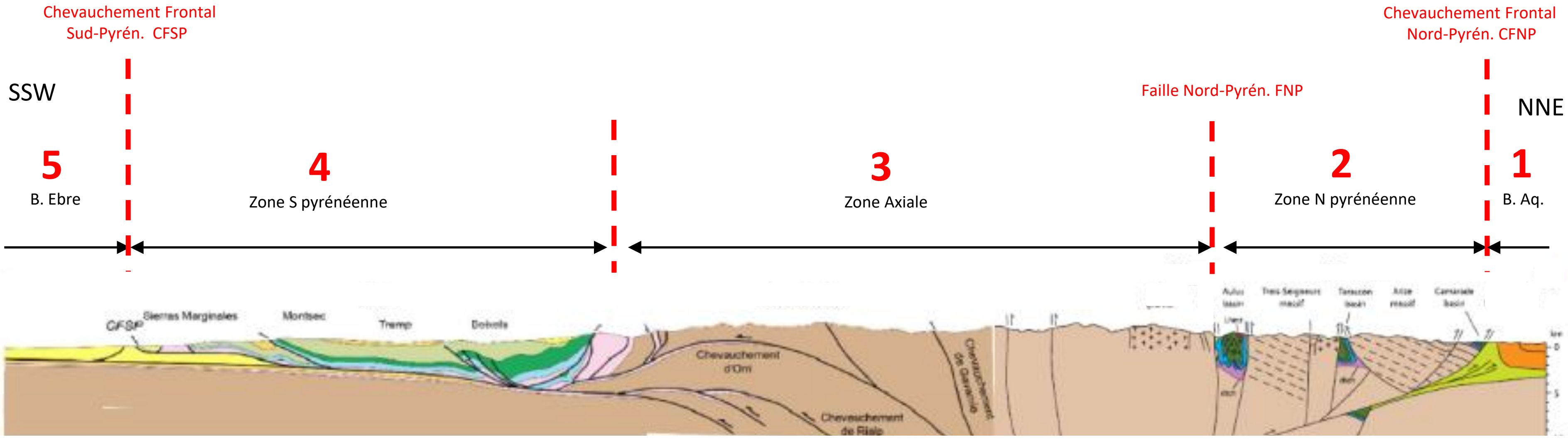
~ COUPE A


SSW
NNE
Axial Zone
Lakoura thrust
"Chaînons Béarnais"
North-Pyrenean frontal thrust
Pau anticline
Lacq anticline
Audignon ridge
km
0
5
10
inverted southern margin of Albian basin
Gavarnie thrust
Grand-Rieu high
1
2
3
4
5
6
10 km


W
E
S
Bassin de l'Ebre
Sierras Exteriores
CFSP
Jaca
ZSP
Zone Axiale
N
a
Chevauchement de Guarga
Chevauchement de Bielsa
Chevauchement de Gavarnie
S
Bassin de l'Ebre
CFSP
Jaca
ZSP
Bielsa
Zone Axiale
Néouvielle
N
FNP
b
Chevauchement de Bielsa
Chevauchement de Gavarnie
Chevauchement de Guarga
5 km
5 km
S
Bassin de l'Ebre
CFSP
Sierras Marginales
Montsec
ZSP
Tremp
Boixols
Zone Axiale
N
c
Chevauchement d'Orri
Chevauchement de Rialp
Chevauchement de Gavarnie
Oligocène - Miocène
Paléocène- Eocène
Crétacé Supérieur
Crétacé Inférieur
Jurassique
Trias
Socle Paléozoïque

(D'après Teixell)


TOULOUSE
SAN-SEBASTIAN
PAMPLONA
PERPIGNAN
Huesca
1
2
3
4
5



Chevauchement Frontal Sud-Pyrén. CFSP

Chevauchement Frontal Nord-Pyrén. CFNP

Faille Nord-Pyrén. FNP

SSW

NNE

5 B. Ebre

4 Zone S pyrénéenne

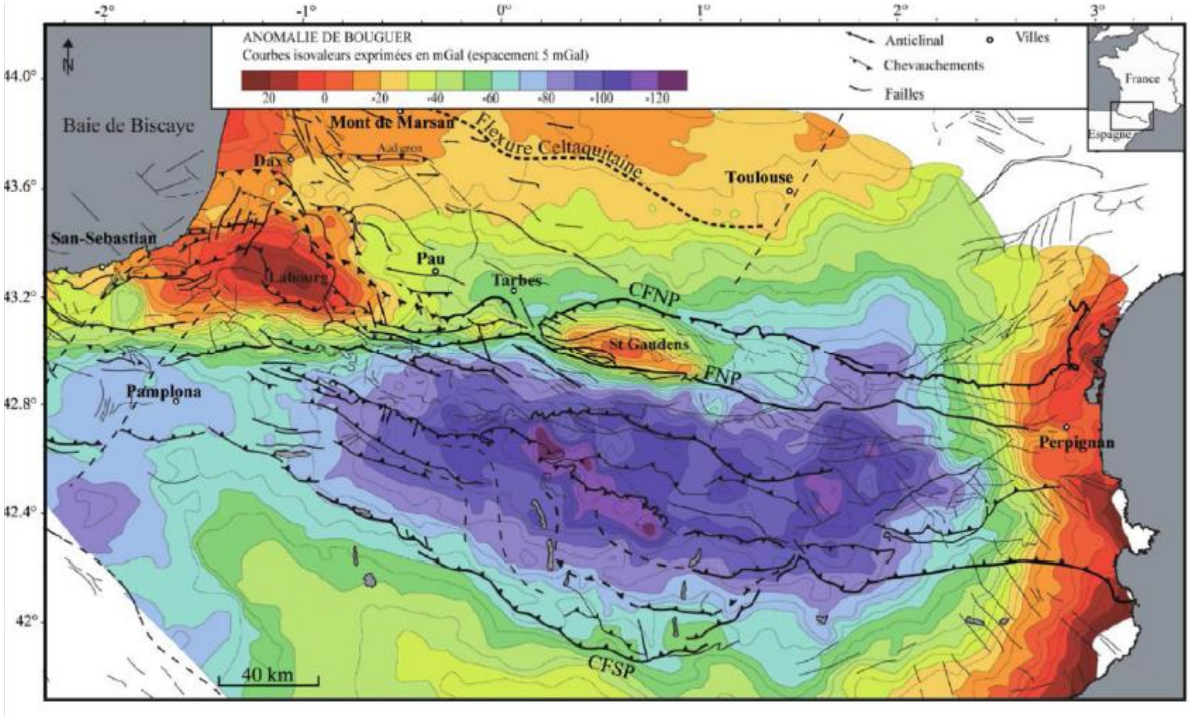
3 Zone Axiale

2 Zone N pyrénéenne

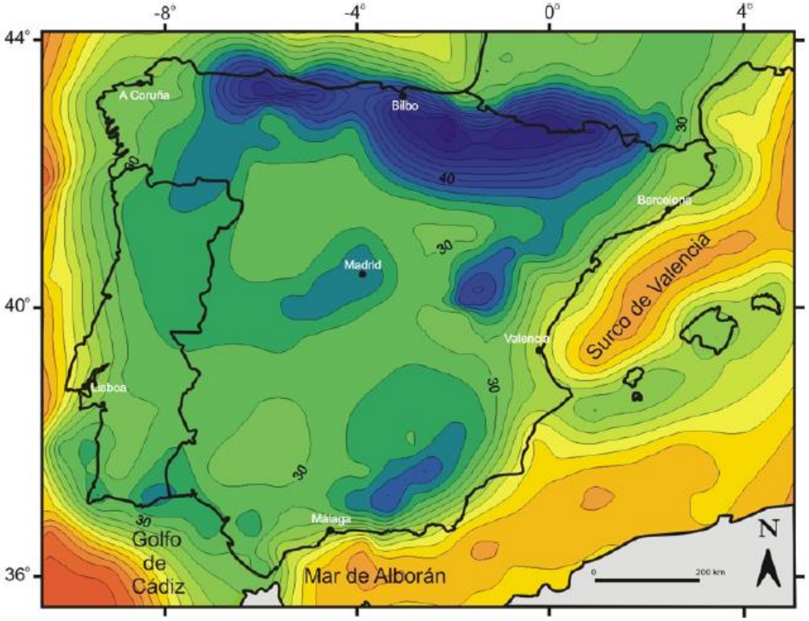
1 B. Aq.

CFSP
Sierras Marginales
Montsec
Tremp
Boixols
Chevauchement d'Orri
Chevauchement de Gavarnie
Chevauchement de Rialp
Aulus basin
Trois Seigneurs massif
Tarascon basin
Arize massif
Camarade basin
km
0
5

B. La structure profonde vue par la géophysique

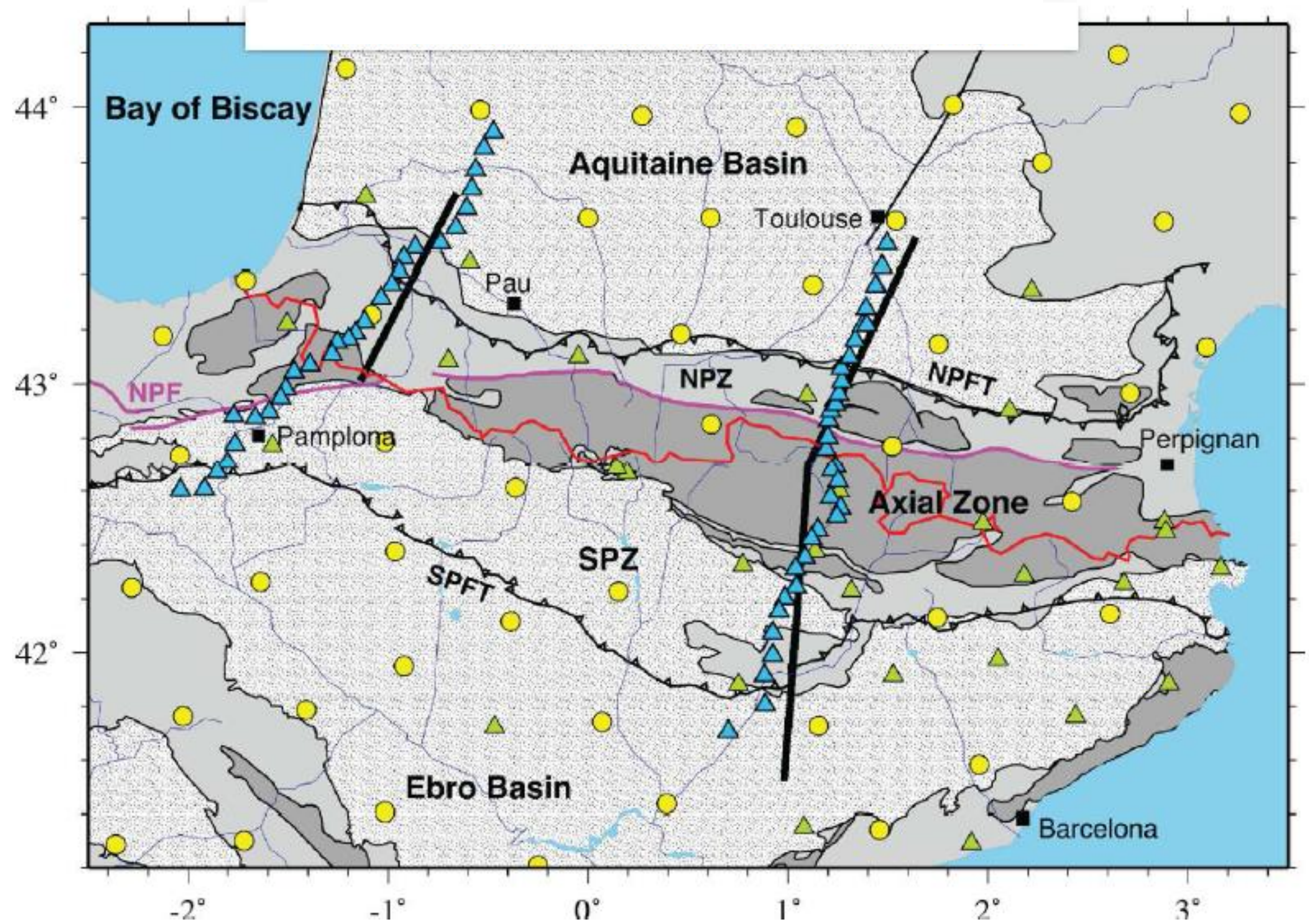

ANOMALIE DE BOUGUER
Courbes isovaleurs exprimées en mGal (espacement 5 mGal)
20
0
-20
-40
-60
-80
-100
-120
Anticlinal
Chevauchements
Failles
Villes
France
Espagne
-2°
-1°
0°
1°
2°
3°
44.0°
43.6°
43.2°
42.8°
42.4°
42°
Baie de Biscaye
Mont de Marsan
Dax
Audignon
Flexure Celtaquitaine
Toulouse
San-Sebastian
Labourd
Pau
Tarbes
CFNP
St Gaudens
FNP
Pamplona
Perpignan
CFSP
40 km

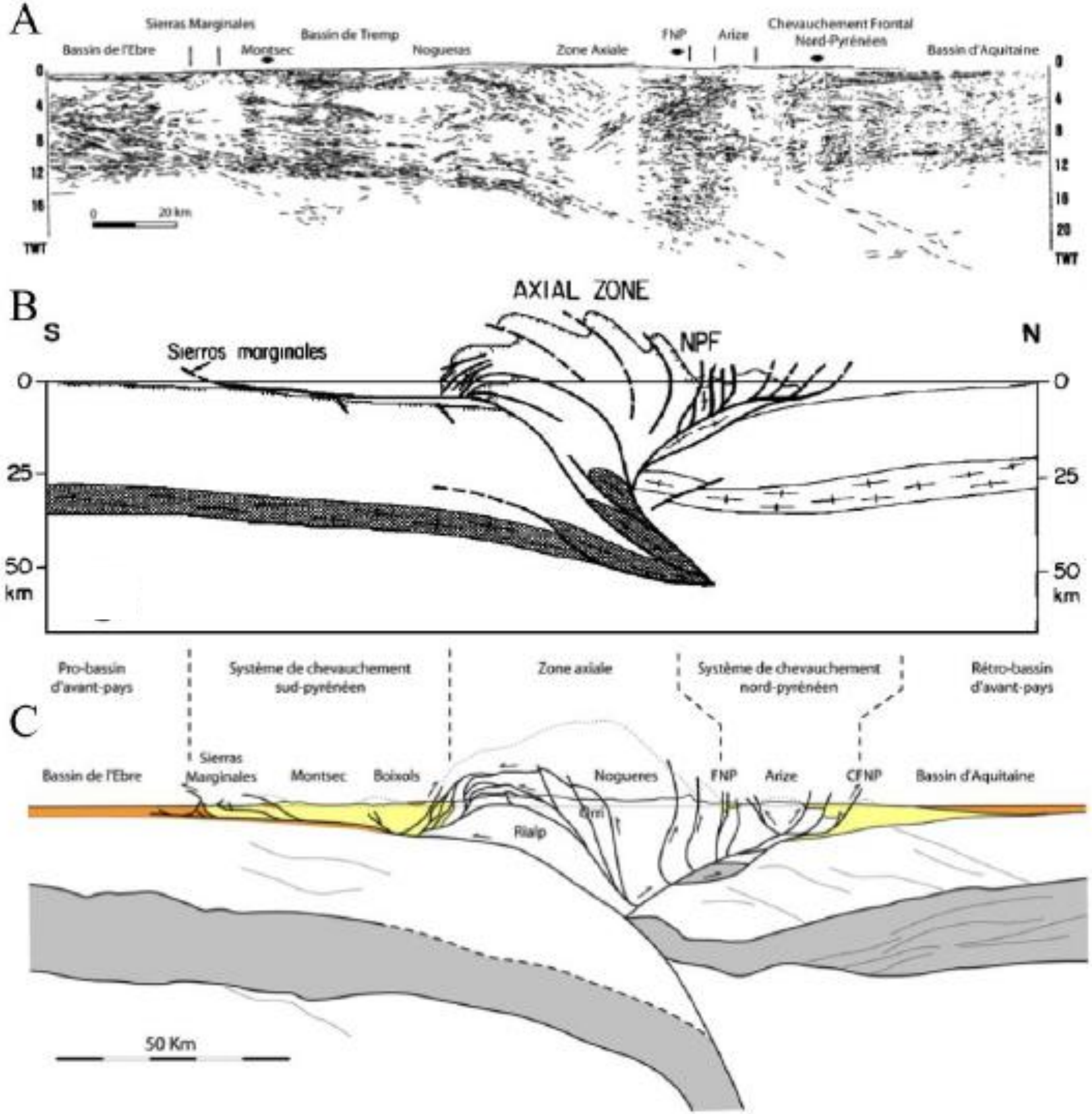
Carte de l'anomalie de Bouguer
dans les Pyrénées


-8°
-4°
0°
4°
44°
40°
36°
A Coruña
Bilbo
Barcelona
Madrid
Valencia
Lisboa
Málaga
Surco de Valencia
Golfo de Cádiz
Mar de Alborán
40
30
N
0
200 km

Carte de la profondeur du Moho
sous l'Ibérie et les Pyrénées

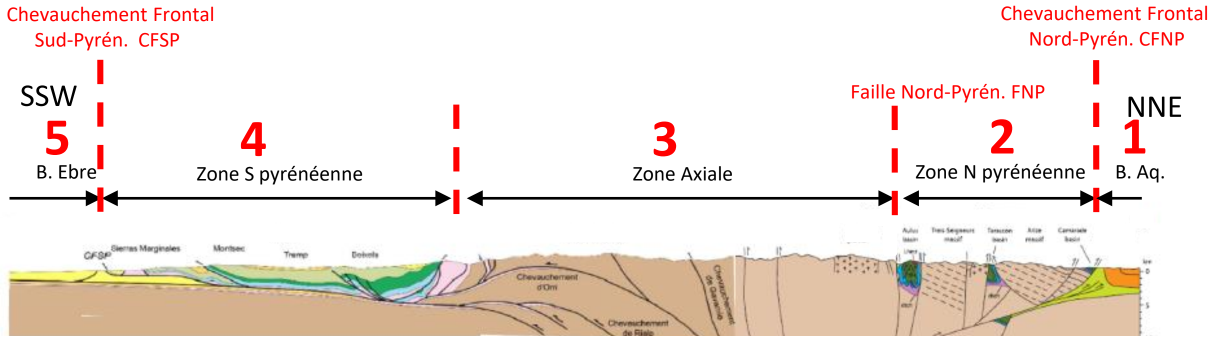
(Vera, 2004)

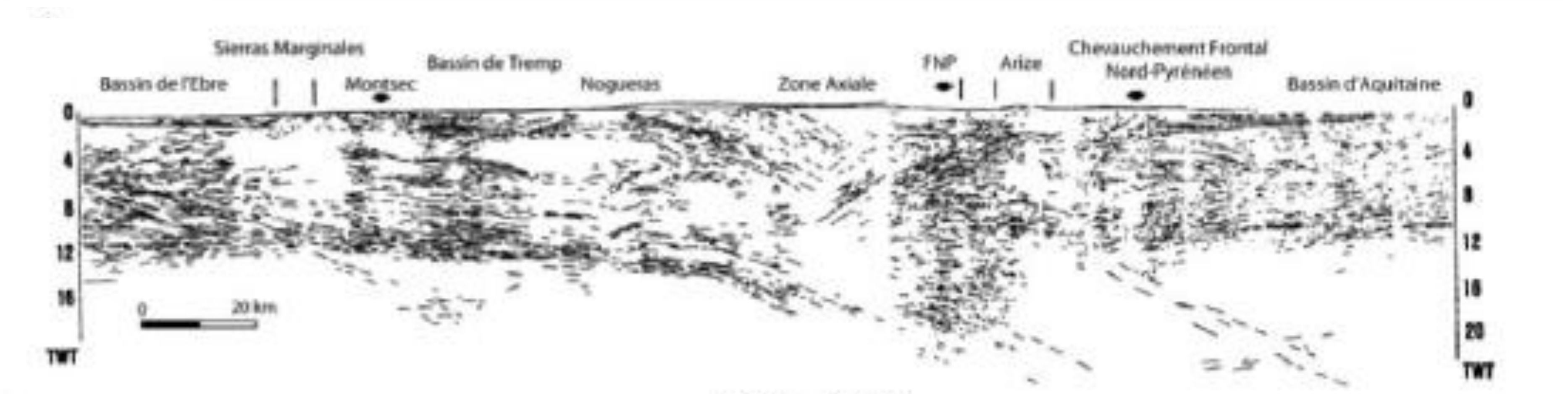

44°
43°
42°
-2°
-1°
0°
1°
2°
3°
Bay of Biscay
Aquitaine Basin
Toulouse
Pau
NPF
NPZ
NPFT
Pamplona
Perpignan
Axial Zone
SPZ
SPFT
Ebro Basin
Barcelona

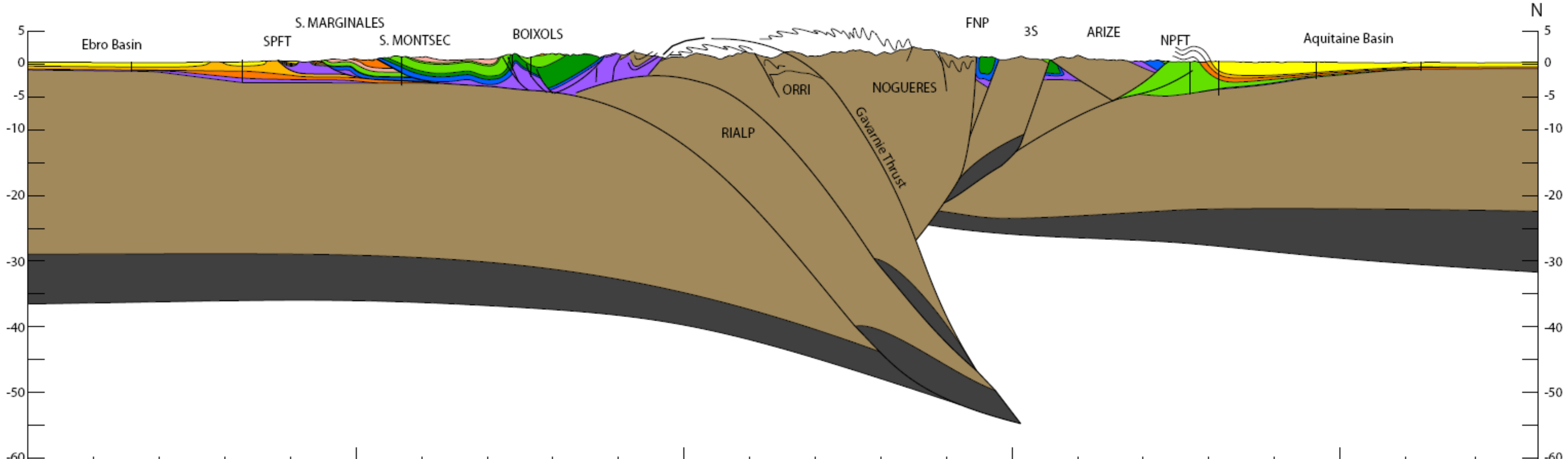

A
Sierras Marginales
Bassin de l'Ebre
Montsec
Bassin de Tremp
Nogueras
Zone Axiale
FNP
Arize
Chevauchement Frontal Nord-Pyrénéen
Bassin d'Aquitaine
0
4
8
12
16
TWT
0
4
8
12
16
20
TWT
0
20 km
B
S
N
AXIAL ZONE
Sierros morginoles
NPF
0
25
50
km
0
25
50
km
Pro-bassin d'avant-pays
Système de chevauchement sud-pyrénéen
Zone axiale
Système de chevauchement nord-pyrénéen
Rétro-bassin d'avant-pays
C
Bassin de l'Ebre
Sierras Marginales
Montsec
Boixols
Nogueres
FNP
Arize
CFNP
Bassin d'Aquitaine
Rialp
Orri
50 Km

According to *Roure et al.* [1989], the deep Iberian crust is currently stacked beneath the axial zone, while *Munoz* [1992] favors continental subduction, with a minimum of 65 km of lower crust that has disappeared beneath the European crust, together with the Iberian lithospheric mantle.

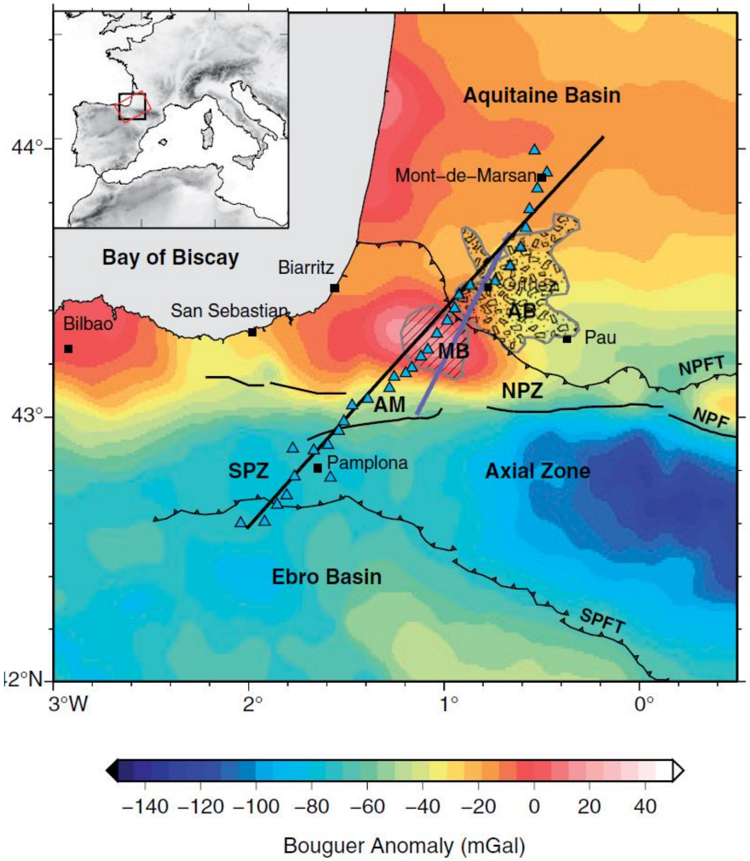
These two extreme models represent two possible interpretations of the ECORS seismic profile beneath the axial zone, simply because seismic reflectors in the deeper levels of the crust are poorly resolved.

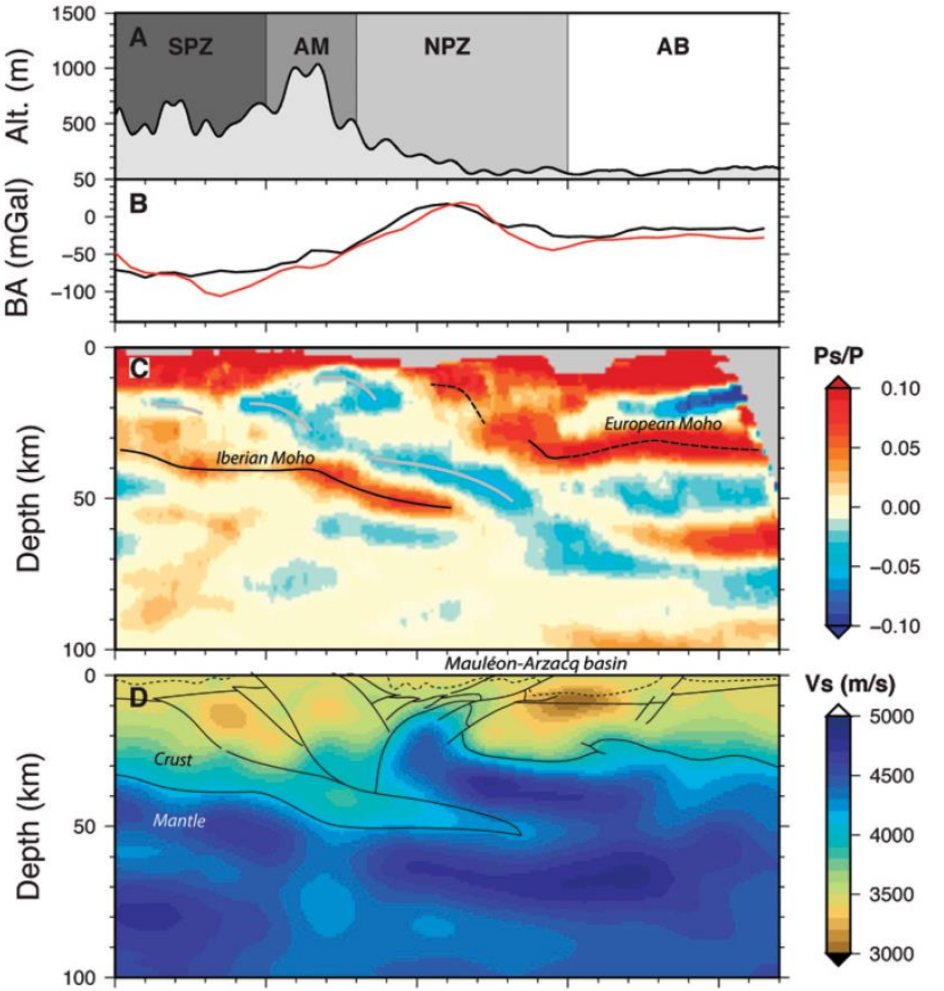

Chevauchement Frontal
Sud-Pyrén. CFSP
Chevauchement Frontal
Nord-Pyrén. CFNP
Faille Nord-Pyrén. FNP
SSW
NNE
5
B. Ebre
4
Zone S pyrénéenne
3
Zone Axiale
2
Zone N pyrénéenne
1
B. Aq.
CFSP
Sierras Marginales
Montsec
Tremp
Boixols
Chevauchement d'Orri
Chevauchement de Gavarnie
Chevauchement de Rialp

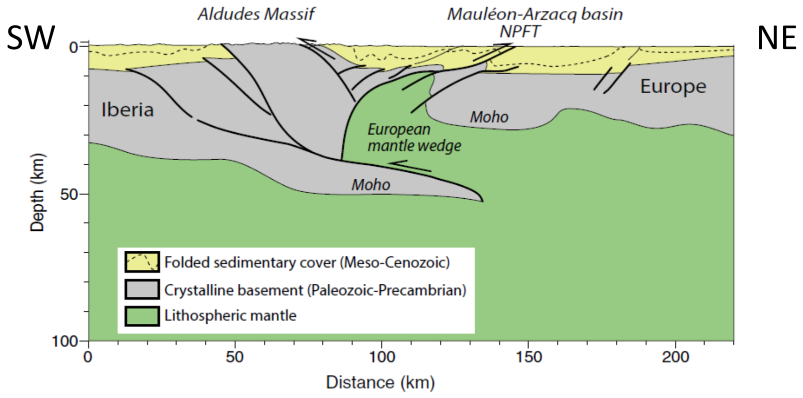

Sierras Marginales
Bassin de l'Ebre
Montsec
Bassin de Tremp
Nogueras
Zone Axiale
FNP
Arize
Chevauchement Frontal
Nord-Pyrénéen
Bassin d'Aquitaine
0
4
8
12
16
20
0
20 km
TWT
TWT


N
Ebro Basin
SPFT
S. MARGINALES
S. MONTSEC
BOIXOLS
ORRI
NOGUERES
RIALP
Gavarnie Thrust
FNP
3S
ARIZE
NPFT
Aquitaine Basin
5
0
-5
-10
-20
-30
-40
-50
-60

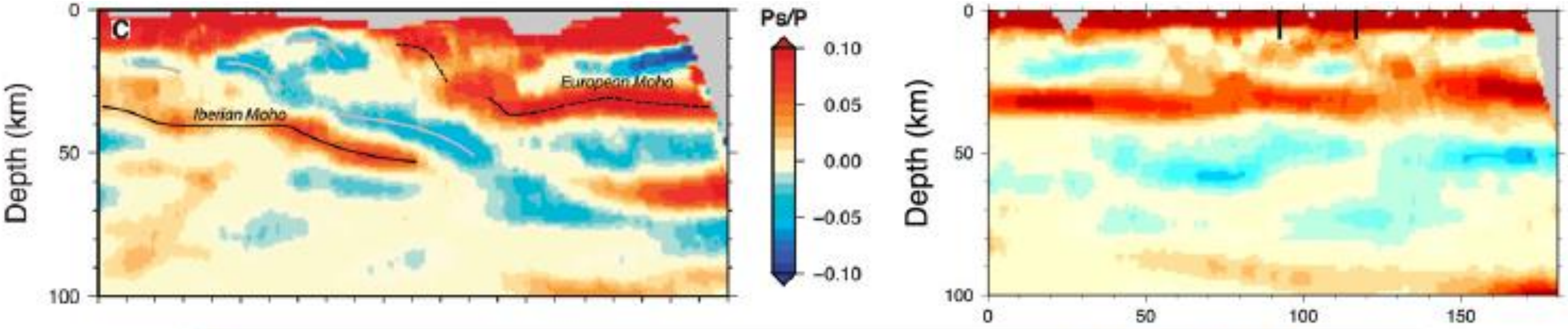
La méthode dite des "fonctions récepteur" (*receiver function* en anglais) est basée sur l'étude des ondes *P* converties en *S* aux différentes interfaces sous une station sismologique. Elle permet notamment d'imager les interfaces majeures de la lithosphère et du manteau terrestre (Moho, discontinuités à 410 et 660km, ...). Pour la lithosphère, la méthode des fonctions récepteur permet de déterminer la profondeur du Moho et la valeur du rapport *VP/VS*.


Aquitaine Basin
Mont–de–Marsan
Bay of Biscay
Biarritz
San Sebastian
Bilbao
AB
MB
Pau
NPFT
NPZ
NPF
AM
Pamplona
SPZ
Axial Zone
Ebro Basin
SPFT
44°
43°
42°N
3°W
2°
1°
0°
−140 −120 −100 −80 −60 −40 −20 0 20 40
Bouguer Anomaly (mGal)

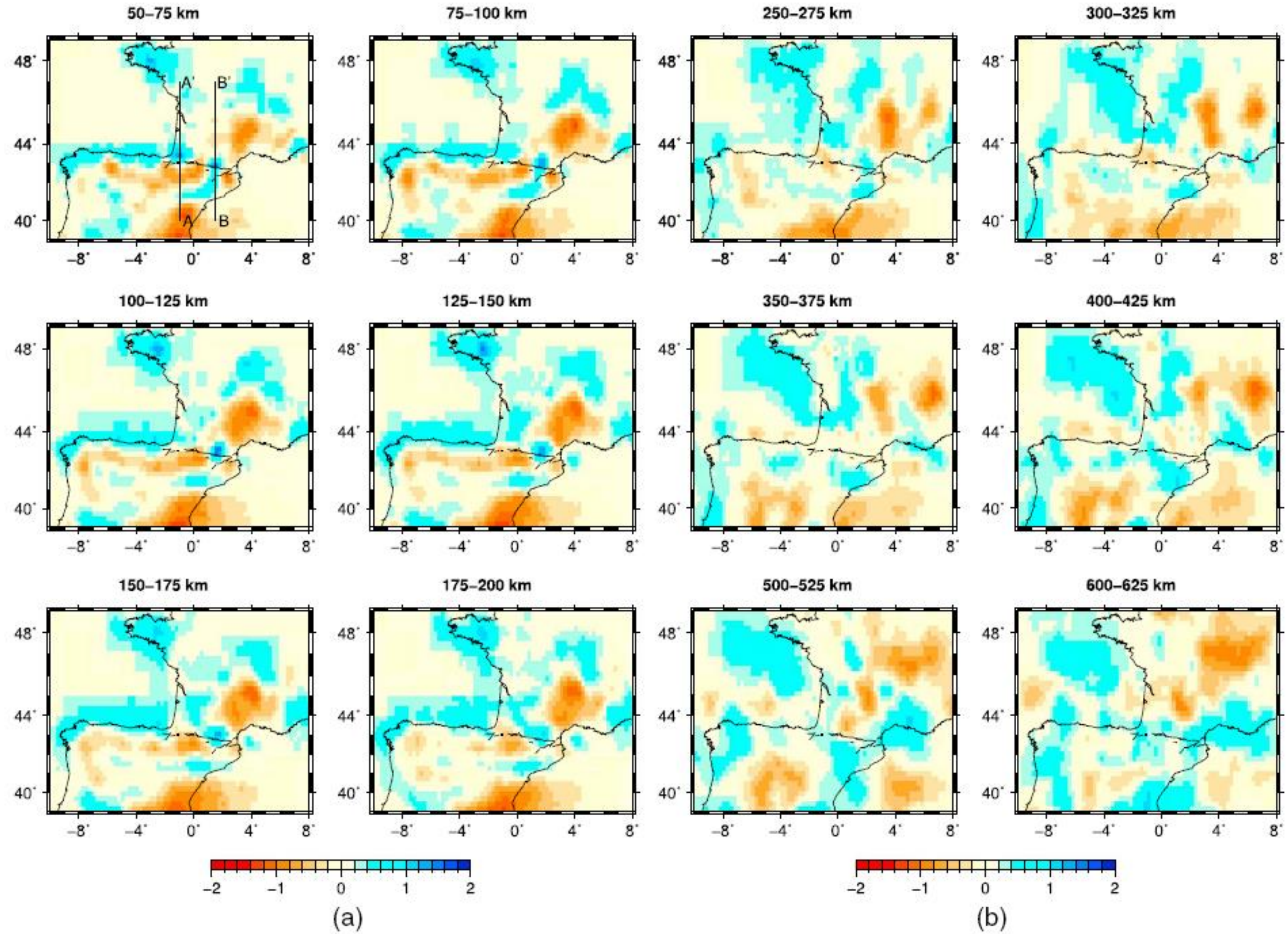



SW
NE
Aldudes Massif
Mauléon-Arzacq basin
NPFT
Iberia
Europe
Moho
European mantle wedge
Moho
Depth (km)
0
50
100
0
50
100
150
200
Distance (km)
Folded sedimentary cover (Meso-Cenozoic)
Crystalline basement (Paleozoic-Precambrian)
Lithospheric mantle

(Wang et al., 2016)

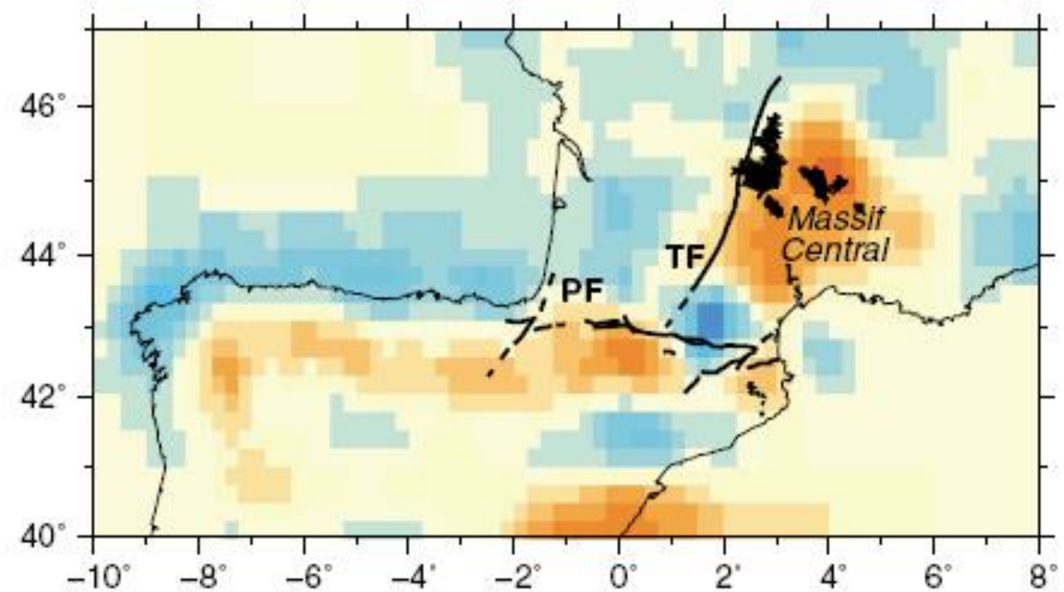


The « orogenic » geometry seen in the west and centre is totally lost in the east


50–75 km
75–100 km
250–275 km
300–325 km
100–125 km
125–150 km
350–375 km
400–425 km
150–175 km
175–200 km
500–525 km
600–625 km
48˚
44˚
40˚
−8˚
−4˚
0˚
4˚
8˚
A'
B'
A
B
−2
−1
0
1
2
(a)
(b)

. (a) Map views of the *P* velocity model obtained after crustal corrections at 50, 75, 100, 125, 150, and 175 km depth. (b) Map views of the model for *P* velocity anomalies at 250, 300, 350, 400, 500, and 600 km depth. The color scale, in percents with respect to the ak135 reference Earth model, is the same in all the plots.

(Chevrot et al., 2014)



Map of *P* velocity anomalies between 125 and 150 km depth. The volcanic regions are the black shaded domains. The main faults in the Pyrenees are drawn with thin black solid lines while the Pamplona (PF) and Toulouse (TF) faults are drawn with thick black dashed lines.

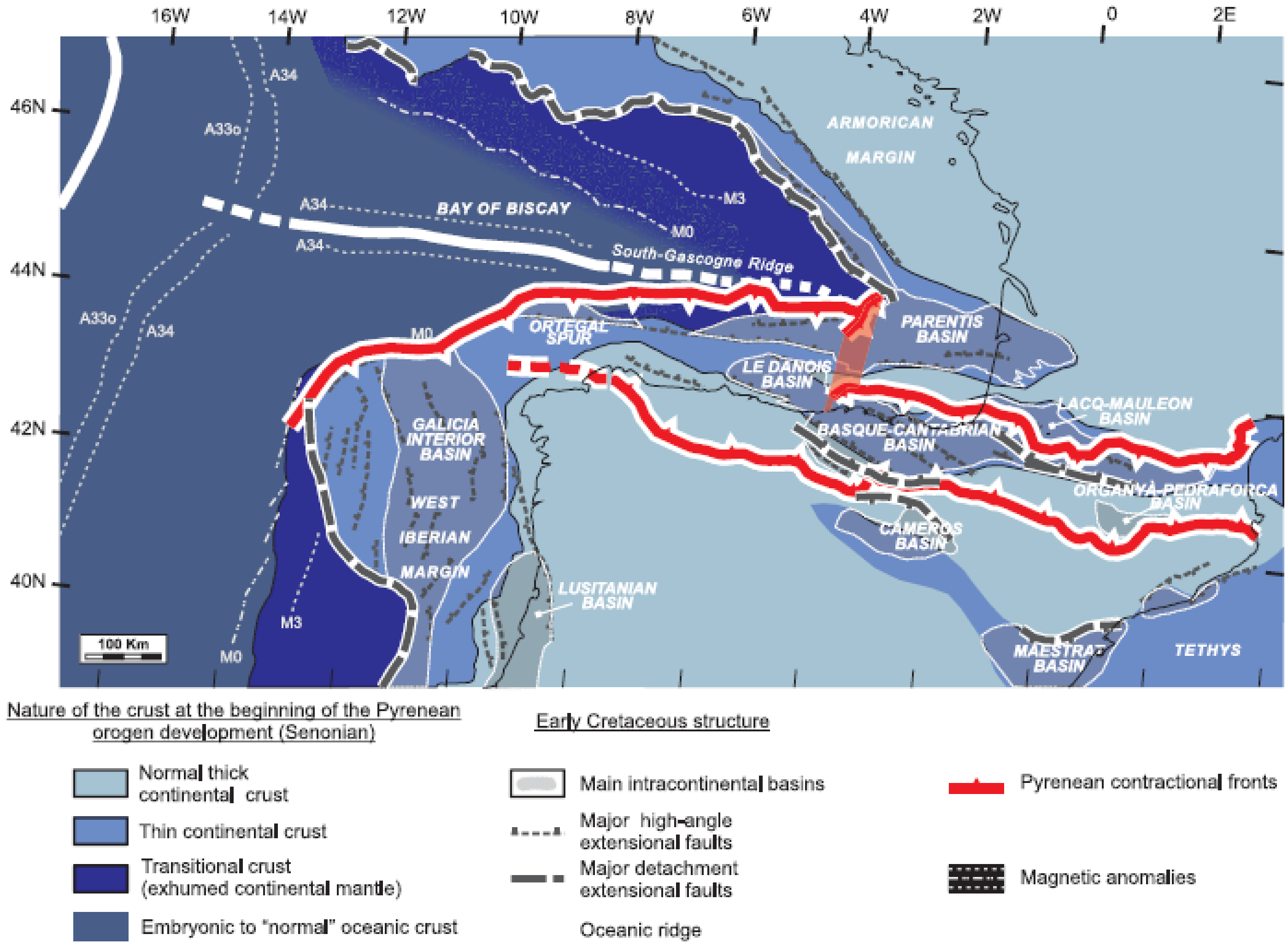
Along-strike variations of the deep architecture of the Pyrenean domain : lithospheric structures appear clearly segmented).

Absence of a deep pronounced high-velocity anomaly in the upper mantle and transition zone, which seems to rule out the presence of a detached oceanic lithosphere beneath the European plate.

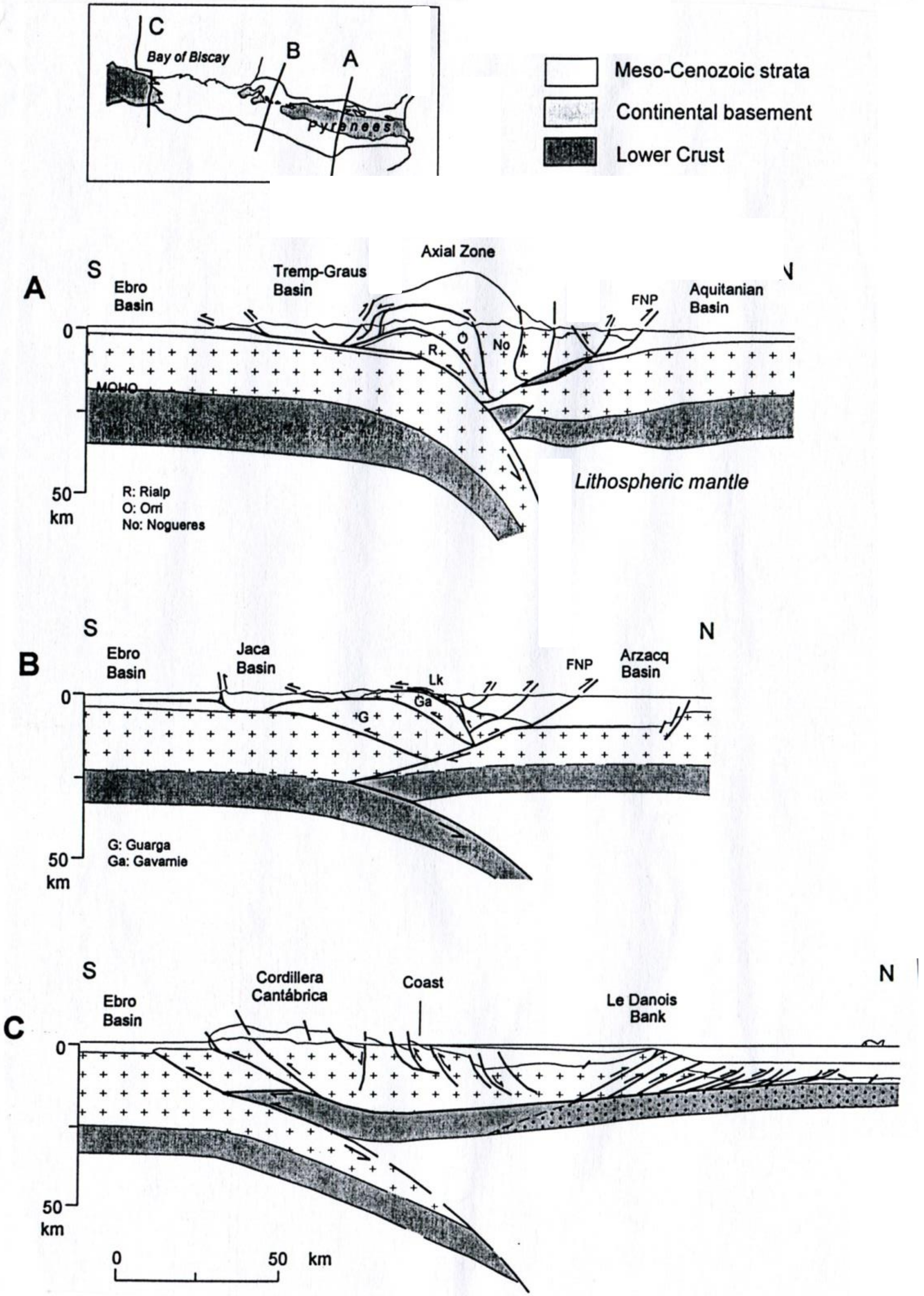
Crust and mantle lithosphere show similar offsets across the Pamplona fault, which suggests that it is a major transfer zone that affects the whole lithosphere.
Major inherited Hercynian faults controlled and localized the deformation during both the extensional rifting episode and the convergence.

Little coherence between deep lithospheric structures beneath the Pyrenees and the trace of the North Pyrenean Fault at the surface

(Chevrot et al., 2014)

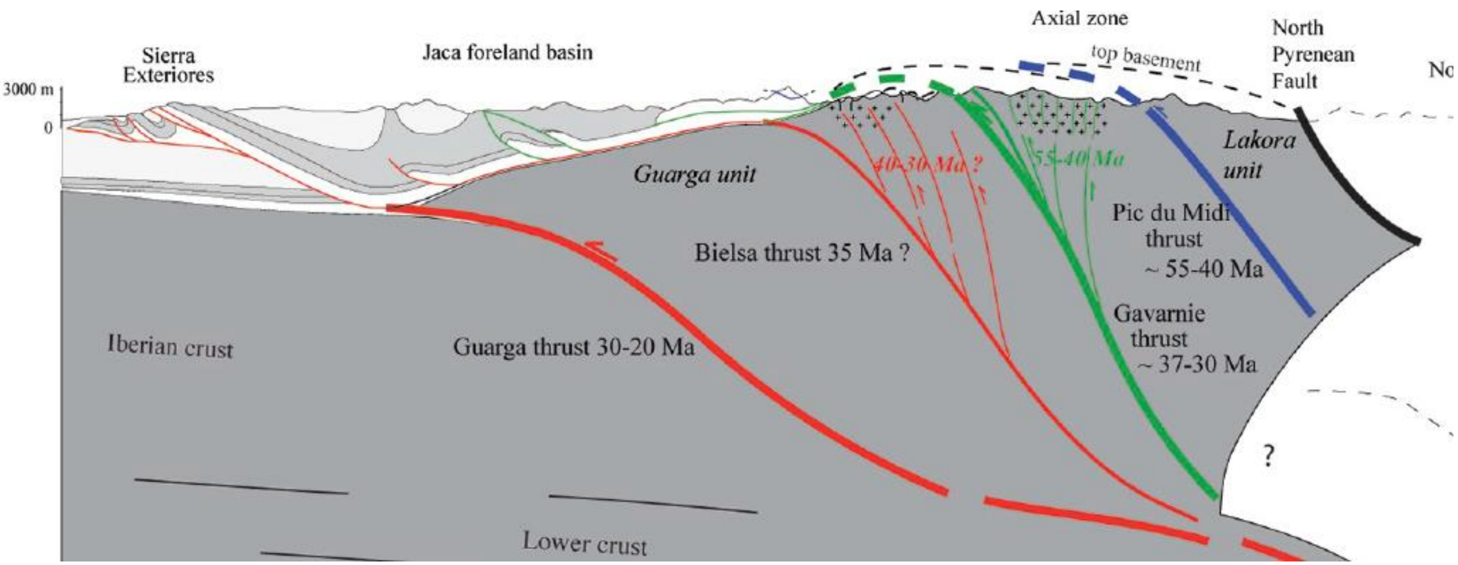

16W
14W
12W
10W
8W
6W
4W
2W
0
2E
46N
44N
42N
40N
A34
A33o
A34
A34
A33o
A34
M3
M0
M0
M3
M0
BAY OF BISCAY
South-Gascogne Ridge
ARMORICAN MARGIN
PARENTIS BASIN
ORTEGAL SPUR
LE DANOIS BASIN
LACQ-MAULEON BASIN
BASQUE-CANTABRIAN BASIN
GALICIA INTERIOR BASIN
WEST IBERIAN MARGIN
ORGANYÀ-PEDRAFORCA BASIN
CAMEROS BASIN
LUSITANIAN BASIN
MAESTRAT BASIN
TETHYS
100 Km
Nature of the crust at the beginning of the Pyrenean orogen development (Senonian)
Normal thick continental crust
Thin continental crust
Transitional crust (exhumed continental mantle)
Embryonic to "normal" oceanic crust
Early Cretaceous structure
Main intracontinental basins
Major high-angle extensional faults
Major detachment extensional faults
Oceanic ridge
Pyrenean contractional fronts
Magnetic anomalies

Carte du Golfe de Gascogne, des Pyrénées et des zones adjacentes illustrant les relations entre les structures compressives pyrénéennes et le système extensif développé entre l'Ibérie et l'Eurasie au Crétacé inférieur (Roca et al.*, 2011). La position des anomalies magnétiques est donnée par Sibuet* et al. *(2004). Les limites entre le domaine océanique, transitionnel et continental dans l'Atlantique et le Golfe de Gascogne sont basées sur les travaux de Thinon (1999), Tucholke* et al. *(2007) et Jammes* et al. *(2009).*

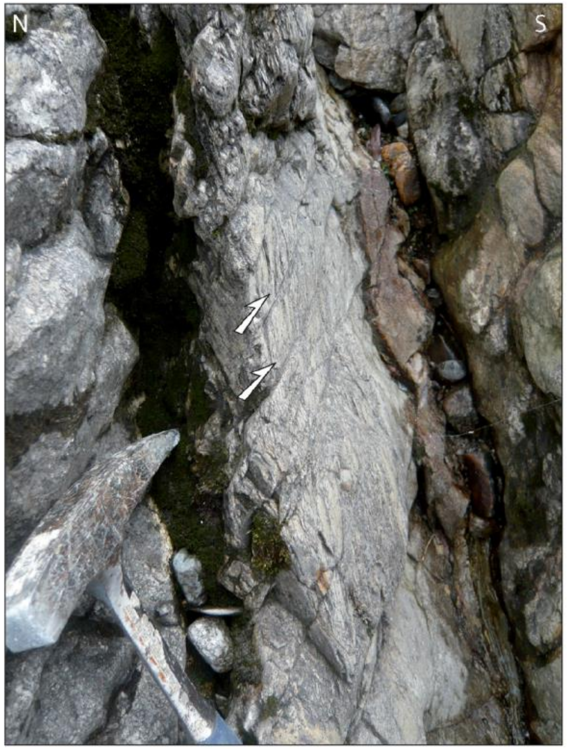

C
Bay of Biscay
B
A
Pyrenees
Meso-Cenozoic strata
Continental basement
Lower Crust
A
S
Ebro Basin
Tremp-Graus Basin
Axial Zone
N
FNP
Aquitanian Basin
0
R
O
No
MOHO
Lithospheric mantle
50
km
R: Rialp
O: Orri
No: Nogueres
B
S
Ebro Basin
Jaca Basin
Lk
Ga
G
FNP
Arzacq Basin
N
0
50
km
G: Guarga
Ga: Gavarnie
C
S
Ebro Basin
Cordillera Cantábrica
Coast
Le Danois Bank
N
0
50
km
0
50 km

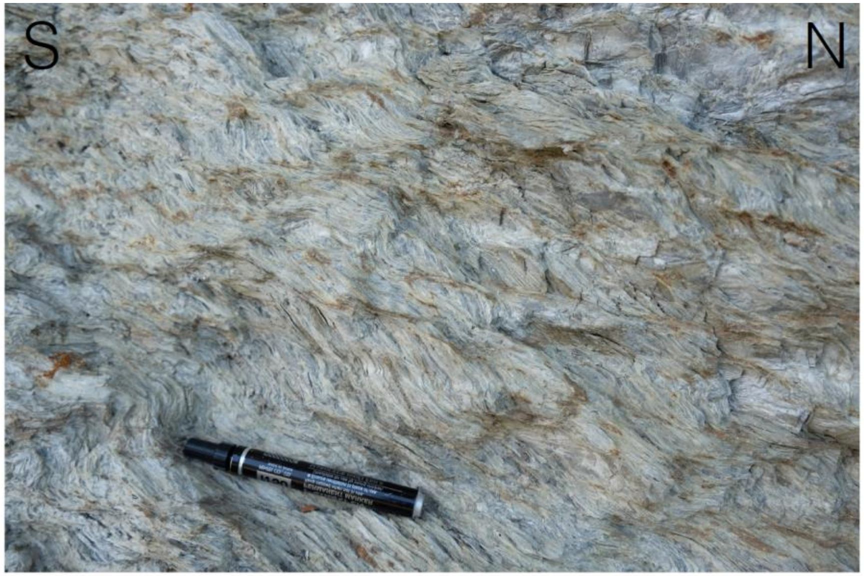
C. Une absence totale d’ophiolites

D. Un métamorphisme orogénique MP-MT « collisionnel » d'âge éocène dans la Zone Axiale, mais une absence totale de métamorphisme HP-BT et de magmatisme orogénique (type subduction)


Sierra Exteriores
Jaca foreland basin
Axial zone
top basement
North Pyrenean Fault
No
3000 m
0
Guarga unit
40-30 Ma ?
55-40 Ma
Lakora unit
Pic du Midi thrust ~ 55-40 Ma
Bielsa thrust 35 Ma ?
Gavarnie thrust ~ 37-30 Ma
Iberian crust
Guarga thrust 30-20 Ma
?
Lower crust

Cisaillements cassants/ductiles dans le socle de la Zone Axiale, ~3kb-300°C, facies Schistes Verts, ~55-35 Ma



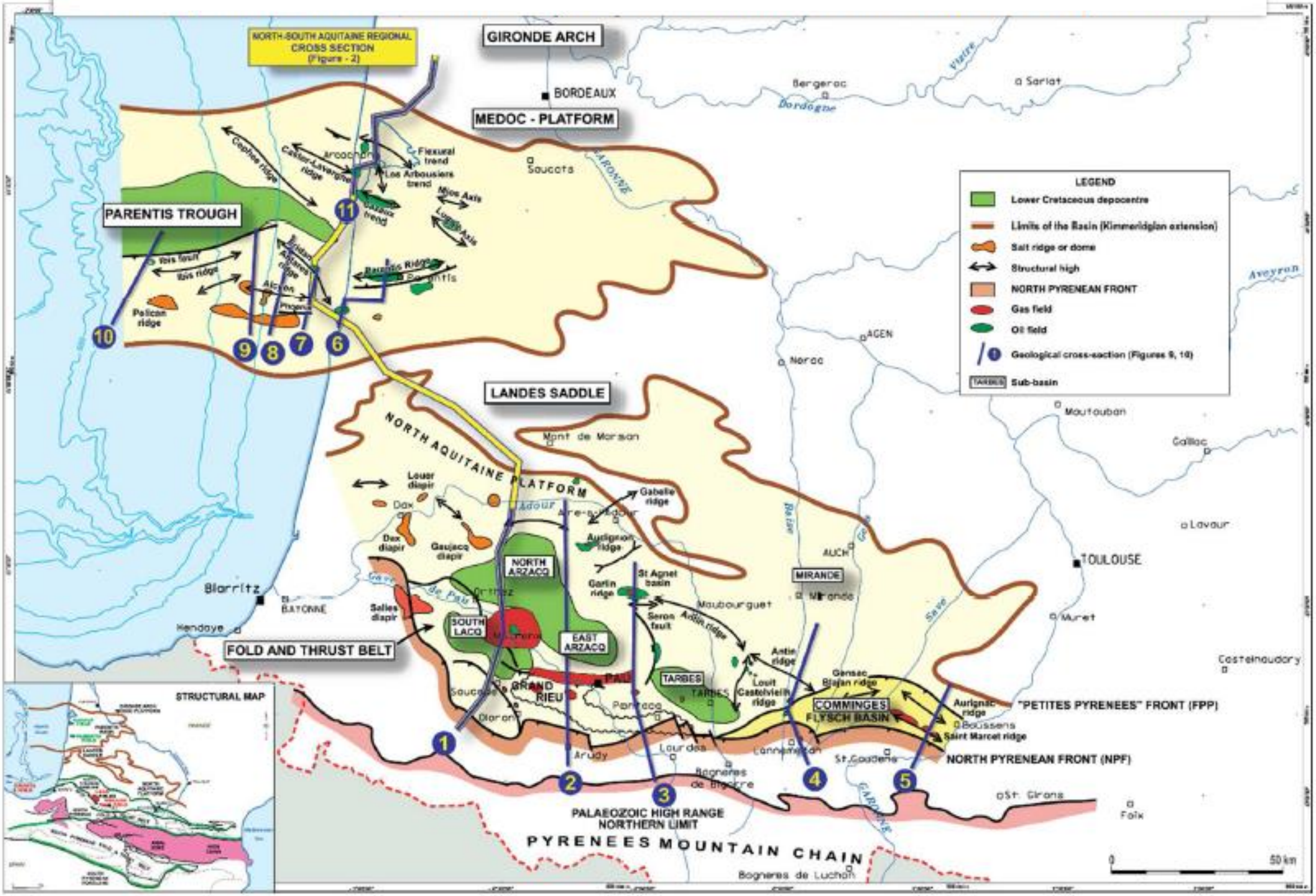


Photos
N. Bellahsen

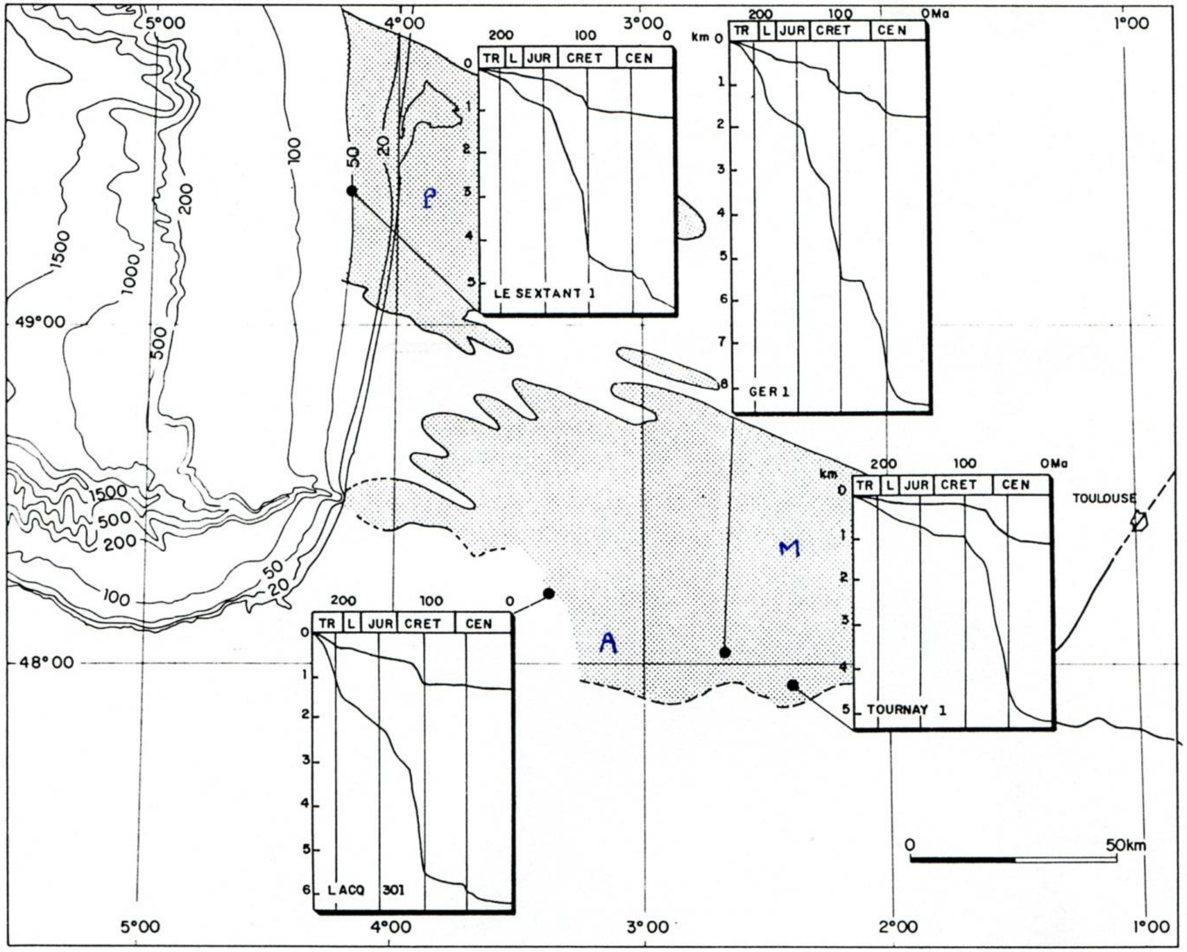
II. Le domaine pyrénéen : une structure résultant de l'inversion d'un rift non océanisé

A. Les données géologiques

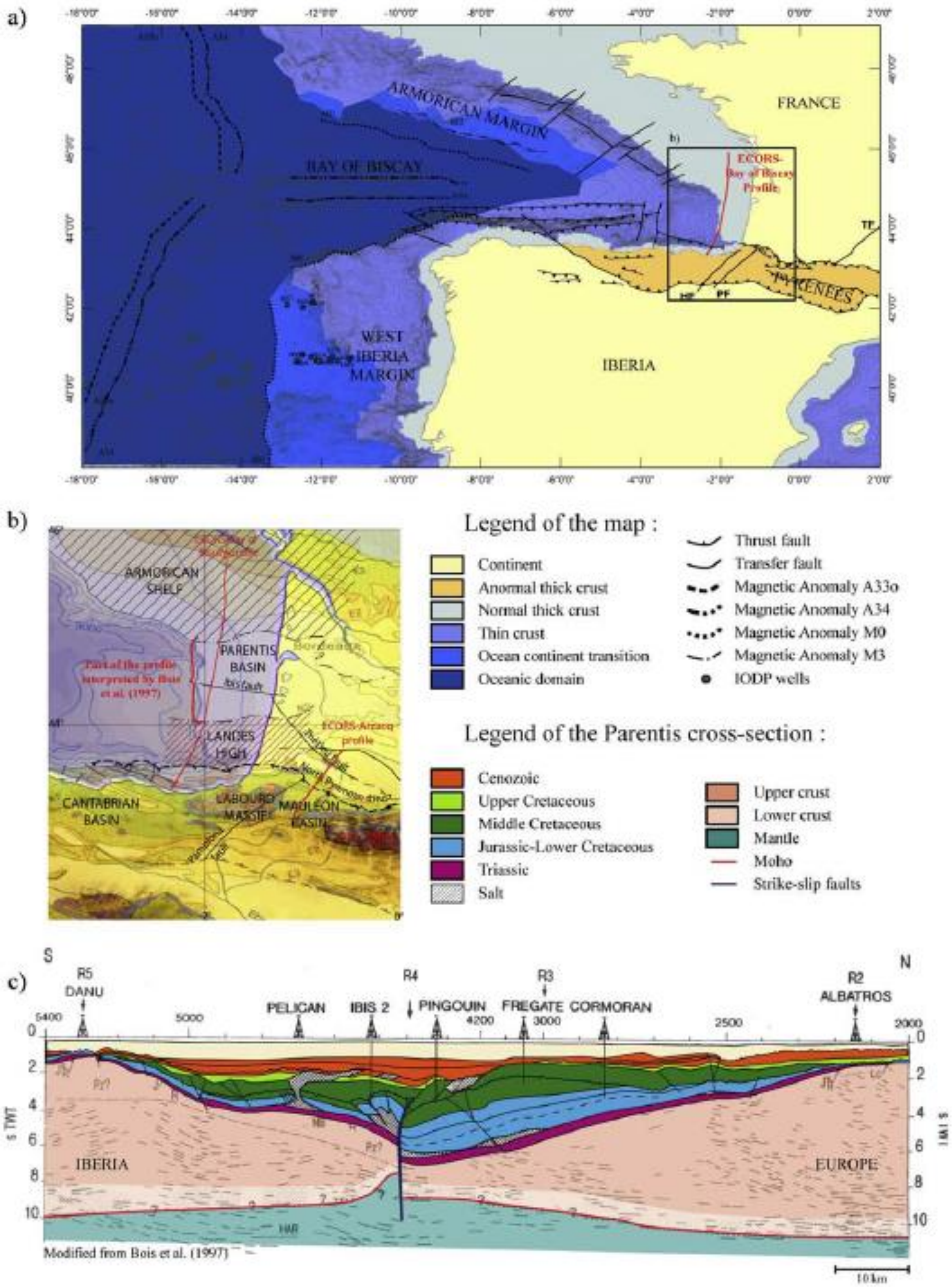
La distension jurassique


NORTH-SOUTH AQUITAINE REGIONAL CROSS SECTION (Figure - 2)
GIRONDE ARCH
BORDEAUX
MEDOC - PLATFORM
PARENTIS TROUGH
LANDES SADDLE
NORTH AQUITAINE PLATFORM
FOLD AND THRUST BELT
PALAEOZOIC HIGH RANGE NORTHERN LIMIT
PYRENEES MOUNTAIN CHAIN
"PETITES PYRENEES" FRONT (FPP)
NORTH PYRENEAN FRONT (NPF)
COMMINGES FLYSCH BASIN
NORTH ARZACQ
SOUTH LACQ
EAST ARZACQ
GRAND RIEU
TARBES
MIRANDE
Cephee ridge
Castor-Lavergne ridge
Arcachon
Flexural trend
Los Arbousiers trend
Cazaux trend
Mios Axis
Lugos Axis
Ibis fault
Ibis ridge
Pelican ridge
Alcyon
Phoenix
Antares ridge
Parentis Ridge
Parentis
Saucats
Louer diapir
Dax
Dax diapir
Gaujacq diapir
Salies diapir
Gabelle ridge
Aire-sur-Adour
Aurignon ridge
Garlin ridge
St Agnet basin
Seron fault
Antin ridge
Antie ridge
Louit Castelvieilh ridge
Gensac Bajan ridge
Aurignac ridge
Saint Marcet ridge
Orthez
Lacq
PAU
Pontacq
Lourdes
Arudy
Oloron
Sauveterre
Bagneres de Bigorre
Lannemezan
St Gaudens
Boussens
St. Girons
Foix
Bagneres de Luchon
Biarritz
BAYONNE
Hendaye
Mont de Marsan
Moubourguet
Mirande
AUCH
AGEN
Nerac
Montauban
Gaillac
Lavaur
TOULOUSE
Muret
Castelnaudary
Bergerac
Sarlat
Dordogne
Vezere
Aveyron
GARONNE
Adour
Gave de Pau
Baise
Gers
Save
1
2
3
4
5
6
7
8
9
10
11
LEGEND
🟩 Lower Cretaceous depocentre
Limits of the Basin (Kimmeridgian extension)
Salt ridge or dome
↔ Structural high
NORTH PYRENEAN FRONT
Gas field
Oil field
Geological cross-section (Figures 9, 10)
TARBES Sub-basin
STRUCTURAL MAP
0
50 km

(D’après Boillot et al.)

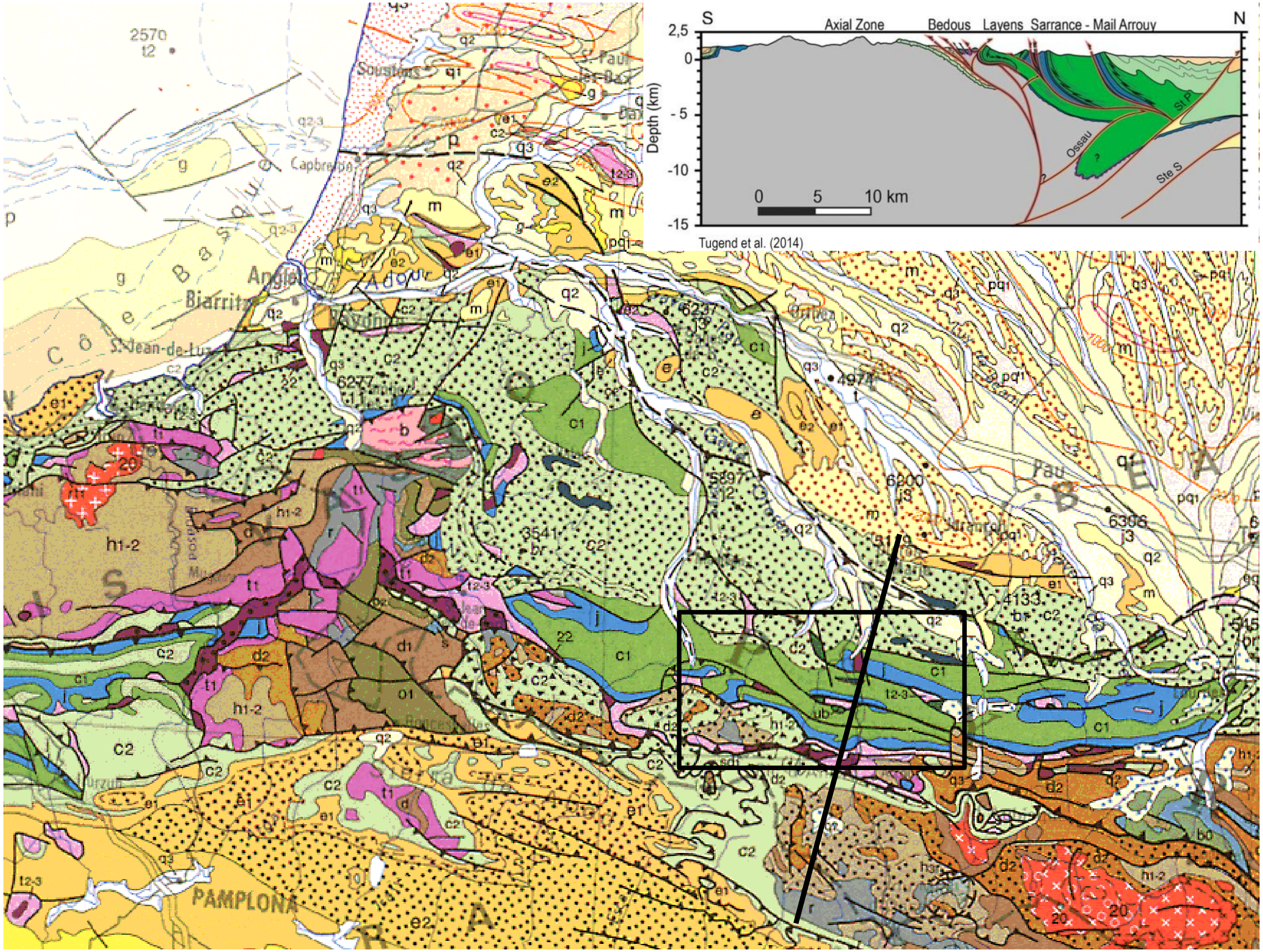

5°00
4°00
3°00
2°00
1°00
49°00
48°00
1500
1000
500
200
100
50
20
P
M
A
TOULOUSE
TR
L
JUR
CRET
CEN
200
100
0
0 Ma
km
LE SEXTANT 1
GER 1
TOURNAY 1
LACQ 301
0
50km

Quatre courbes de subsidence dans le bassin Aquitain, calculées d’après l’analyse de forages de recherche pétrolière. Dans chaque encadré, la courbe inférieure montre l’enfouissement avec le temps du socle anté-triasique (sédiments décompactés), la courbe supérieure montre la subsidence « tectonique », c’est-à-dire la subsidence corrigée de l’effet de charge des sédiments et de l’eau emplissant le bassin (compensation isostatique locale par du matériel mantellique de densité 3, 2). La subsidence est rapide au Trias et au Lias inférieur (distension initiale), ralentie pendant le Jurassique moyen (refroidissement lithosphérique), de nouveau rapide au Jurassique supérieur, puis à l’Albo-Aptien (nouvelles phases de distension tectonique), ralentie au Crétacé supérieur (nouveau refroidissement lithosphérique), et reprend brusquement à la fin du Crétacé jusqu’à la fin de l’Éocène (effet de la compression pyrénéenne). Des différences apparaissent cependant selon les puits, qui ne montrent pas tous les trois phases de subsidence rapide énumérées précédemment. Les bassins du Crétacé inférieur (Parentis, Mirande, Adour ;
sont ombrés (d’après Brunet, 1983 ; coordonnées en grades).

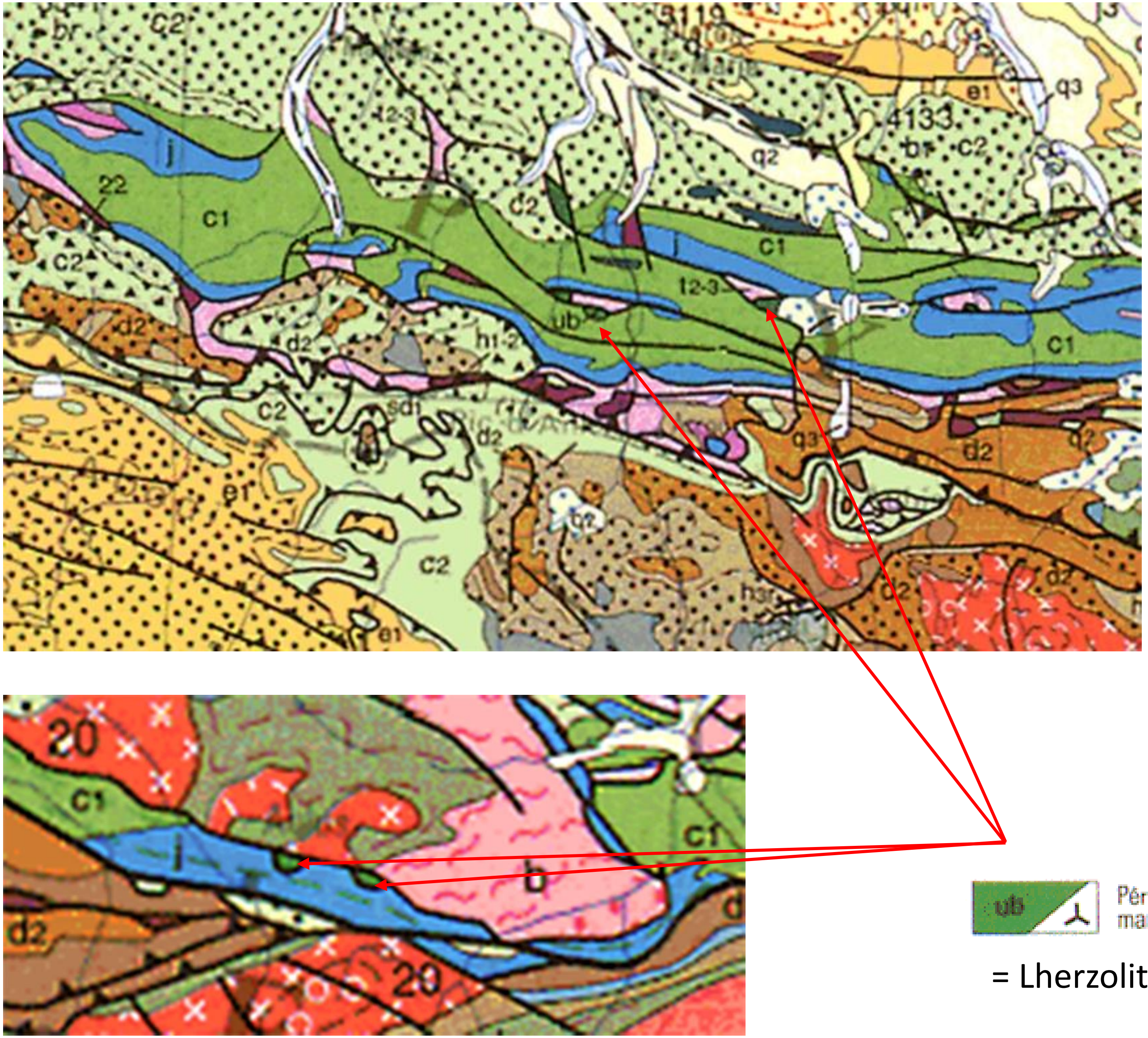

a)
FRANCE
ARMORICAN MARGIN
BAY OF BISCAY
ECORS-Bay of Biscay Profile
b)
TF
HF
PF
PYRENEES
WEST IBERIA MARGIN
IBERIA
b)
ARMORICAN SHELF
PARENTIS BASIN
Part of the profile interpreted by Bois et al. (1997)
LANDES HIGH
ECORS-Arzacq profile
CANTABRIAN BASIN
LABOURD MASSIF
MAULEON BASIN
Legend of the map :
Continent
Anormal thick crust
Normal thick crust
Thin crust
Ocean continent transition
Oceanic domain
Thrust fault
Transfer fault
Magnetic Anomaly A33o
Magnetic Anomaly A34
Magnetic Anomaly M0
Magnetic Anomaly M3
IODP wells
Legend of the Parentis cross-section :
Cenozoic
Upper Cretaceous
Middle Cretaceous
Jurassic-Lower Cretaceous
Triassic
Salt
Upper crust
Lower crust
Mantle
Moho
Strike-slip faults
c)
S
N
R5 DANU
PELICAN
IBIS 2
R4
PINGOUIN
R3 FREGATE
CORMORAN
R2 ALBATROS
5400
5000
4200
3000
2500
2000
s TWT
IBERIA
EUROPE
Modified from Bois et al. (1997)
10 km

(Jammes et al., 2009)

Les bassins crétacés et l'exhumation des roches profondes de la croûte et du manteau (120-110 Ma : Aptien sup-Albien inf)


S
Axial Zone
Bedous
Layens
Sarrance - Mail Arrouy
N
2,5
0
- 5
-10
-15
Depth (km)
Ossau
St P
Ste S
0
5
10 km
Soustons
Dax
Capbreton
Anglet
Adour
Biarritz
St-Jean-de-Luz
Pau
PAMPLONA
h1-2
c1
c2
t1
d2
e1
q2
m
pq1

Tugend et al. (2014)

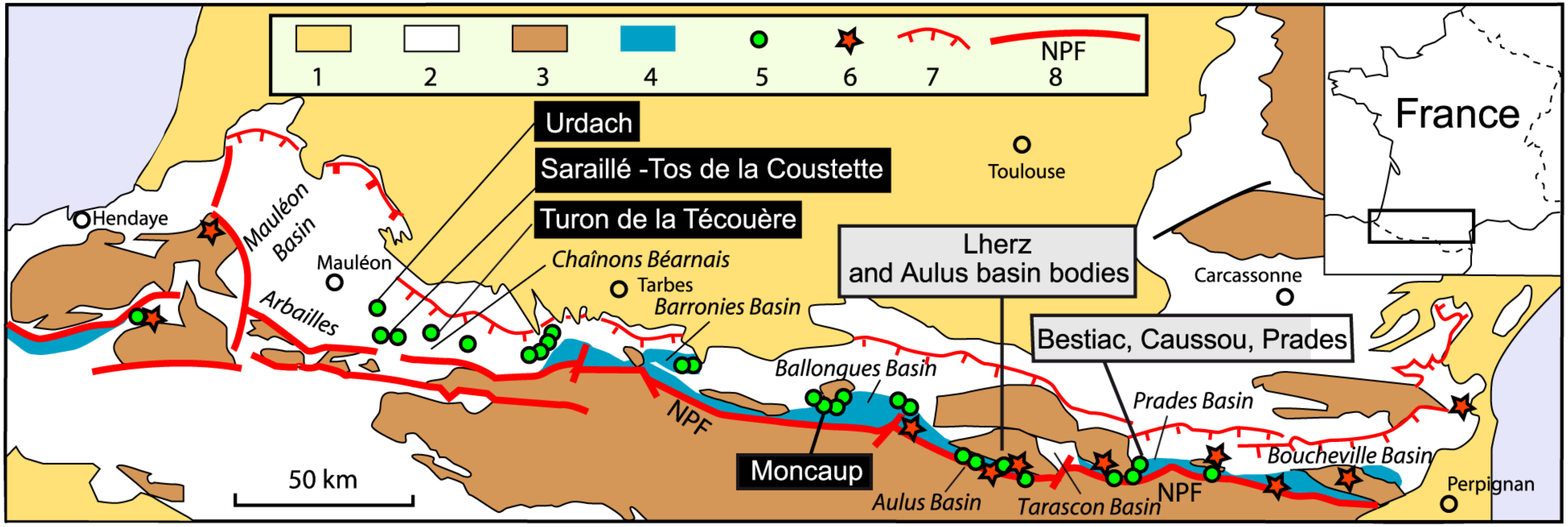

br
c2
c1
j
22
d2
h1-2
l2-3
ub
q2
q3
e1
4133
sd1
h3r
20
b

ub Péridotites mantelliques

= Lherzolites

Geological settings of the Pyrenean ultramafic bodies

type S : sedimented	Reworked as debris flows in Cretaceous flysch deposits
type T : tectonic	In fault contact with mesozoic limestones. Associated with tectonic lenses of basement rocks and triassic sediments and volcanics, within cataclastic-rich fault rocks

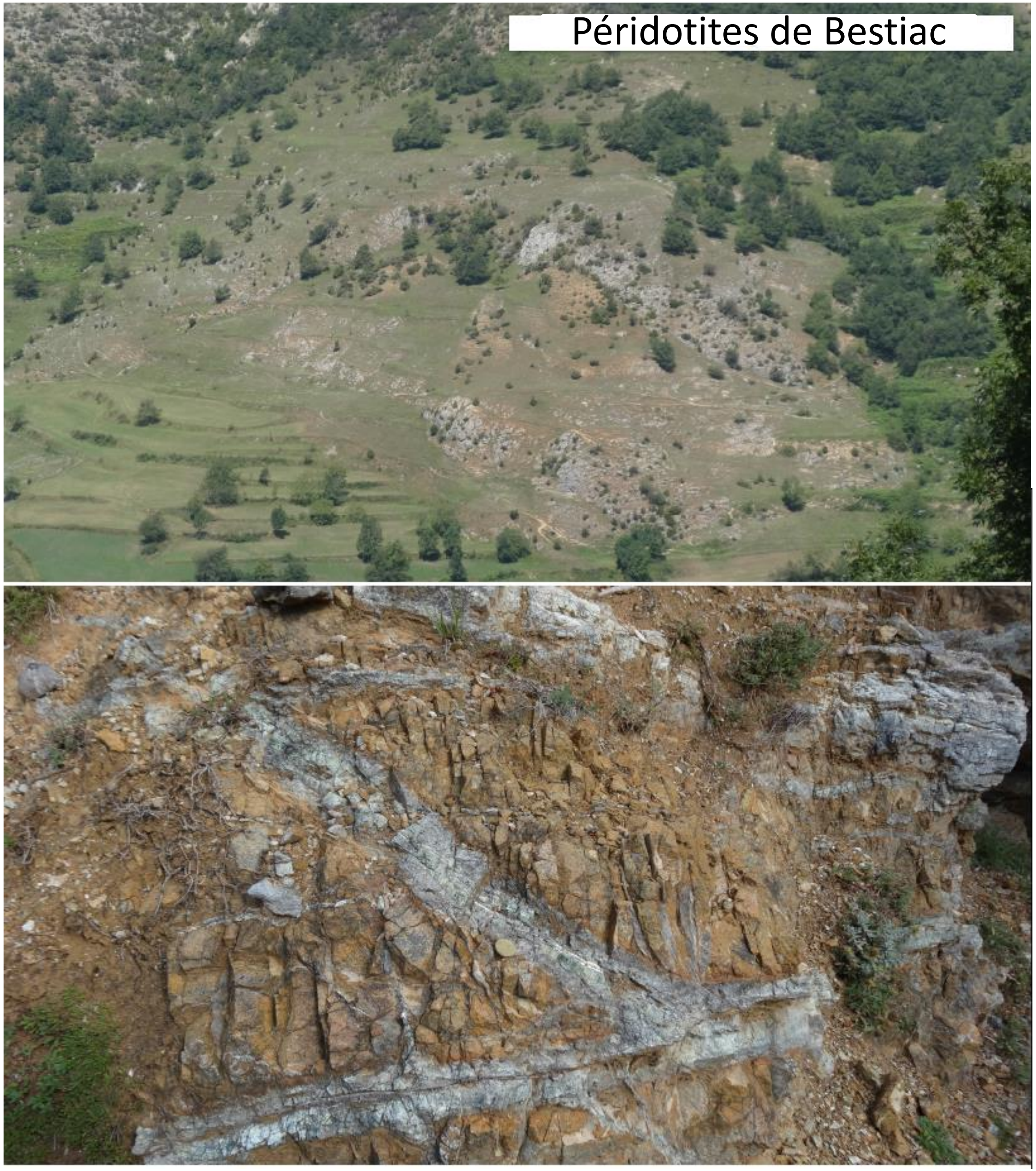

1
2
3
4
5
6
7
NPF
8
France
Urdach
Saraillé -Tos de la Coustette
Turon de la Técouère
Toulouse
Hendaye
Mauléon Basin
Mauléon
Chaînons Béarnais
Tarbes
Barronies Basin
Lherz
and Aulus basin bodies
Carcassonne
Arbailles
Bestiac, Caussou, Prades
Ballongues Basin
Prades Basin
NPF
Boucheville Basin
Perpignan
50 km
Moncaup
Aulus Basin
Tarascon Basin
NPF

1 : Oligocene and post-Oligocene ; 2 : Mesozoic and Eocene ; 3 : Paleozoic basement ; 4 : area of HT-LP Pyrenean metamorphism ; 5 : lherzolite bodies ; 6 : outcrops of granulitic basement rocks ; 7 : main external thrusts ; 8 : North Pyrenean Fault

(Lagabrielle et Bodiner, 2008)

(Filleaudeau, thèse, 2011)

Péridotites de Bestiac



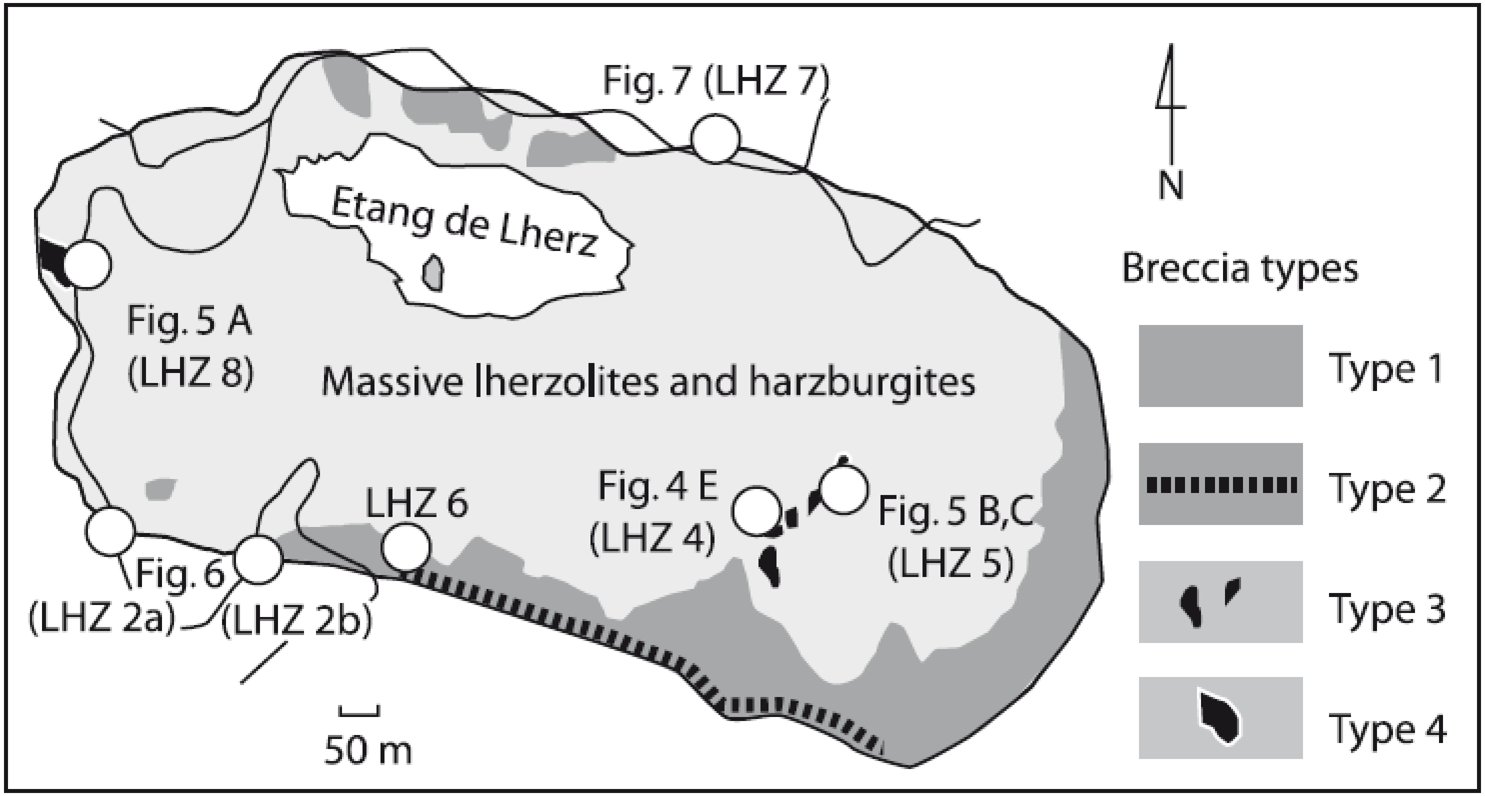
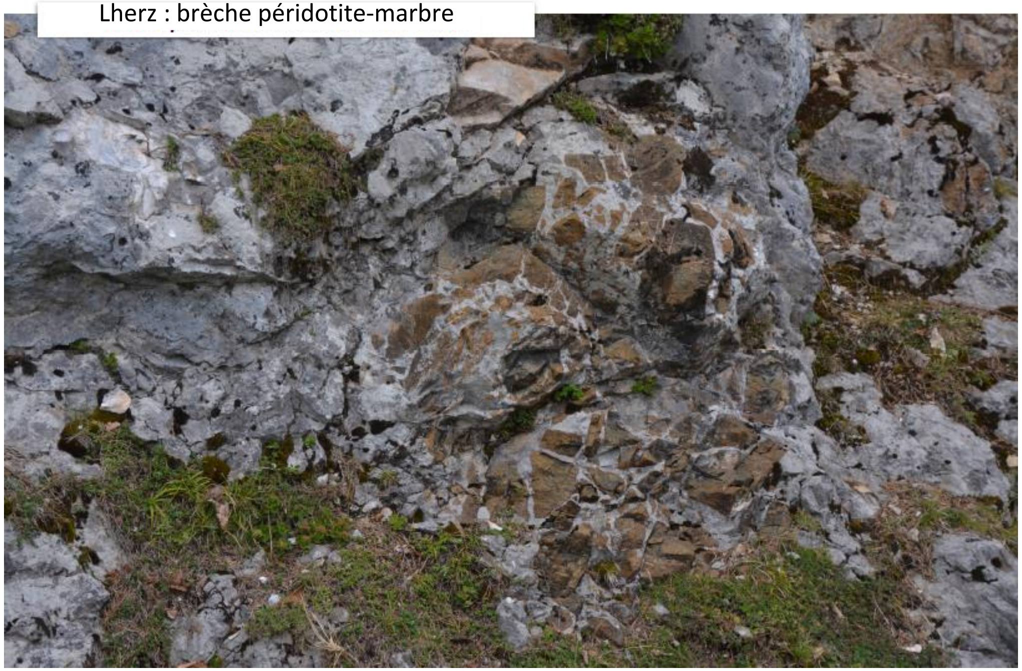
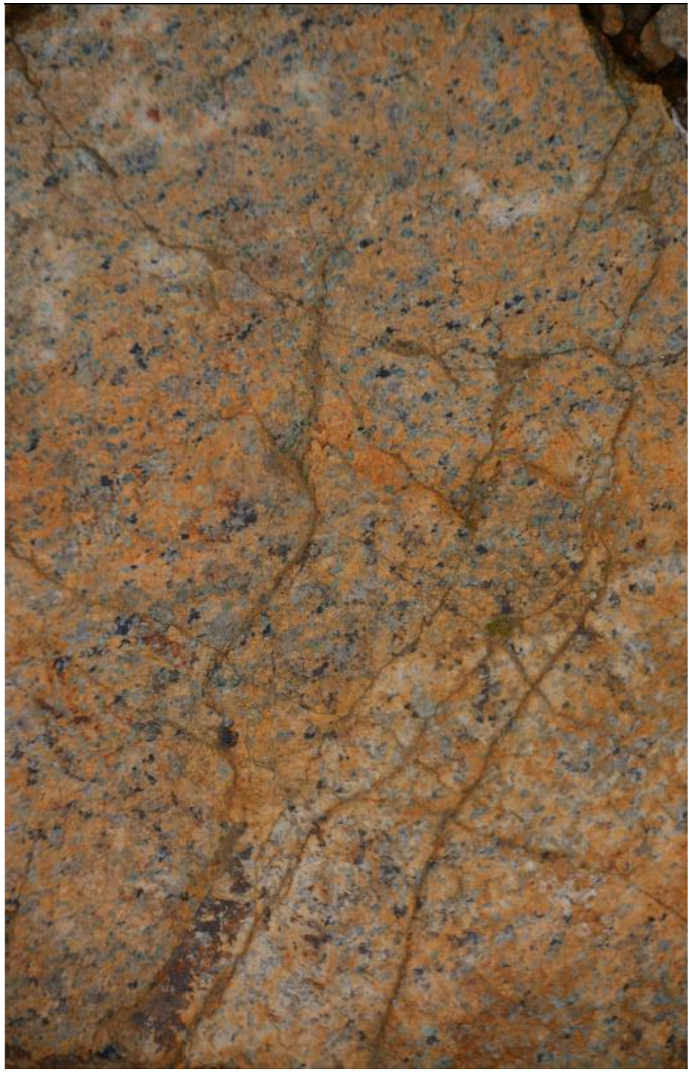


Fig. 7 (LHZ 7)
N
Etang de Lherz
Fig. 5 A
(LHZ 8)
Massive lherzolites and harzburgites
Breccia types
Type 1
Type 2
Type 3
Type 4
Fig. 4 E
(LHZ 4)
Fig. 5 B,C
(LHZ 5)
LHZ 6
Fig. 6
(LHZ 2a)
(LHZ 2b)
50 m

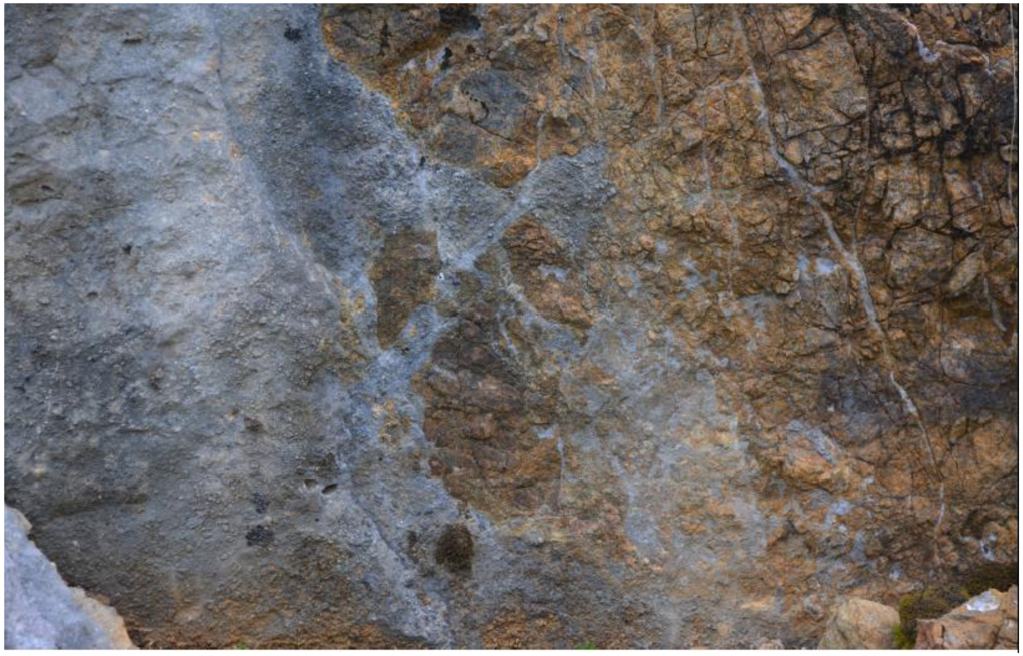
(Lagabrielle et Bodiner, 2008)

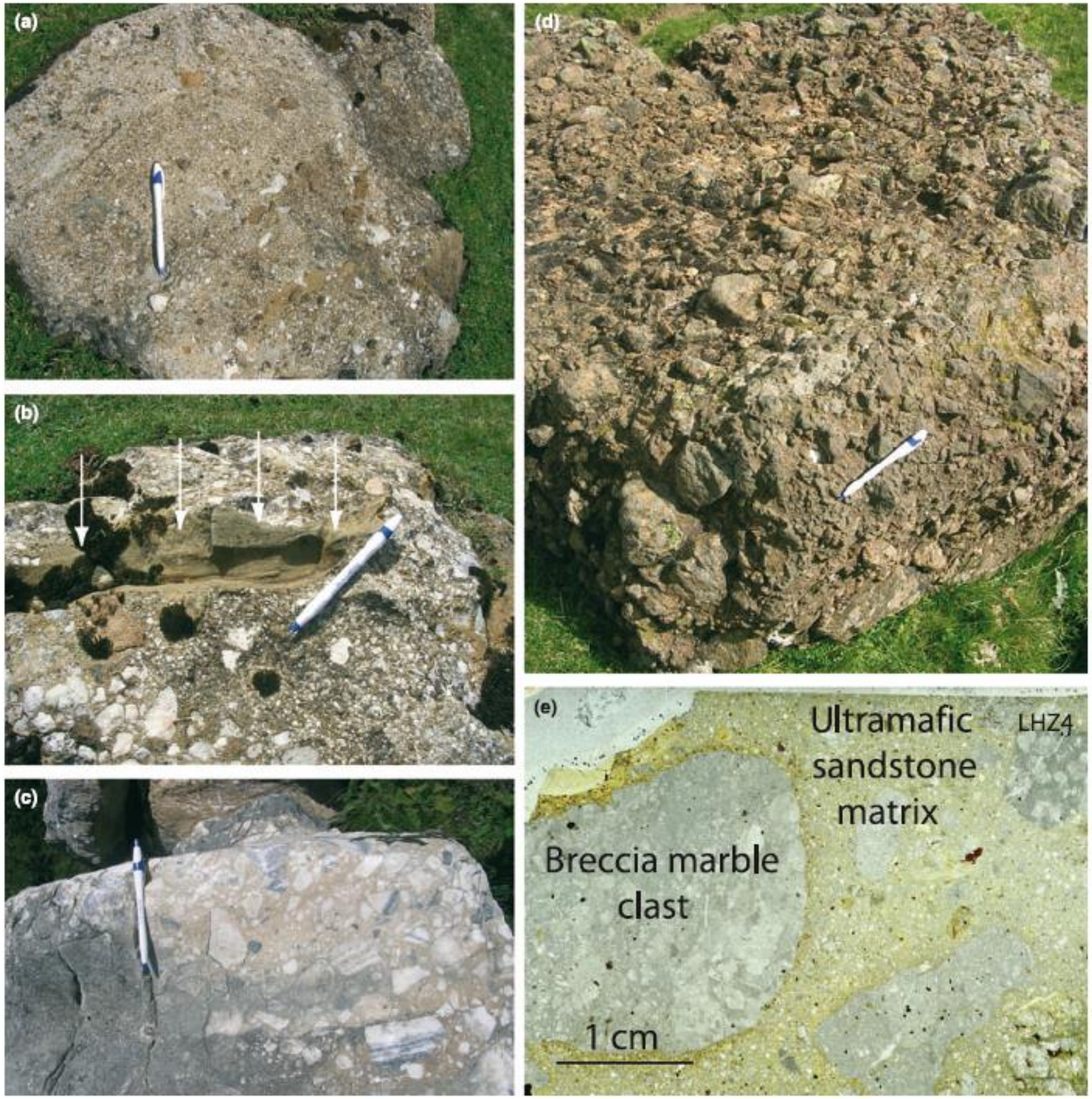
Lherz : brèche péridotite-marbre





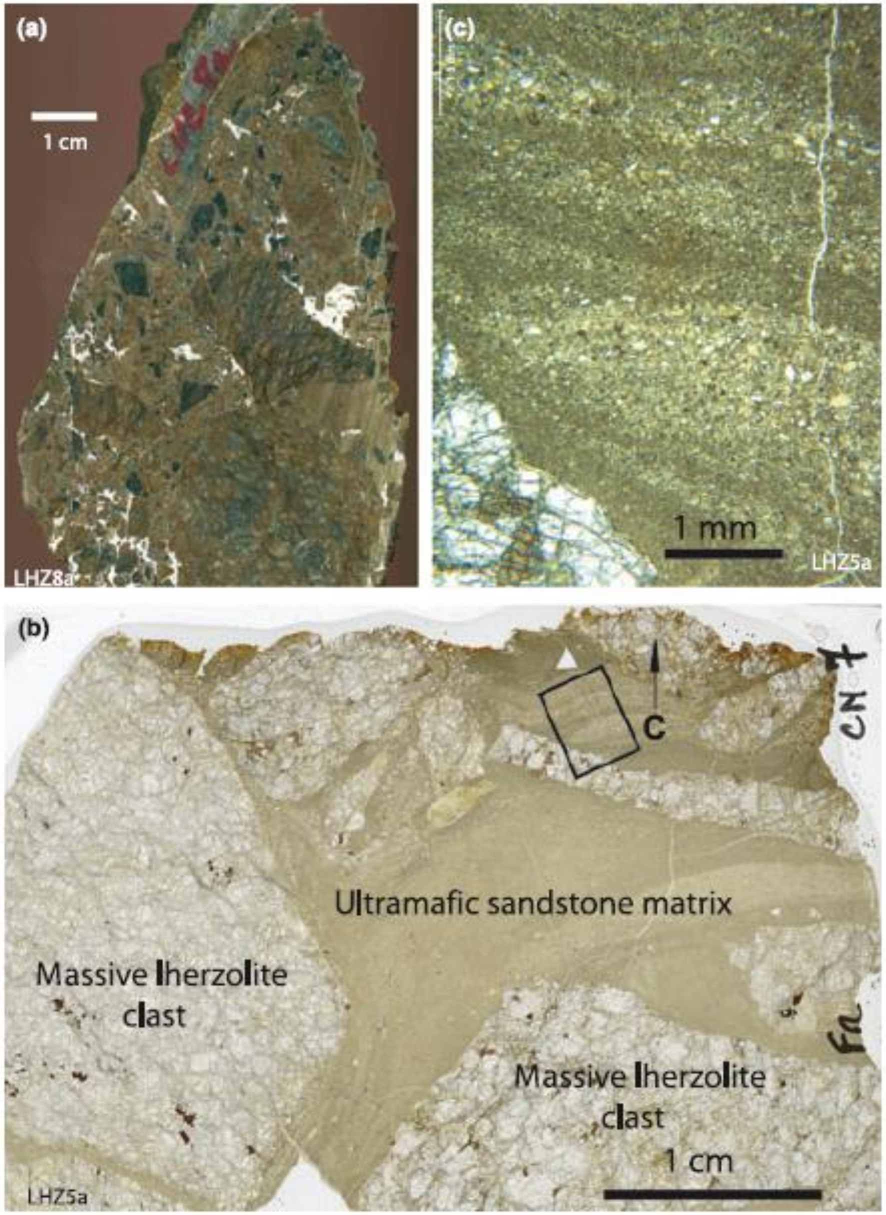
Lherz : Lherzolite massive





The polymictic breccias. Numerous examples of sedimentary breccias are well exposed in the region between the Lherz and Fontete Rouge bodies, an area delineated by a thick dotted line in the map of Fig. 2. Evidence of sedimentary origin and subaqueous transport of clasts includes graded bedding, frequent erosional channels and cross-bedding, mixing from different sources, round shape of some clasts, etc. (a) Graded polymictic carbonate-lherzolite breccias with interlayered polymictic sandstone beds. (b) Lens of bedded, pure ultramafic sandstone (white arrows) within polymictic carbonate-ultramafic breccia. (c) Matrix-supported breccia. Angular clasts are deformed marbles, the orange-coloured matrix is made up of lherzolitic sandstone. (d) Monomictic ultramafic breccia. (e) Thin section of a fine-grained ultramafic sandstone (grains of serpentinite and millimetric fragments of deformed marbles), breccia of Type 3, location Fig. 3.

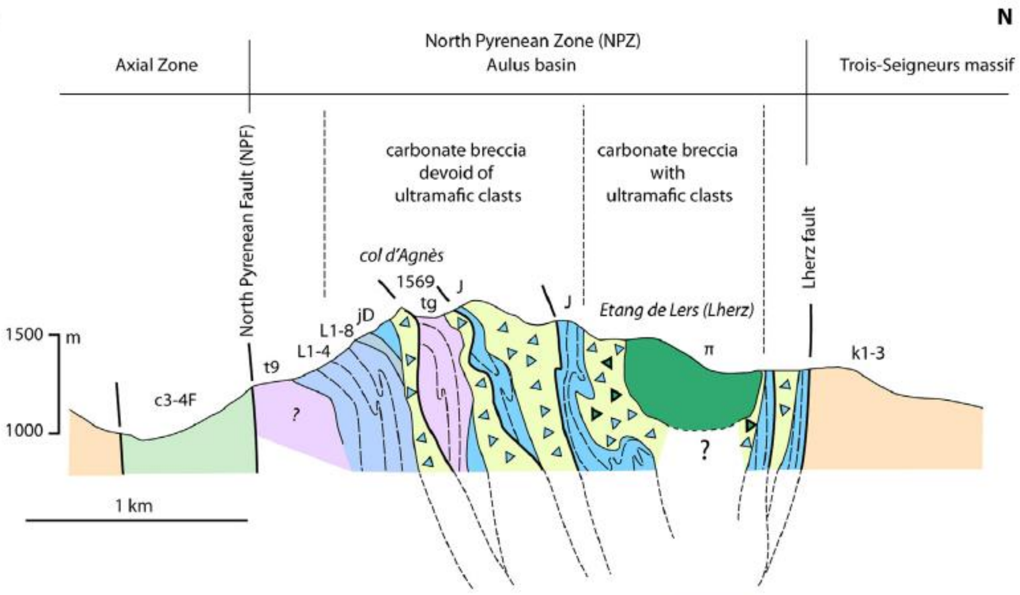
(Lagabrielle et Bodiner, 2008)


(a)
1 cm
LHZ8a
(c)
1 mm
LHZ5a
(b)
C
CN 7
Ultramafic sandstone matrix
Massive lherzolite clast
Massive lherzolite clast
Fa
1 cm
LHZ5a

(a) Ophicarbonate and (b) lherzolitic pebbly sandstones containing angular clasts of coarse-grained lherzolite, (c, enlargement of b). (a) is a Type 4 breccia, (b) belongs to the Type 3 breccias (see text for descriptions and Fig. 3 for location of samples).

(Lagabrielle et Bodiner, 2008)

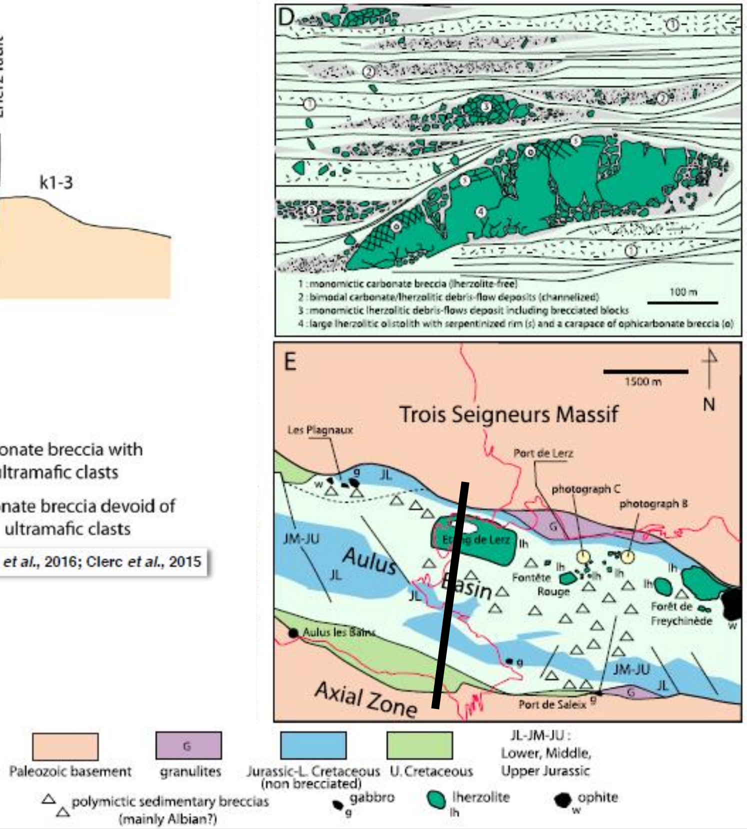
S-type peridotites


S
N
Axial Zone
North Pyrenean Zone (NPZ)
Aulus basin
Trois-Seigneurs massif
North Pyrenean Fault (NPF)
carbonate breccia devoid of ultramafic clasts
carbonate breccia with ultramafic clasts
Lherz fault
col d'Agnès
1569
tg
J
J
jD
L1-8
L1-4
t9
Etang de Lers (Lherz)
π
k1-3
1500 m
1000
c3-4F
?
?
1 km

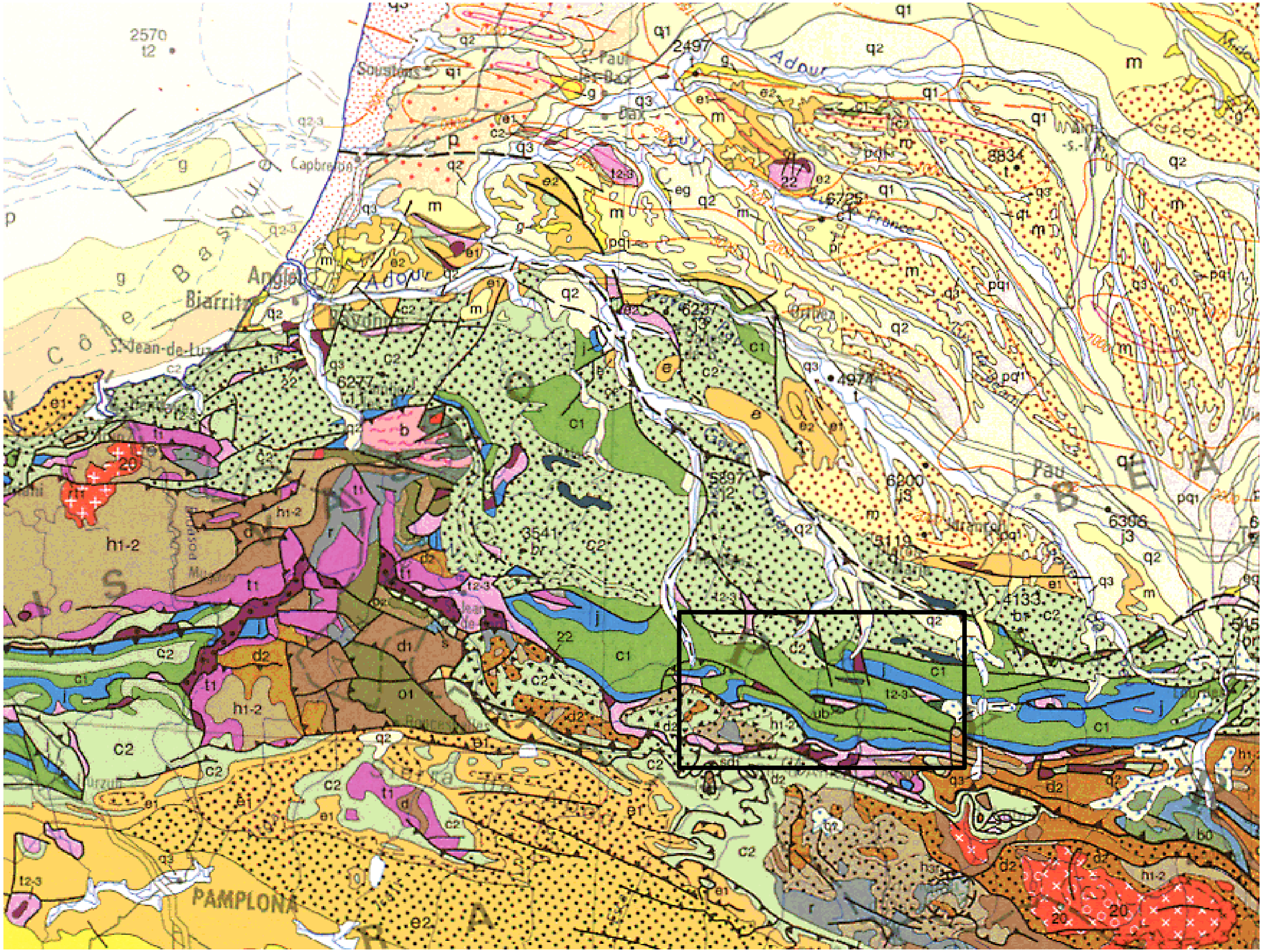
t9 : massive Triassic carbonates, «cornéennes tachetées», skarns and meta-ophites
L1-4 and L1-8 : massive Liassic carbonates (marbles, meta-dolostones, black schists)
J : massive Jurassic marbles
jD : massive Jurassic meta-dolostones
c3-4F : Flysch à Fucoïdes (Turonian-Lower Senonian)

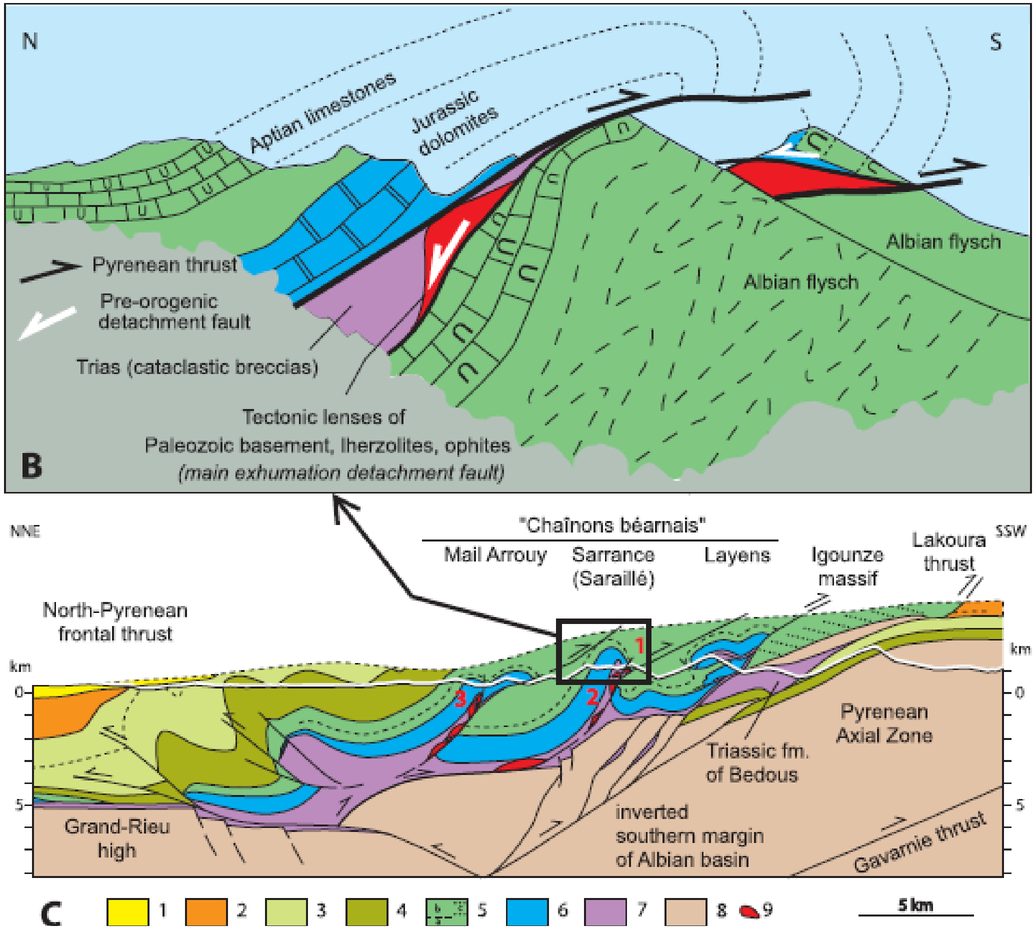
▶ ◁ carbonate breccia with ultramafic clasts
▷ ◁ carbonate breccia devoid of ultramafic clasts

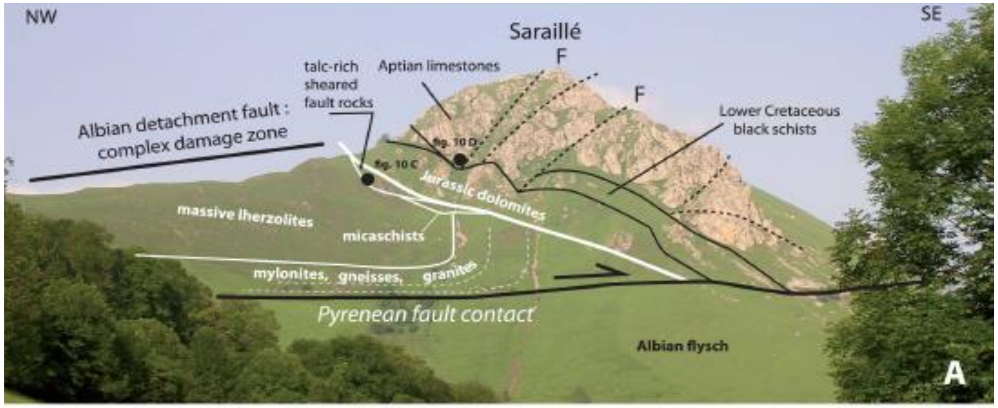
Lagabrielle *et al.*, 2016; Clerc *et al.*, 2015


D
①
②
③
④
1 : monomictic carbonate breccia (lherzolite-free)
2 : bimodal carbonate/lherzolitic debris-flow deposits (channelized)
3 : monomictic lherzolitic debris-flows deposit including brecciated blocks
4 : large lherzolitic olistolith with serpentinized rim (s) and a carapace of ophicarbonate breccia (o)
100 m
E
1500 m
N
Trois Seigneurs Massif
Les Plagnaux
Port de Lerz
photograph C
photograph B
JL
JM-JU
JL
JL
Aulus Basin
Etang de Lerz
lh
G
Fontête Rouge
Forêt de Freychinède
w
Aulus les Bains
g
JM-JU
JL
G
Port de Saleix
Axial Zone
Paleozoic basement
granulites
Jurassic-L. Cretaceous (non brecciated)
U. Cretaceous
JL-JM-JU : Lower, Middle, Upper Jurassic
polymictic sedimentary breccias (mainly Albian?)
gabbro
lherzolite
ophite

Lagabrielle *et al.*, 2010

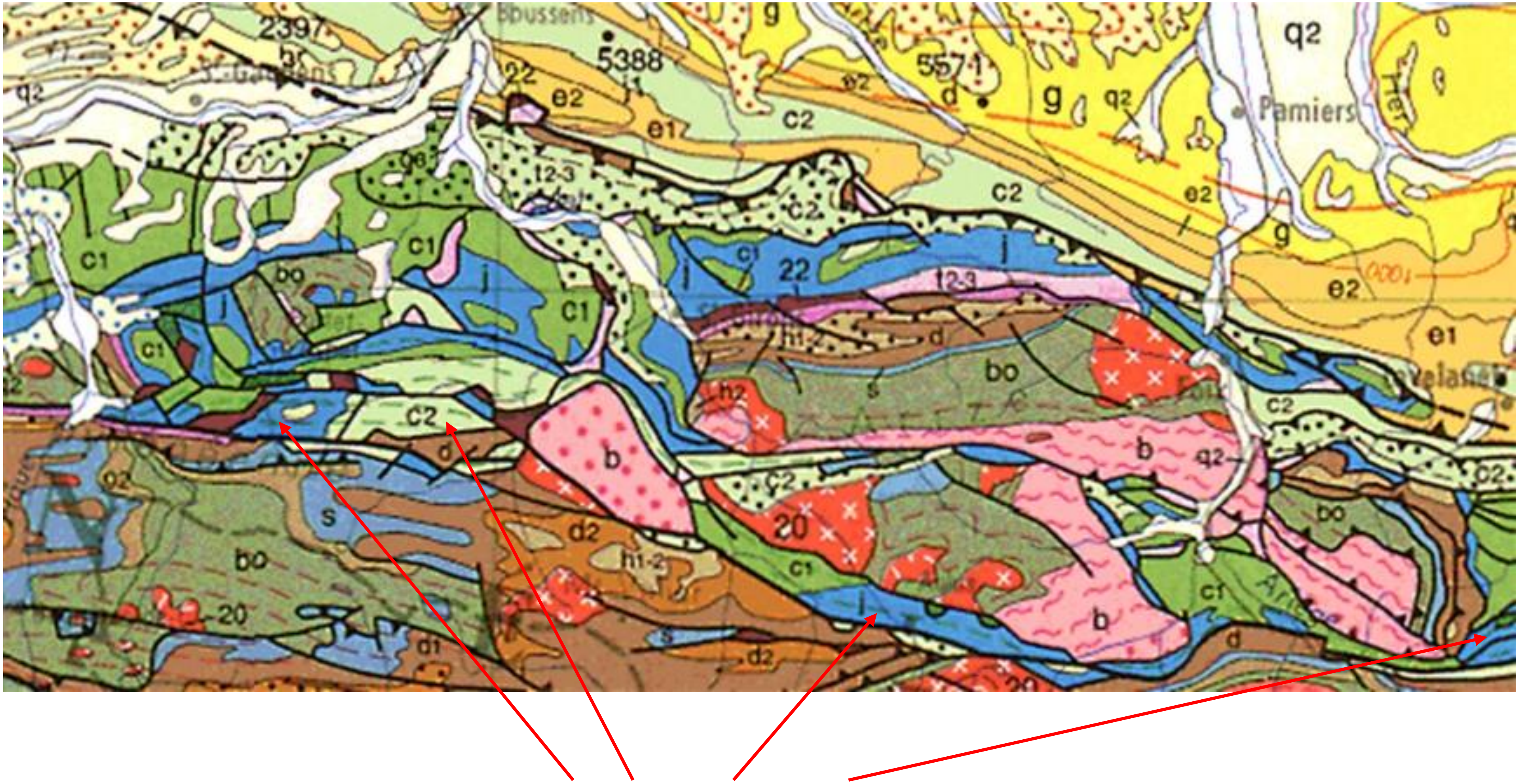

Soustons
Capbreton
Anglet
Biarritz
St-Jean-de-Luz
Dax
Adour
Côte Basque
Pau
PAMPLONA
2570
2497
6277
6237
4974
5897
6200
6834
6725
3541
4119
4133
6306


N
S
Aptian limestones
Jurassic dolomites
Pyrenean thrust
Pre-orogenic detachment fault
Albian flysch
Albian flysch
Trias (cataclastic breccias)
Tectonic lenses of Paleozoic basement, lherzolites, ophites
(main exhumation detachment fault)
B
NNE
SSW
"Chaînons béarnais"
Mail Arrouy
Sarrance (Saraillé)
Layens
Igounze massif
Lakoura thrust
North-Pyrenean frontal thrust
km
0
5
1
2
3
Pyrenean Axial Zone
Triassic fm. of Bedous
inverted southern margin of Albian basin
Grand-Rieu high
Gavarnie thrust
C
1
2
3
4
5
6
7
8
9
5 km

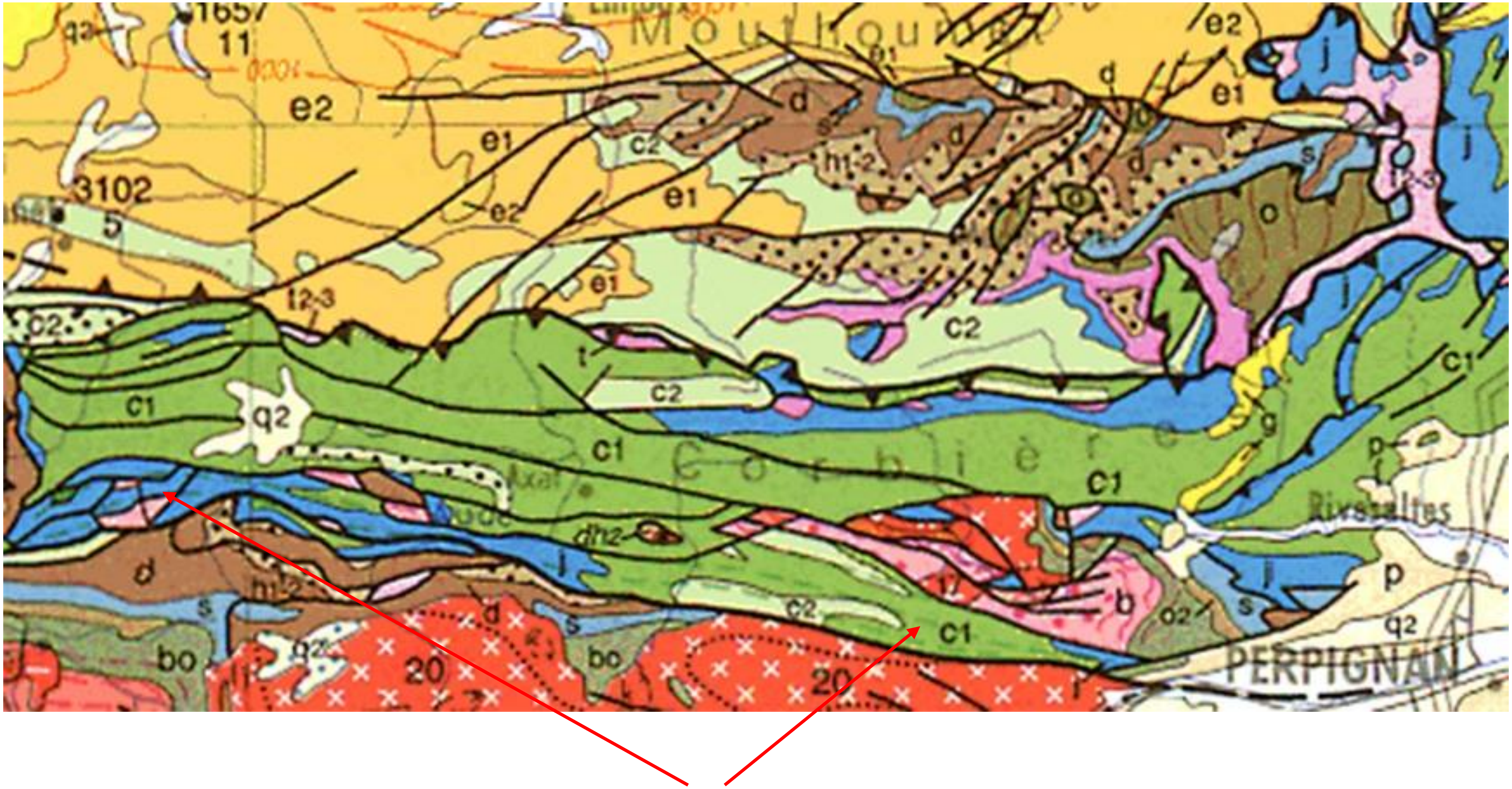

NW
SE
Saraillé
F
F
talc-rich sheared fault rocks
Aptian limestones
Albian detachment fault : complex damage zone
fig. 10 D
fig. 10 C
Lower Cretaceous black schists
Jurassic dolomites
massive lherzolites
micaschists
mylonites, gneisses, granites
Pyrenean fault contact
Albian flysch
A

(Lagabrielle et al., 2010)

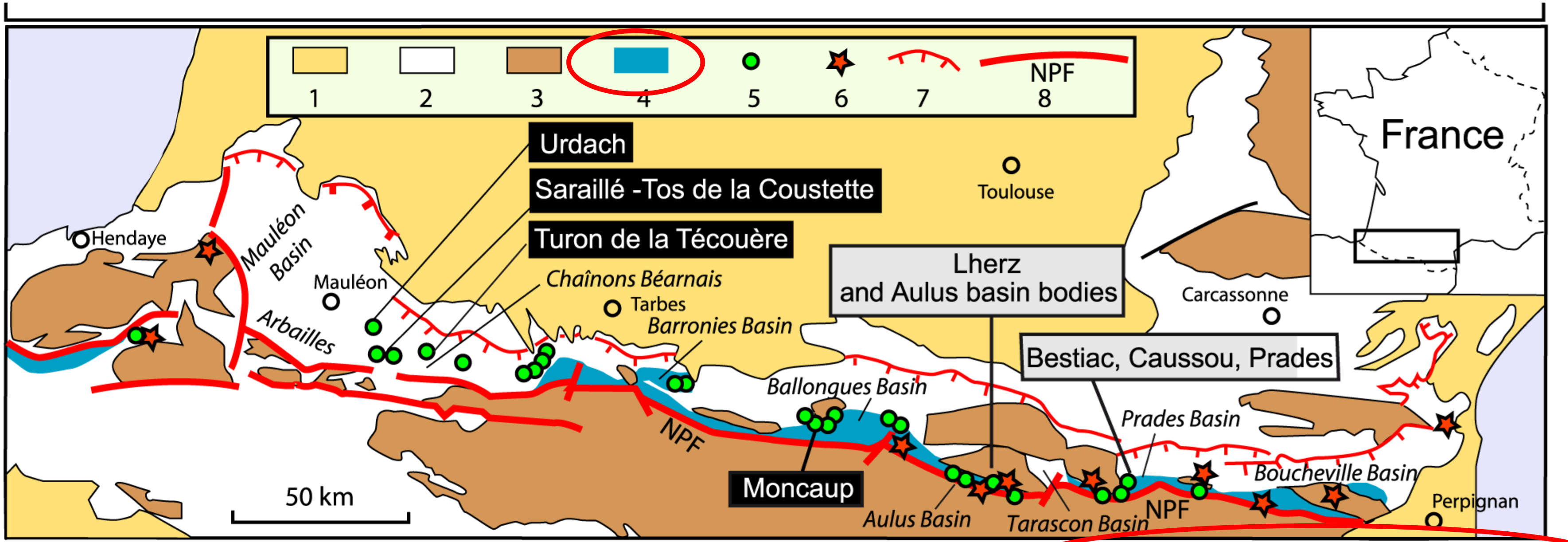
Le métamorphisme HT-BP
(110-90 Ma : Albien-Cénomanien-Turonien)


Boussens
2397
5388
5571
St-Gaudens
Pamiers
Hers
Lavelanet
Foix
Ariège
q2
g
e2
e1
c2
c1
j
22
t2-3
d
h1-2
h2
bo
b
s
20
d1
d2
o2

Métamorphisme de HT-BP affectant les séries mésozoïques
dans la partie interne de la zone nord-pyrénéenne

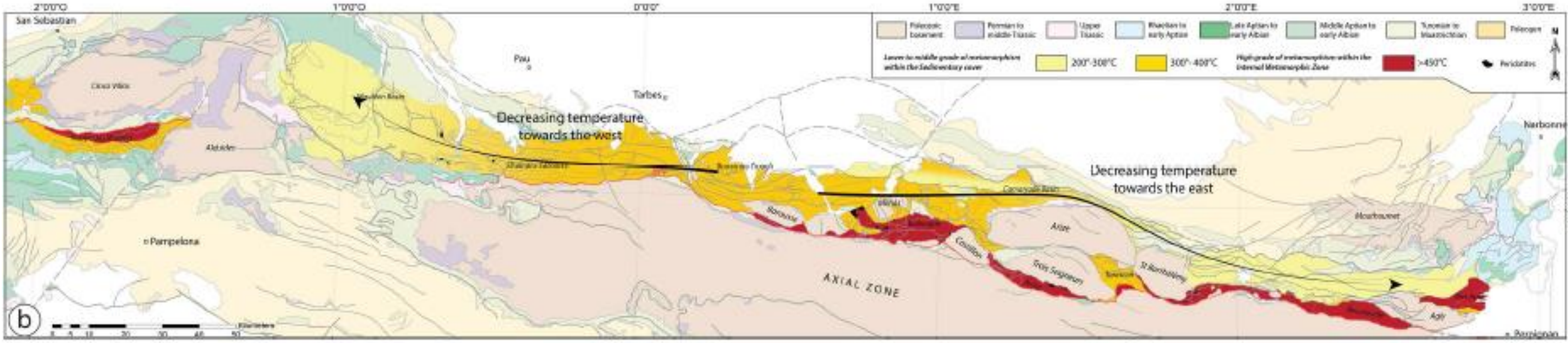

1657
11
Mouthoumet
e2
e1
d
c2
h1-2
3102
5
j
s
o
t2-3
c1
q2
t
Corbières
g
p
Rivesaltes
dh2
Aude
b
o2
bo
20
PERPIGNAN

Métamorphisme HT-BP : des températures élevées, pouvant dépasser 550°C, à faible profondeur (quelques kilomètres)
=> paléo-gradient géothermique très fort (> 50°C/km)


1
2
3
4
5
6
7
NPF
8
France
Urdach
Saraillé -Tos de la Coustette
Turon de la Técouère
Toulouse
Hendaye
Mauléon Basin
Mauléon
Arbailles
Chaînons Béarnais
Tarbes
Barronies Basin
Lherz
and Aulus basin bodies
Carcassonne
Bestiac, Caussou, Prades
Ballongues Basin
Prades Basin
NPF
Moncaup
Boucheville Basin
Perpignan
50 km
Aulus Basin
Tarascon Basin
NPF

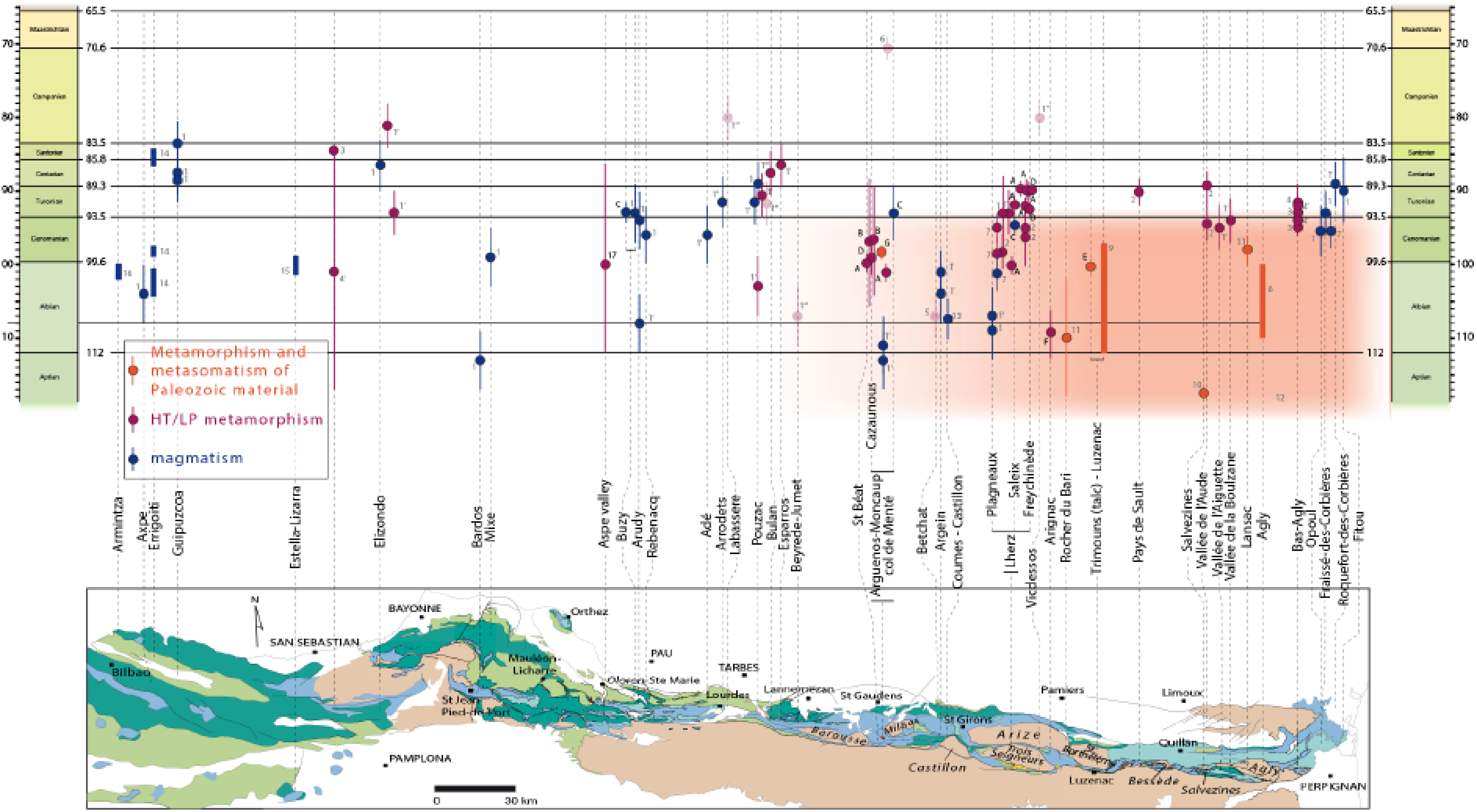
1 : Oligocene and post-Oligocene ; 2 : Mesozoic and Eocene ; 3 : Paleozoic basement ; 4 : area of HT-LP Pyrenean metamorphism ; 5 : lherzolite bodies ; 6 : outcrops of granulitic basement rocks ; 7 : main external thrusts ; 8 : North Pyrenean Fault

(Lagabrielle et Bodiner, 2008; Ducoux, thèse, 2018)


2°0'0"O
1°0'0"O
0°0'0"
1°0'0"E
2°0'0"E
3°0'0"E
Paleozoic basement
Permian to middle Triassic
Upper Triassic
Rhaetian to early Aptian
Late Aptian to early Albian
Middle Aptian to early Albian
Turonian to Maastrichtian
Paleogene
200°-300°C
300°-400°C
>450°C
Peridotites
N
San Sebastian
Pau
Tarbes
Narbonne
Decreasing temperature towards the west
Decreasing temperature towards the east
Pampelona
AXIAL ZONE
Perpignan
b

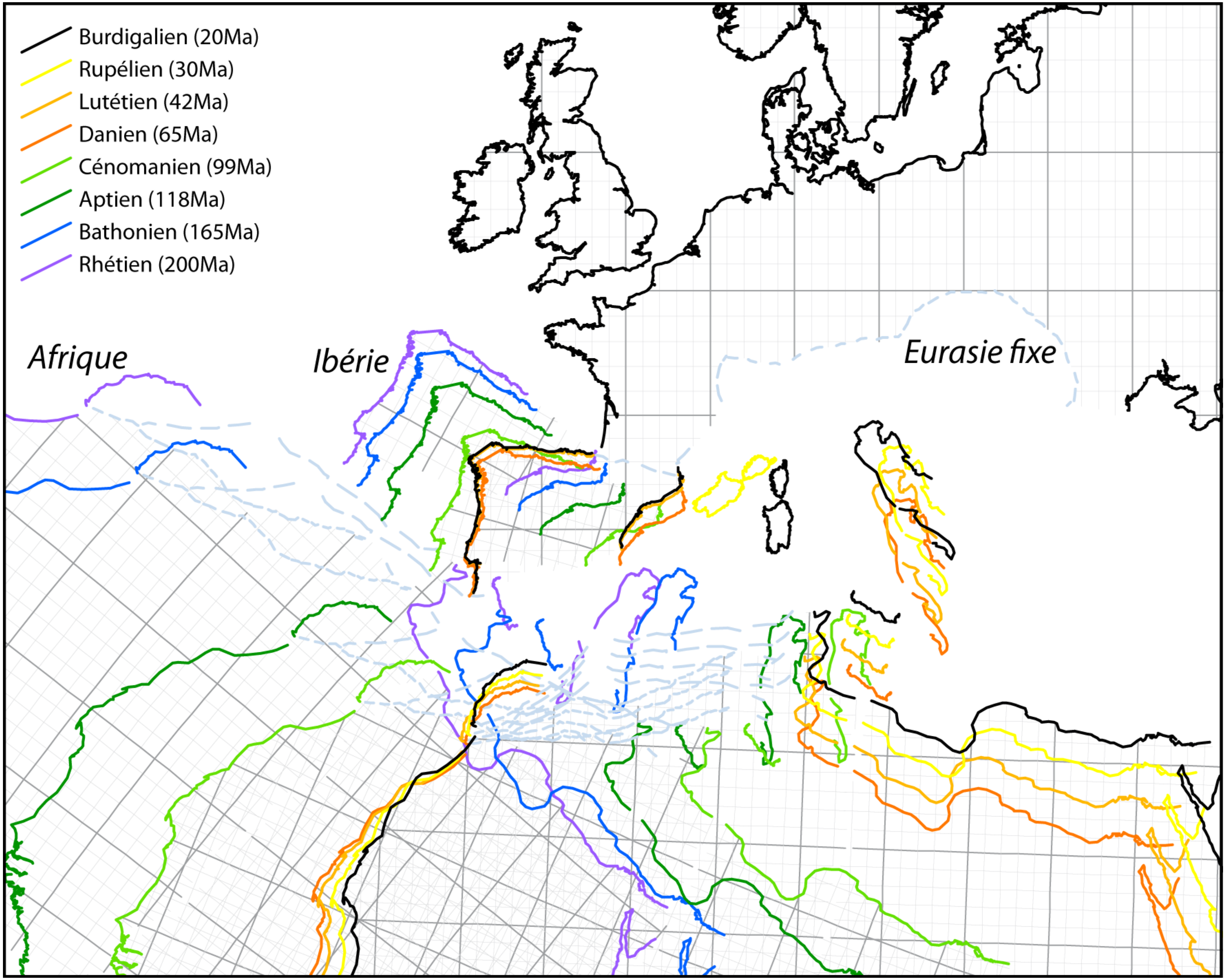
Métamorphisme HT-BP : des températures élevées, pouvant dépasser 550°C,
à faible profondeur (quelques kilomètres)
=> paléo-gradient géothermique très fort (> 50°C/km)

Le magmatisme
(110-85 Ma : Albien-Cénomanien)



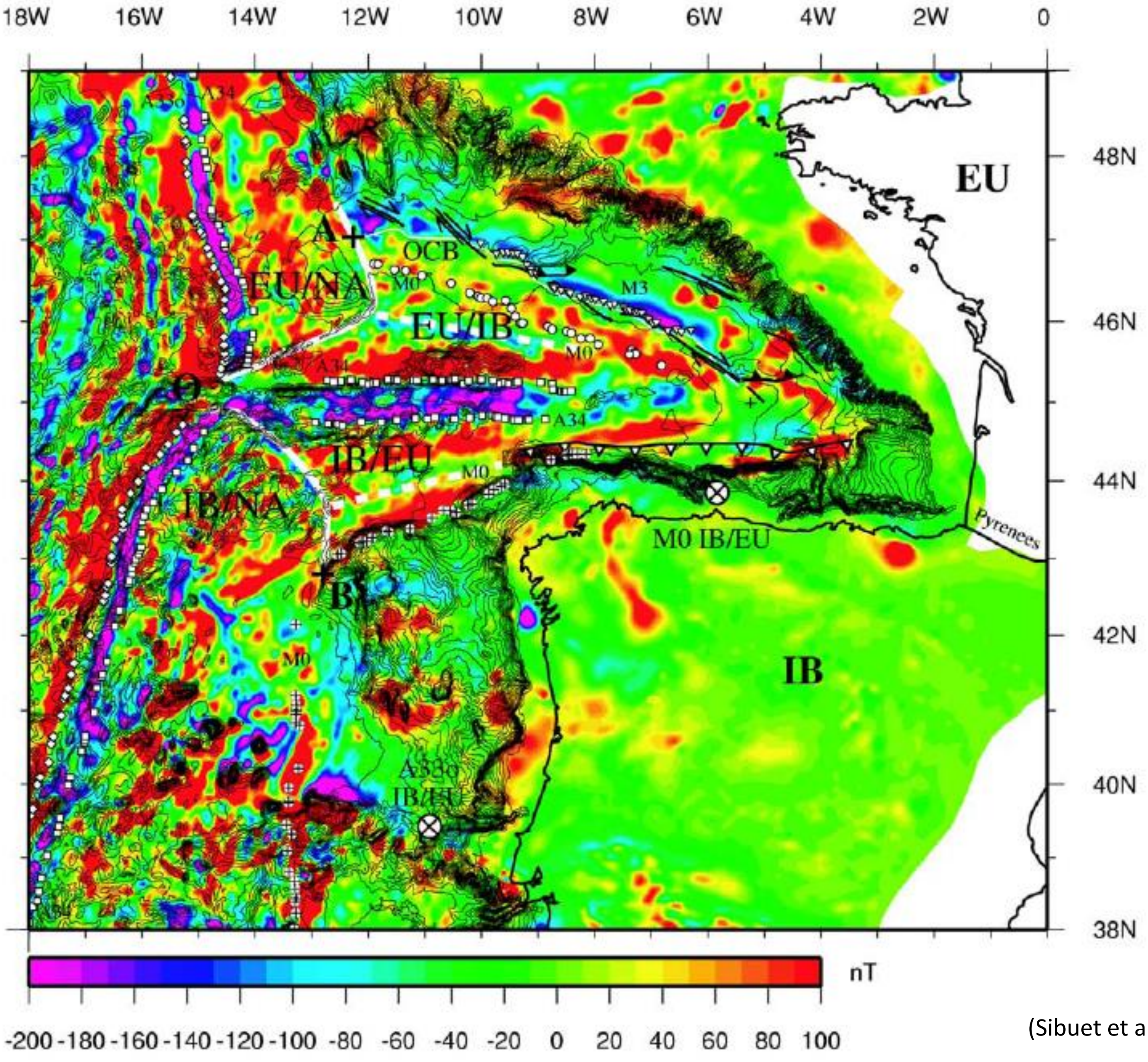
(Clerc et al., 2015)

B. Les données cinématiques


Burdigalien (20Ma)
Rupélien (30Ma)
Lutétien (42Ma)
Danien (65Ma)
Cénomanien (99Ma)
Aptien (118Ma)
Bathonien (165Ma)
Rhétien (200Ma)
Afrique
Ibérie
Eurasie fixe

La anomalies magnétiques
et l'ouverture du Golfe de Gascogne

-Anomalie 34 (83-84 Ma)
- Anomalies Mo (125 Ma) et M3 (~160 Ma) ?

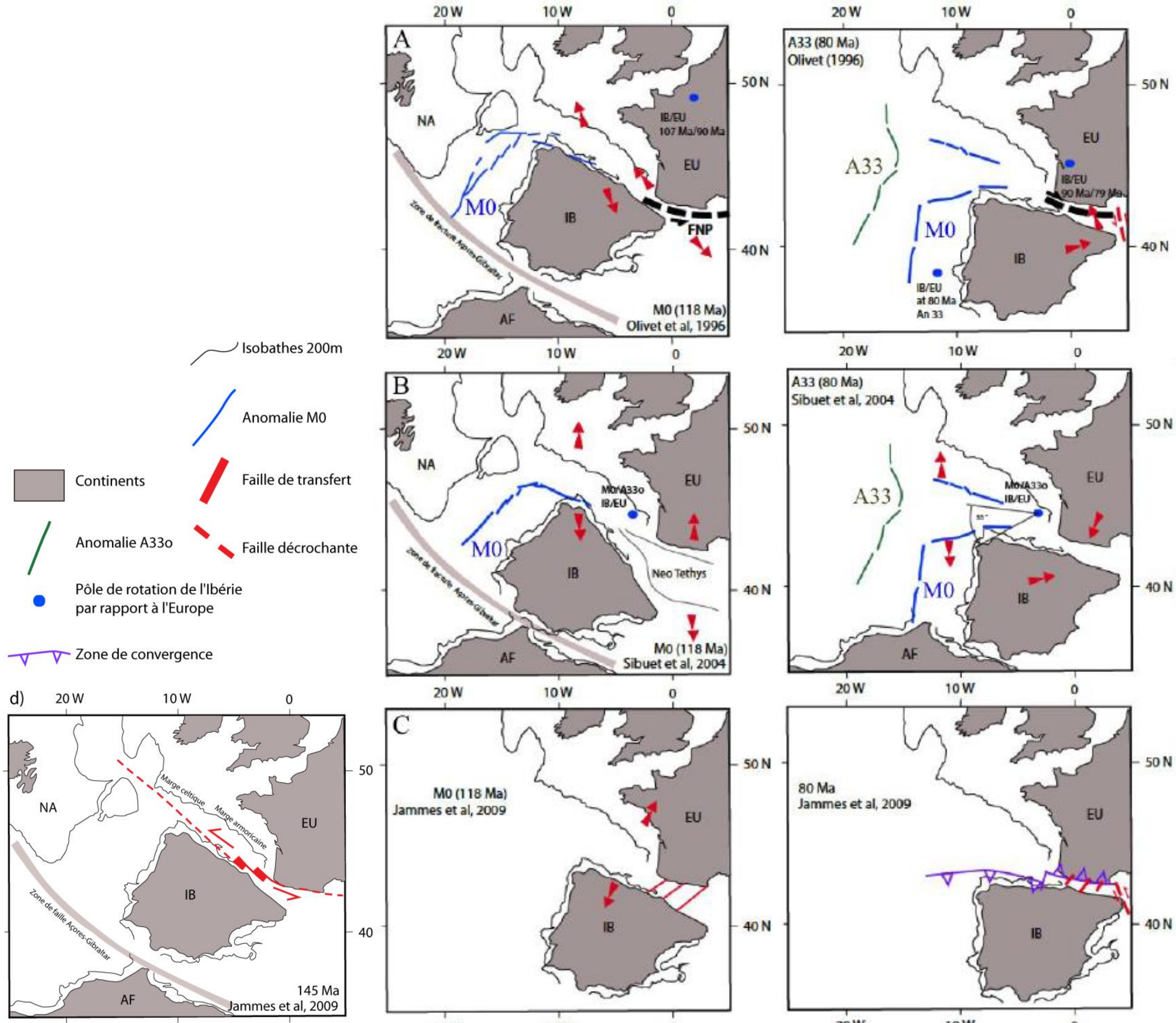

18W
16W
14W
12W
10W
8W
6W
4W
2W
0
48N
46N
44N
42N
40N
38N
EU
A33o
A34
A
OCB
EU/NA
M0
M3
EU/IB
M0
A34
A34
IB/EU
M0
IB/NA
M0 IB/EU
Pyrenees
B
M0
IB
A33o
IB/EU
A34
nT
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100

(Sibuet et al., 2004)

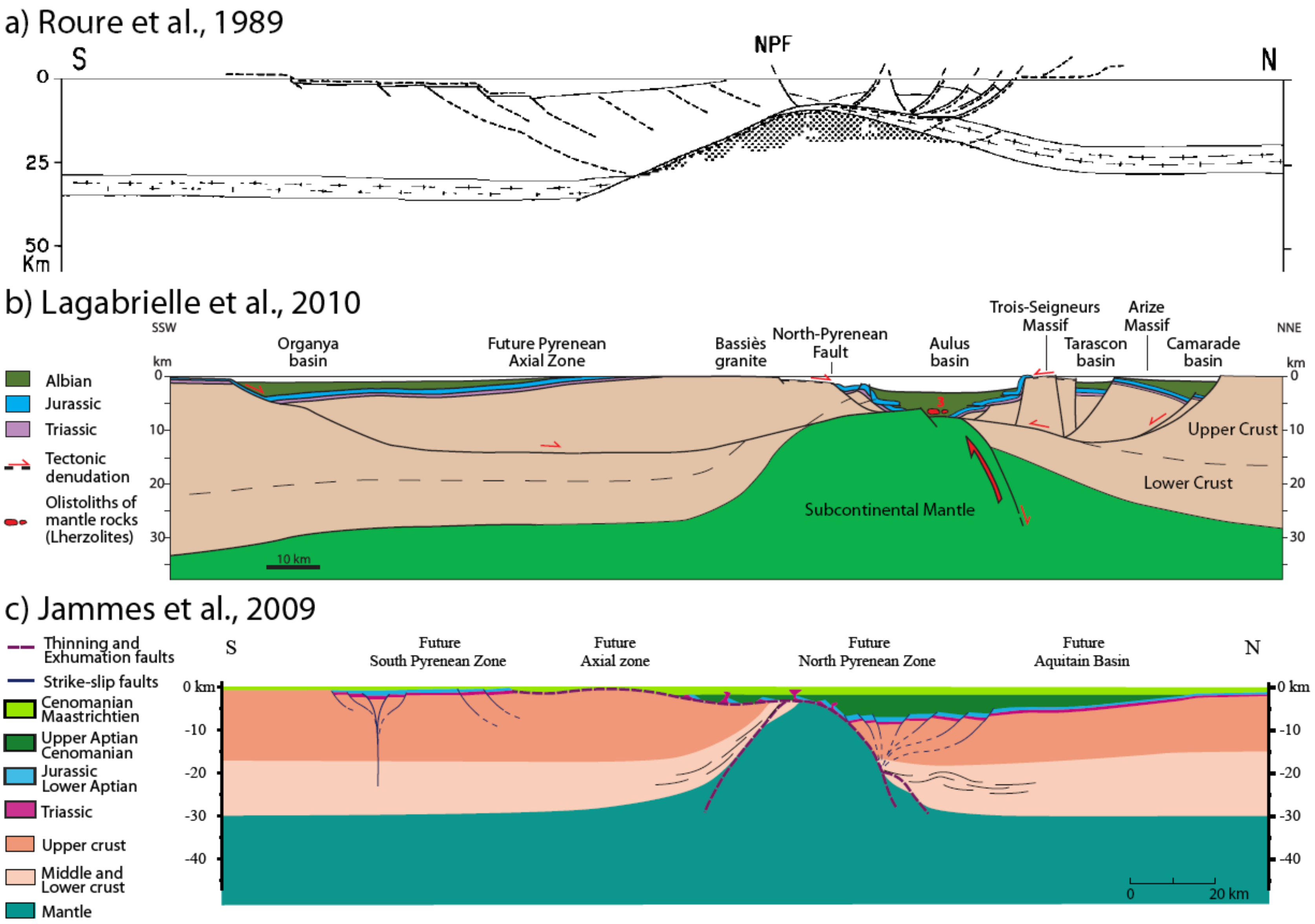
Les données paléomagnétiques et la rotation de l'Ibérie (125-112 Ma : Aptien)

Un mouvement décrochant sénestre important entre Ibérie et Europe au Crétacé ?

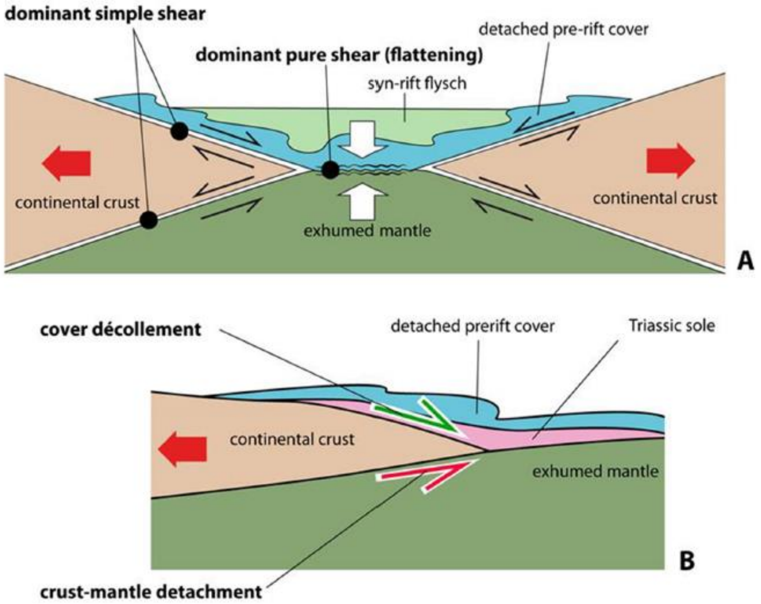
C. Des modèles d'évolution mésozoïque variés (et contradictoires !)

A
M0 (118 Ma)
Olivet et al, 1996
NA
EU
IB
AF
M0
FNP
IB/EU
107 Ma/90 Ma
Zone de fracture Açores-Gibraltar
A33 (80 Ma)
Olivet (1996)
A33
IB/EU
90 Ma/79 Ma
IB/EU
at 80 Ma
An 33
B
M0 (118 Ma)
Sibuet et al, 2004
M0/A33o
IB/EU
Neo Tethys
A33 (80 Ma)
Sibuet et al, 2004
55°
C
M0 (118 Ma)
Jammes et al, 2009
80 Ma
Jammes et al, 2009
d)
145 Ma
Jammes et al, 2009
Marge celtique
Marge armoricaine
Zone de faille Açores-Gibraltar
20 W
10 W
0
50 N
40 N
50
40
Isobathes 200m
Anomalie M0
Faille de transfert
Faille décrochante
Continents
Anomalie A33o
Pôle de rotation de l'Ibérie par rapport à l'Europe
Zone de convergence

D. Quelques reconstitutions

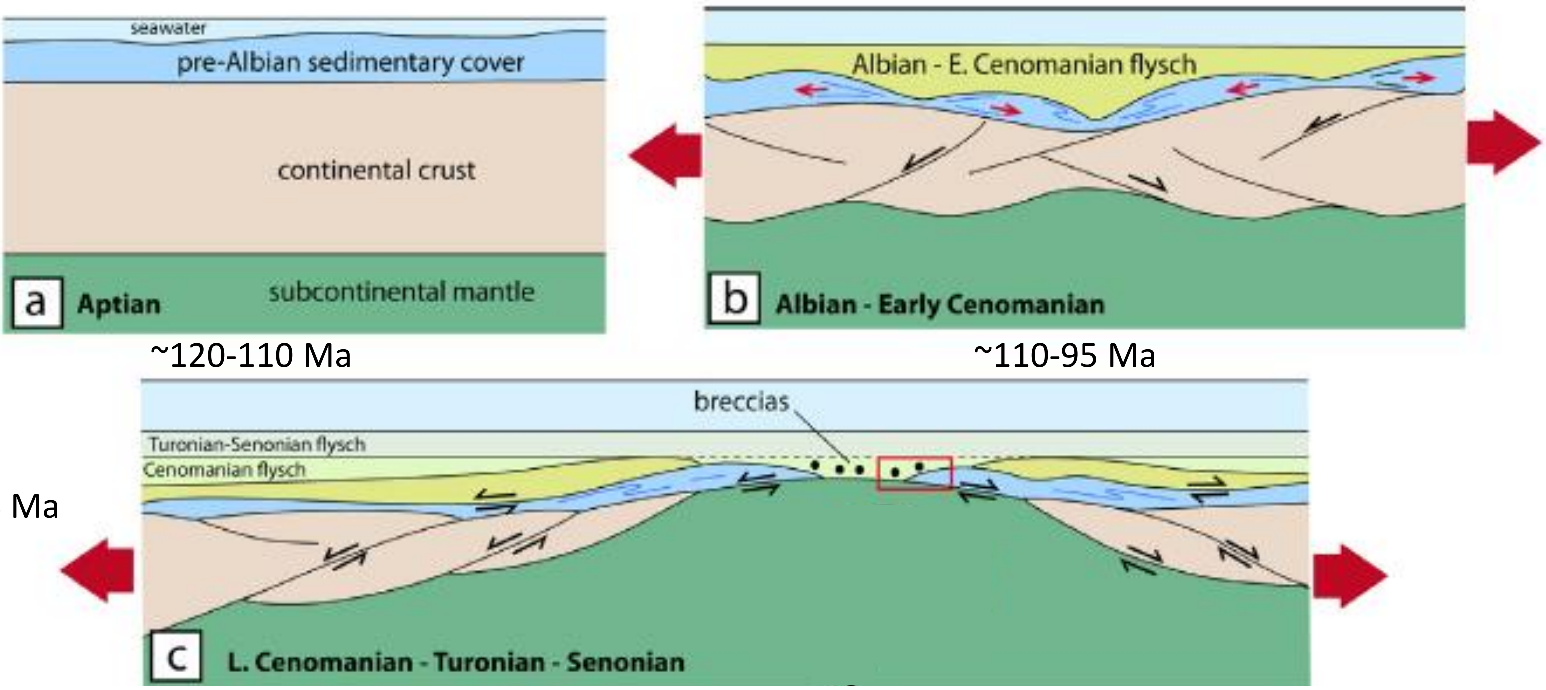

a) Roure et al., 1989
S
N
NPF
0
25
50
Km
b) Lagabrielle et al., 2010
SSW
NNE
km
0
10
20
30
Organya basin
Future Pyrenean Axial Zone
Bassiès granite
North-Pyrenean Fault
Aulus basin
Trois-Seigneurs Massif
Tarascon basin
Arize Massif
Camarade basin
Upper Crust
Lower Crust
Subcontinental Mantle
10 km
Albian
Jurassic
Triassic
Tectonic denudation
Olistoliths of mantle rocks (Lherzolites)
c) Jammes et al., 2009
Thinning and Exhumation faults
Strike-slip faults
Cenomanian Maastrichtien
Upper Aptian Cenomanian
Jurassic Lower Aptian
Triassic
Upper crust
Middle and Lower crust
Mantle
S
N
Future South Pyrenean Zone
Future Axial zone
Future North Pyrenean Zone
Future Aquitain Basin
0 km
-10
-20
-30
-40
0
20 km

(Lagabrielle et al., 2019)


dominant simple shear
detached pre-rift cover
dominant pure shear (flattening)
syn-rift flysch
continental crust
exhumed mantle
continental crust
A
cover décollement
detached prerift cover
Triassic sole
continental crust
exhumed mantle
crust-mantle detachment
B

Modèles conceptuels d'amincissement crustal extrême avec exhumation du manteau

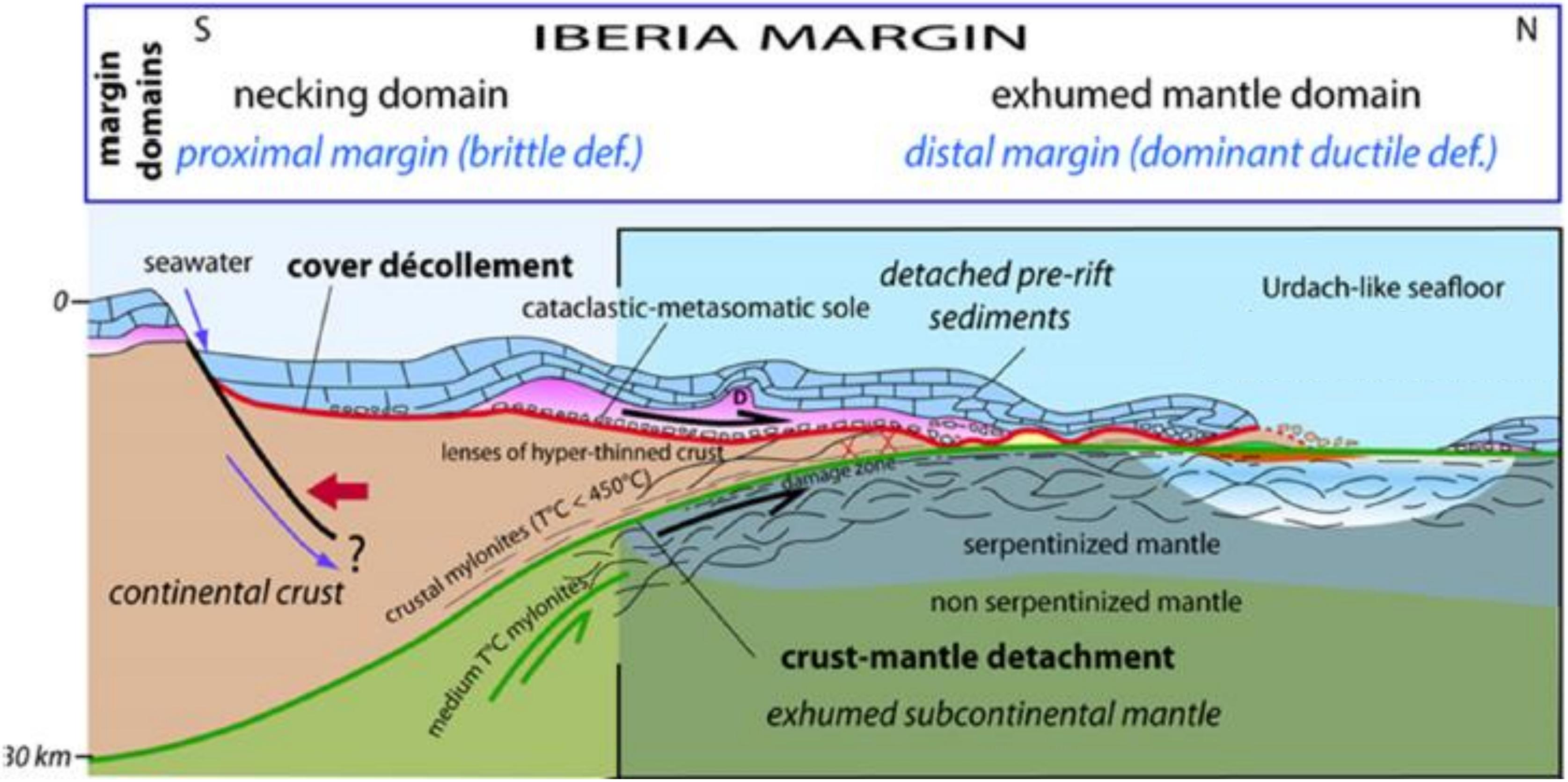
Un modèle possible pour l'extension crétacée dans le domaine pyrénéen


seawater
pre-Albian sedimentary cover
continental crust
subcontinental mantle
a
Aptian
Albian - E. Cenomanian flysch
b
Albian - Early Cenomanian
breccias
Turonian-Senonian flysch
Cenomanian flysch
c
L. Cenomanian - Turonian - Senonian

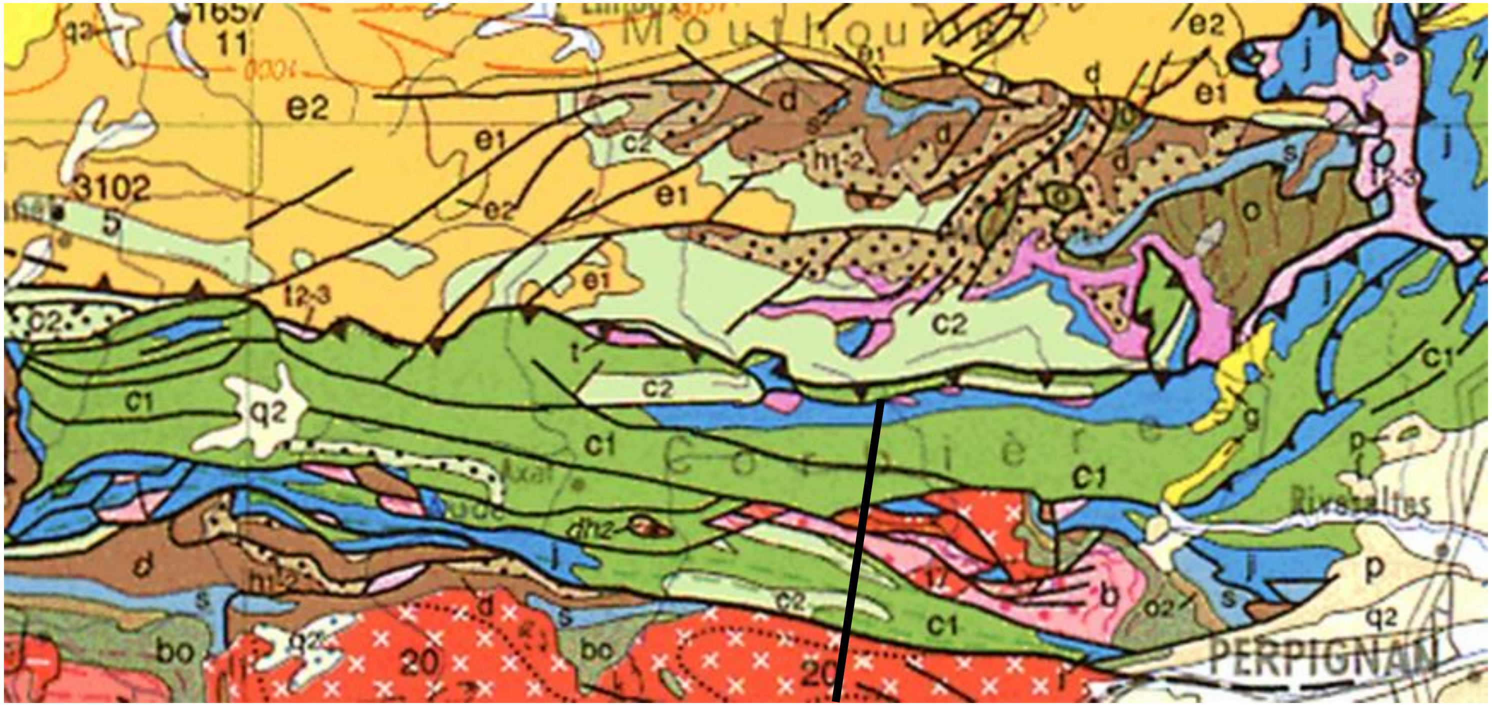
~120-110 Ma

~110-95 Ma

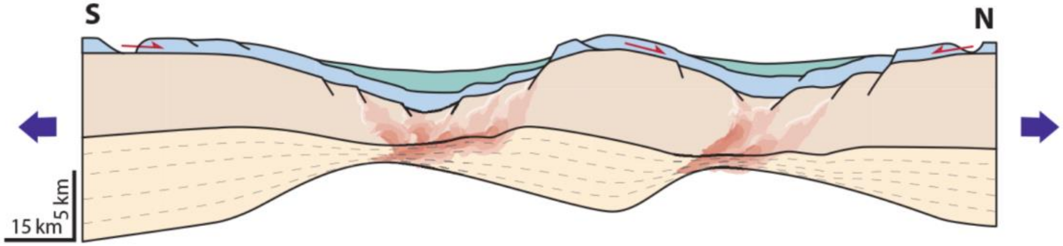
~95-84 Ma


margin domains
S
IBERIA MARGIN
N
necking domain
exhumed mantle domain
proximal margin (brittle def.)
distal margin (dominant ductile def.)
seawater
cover décollement
cataclastic-metasomatic sole
detached pre-rift sediments
Urdach-like seafloor
0
D
lenses of hyper-thinned crust
damage zone
crustal mylonites (T°C < 450°C)
?
continental crust
serpentinized mantle
non serpentinized mantle
medium T°C mylonites
crust-mantle detachment
exhumed subcontinental mantle
30 km

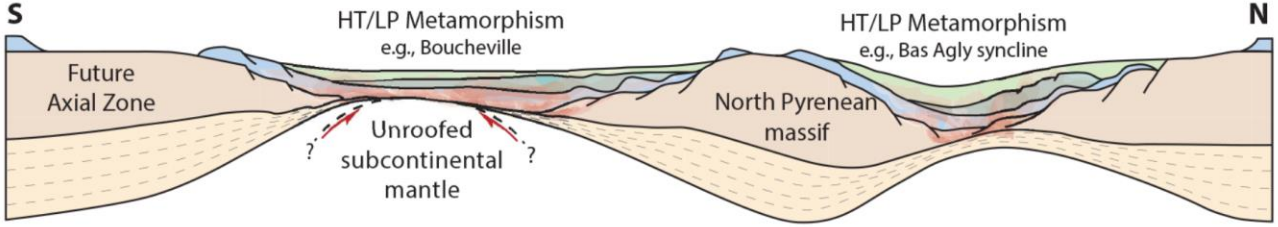
(Lagabrielle et al., 2019)


Mouthoumet
1657
11
3102
e2
e1
d
c2
c1
q2
h1-2
t2-3
t
o
j
s
g
p
b
bo
dh2
o2
20
Corbières
Axat
Rivesaltes
PERPIGNAN

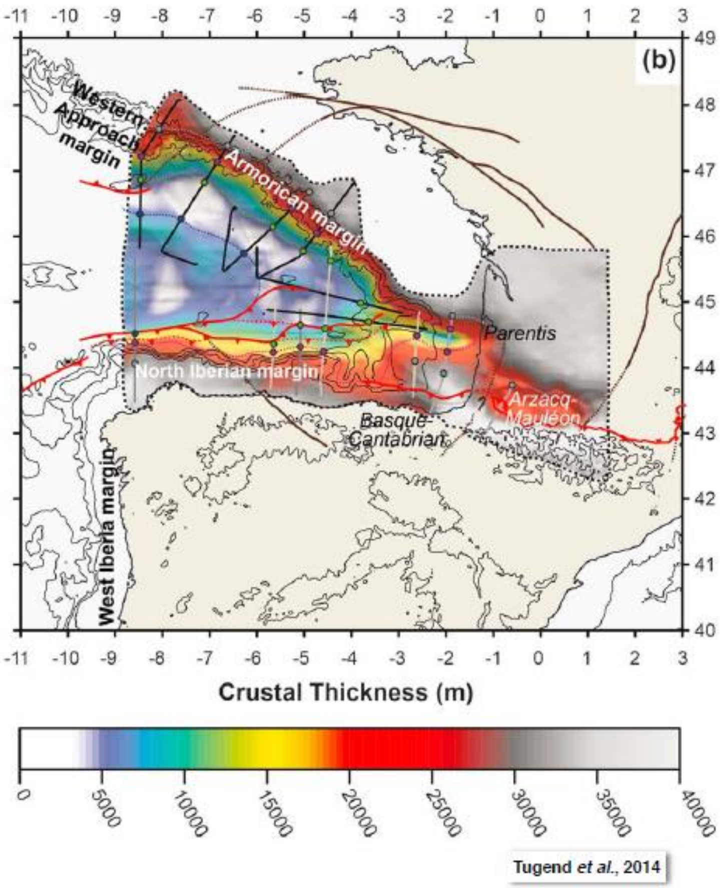
Late Aptian–Albian: fluids and metasomatism in the crust

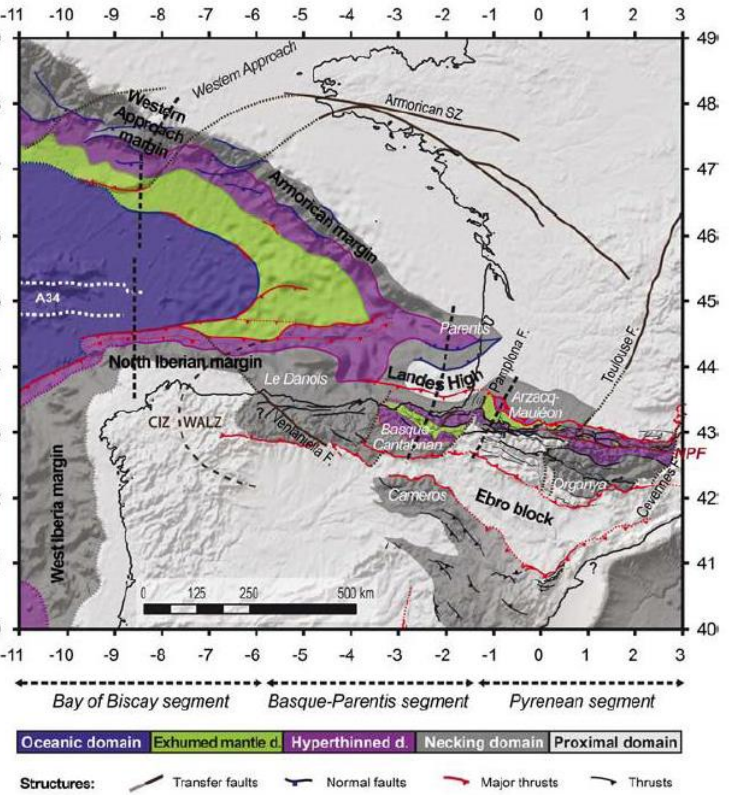


Cenomanian to Coniacian: HT/LP metamorphism in the Mesozoic cover

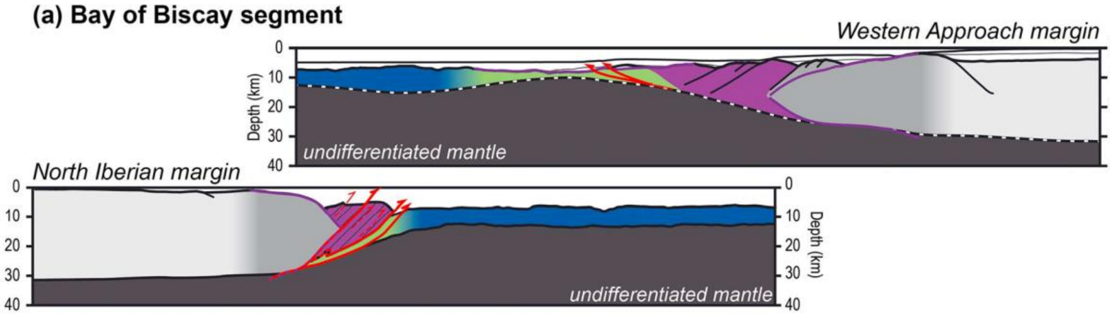

S
N
HT/LP Metamorphism
e.g., Boucheville
HT/LP Metamorphism
e.g., Bas Agly syncline
Future
Axial Zone
Unroofed
subcontinental
mantle
North Pyrenean
massif
?
?

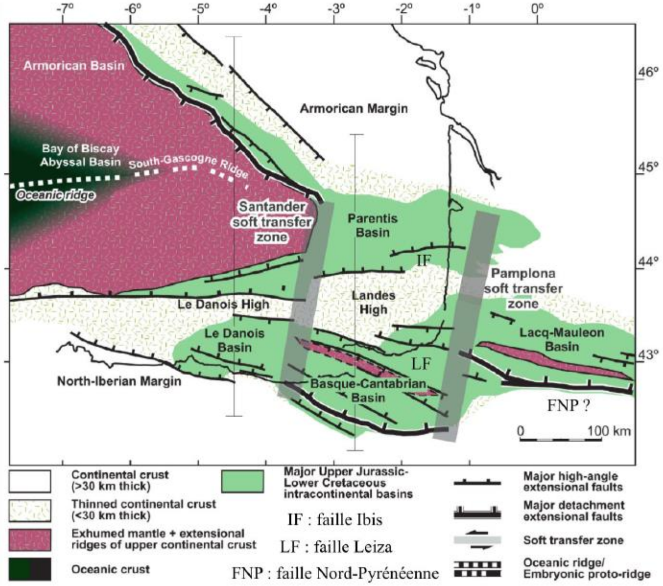
Clerc et al. (2015)


(b)
Western Approach margin
Armorican margin
Parentis
North Iberian margin
Basque-Cantabrian
Arzacq-Mauléon
West Iberia margin
Crustal Thickness (m)
0
5000
10000
15000
20000
25000
30000
35000
40000
Tugend et al., 2014

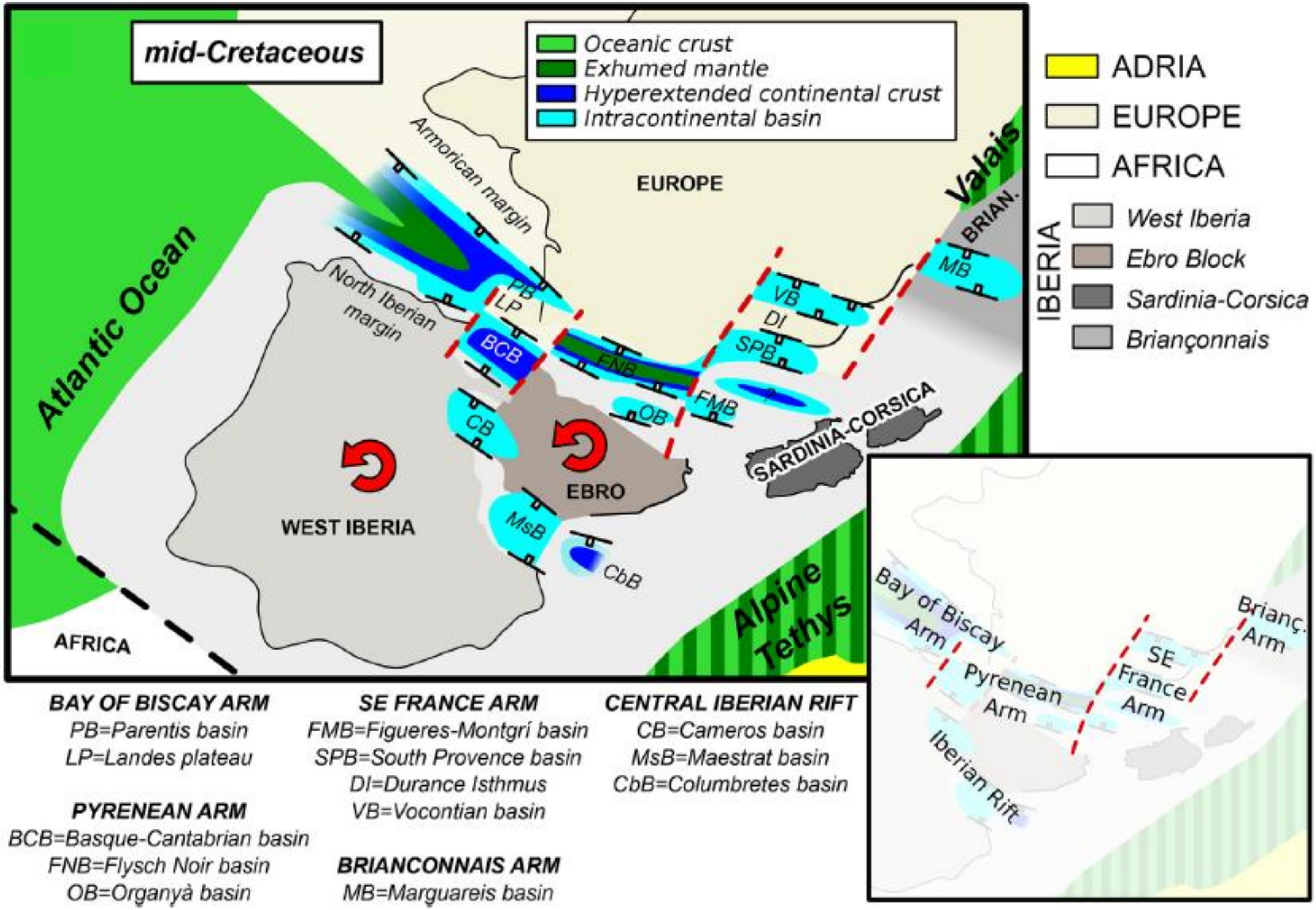

Western Approach
Armorican SZ
Western Approach margin
Armorican margin
A34
Parentis
North Iberian margin
Le Danois
Landes High
Pamplona F.
Toulouse F.
Arzacq-Mauléon
CIZ
WALZ
Ventaniella F.
Basque-Cantabrian
NPF
West Iberia margin
Cameros
Ebro block
Organya
Cevennes F.
0 125 250 500 km
Bay of Biscay segment
Basque-Parentis segment
Pyrenean segment
Oceanic domain
Exhumed mantle d.
Hyperthinned d.
Necking domain
Proximal domain
Structures:
Transfer faults
Normal faults
Major thrusts
Thrusts

(Tugend et al., 2014)


(a) Bay of Biscay segment
Western Approach margin
Depth (km)
undifferentiated mantle
North Iberian margin
Depth (km)
undifferentiated mantle


Armorican Basin
Armorican Margin
Bay of Biscay Abyssal Basin
South-Gascogne Ridge
Oceanic ridge
Santander soft transfer zone
Parentis Basin
IF
Landes High
Pamplona soft transfer zone
Le Danois High
Le Danois Basin
LF
Lacq-Mauleon Basin
Basque-Cantabrian Basin
North-Iberian Margin
FNP ?
0 100 km
Continental crust (>30 km thick)
Thinned continental crust (<30 km thick)
Exhumed mantle + extensional ridges of upper continental crust
Oceanic crust
Major Upper Jurassic-Lower Cretaceous intracontinental basins
IF : faille Ibis
LF : faille Leiza
FNP : faille Nord-Pyrénéenne
Major high-angle extensional faults
Major detachment extensional faults
Soft transfer zone
Oceanic ridge/ Embryonic proto-ridge

(Roca et al., 2010)


mid-Cretaceous
🟩 Oceanic crust
🟩 Exhumed mantle
🟦 Hyperextended continental crust
🟦 Intracontinental basin
🟨 ADRIA
▭ EUROPE
☐ AFRICA
IBERIA
▭ West Iberia
▭ Ebro Block
▭ Sardinia-Corsica
▭ Briançonnais
Atlantic Ocean
Armorican margin
EUROPE
Valais
BRIAN.
North Iberian margin
PB
LP
BCB
FNB
OB
FMB
VB
DI
SPB
MB
CB
MsB
CbB
WEST IBERIA
EBRO
SARDINIA-CORSICA
Alpine Tethys
AFRICA
Bay of Biscay Arm
Pyrenean Arm
SE France Arm
Brianç. Arm
Iberian Rift

BAY OF BISCAY ARM
PB=Parentis basin
LP=Landes plateau

PYRENEAN ARM
BCB=Basque-Cantabrian basin
FNB=Flysch Noir basin
OB=Organyà basin

SE FRANCE ARM
FMB=Figueres-Montgrí basin
SPB=South Provence basin
DI=Durance Isthmus
VB=Vocontian basin

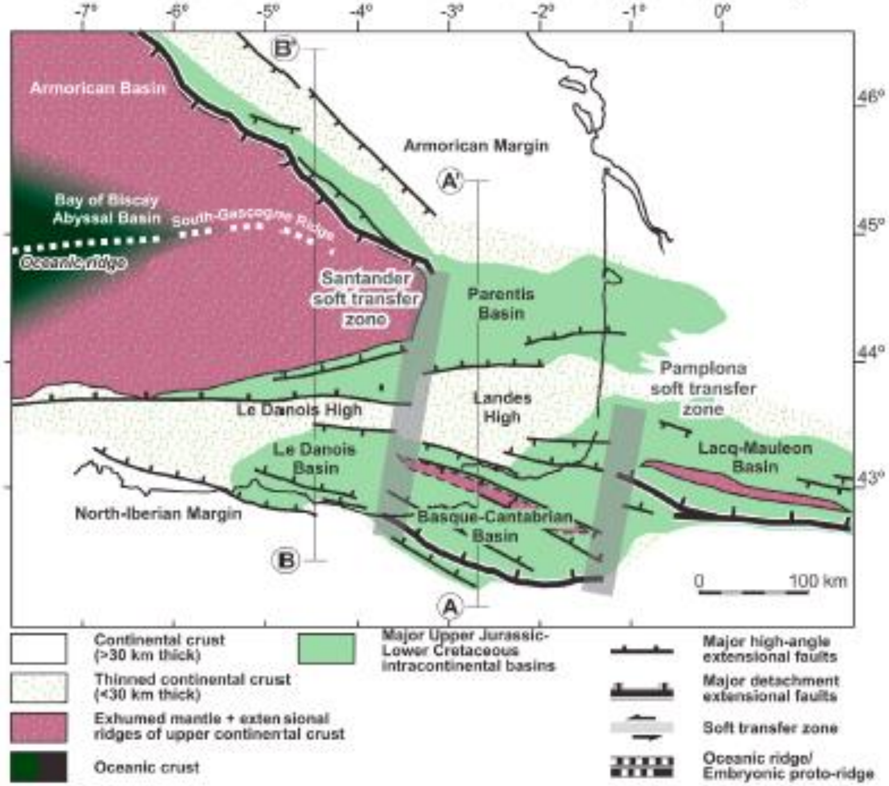
BRIANCONNAIS ARM
MB=Marguareis basin

CENTRAL IBERIAN RIFT
CB=Cameros basin
MsB=Maestrat basin
CbB=Columbretes basin

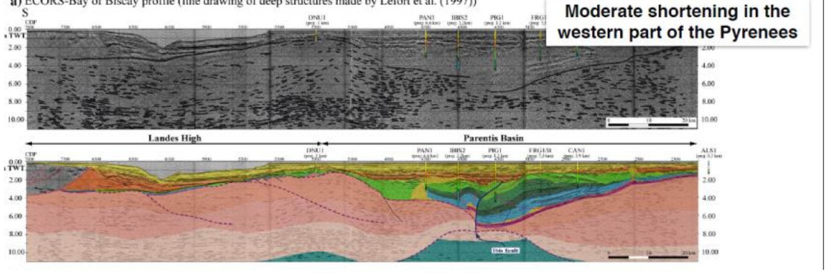
Tavani et al., 2019

D. La fermeture du sillon pyrénéen

END OF EXTENSIONAL BAY OF BISCAY OPENING (CENOMANIAN)

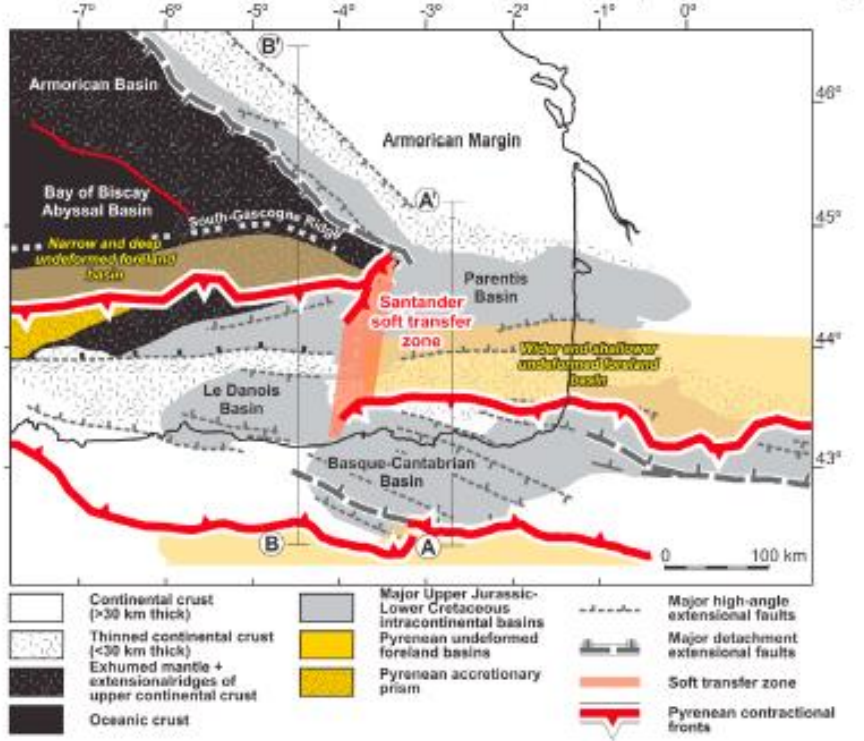

-7°
-6°
-5°
-4°
-3°
-2°
-1°
0°
46°
45°
44°
43°
Armorican Basin
Armorican Margin
B'
A'
Bay of Biscay Abyssal Basin
South-Gascogne Ridge
Oceanic ridge
Santander soft transfer zone
Parentis Basin
Pamplona soft transfer zone
Le Danois High
Landes High
Le Danois Basin
Lacq-Mauleon Basin
North-Iberian Margin
Basque-Cantabrian Basin
B
A
0
100 km
Continental crust (>30 km thick)
Thinned continental crust (<30 km thick)
Exhumed mantle + extensional ridges of upper continental crust
Oceanic crust
Major Upper Jurassic-Lower Cretaceous intracontinental basins
Major high-angle extensional faults
Major detachment extensional faults
Soft transfer zone
Oceanic ridge/ Embryonic proto-ridge

a) ECORS-Bay of Biscay profile (line drawing of deep structures made by Lefort et al. (1997))

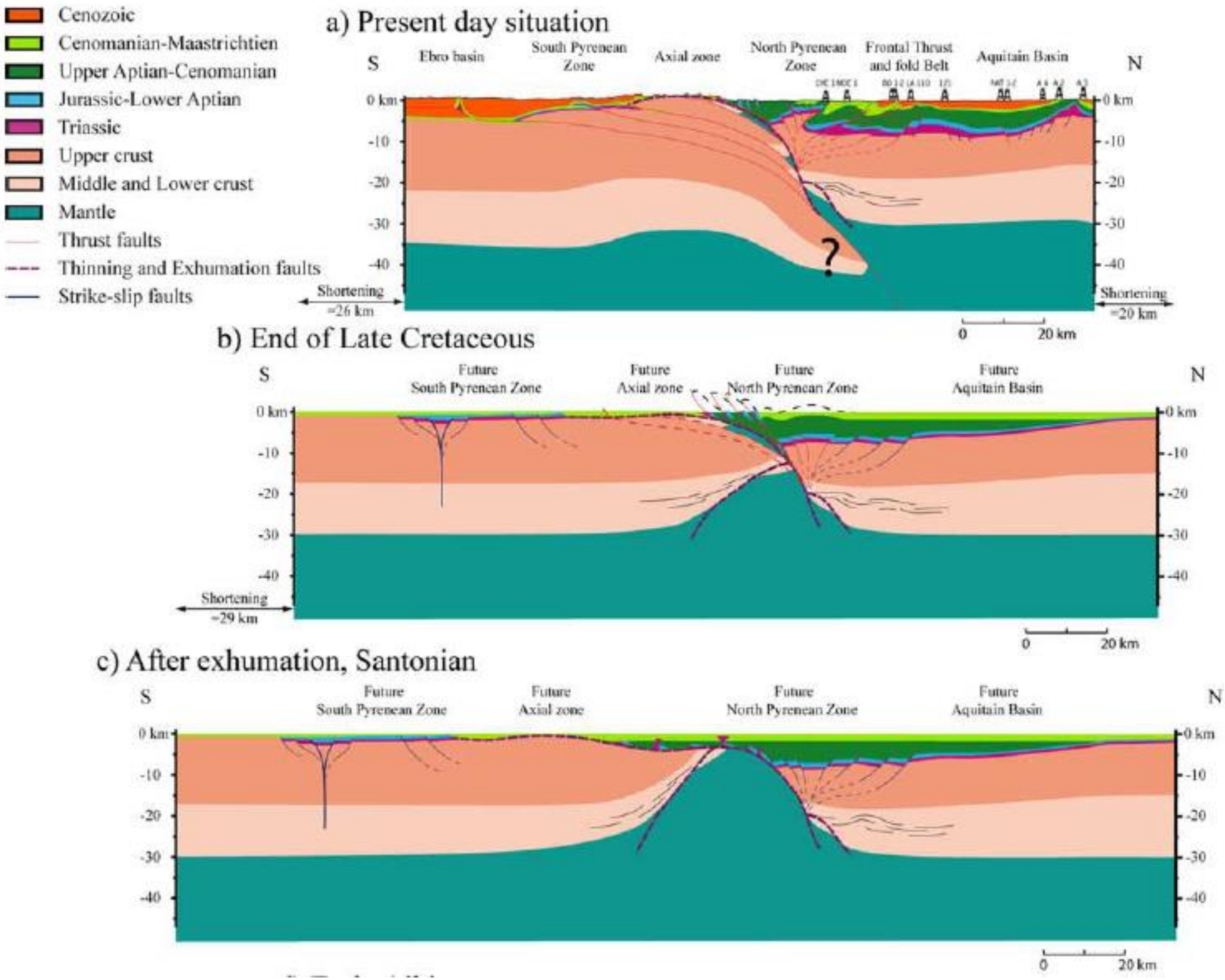

S
CDP
TWT
0.00
2.00
4.00
6.00
8.00
10.00
DNU1
PAN1
BBIS2
PIG1
FRG1
Landes High
Parentis Basin
FRG1/8
CAN1
ALS1
0
10
20 km

Moderate shortening in the western part of the Pyrenees

END OF PYRENEAN CONTRACTIONAL DEFORMATION (MIDDLE MIOCENE)


-7°
-6°
-5°
-4°
-3°
-2°
-1°
0°
46°
45°
44°
43°
Armorican Basin
Armorican Margin
B'
A'
Bay of Biscay Abyssal Basin
South-Gascogne Ridge
Narrow and deep undeformed foreland basin
Santander soft transfer zone
Parentis Basin
Wider and shallower undeformed foreland basin
Le Danois Basin
Basque-Cantabrian Basin
B
A
0
100 km
Continental crust (>30 km thick)
Thinned continental crust (<30 km thick)
Exhumed mantle + extensionalridges of upper continental crust
Oceanic crust
Major Upper Jurassic-Lower Cretaceous intracontinental basins
Pyrenean undeformed foreland basins
Pyrenean accretionary prism
Major high-angle extensional faults
Major detachment extensional faults
Soft transfer zone
Pyrenean contractional fronts

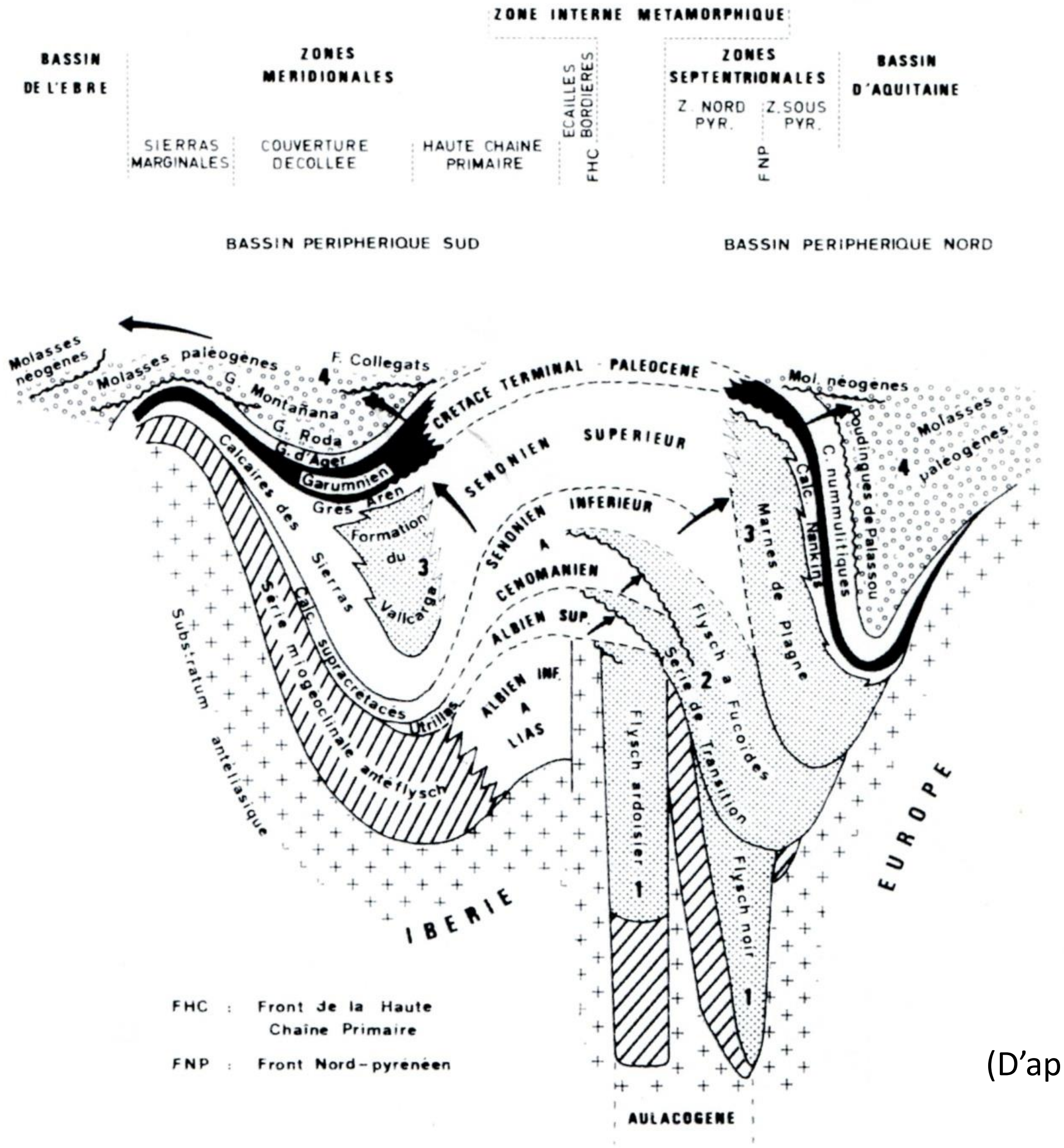
Roca *et al.*, 2011


Cenozoic
Cenomanian-Maastrichtien
Upper Aptian-Cenomanian
Jurassic-Lower Aptian
Triassic
Upper crust
Middle and Lower crust
Mantle
Thrust faults
Thinning and Exhumation faults
Strike-slip faults
a) Present day situation
S
Ebro basin
South Pyrenean Zone
Axial zone
North Pyrenean Zone
Frontal Thrust and fold Belt
Aquitain Basin
N
0 km
-10
-20
-30
-40
?
Shortening =26 km
Shortening =20 km
0
20 km
b) End of Late Cretaceous
S
Future South Pyrenean Zone
Future Axial zone
Future North Pyrenean Zone
Future Aquitain Basin
N
0 km
-10
-20
-30
-40
Shortening =29 km
0
20 km
c) After exhumation, Santonian
S
Future South Pyrenean Zone
Future Axial zone
Future North Pyrenean Zone
Future Aquitain Basin
N
0 km
-10
-20
-30
-40
0
20 km

(Jammes et al., 2009)

III. Calendrier et modèle d'évolution du domaine pyrénéen ; évolution récente;

A. Calendrier


ZONE INTERNE METAMORPHIQUE
BASSIN DE L'EBRE
ZONES MERIDIONALES
ECAILLES BORDIERES
ZONES SEPTENTRIONALES
BASSIN D'AQUITAINE
Z. NORD PYR.
Z. SOUS PYR.
SIERRAS MARGINALES
COUVERTURE DECOLLEE
HAUTE CHAINE PRIMAIRE
FHC
FNP
BASSIN PERIPHERIQUE SUD
BASSIN PERIPHERIQUE NORD
Molasses neogenes
Molasses paléogènes
F. Collegats
4
G. Montañana
G. Roda
G. d'Ager
Garumnien
Gres Aren
Formation du Vallcarga
3
Calcaires des Sierras
Calc. supracrétacés
Trilles
Série miogéoclinale antéflysch
Substratum antéliasique
CRETACE TERMINAL - PALEOCENE
SENONIEN SUPERIEUR
SENONIEN INFERIEUR A CENOMANIEN
ALBIEN SUP.
ALBIEN INF. A LIAS
Flysch ardoisier
1
Série de Transition
2
Flysch à Fucoides
Flysch noir
1
Marnes de Plagne
3
Calc. Nankin
C. nummulitiques
Poudingues de Palassou
Mol. néogènes
Molasses paléogènes
4
IBERIE
EUROPE
AULACOGENE
FHC : Front de la Haute Chaîne Primaire
FNP : Front Nord-pyrénéen

Principales séries synorogéniques des Pyrénées sur une transversale navarro-languedocienne.

Le schéma illustre les situations tectoniques, faciès, variations d'épaisseurs, relations et significations tecto-sédimentaires.

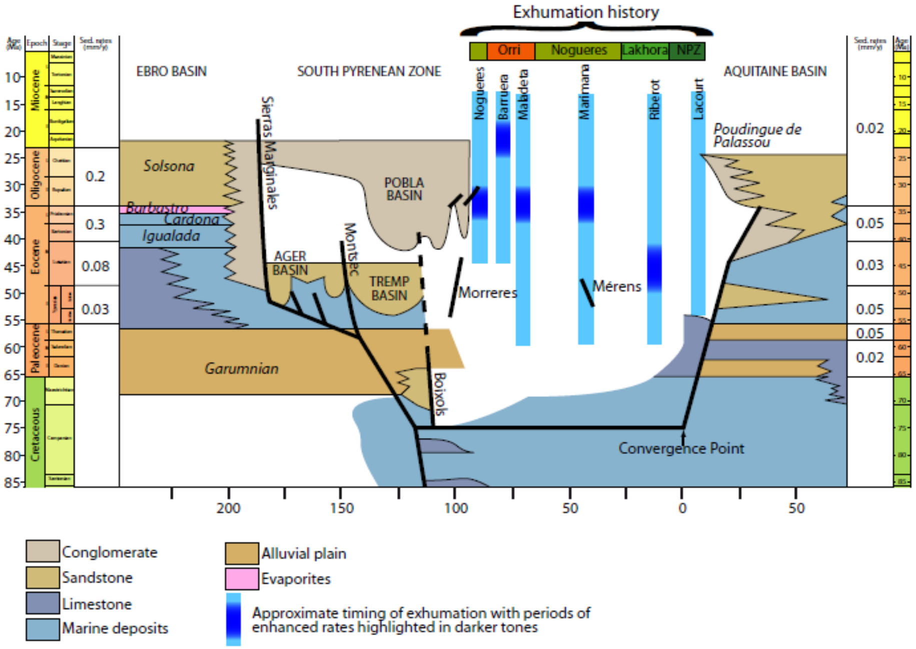
Stade aulacogène : séries à turbidites du Crétacé moyen (1) en position intercratonique dans un rift sur des ensembles miogéoclinaux antéflysch très érodés.

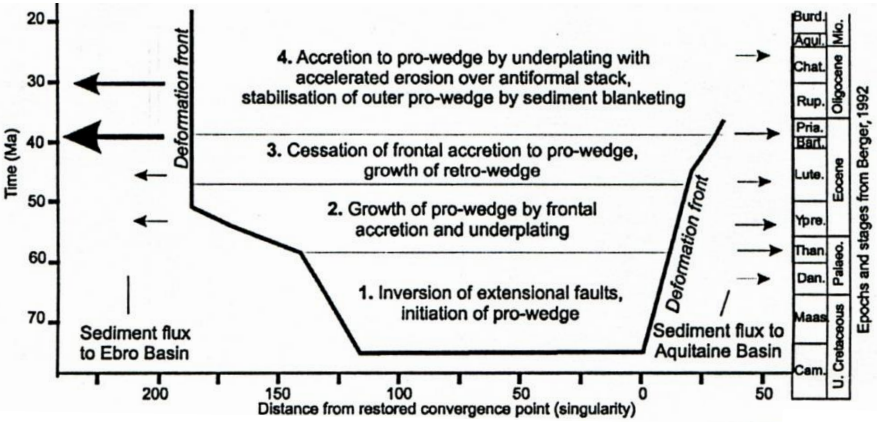
Stade bassins périphériques (postcollision cratonique) : migration des dépoaxes en avant des deux fronts orogéniques actifs (flèches), pour les séries à turbidites du Cénomanien au Sénonien inférieur (2), les séries à turbidites et littorales du Sénonien supérieur (3), les séries fluvio-continentales du Paléogène (4).

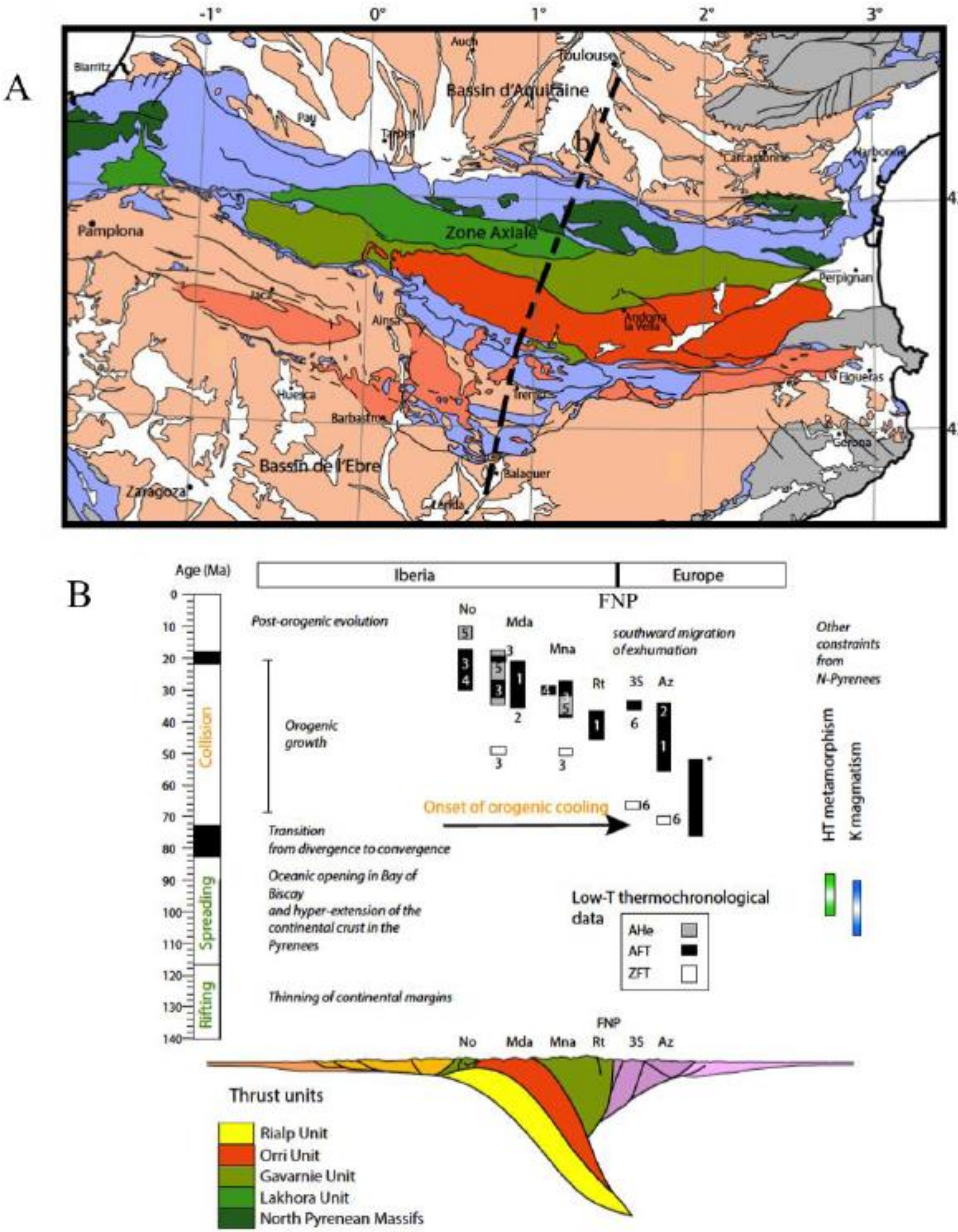
(D'après Souquet et al)

Synthèse de la séquence de déformation (exhumation chaîne axiale + chevauchements + sédimentation dans l'avant-pays).

Sinclair et al., AJS, 2005


Exhumation history
Orri
Nogueres
Lakhora
NPZ
Age (Ma)
Epoch
Stage
Sed. rates (mm/y)
Miocene
Oligocene
Eocene
Paleocene
Cretaceous
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
0.2
0.3
0.08
0.03
0.02
0.05
0.03
0.05
0.05
0.02
EBRO BASIN
SOUTH PYRENEAN ZONE
AQUITAINE BASIN
Solsona
Barbastro
Cardona
Igualada
Sierras Marginales
AGER BASIN
Montsec
TREMP BASIN
POBLA BASIN
Boixols
Garumnian
Nogueres
Barrueia
Maladeta
Marimana
Riberot
Lacourt
Morreres
Mérens
Poudingue de Palassou
Convergence Point
200
150
100
50
0
50
Conglomerate
Sandstone
Limestone
Marine deposits
Alluvial plain
Evaporites
Approximate timing of exhumation with periods of enhanced rates highlighted in darker tones


Time (Ma)
20
30
40
50
60
70
Deformation front
Deformation front
4. Accretion to pro-wedge by underplating with accelerated erosion over antiformal stack, stabilisation of outer pro-wedge by sediment blanketing
3. Cessation of frontal accretion to pro-wedge, growth of retro-wedge
2. Growth of pro-wedge by frontal accretion and underplating
1. Inversion of extensional faults, initiation of pro-wedge
Sediment flux to Ebro Basin
Sediment flux to Aquitaine Basin
200
150
100
50
0
50
Distance from restored convergence point (singularity)
Burd.
Aqui.
Chat.
Rup.
Pria.
Bart.
Lute.
Ypre.
Than.
Dan.
Maas.
Cam.
Mio.
Oligocene
Eocene
Palaeo.
U. Cretaceous
Epochs and stages from Berger, 1992


A
-1°
0°
1°
2°
3°
43°
42°
Biarritz
Auch
Toulouse
Bassin d'Aquitaine
Pau
Tarbes
Carcassonne
Narbonne
Pamplona
Zone Axiale
Perpignan
Ainsa
Andorra la Vella
Figueras
Huesca
Barbastro
Tremp
Gerona
Bassin de l'Ebre
Zaragoza
Balaguer
Lerida
B
Age (Ma)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Collision
Spreading
Rifting
Iberia
Europe
FNP
Post-orogenic evolution
Orogenic growth
Transition from divergence to convergence
Oceanic opening in Bay of Biscay and hyper-extension of the continental crust in the Pyrenees
Thinning of continental margins
No
Mda
Mna
Rt
3S
Az
southward migration of exhumation
Onset of orogenic cooling
Other constraints from N-Pyrenees
HT metamorphism
K magmatism
Low-T thermochronological data
AHe
AFT
ZFT
Thrust units
Rialp Unit
Orri Unit
Gavarnie Unit
Lakhora Unit
North Pyrenean Massifs

(Mouthereau et al., 2014)

Le début de la convergence à la fin du Santonien (~84 Ma) entre Ibérie et Europe se traduit dans les Pyrénées par l'inversion des accidents extensifs et des bassins Crétacé Inférieurs. Dans la ZNP, le Crétacé Supérieur est marqué par des dépôts de type flyschs calcaires voire des marnes. Dans la ZSP, dès le début du Campanien, le bassin d'Organya est inversé par le jeu du chevauchement de Boixols , relié au mouvement de l'unité de socle de Gavarnie dans la Zone Axiale. Les dépôts d'abord marins deviennent de plus en plus continentaux (fluviatiles) .

Au début de l'Eocène (Yprésien), soulèvement de la Zone Axiale.

Du milieu de l'Eocène (Lutétien) à l'Oligocène, l'exhumation de la zone axiale s'accélère. Le Nord des Pyrénées connaît une importante régression associée au développement d'un large système fluviatile orienté vers l'Ouest et le dépôt des Poudingues de Palassou en réponse à l'érosion de la chaîne. Ce soulèvement affecte également l'Ouest de la chaîne refermant ainsi les connexions avec l'océan Atlantique. Le bassin de l'Ebre devient endoréique.

A l'Oligocène Supérieur, le Sud des Pyrénées se soulève par l'activation du Chevauchement Frontal Sud-Pyrénéen et des Sierra Exteriores vers le Sud, sur le bassin de l'Ebre jusqu'au Miocène. Cela permet l'individualisation du bassin de Jaca en piggyback sur la nappe de Gavarnie, marquant ainsi la fin des déformations enregistrées dans la ZSP . A cette période, la convergence Ibérie-Europe s'arrête, entrainant le ralentissement du soulèvement de la Zone Axiale. Les dernières déformations enregistrées au Nord des Pyrénées sont datées du début du Miocène avec la formation des anticlinaux du Mas d'Azil ou de Lavelanet.

Bilan :

Domaine pyrénéen inclus dans une frontière de plaque décrochante diffuse Eurasie-Ibérie pendant le J sup-Crétacé inf.

Les indices de rifting crétacé (« marges » ?) dans les Pyrénées (~120-90 Ma):

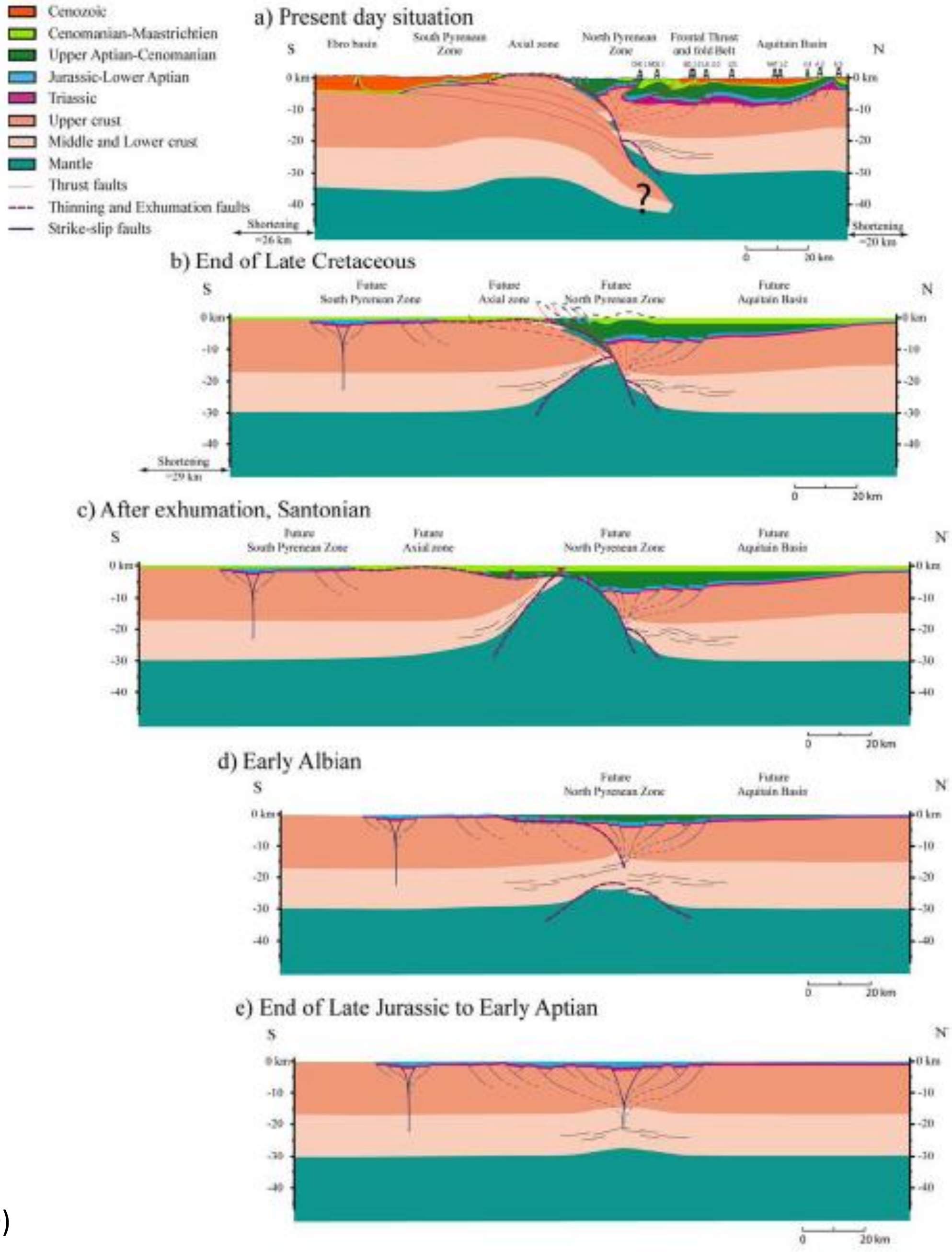
- la forte subsidence et les bassins extensifs
- l'amincissement extrême / rupture de la croûte continentale et l'exhumation du manteau lithosphérique
- le métamorphisme HT-BP
- le magmatisme alcalin

Les indices d'orogenèse « ~collisionnelle » dans les Pyrénées (~70-20 Ma) :

- l'inversion en compression des bassins extensifs au Crétacé sup. (CFNP dès 80-70Ma)
- le métamorphisme MP-MT éocène (~55-35 Ma) dans la Zone Axiale
- le raccourcissement / l'épaississement crustal et la genèse des reliefs (Zone axiale : raccourcissement/dénudation distribué 70-40Ma/localisé 40-20 Ma)
- la formation du bassin molassique sud-aquitain (Eocène sup-Oligocène-Miocène)

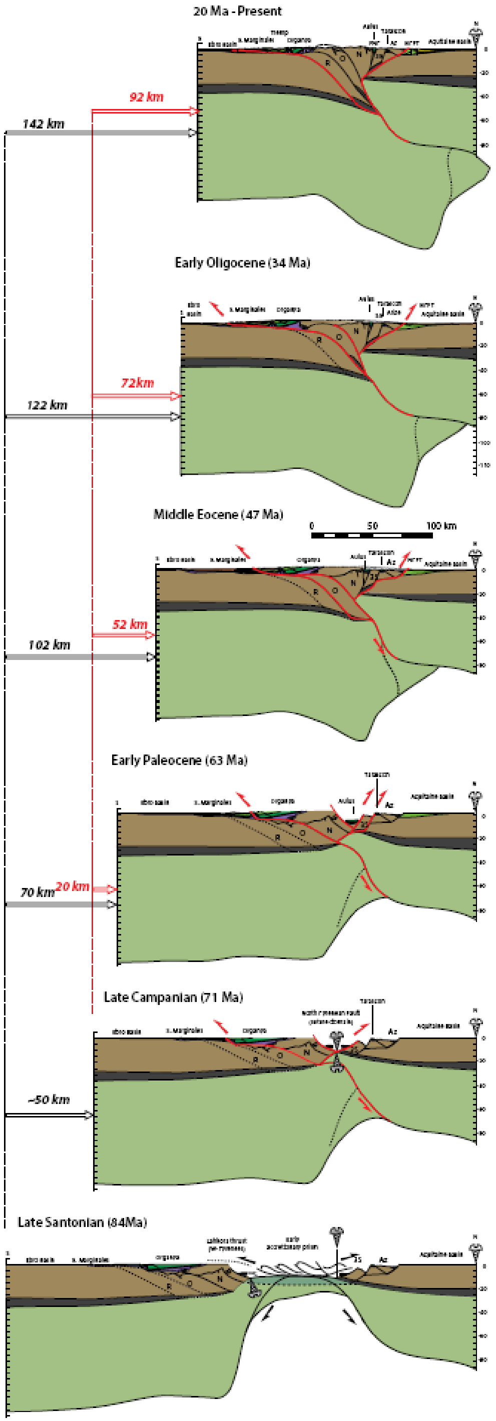
La chaîne pyrénéenne : chaîne intracontinentale / chaîne de « collision » ?

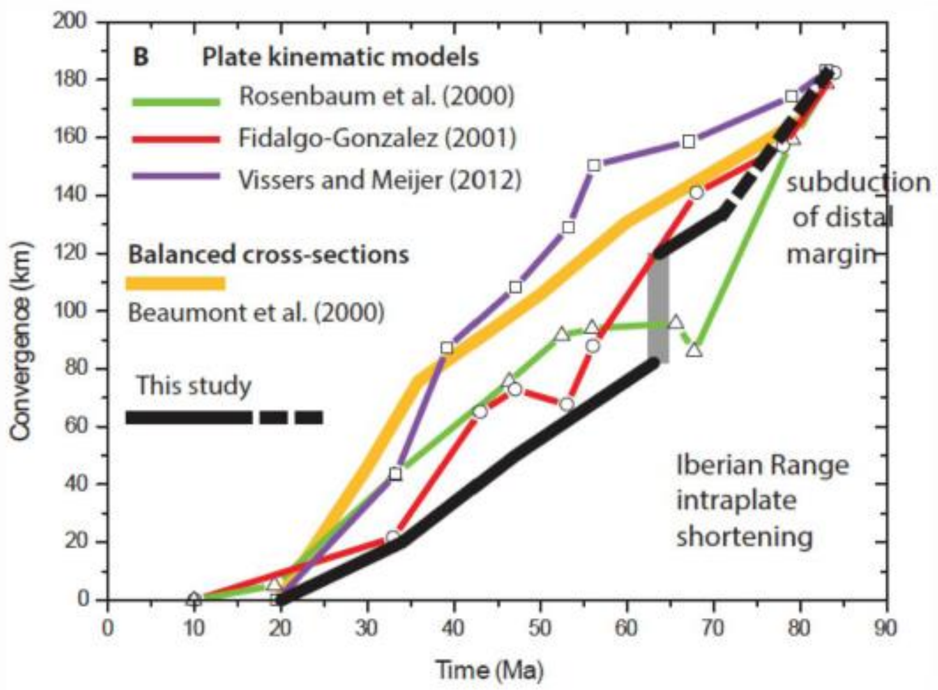
B. Modèles d’évolution orogénique

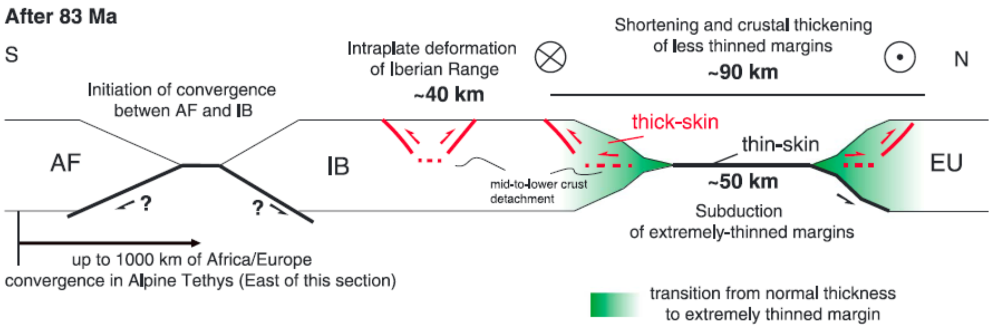


🟥 Cenozoic
🟩 Cenomanian-Maastrichtien
🟩 Upper Aptian-Cenomanian
🟦 Jurassic-Lower Aptian
🟪 Triassic
🟧 Upper crust
🟧 Middle and Lower crust
🟩 Mantle
Thrust faults
Thinning and Exhumation faults
Strike-slip faults
a) Present day situation
S
Ebro basin
South Pyrenean Zone
Axial zone
North Pyrenean Zone
Frontal Thrust and fold Belt
Aquitain Basin
N
0 km
-10
-20
-30
-40
?
Shortening ≈26 km
Shortening ≈20 km
0
20 km
b) End of Late Cretaceous
Future South Pyrenean Zone
Future Axial zone
Future North Pyrenean Zone
Future Aquitain Basin
Shortening ≈29 km
c) After exhumation, Santonian
Future South Pyrenean Zone
Future Axial zone
Future North Pyrenean Zone
Future Aquitain Basin
d) Early Albian
Future North Pyrenean Zone
Future Aquitain Basin
e) End of Late Jurassic to Early Aptian

(Jammes et al., 2009)


20 Ma - Present
92 km
142 km
Early Oligocene (34 Ma)
72km
122 km
Middle Eocene (47 Ma)
0
50
100 km
52 km
102 km
Early Paleocene (63 Ma)
70 km
20 km
Late Campanian (71 Ma)
~50 km
Late Santonian (84Ma)
R
O
N
Az




After 83 Ma

S

N

Initiation of convergence betwen AF and IB

Intraplate deformation of Iberian Range
~40 km

Shortening and crustal thickening of less thinned margins
~90 km

thick-skin

thin-skin

AF

IB

EU

mid-to-lower crust detachment

~50 km

Subduction of extremely-thinned margins

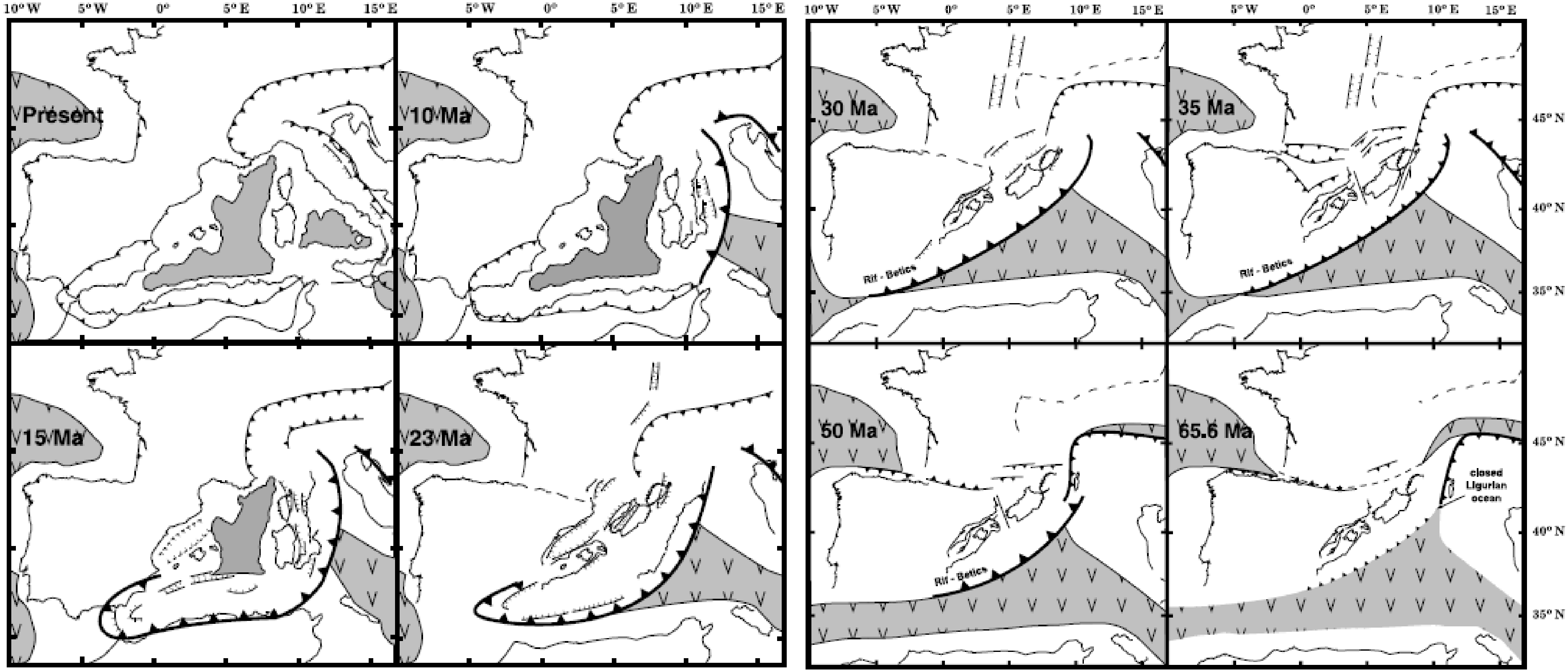
?

?

up to 1000 km of Africa/Europe convergence in Alpine Tethys (East of this section)

🟩 transition from normal thickness to extremely thinned margin

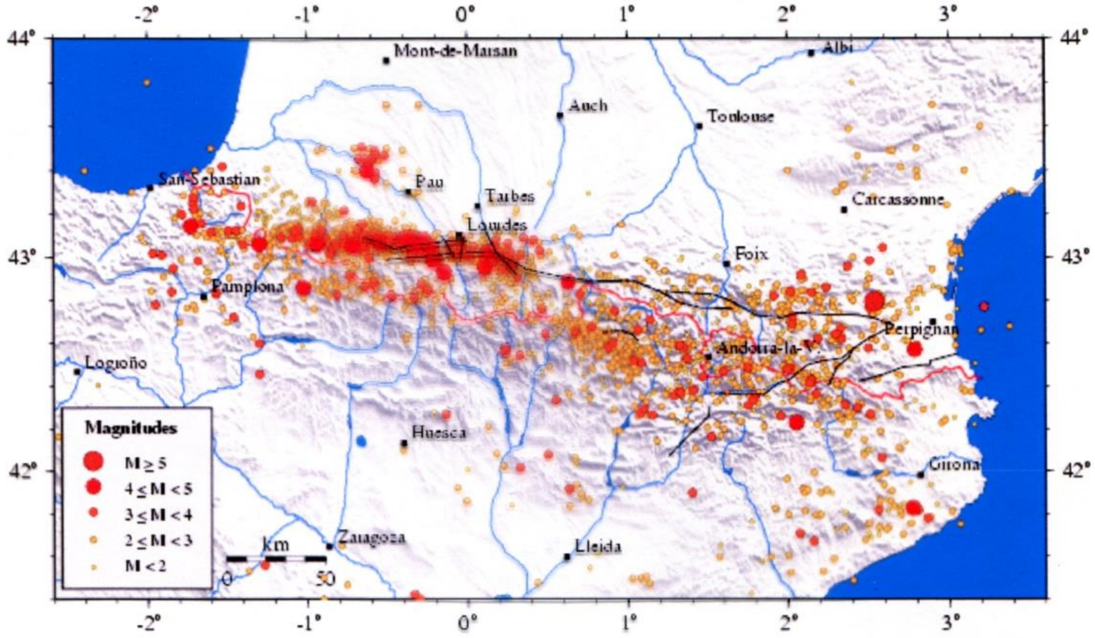
(Mouthereau et al., 2014)


10° W
5° W
0°
5° E
10° E
15° E
45° N
40° N
35° N
Present
10 Ma
15 Ma
23 Ma
30 Ma
35 Ma
50 Ma
65.6 Ma
Rif - Betics
closed Ligurian ocean

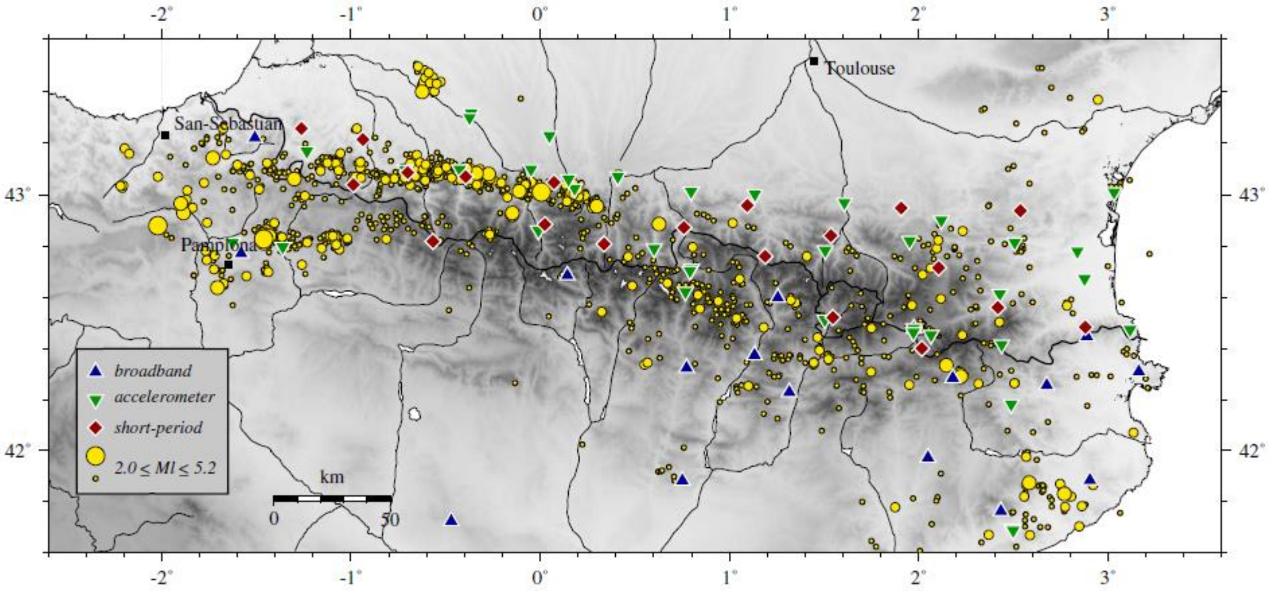
(Lacombe et Jolivet, 2005)

C. Evolution récente à actuelle

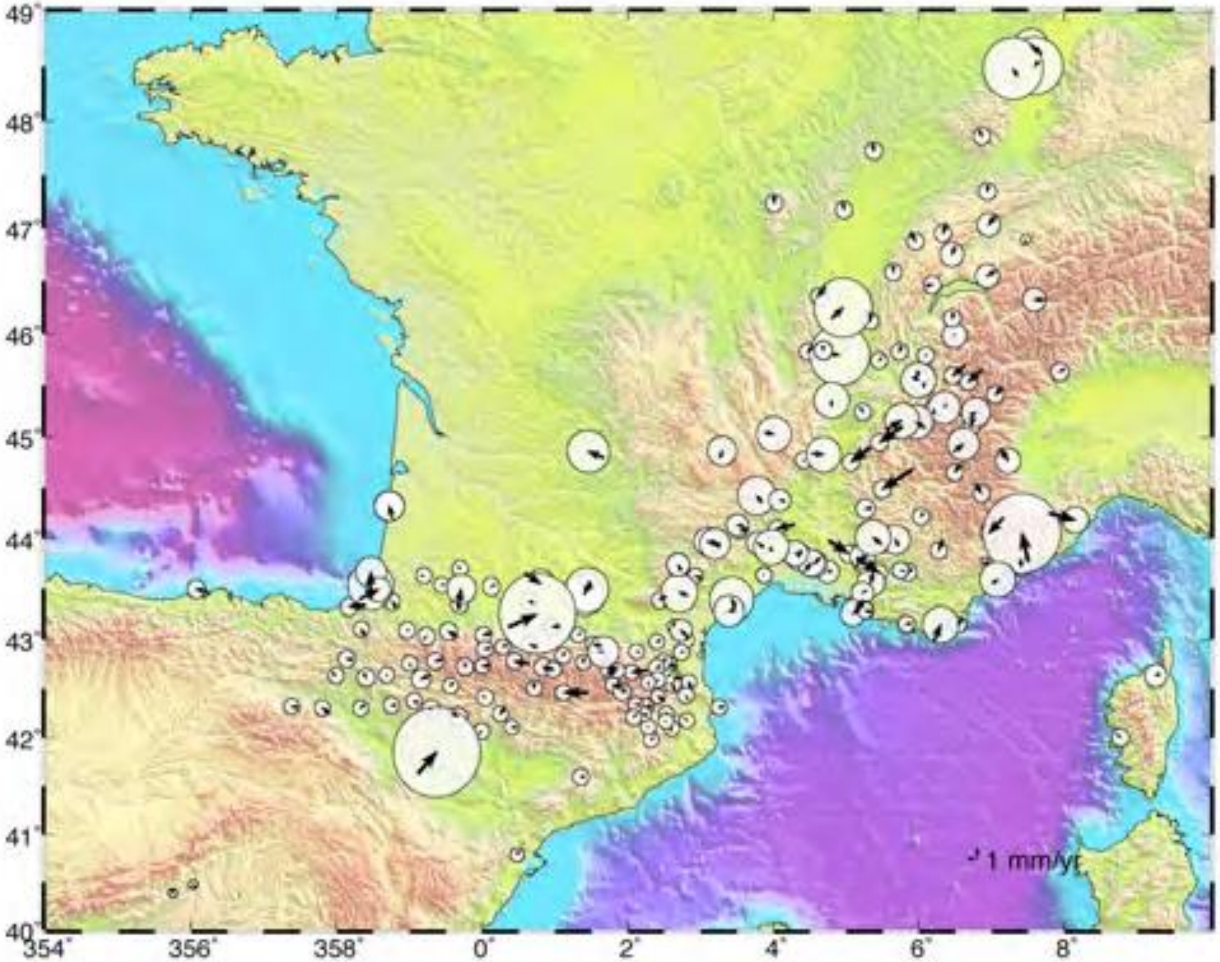
Sismicité dans les Pyrénées de 1989 à 2002 - Document OMP


-2°
-1°
0°
1°
2°
3°
44°
43°
42°
Mont-de-Marsan
Auch
Albi
Toulouse
San-Sebastian
Pau
Tarbes
Lourdes
Carcassonne
Foix
Pamplona
Perpignan
Andorra-la-V.
Logroño
Huesca
Girona
Zaragoza
Lleida
Magnitudes
M ≥ 5
4 ≤ M < 5
3 ≤ M < 4
2 ≤ M < 3
M < 2
km
0
50

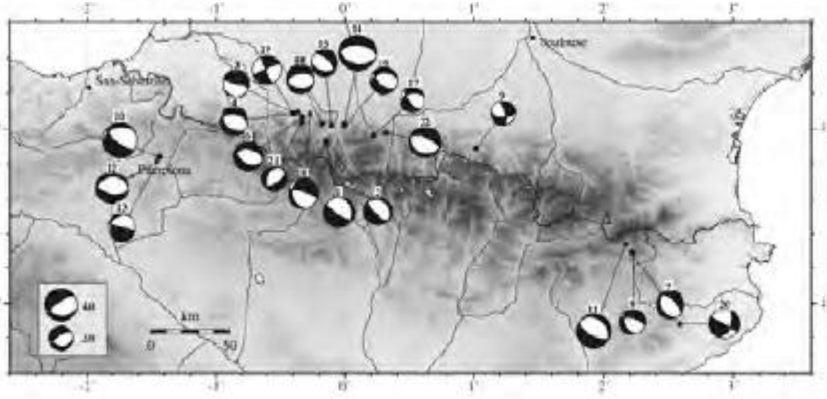
Pyrenean seismicity 1997/2010 (June)


-2°
-1°
0°
1°
2°
3°
43°
42°
Toulouse
San-Sebastian
Pamplona
broadband
accelerometer
short-period
2.0 ≤ Ml ≤ 5.2
km
0
50

Chevrot et al., 2011


49°
48°
47°
46°
45°
44°
43°
42°
41°
40°
354°
356°
358°
0°
2°
4°
6°
8°
1 mm/yr

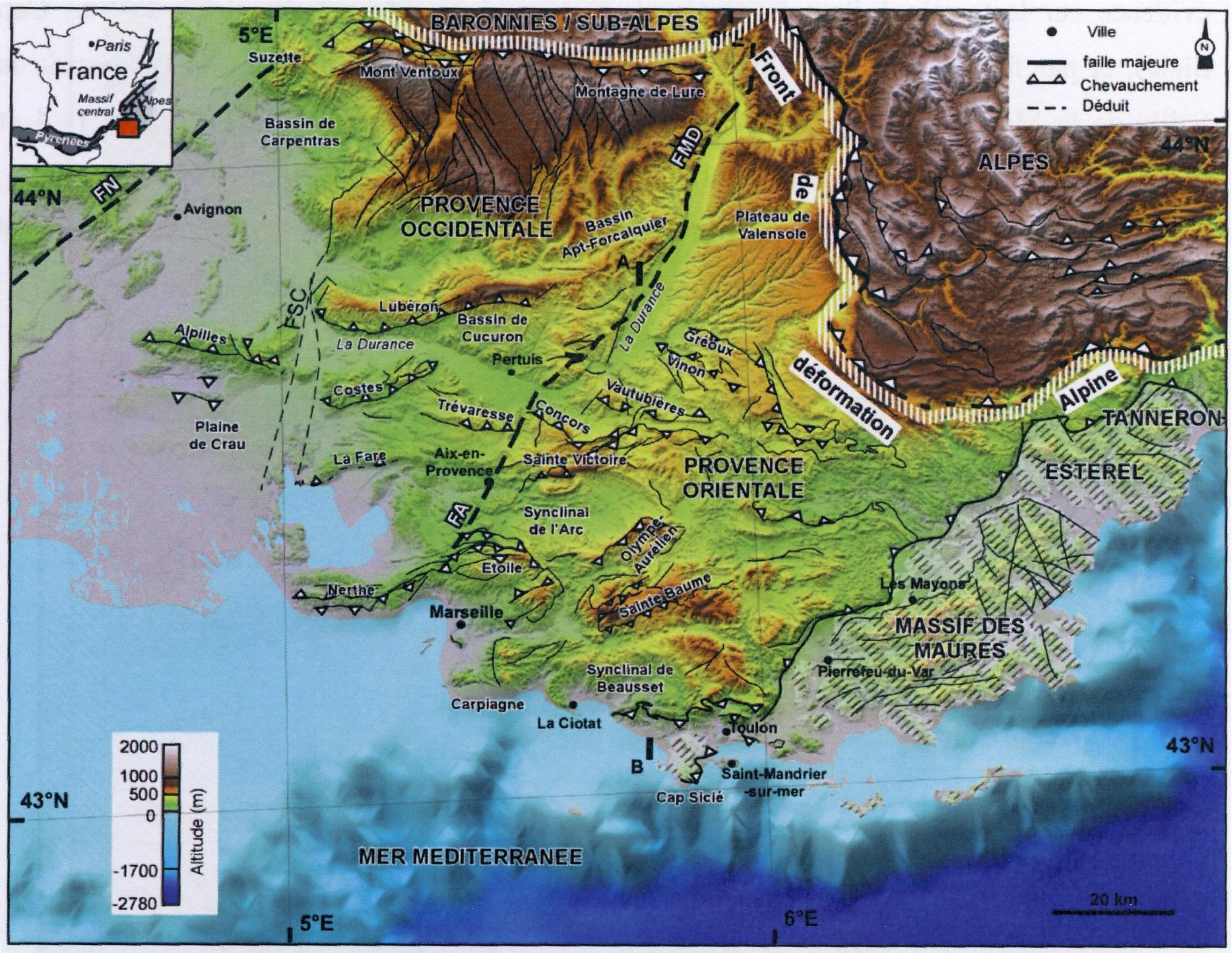
(Vernant, 2013,
unpublished


Toulouse
San Sebastian
Pamplona
km
0
50
2°
1°
0°
-1°
-2°
43°
42°

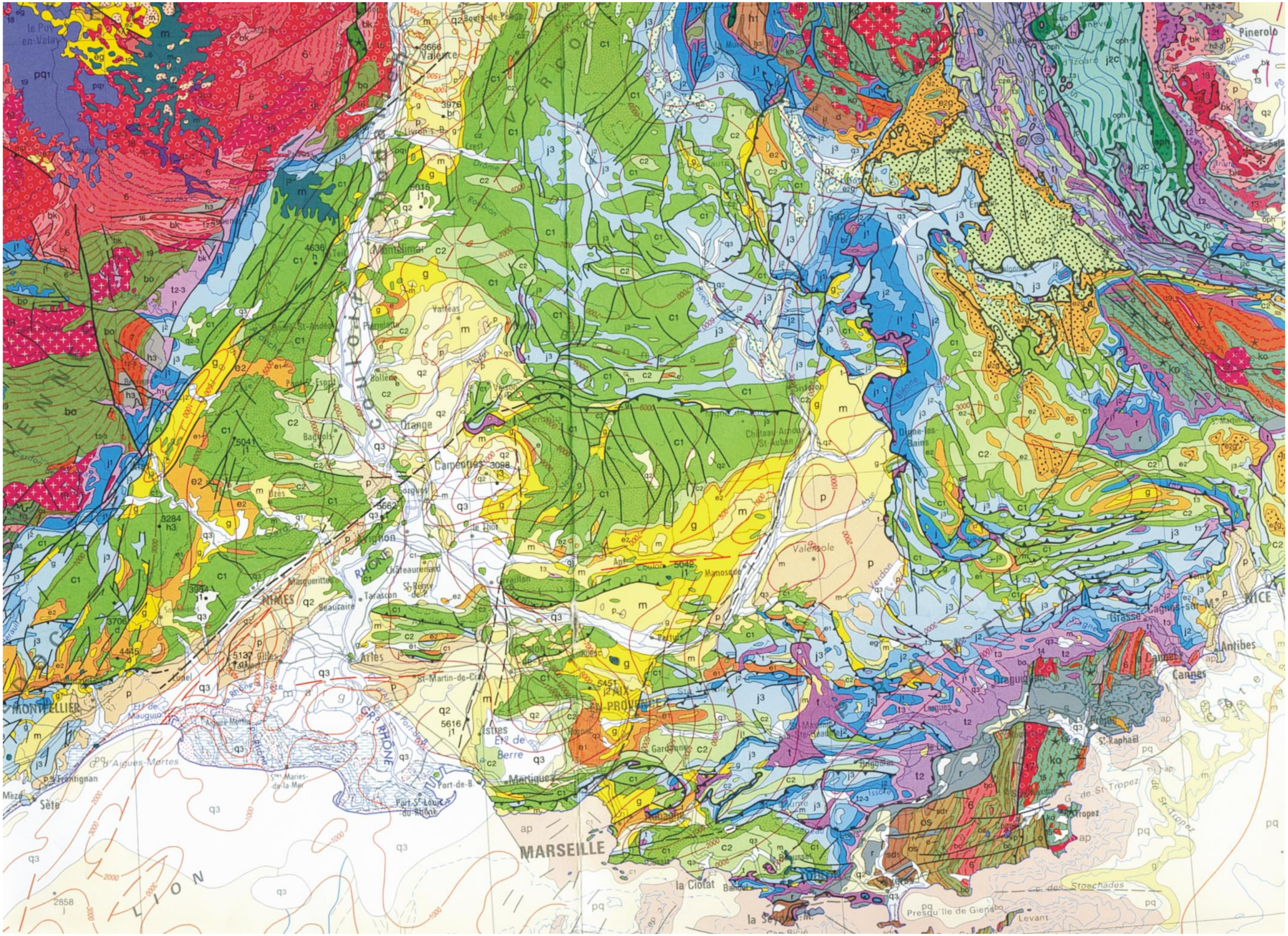
mécanismes au foyer dans les Pyrénées pour la période 2001-2011 (Chevrot *et al.*, 2011).

IV. La Provence :
prolongement vers l'Est de la chaîne pyrénéenne

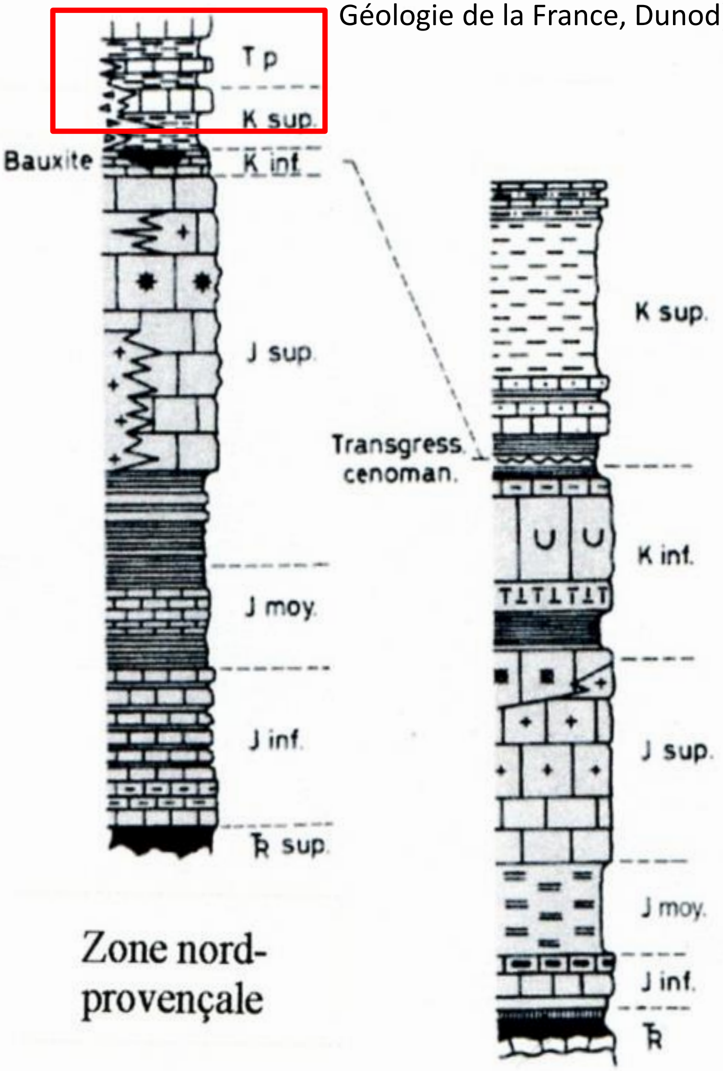
Stratigraphie et structure


BARONNIES / SUB-ALPES
5°E
Suzette
Mont Ventoux
Montagne de Lure
Front de déformation Alpine
FMD
Bassin de Carpentras
PROVENCE OCCIDENTALE
Bassin Apt-Forcalquier
Plateau de Valensole
ALPES
44°N
FN
Avignon
A
La Durance
FSC
Lubéron
Bassin de Cucuron
Alpilles
La Durance
Pertuis
Gréoux
Vinon
Costes
Vautubières
Trévaresse
Concors
Plaine de Crau
La Fare
Aix-en-Provence
Sainte Victoire
PROVENCE ORIENTALE
FA
Synclinal de l'Arc
Olympe-Aurélien
Etoile
Nerthe
Marseille
Sainte Baume
Synclinal de Beausset
Carpiagne
La Ciotat
Toulon
B
Saint-Mandrier-sur-mer
Cap Sicié
TANNERON
ESTEREL
Les Mayons
MASSIF DES MAURES
Pierrefeu-du-Var
43°N
MER MEDITERRANEE
6°E
20 km
Ville
faille majeure
Chevauchement
Déduit
N
Paris
France
Massif central
Alpes
Pyrénées
2000
1000
500
0
-1700
-2780
Altitude (m)

(Bestani, thèse)

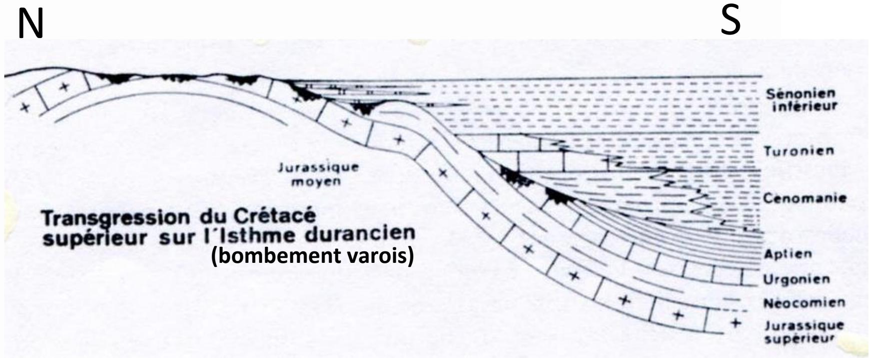

le Puy-en-Velay
Valence
Bourg-de-Péage
Livron-s.-D.
Crest
Drôme
Pinerolo
Montélimar
Pierrelatte
Valréas
Bourg-St-Andéol
Pont-St-Esprit
Bollène
Vaison
Orange
Bagnols
Carpentras
Uzès
Avignon
Châteaurenard
St-Rémy-de-P.
Cavaillon
Apt
Manosque
Valensole
Sisteron
Château-Arnoux-St-Auban
Gap
Embrun
Digne-les-Bains
Bléone
Verdon
Marguerittes
NIMES
Beaucaire
Tarascon
Arles
St-Gilles
Lunel
MONTPELLIER
Et. de Mauguio
Aigues-Mortes
G. d'Aigues-Mortes
Frontignan
Mèze
Sète
Stes-Maries-de-la-Mer
GR. RHÔNE
RHÔNE
Port-St-Louis-du-Rhône
Port-de-B.
St-Martin-de-Crau
Salon
Istres
Et. de Berre
Martigues
AIX-EN-PROVENCE
Pertuis
Gardanne
St-Maximin
Brignoles
Draguignan
Grasse
Cagnes-sur-M.
NICE
Antibes
Cannes
Fréjus
St-Raphaël
G. de St-Tropez
St-Tropez
MARSEILLE
la Ciotat
Bandol
la Seyne-s.-M.
Cap Sicié
Presqu'île de Giens
Levant
G. des Stoechades
LION

(D'après Dercourt,
Géologie de la France, Dunod)

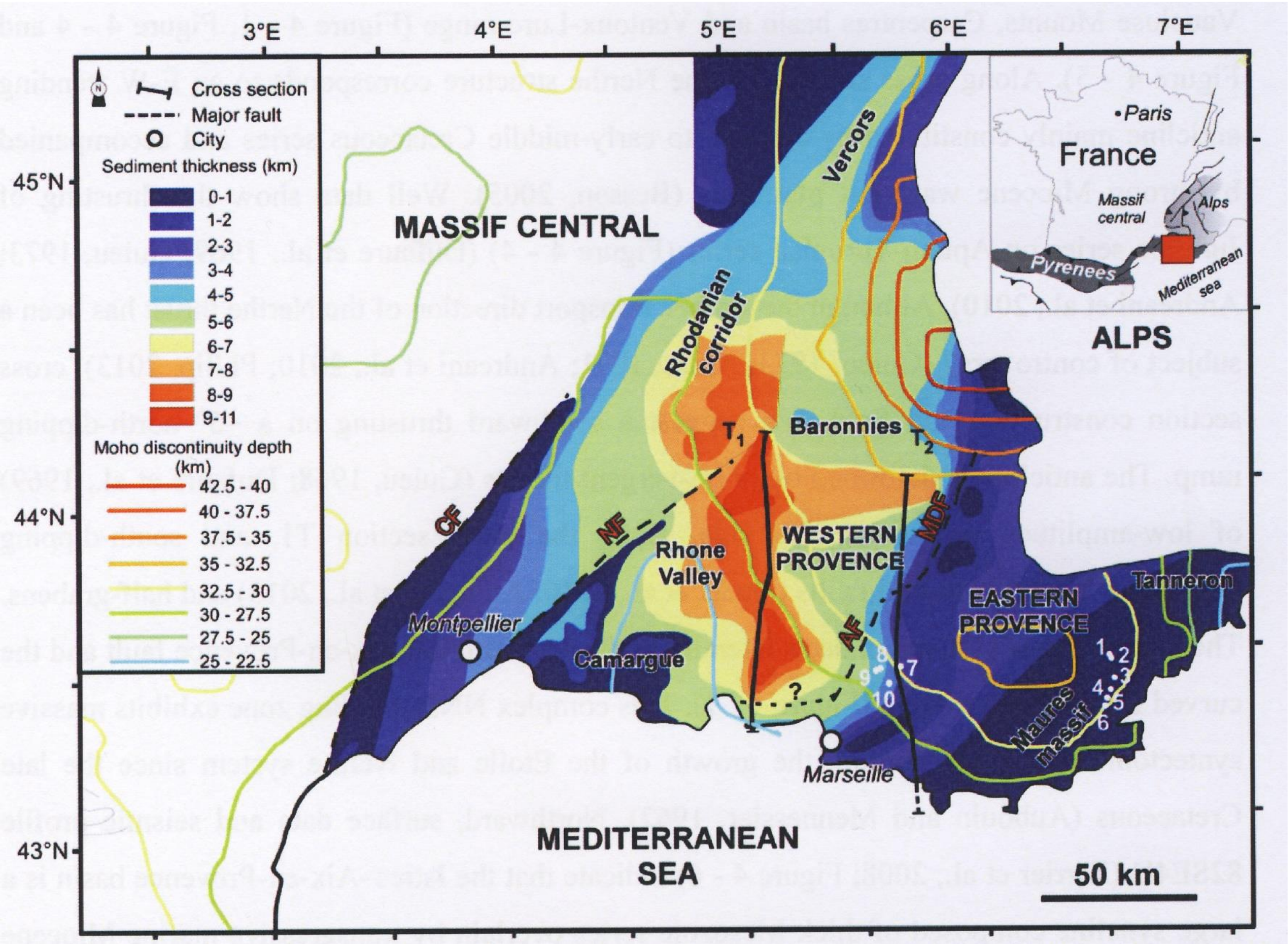

Tp
K sup.
Bauxite
K inf.
J sup.
J moy.
J inf.
Ŧ sup.
Transgress. cenoman.
K sup.
K inf.
J sup.
J moy.
J inf.
Ŧ

Zone nord-provençale

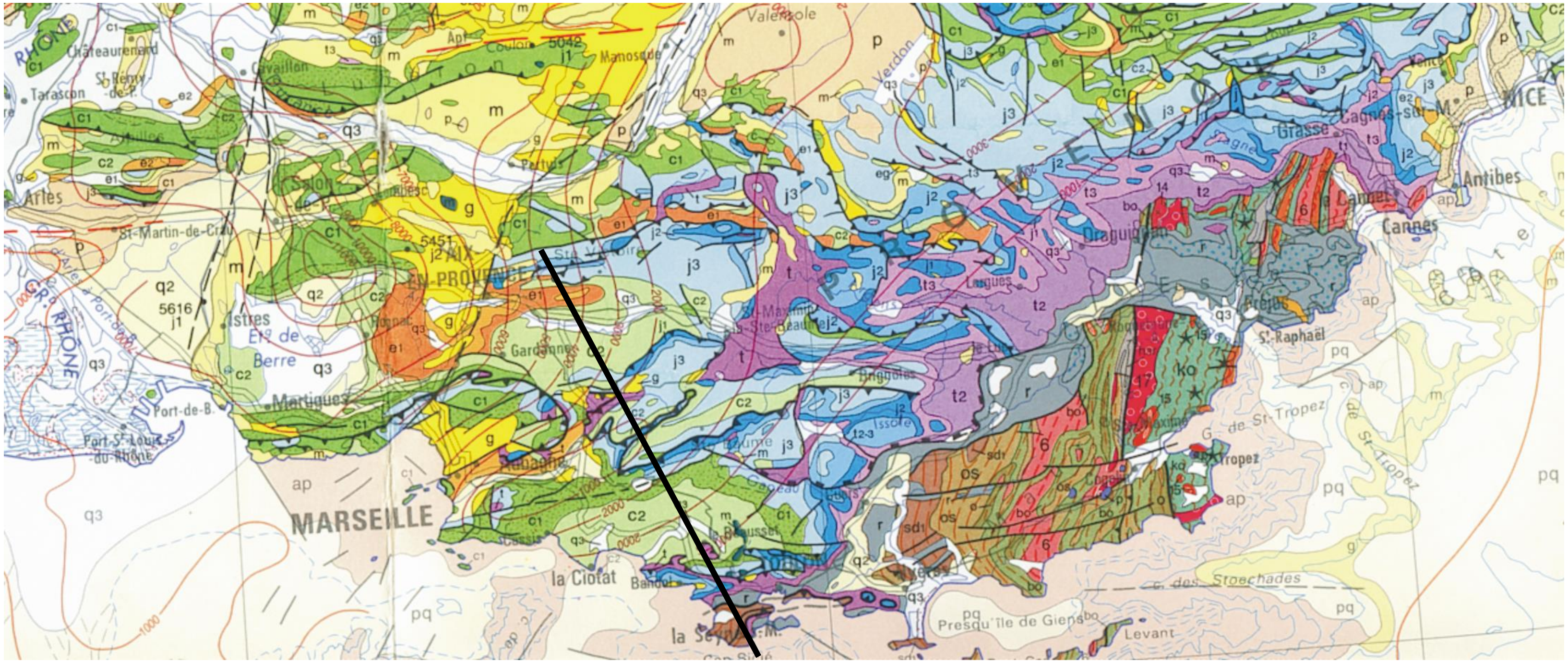
Zone sud-provençale

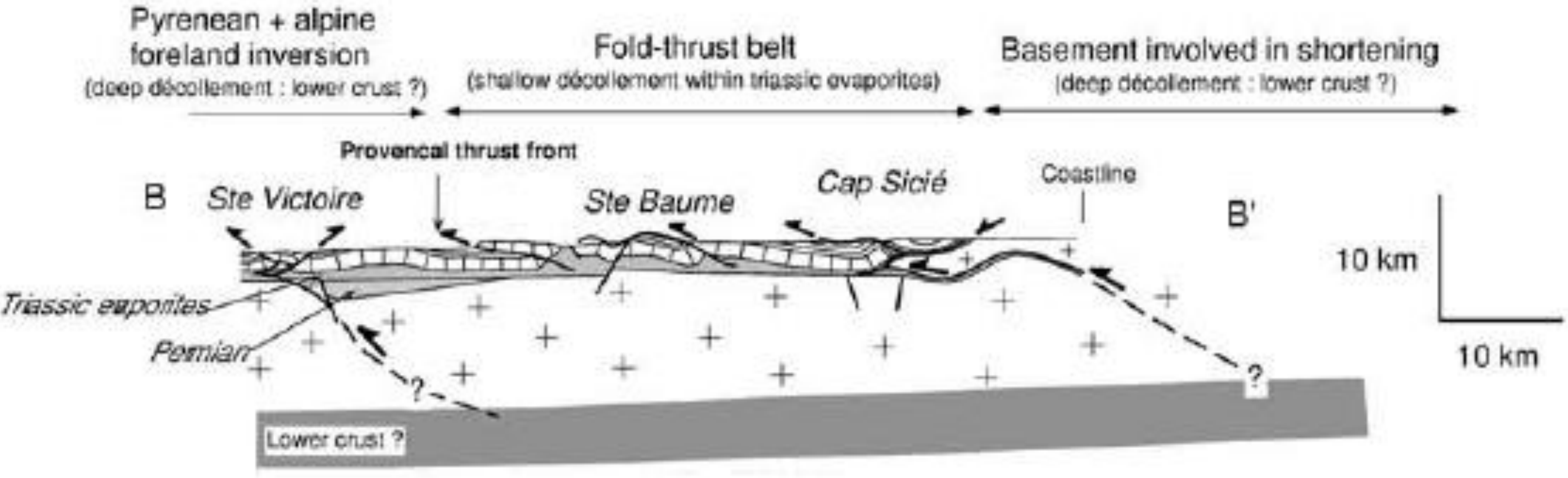

N
S
Jurassique moyen
Sénonien inférieur
Turonien
Cenomanie
Aptien
Urgonien
Neocomien
Jurassique supérieur

Transgression du Crétacé supérieur sur l'Isthme durancien
(bombement varois)

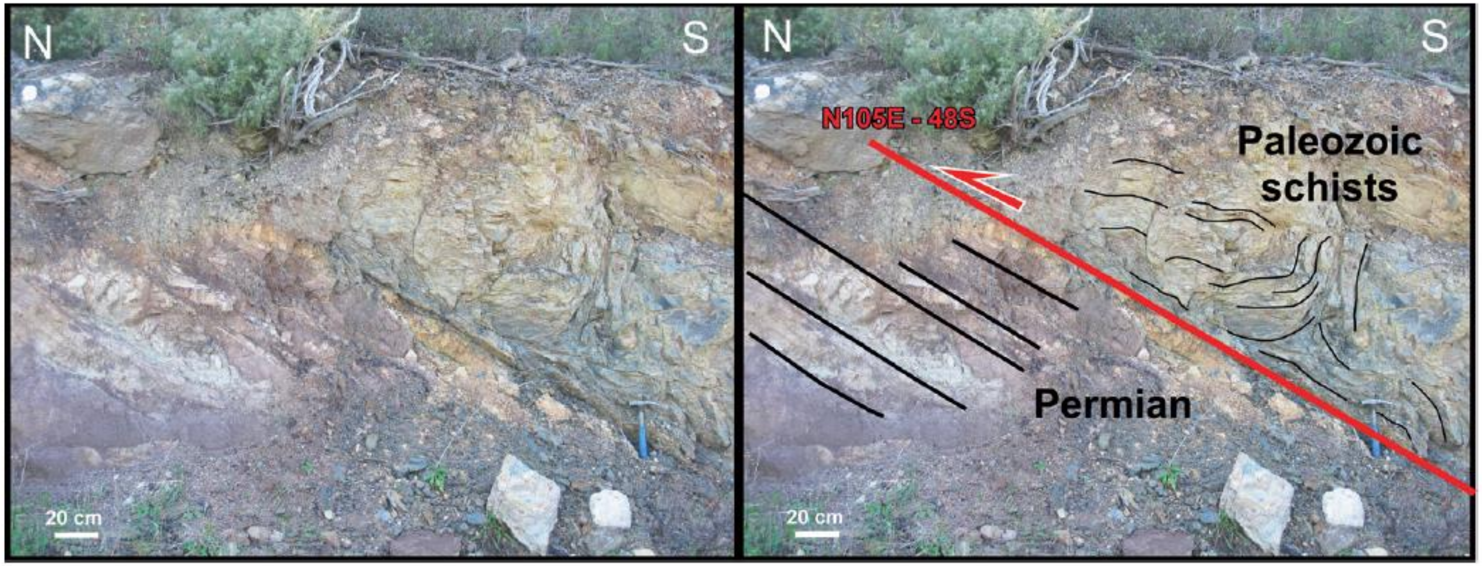

3°E
4°E
5°E
6°E
7°E
45°N
44°N
43°N
Cross section
Major fault
City
Sediment thickness (km)
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-11
Moho discontinuity depth (km)
42.5 - 40
40 - 37.5
37.5 - 35
35 - 32.5
32.5 - 30
30 - 27.5
27.5 - 25
25 - 22.5
MASSIF CENTRAL
Vercors
Rhodamian corridor
T1
Baronnies
T2
CF
NF
MDF
Rhone Valley
WESTERN PROVENCE
EASTERN PROVENCE
Tanneron
Montpellier
Camargue
AF
?
1
2
3
4
5
6
7
8
9
10
Maures massif
Marseille
MEDITERRANEAN SEA
50 km
Paris
France
Massif central
Alps
Pyrenees
Mediterranean sea
ALPS

(Bestani, thèse)


MARSEILLE
Aix-en-Provence
Arles
Istres
Martigues
Aubagne
la Ciotat
Bandol
la Seyne-s-M.
Cap Sicié
Brignoles
St-Maximin
Draguignan
Fréjus
St-Raphaël
Cannes
Antibes
Nice
Grasse
Manosque
Valensole
Tarascon
Châteaurenard
Cavaillon
Salon
Gardanne
Hyères
Presqu'île de Giens
Levant
St-Tropez
Port-de-B.
Port-St-Louis-du-Rhône
Rhône
Et. de Berre

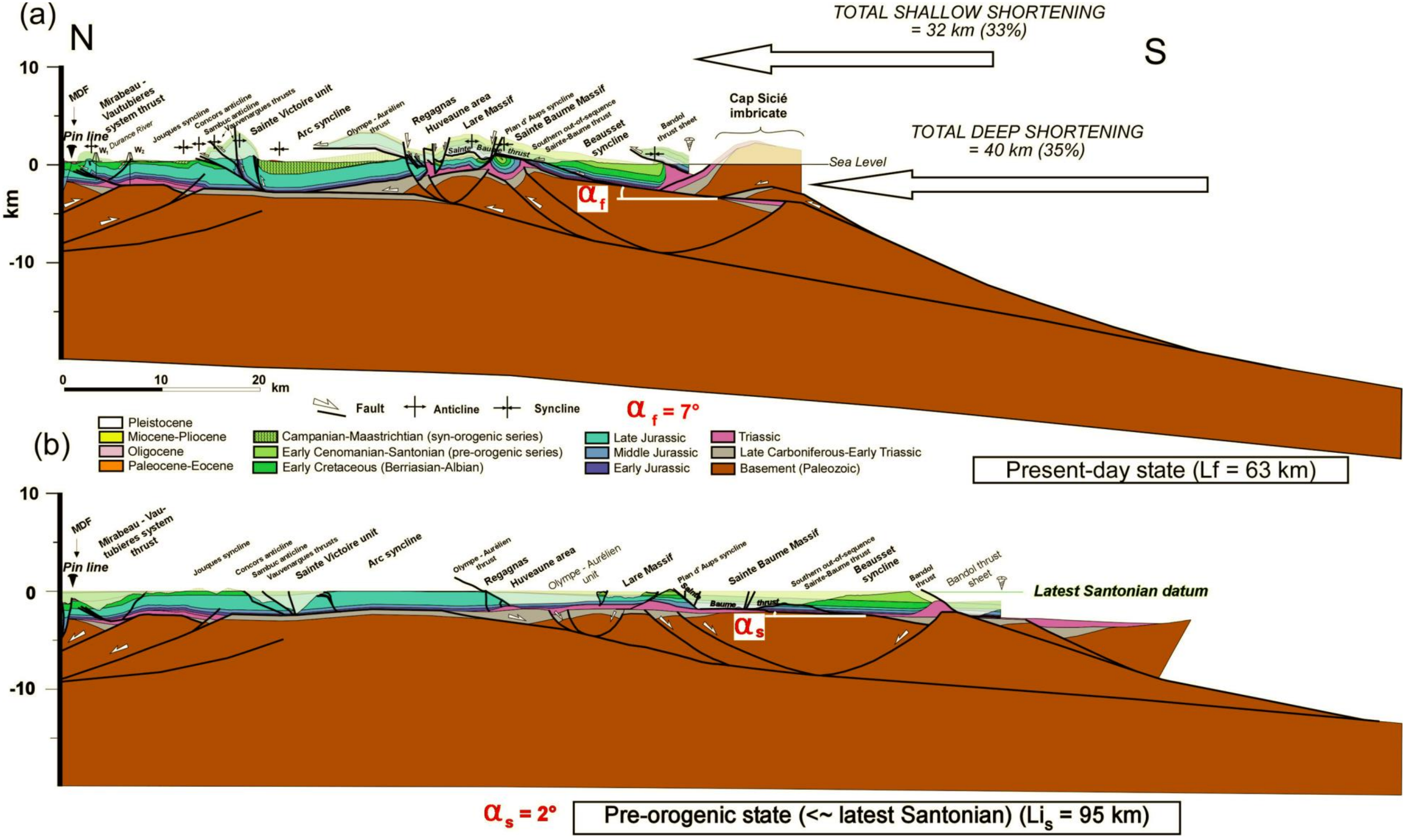

Pyrenean + alpine foreland inversion
(deep décollement : lower crust ?)
Fold-thrust belt
(shallow décollement within triassic evaporites)
Basement involved in shortening
(deep décollement : lower crust ?)
Provencal thrust front
B
Ste Victoire
Ste Baume
Cap Sicié
Coastline
B'
10 km
10 km
Triassic evaporites
Permian
?
?
Lower crust ?

(Lacombe et Jolivet, 2005)

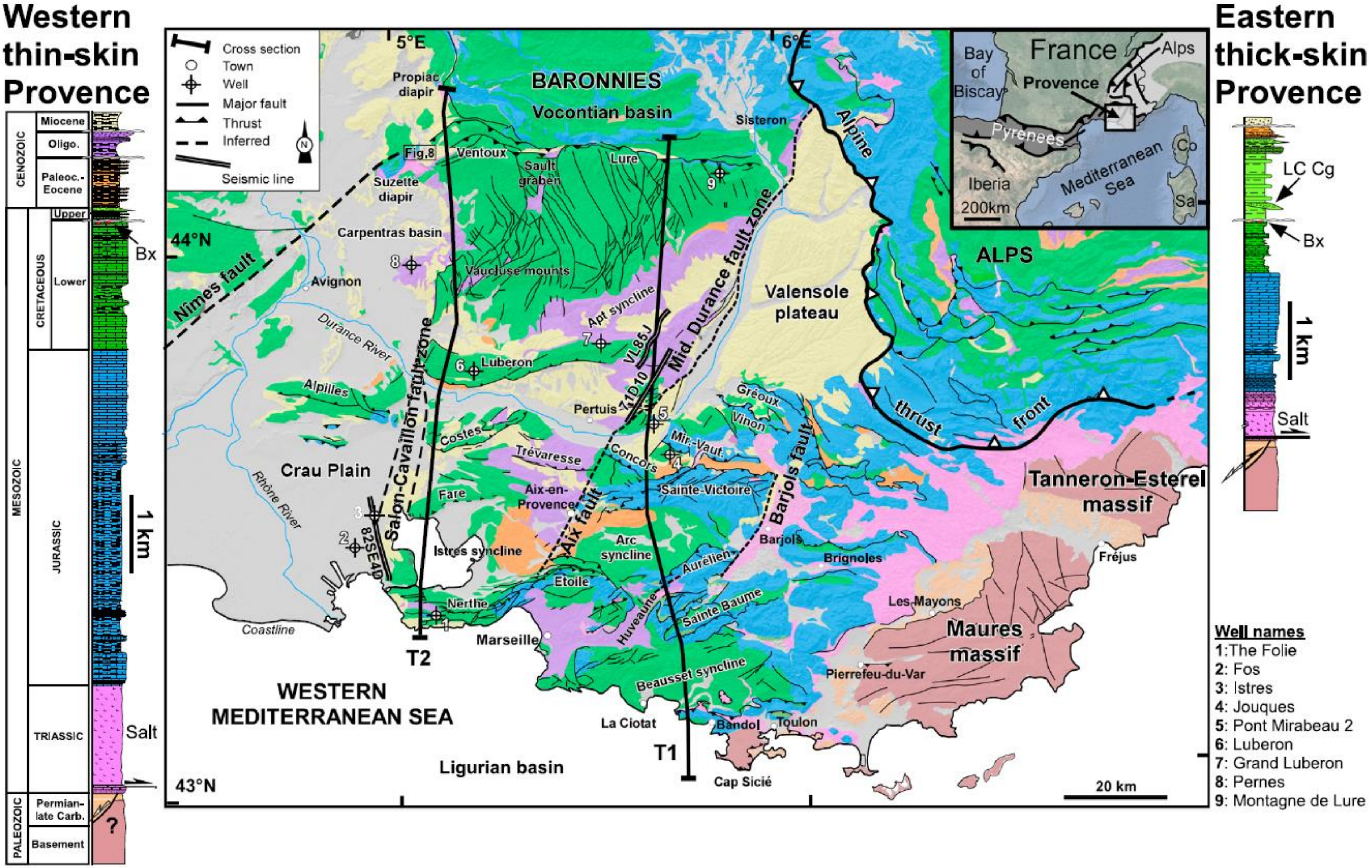


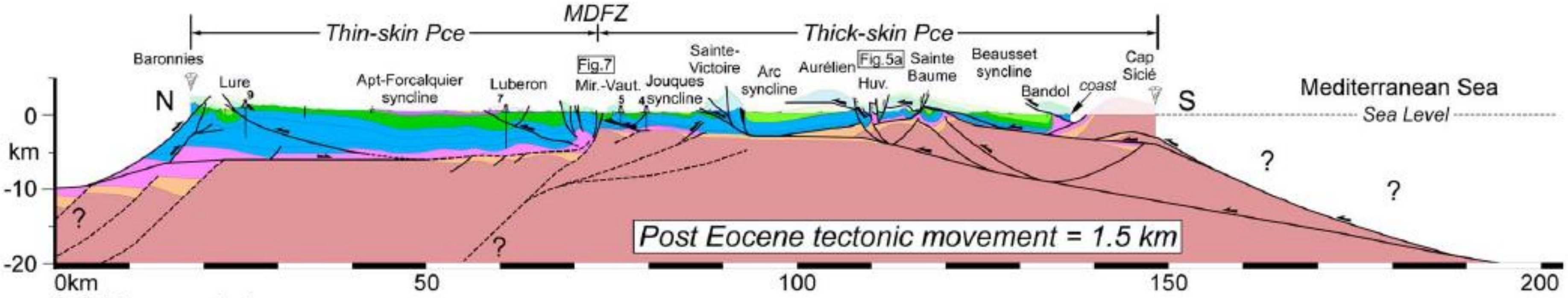
N
S
20 cm
N
S
N105E - 48S
Paleozoic schists
Permian
20 cm

(Bestani et al., 2014)

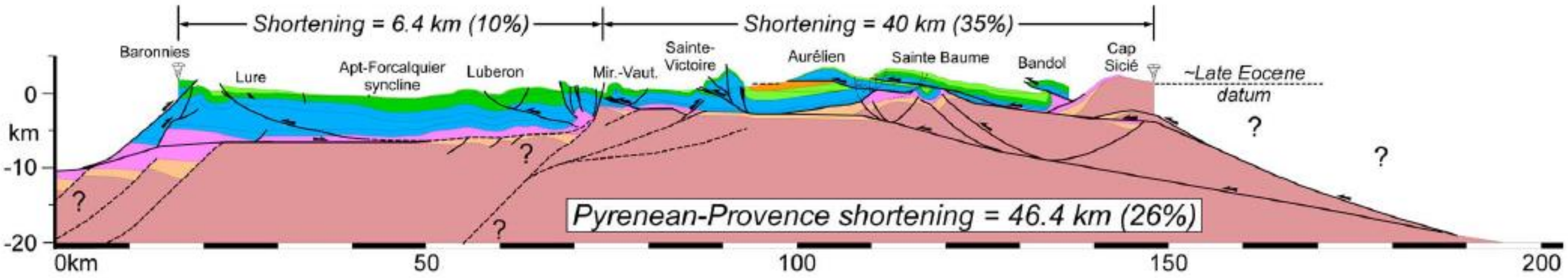

(a)
N
S
TOTAL SHALLOW SHORTENING = 32 km (33%)
TOTAL DEEP SHORTENING = 40 km (35%)
10
0
-10
km
MDF
Pin line
Mirabeau - Vautubieres system thrust
Durance River
W1
W2
Jouques syncline
Concors anticline
Sambuc anticline
Vauvenargues thrusts
Sainte Victoire unit
Arc syncline
Olympe - Aurélien thrust
Regagnas
Huveaune area
Lare Massif
Plan d' Aups syncline
Sainte Baume Massif
Sainte Baume thrust
Southern out-of-sequence Sainte-Baume thrust
Beausset syncline
Bandol thrust sheet
Cap Sicié imbricate
Sea Level
α_f
0 10 20 km
Fault
Anticline
Syncline
$\alpha_f = 7°$
Pleistocene
Miocene-Pliocene
Oligocene
Paleocene-Eocene
Campanian-Maastrichtian (syn-orogenic series)
Early Cenomanian-Santonian (pre-orogenic series)
Early Cretaceous (Berriasian-Albian)
Late Jurassic
Middle Jurassic
Early Jurassic
Triassic
Late Carboniferous-Early Triassic
Basement (Paleozoic)
Present-day state (Lf = 63 km)
(b)
10
0
-10
MDF
Pin line
Mirabeau - Vautubieres system thrust
Jouques syncline
Concors anticline
Sambuc anticline
Vauvenargues thrusts
Sainte Victoire unit
Arc syncline
Olympe - Aurélien thrust
Regagnas
Huveaune area
Olympe - Aurélien unit
Lare Massif
Plan d' Aups syncline
Sainte Baume Massif
Sainte Baume thrust
Southern out-of-sequence Sainte-Baume thrust
Beausset syncline
Bandol thrust
Bandol thrust sheet
Latest Santonian datum
α_s
$\alpha_s = 2°$
Pre-orogenic state (<~ latest Santonian) (Li_s = 95 km)

(Bestani et al., 2014)

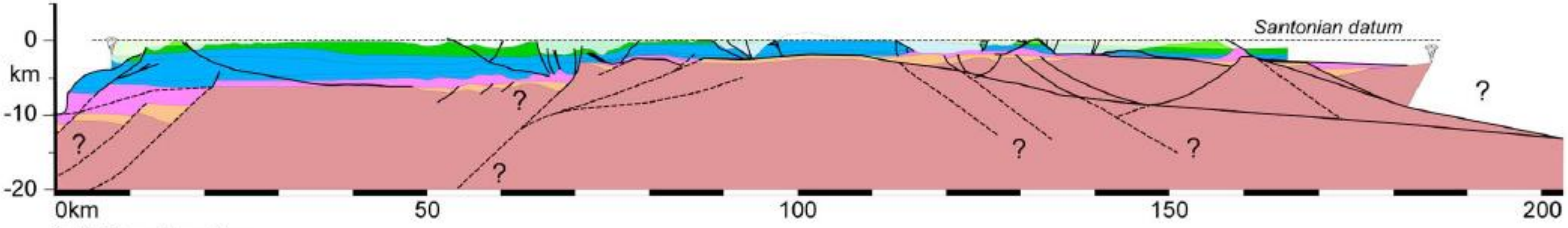
Western thin-skin Provence
Eastern thick-skin Provence
CENOZOIC
Miocene
Oligo.
Paleoc.-Eocene
MESOZOIC
CRETACEOUS
Upper
Lower
JURASSIC
TRIASSIC
PALEOZOIC
Permian-late Carb.
Basement
Bx
1 km
Salt
?
LC Cg
Cross section
Town
Well
Major fault
Thrust
Inferred
Seismic line
N
5°E
6°E
44°N
43°N
France
Bay of Biscay
Alps
Provence
Pyrenees
Iberia
Mediterranean Sea
Co
Sa
200km
BARONNIES
Vocontian basin
Propiac diapir
Fig.8
Ventoux
Sault graben
Lure
Sisteron
Suzette diapir
Carpentras basin
Vaucluse mounts
Apt syncline
Nîmes fault
Avignon
Durance River
Salon-Cavaillon fault zone
Luberon
Alpilles
VL85J
71D10
Mid. Durance fault zone
Valensole plateau
Alpine thrust front
ALPS
Pertuis
Gréoux
Vinon
Mir.-Vaut.
Concors
Costes
Trévaresse
Crau Plain
Rhône River
Fare
Aix-en-Provence
Aix fault
Sainte-Victoire
Barjols fault
Barjols
Tanneron-Esterel massif
Fréjus
82SE4D
Istres syncline
Arc syncline
Etoile
Aurélien
Brignoles
Nerthe
Huveaune
Sainte Baume
Les Mayons
Maures massif
Coastline
Marseille
T2
Beausset syncline
Pierrefeu-du-Var
WESTERN MEDITERRANEAN SEA
La Ciotat
Bandol
Toulon
T1
Ligurian basin
Cap Sicié
20 km
1
2
3
4
5
6
7
8
9
Well names
1: The Folie
2: Fos
3: Istres
4: Jouques
5: Pont Mirabeau 2
6: Luberon
7: Grand Luberon
8: Pernes
9: Montagne de Lure


MDFZ
Thin-skin Pce
Thick-skin Pce
Baronnies
Lure
Apt-Forcalquier syncline
Luberon
Fig.7
Mir.-Vaut.
Jouques syncline
Sainte-Victoire
Arc syncline
Aurélien
Fig.5a
Huv.
Sainte Baume
Beausset syncline
Bandol
coast
Cap Sicié
N
S
Mediterranean Sea
Sea Level
0
km
-10
-20
?
Post Eocene tectonic movement = 1.5 km
0km
50
100
150
200

(a) Present-day


Shortening = 6.4 km (10%)
Shortening = 40 km (35%)
Baronnies
Lure
Apt-Forcalquier syncline
Luberon
Mir.-Vaut.
Sainte-Victoire
Aurélien
Sainte Baume
Bandol
Cap Sicié
~Late Eocene datum
0
km
-10
-20
?
Pyrenean-Provence shortening = 46.4 km (26%)
0km
50
100
150
200

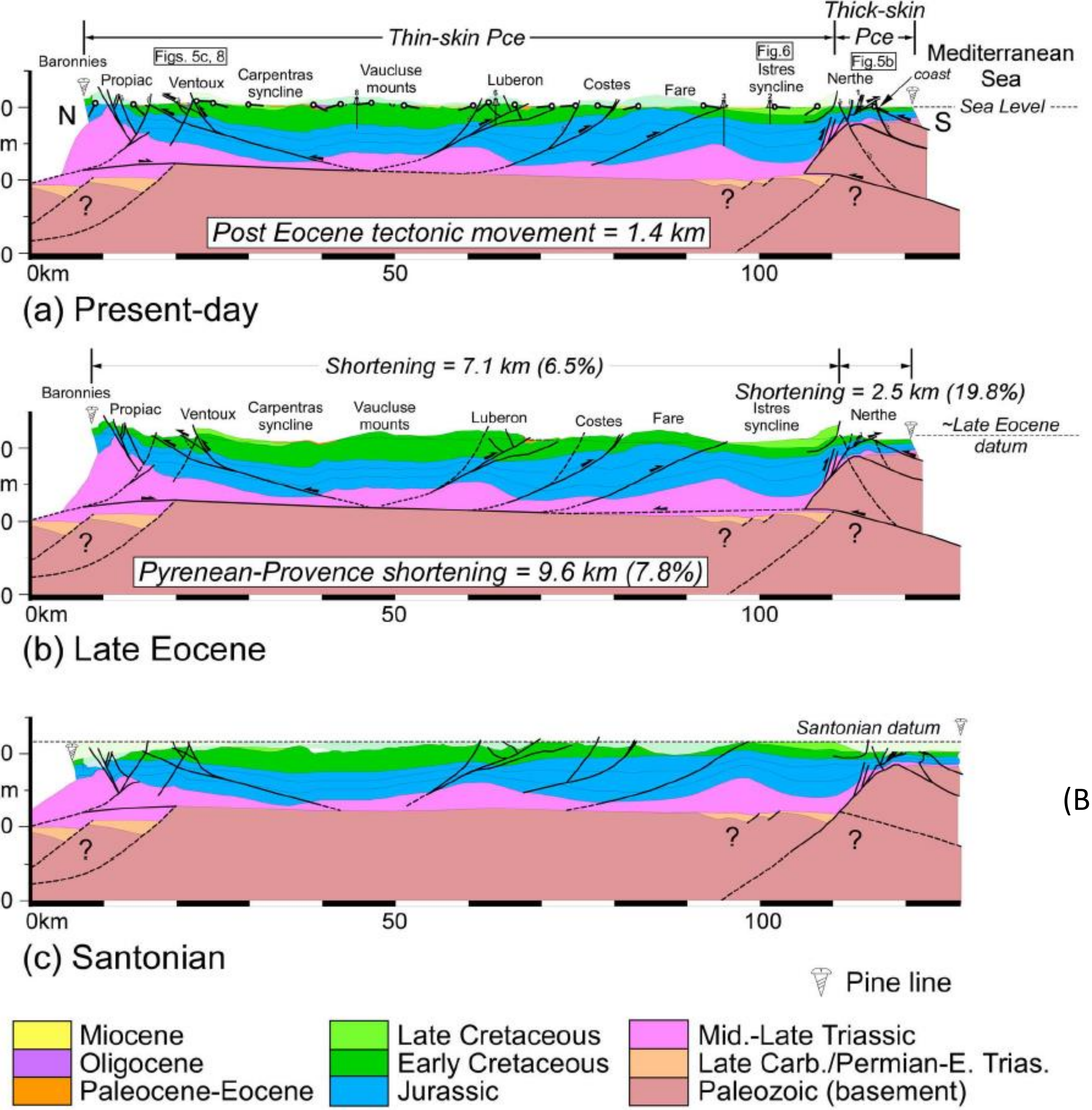
(b) Late Eocene


Santonian datum
0
km
-10
-20
?
0km
50
100
150
200

(c) Santonian

- 🟨 Miocene
- 🟪 Oligocene
- 🟧 Paleocene-Eocene
- 🟩 Late Cretaceous
- 🟩 Early Cretaceous
- 🟦 Jurassic
- 🟪 Mid.-Late Triassic
- 🟧 Late Carboniferous/Permian-Early Triassic
- 🟥 Paleozoic (basement)
- Pine line

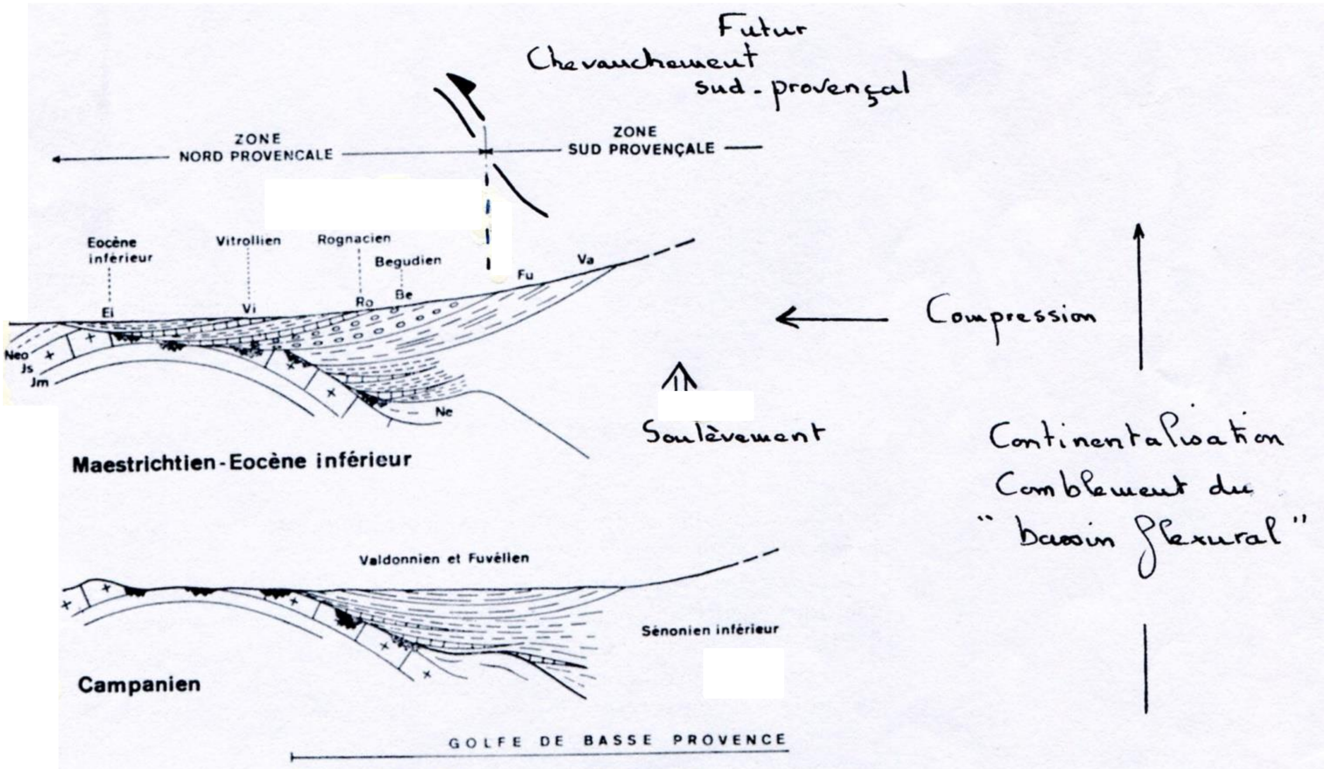
(Bestani et al., 2016)

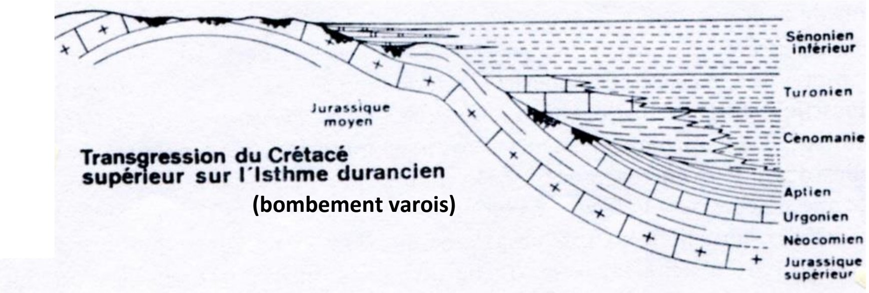

Thin-skin Pce
Thick-skin Pce
Baronnies
Figs. 5c, 8
Propiac
Ventoux
Carpentras syncline
Vaucluse mounts
Luberon
Costes
Fare
Fig.6
Istres syncline
Nerthe
Fig.5b
coast
Mediterranean Sea
Sea Level
N
S
0
km
-10
-20
?
Post Eocene tectonic movement = 1.4 km
0km
50
100
(a) Present-day
Shortening = 7.1 km (6.5%)
Shortening = 2.5 km (19.8%)
Baronnies
Propiac
Ventoux
Carpentras syncline
Vaucluse mounts
Luberon
Costes
Fare
Istres syncline
Nerthe
~Late Eocene datum
0
km
-10
-20
?
Pyrenean-Provence shortening = 9.6 km (7.8%)
0km
50
100
(b) Late Eocene
Santonian datum
0
km
-10
-20
?
0km
50
100
(c) Santonian
Pine line
Miocene
Oligocene
Paleocene-Eocene
Late Cretaceous
Early Cretaceous
Jurassic
Mid.-Late Triassic
Late Carb./Permian-E. Trias.
Paleozoic (basement)

(Bestani et al., 2016)

Calendrier et

évolution géodynamique

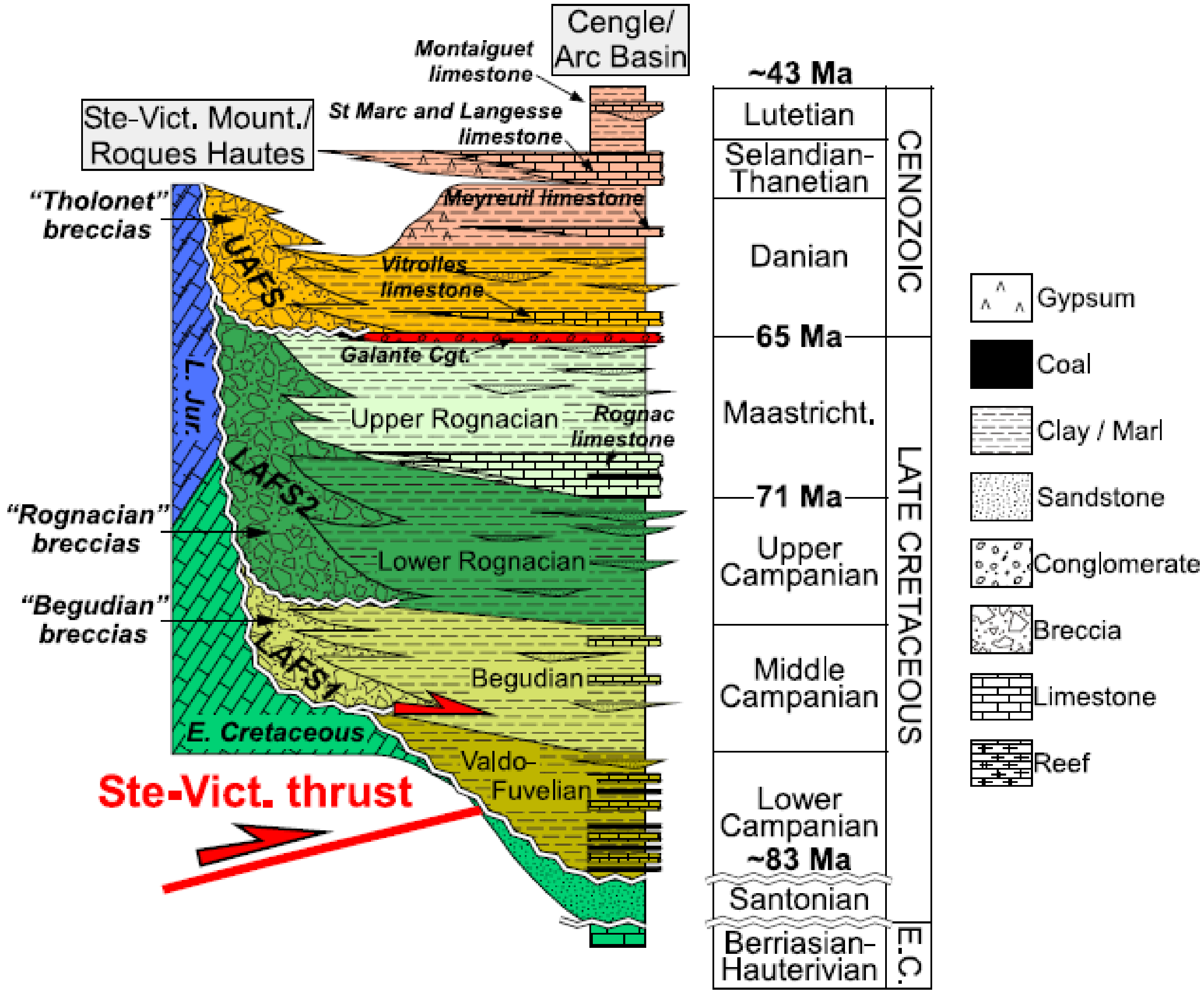

Futur
Chevauchement
sud-provençal
ZONE
NORD PROVENCALE
ZONE
SUD PROVENÇALE
Eocène inférieur
Vitrollien
Rognacien
Begudien
Ei
Vi
Ro
Be
Fu
Va
Neo
Js
Jm
Ne
Compression
Soulèvement
Continentalisation
Comblement du
"bassin flexural"
Maestrichtien-Eocène inférieur
Valdonnien et Fuvélien
Sénonien inférieur
Campanien
GOLFE DE BASSE PROVENCE


Sénonien inférieur
Turonien
Cenomanie
Aptien
Urgonien
Néocomien
Jurassique supérieur
Jurassique moyen

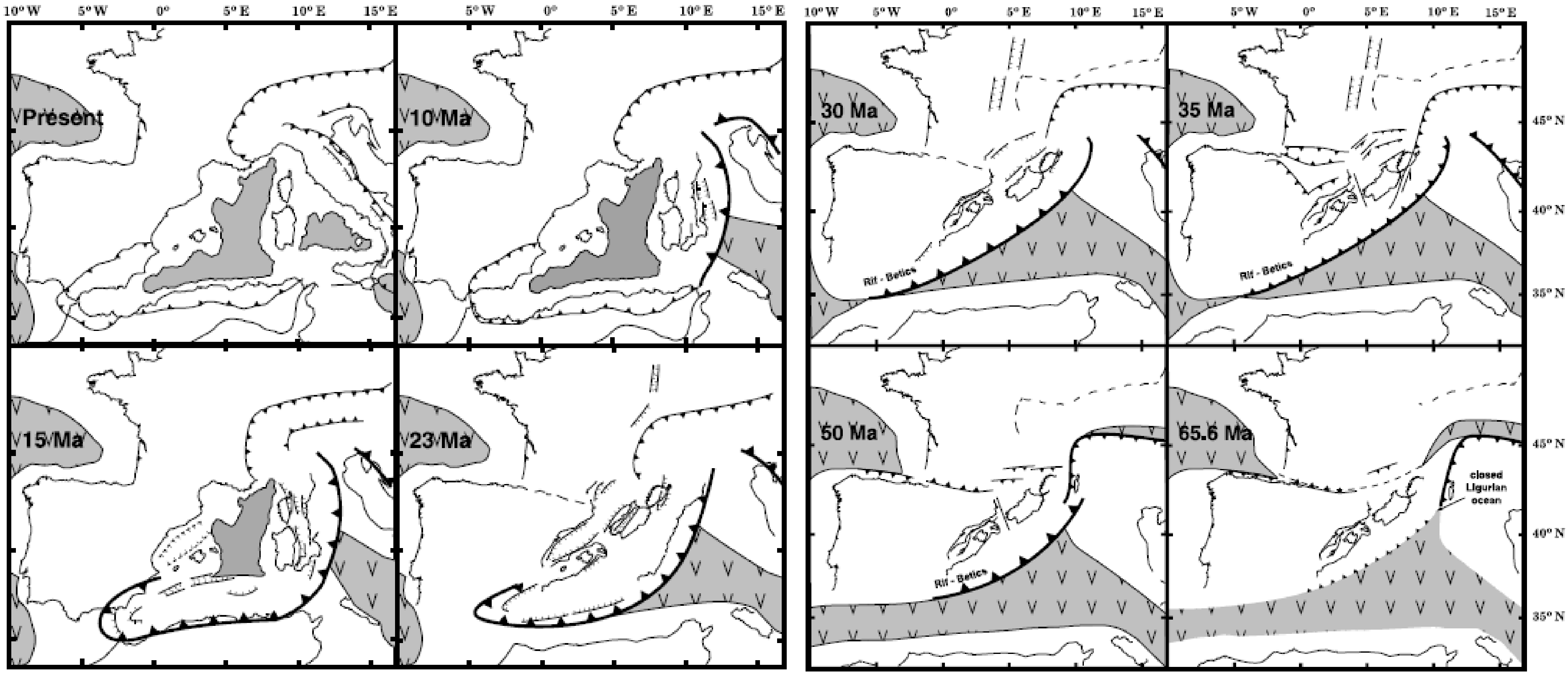
Transgression du Crétacé supérieur sur l'Isthme durancien

(bombement varois)

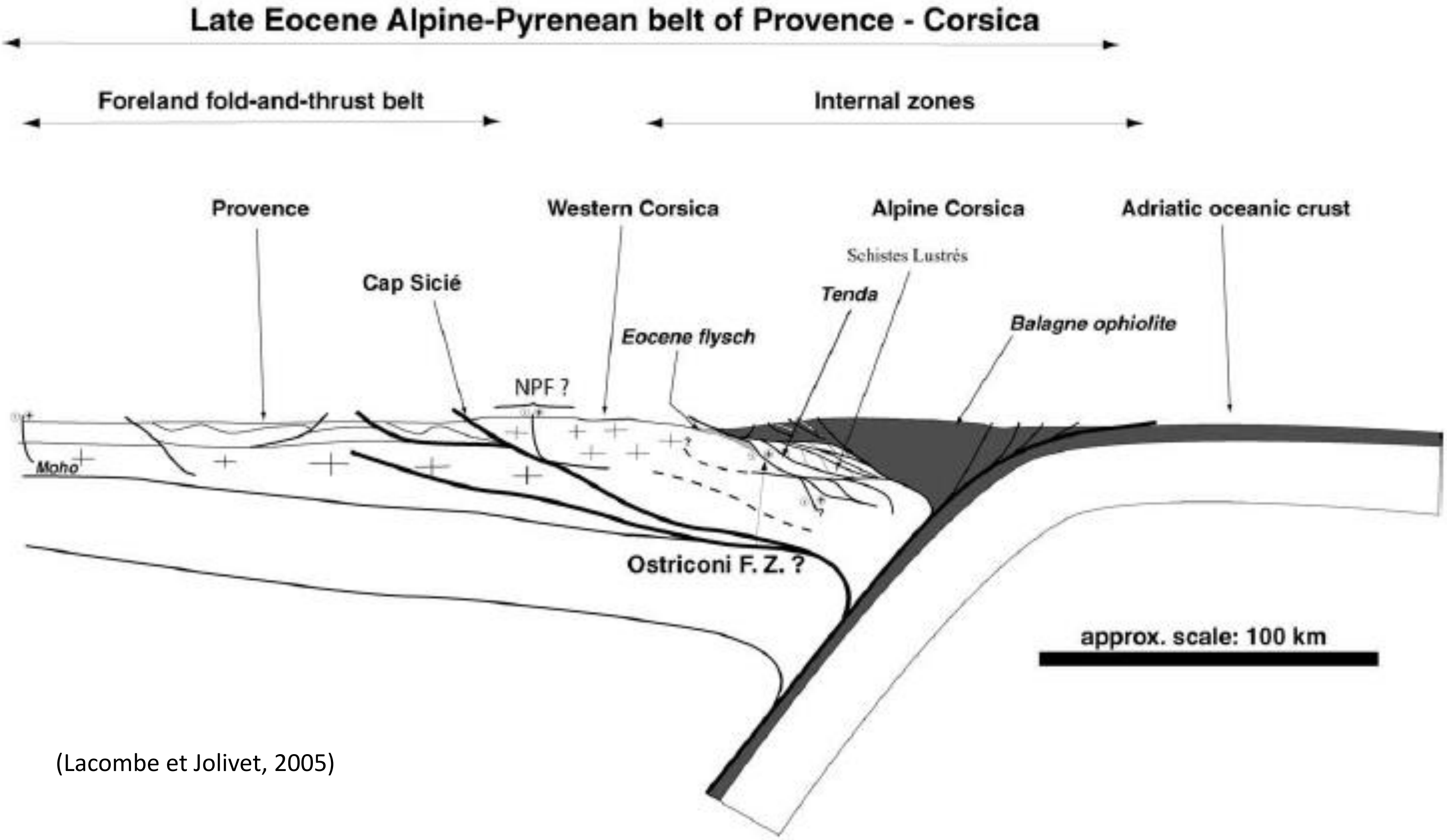
(D'après Aubouin et al.
Dunod)


Cengle/ Arc Basin
Montaiguet limestone
St Marc and Langesse limestone
Ste-Vict. Mount./ Roques Hautes
"Tholonet" breccias
Meyreuil limestone
UAFS
Vitrolles limestone
Galante Cgt.
L. Jur.
Upper Rognacian
Rognac limestone
LAFS2
"Rognacian" breccias
Lower Rognacian
"Begudian" breccias
LAFS1
Begudian
E. Cretaceous
Valdo-Fuvelian
Ste-Vict. thrust
~43 Ma
Lutetian
Selandian-Thanetian
Danian
CENOZOIC
65 Ma
Maastricht.
71 Ma
Upper Campanian
Middle Campanian
Lower Campanian
~83 Ma
Santonian
Berriasian-Hauterivian
LATE CRETACEOUS
E.C.
Gypsum
Coal
Clay / Marl
Sandstone
Conglomerate
Breccia
Limestone
Reef

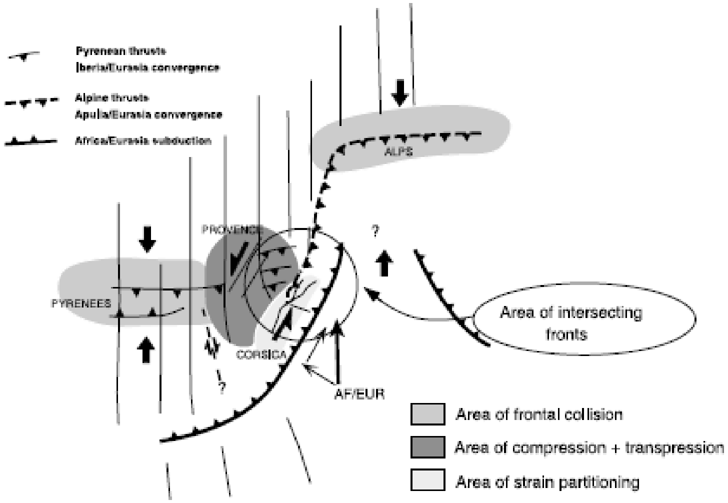
(Espurt et al., 2012)

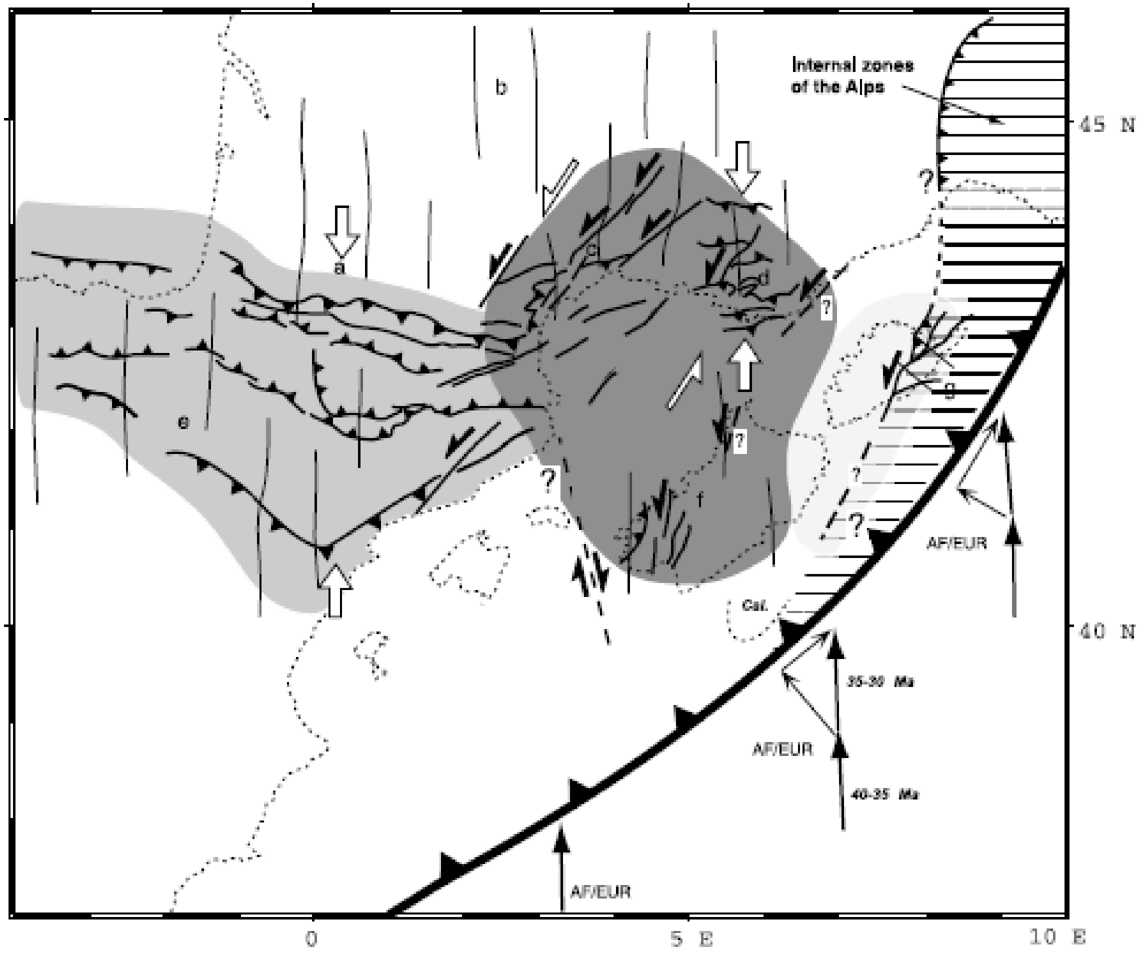

10° W
5° W
0°
5° E
10° E
15° E
45° N
40° N
35° N
Present
10 Ma
15 Ma
23 Ma
30 Ma
35 Ma
50 Ma
65.6 Ma
Rif - Betics
closed Ligurian ocean

(Lacombe et Jolivet, 2005)

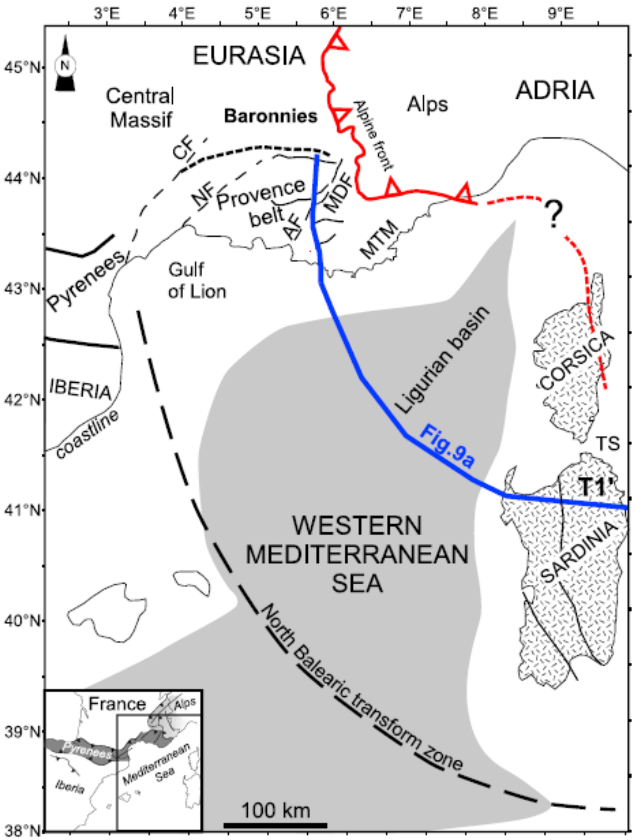

Late Eocene Alpine-Pyrenean belt of Provence - Corsica
Foreland fold-and-thrust belt
Internal zones
Provence
Western Corsica
Alpine Corsica
Adriatic oceanic crust
Schistes Lustrés
Cap Sicié
Tenda
Balagne ophiolite
Eocene flysch
NPF ?
Moho
Ostriconi F. Z. ?
approx. scale: 100 km

(Lacombe et Jolivet, 2005)

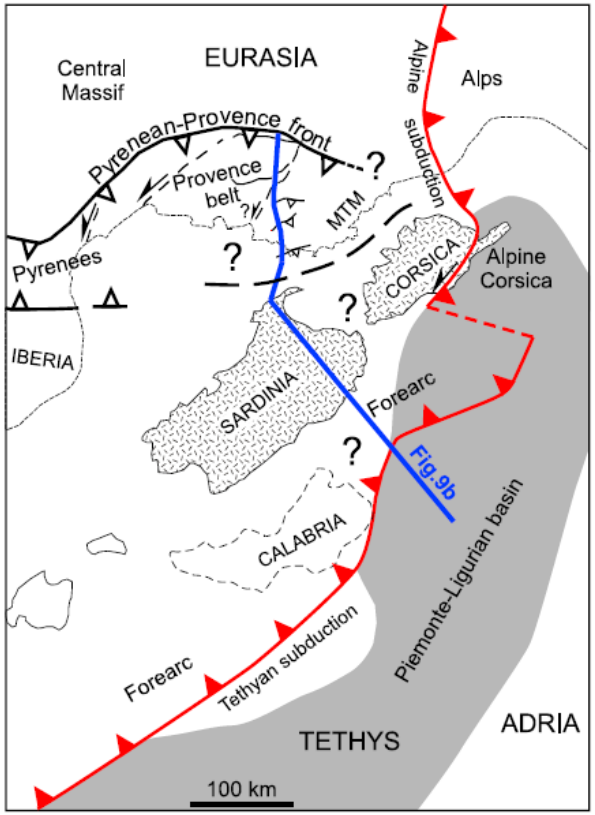

Pyrenean thrusts
Iberia/Eurasia convergence
Alpine thrusts
Apulia/Eurasia convergence
Africa/Eurasia subduction
ALPS
PROVENCE
PYRENEES
CORSICA
?
AF/EUR
Area of intersecting fronts
Area of frontal collision
Area of compression + transpression
Area of strain partitioning


Internal zones of the Alps
a
b
c
d
e
f
g
?
Cal.
AF/EUR
35-30 Ma
40-35 Ma
45 N
40 N
0
5 E
10 E

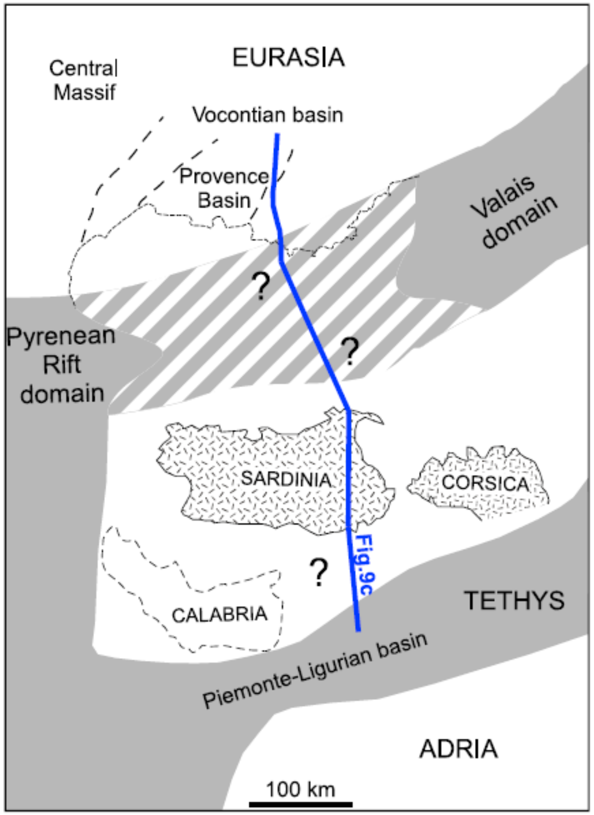
(Lacombe et Jolivet, 2005)


3°E
4°E
5°E
6°E
7°E
8°E
9°E
45°N
44°N
43°N
42°N
41°N
40°N
39°N
38°N
N
EURASIA
Central Massif
Baronnies
Alps
ADRIA
Alpine front
CF
NF
Provence belt
AF
MDF
MTM
?
Pyrenees
Gulf of Lion
Ligurian basin
CORSICA
IBERIA
coastline
Fig.9a
TS
T1'
SARDINIA
WESTERN MEDITERRANEAN SEA
North Balearic transform zone
France
Alps
Pyrenees
Iberia
Mediterranean Sea
100 km

(a) Present day map (after *Dèzes et al*. [2004], *Lacombe and Jolivet* [2005] and *Bache et al*. [2010])

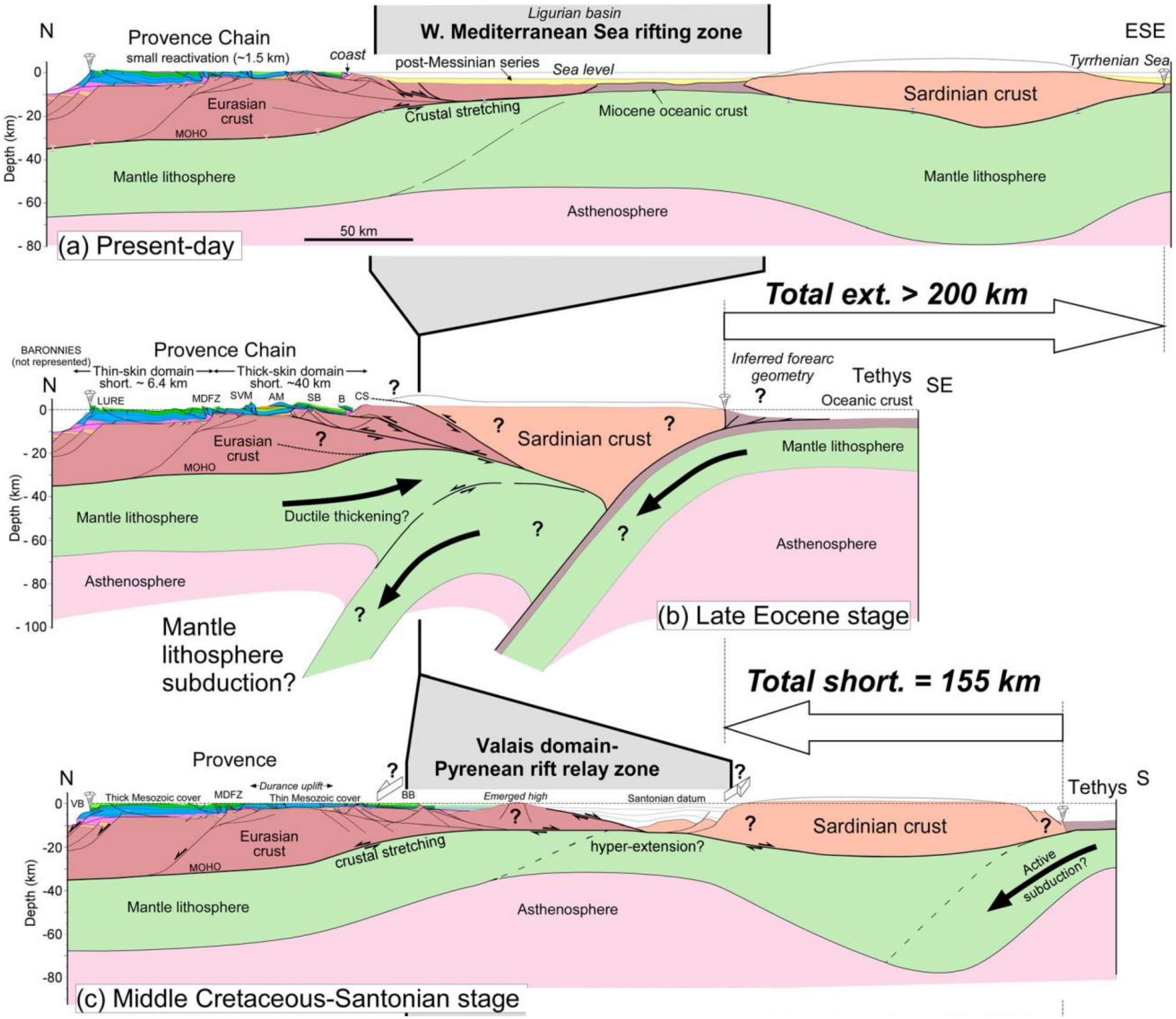

EURASIA
Central Massif
Alpine subduction
Alps
Pyrenean-Provence front
Provence belt
?
MTM
Pyrenees
?
IBERIA
CORSICA
Alpine Corsica
?
SARDINIA
Forearc
?
Fig.9b
CALABRIA
Piemonte-Ligurian basin
Forearc
Tethyan subduction
TETHYS
ADRIA
100 km

(b) Late Eocene map restoration (after *Lacombe and Jolivet* [2005], *Molli and Malavieille* [2011] and *Advokaat et al.* [2014])

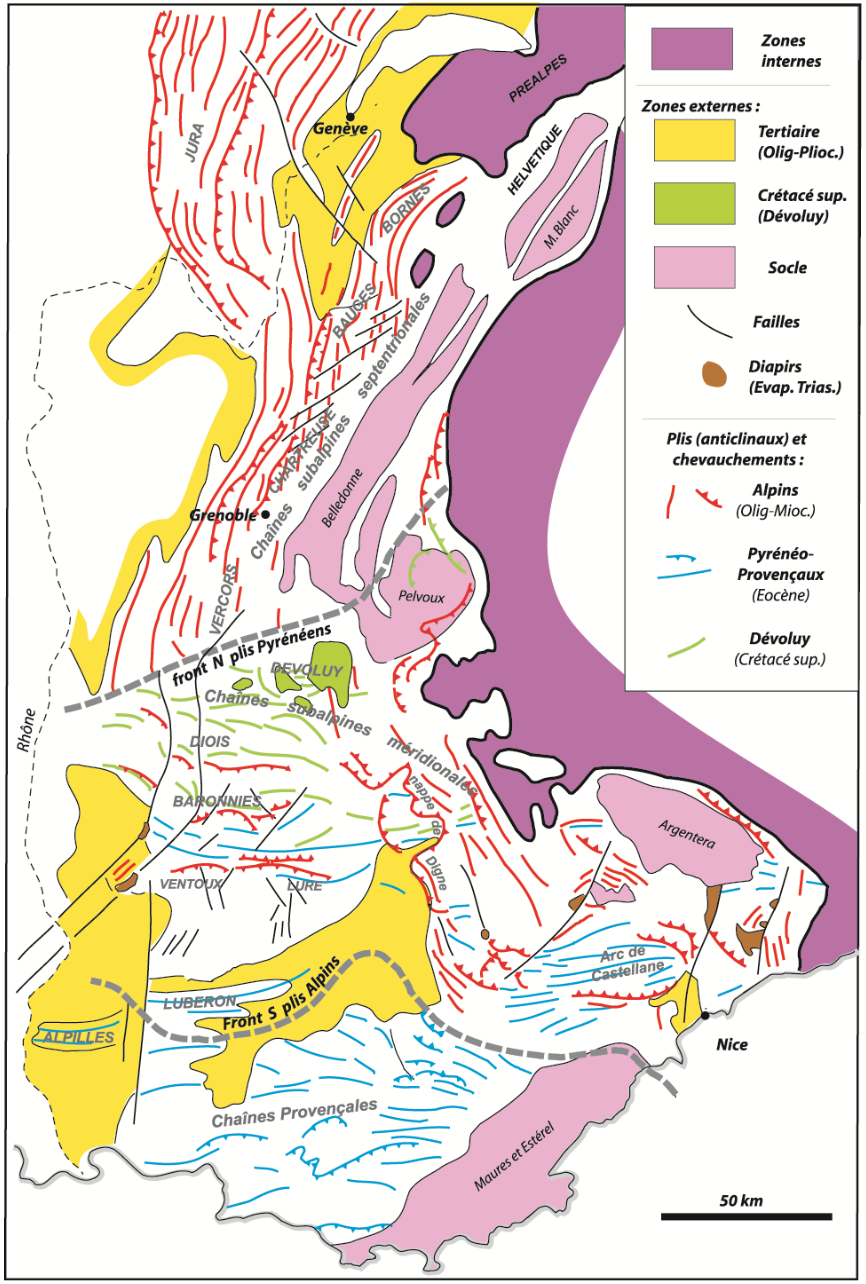

Central Massif
EURASIA
Vocontian basin
Provence Basin
Valais domain
?
Pyrenean Rift domain
?
SARDINIA
CORSICA
Fig.9c
?
CALABRIA
TETHYS
Piemonte-Ligurian basin
ADRIA
100 km

(c) Middle Cretaceous map restoration (after *Advokaat et al.* [2014])

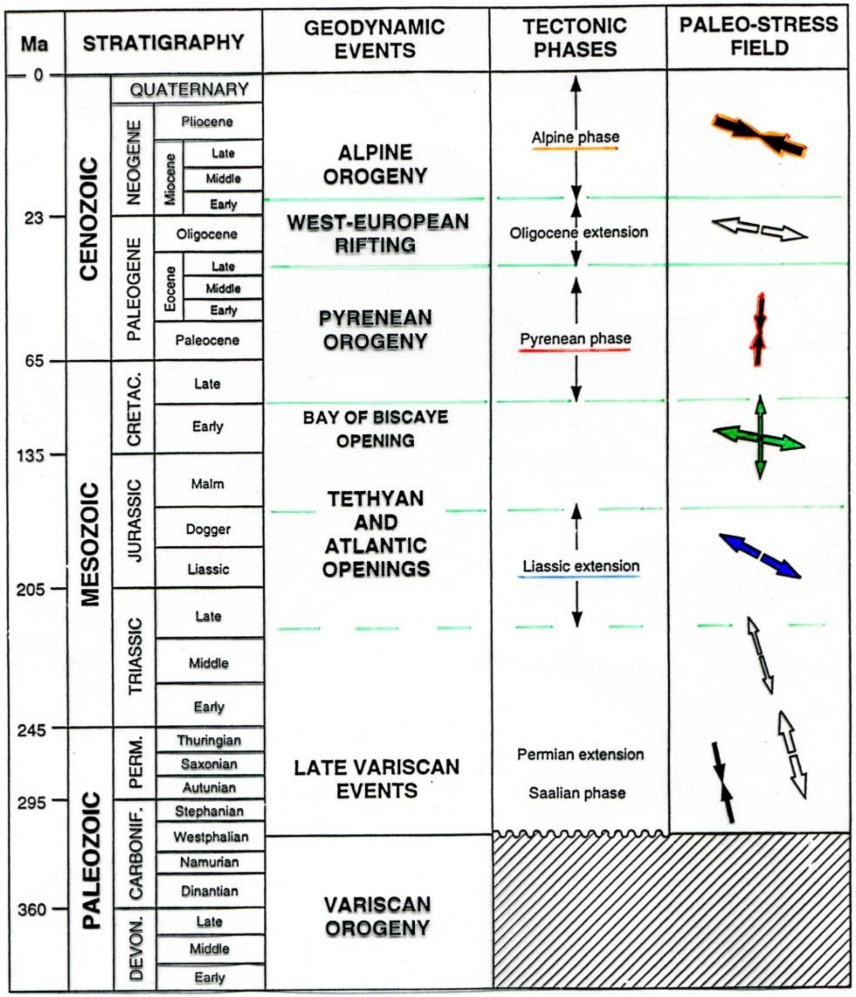
(Bestani et al., 2016)


N
Provence Chain
small reactivation (~1.5 km)
coast
Ligurian basin
W. Mediterranean Sea rifting zone
post-Messinian series
Sea level
ESE
Tyrrhenian Sea
Eurasian crust
MOHO
Crustal stretching
Miocene oceanic crust
Sardinian crust
Mantle lithosphere
Mantle lithosphere
Asthenosphere
Depth (km)
0
- 20
- 40
- 60
- 80
50 km
(a) Present-day
Total ext. > 200 km
BARONNIES (not represented)
Provence Chain
Thin-skin domain short. ~ 6.4 km
Thick-skin domain short. ~40 km
N
LURE
MDFZ
SVM
AM
SB
B
CS
?
Inferred forearc geometry
Tethys
SE
Oceanic crust
Eurasian crust
MOHO
Sardinian crust
Mantle lithosphere
Mantle lithosphere
Ductile thickening?
Asthenosphere
Asthenosphere
Depth (km)
0
- 20
- 40
- 60
- 80
- 100
Mantle lithosphere subduction?
(b) Late Eocene stage
Total short. = 155 km
Provence
Valais domain-
Pyrenean rift relay zone
N
Tethys
S
VB
Thick Mesozoic cover
MDFZ
Durance uplift
Thin Mesozoic cover
BB
Emerged high
Santonian datum
Eurasian crust
MOHO
crustal stretching
hyper-extension?
Sardinian crust
Active subduction?
Mantle lithosphere
Asthenosphere
Depth (km)
0
-20
-40
-60
-80
(c) Middle Cretaceous-Santonian stage

(Bestani et al., 2016)


Zones internes
Zones externes :
Tertiaire (Olig-Plioc.)
Crétacé sup. (Dévoluy)
Socle
Failles
Diapirs (Evap. Trias.)
Plis (anticlinaux) et chevauchements :
Alpins (Olig-Mioc.)
Pyrénéo-Provençaux (Eocène)
Dévoluy (Crétacé sup.)
50 km
JURA
Genève
PREALPES
HELVETIQUE
M. Blanc
BORNES
BAUGES
CHARTREUSE
Chaînes subalpines septentrionales
Belledonne
Grenoble
VERCORS
Pelvoux
front N plis Pyrénéens
DEVOLUY
Chaînes subalpines méridionales
DIOIS
Rhône
BARONNIES
nappe de Digne
Argentera
VENTOUX
LURE
Arc de Castellane
LUBERON
Front S plis Alpins
ALPILLES
Nice
Chaînes Provençales
Maures et Estérel

(d'après Lemoine et a

(Agard et Lemoine, 2003)