

LES ALPES FRANCO-ITALIENNES

Olivier LACOMBE





INTERNATIONAL STRATIGRAPHIC CHART



International Commission on Stratigraphy

Phanerozoic	Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP							
								Cenozoic						
Phanerozoic	Eon	Era	Period	Epoch	Age	Ma	GSSP							
								Cenozoic	Quaternary	Holocene		0.0117	↗	
										Pleistocene	Upper		0.126	
											"Ionian"		0.781	
											Calabrian		1.806	↗
											Gelasian		2.588	↗
									Neogene	Pliocene	Piacenzian		3.800	↗
											Zanclean		5.332	↗
										Miocene	Messinian		7.246	↗
											Tortonian		11.808	↗
											Serravallian		13.82	↗
											Langhian		15.97	↗
											Burdigalian		20.43	↗
											Aquitanian		23.03	↗
											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	↗										
	Thanetian		58.7 ± 0.2	↗										
Paleocene	Selandian		~ 61.1	↗										
	Danian		65.5 ± 0.3	↗										
Mesozoic	Eon	Era	Period	Epoch	Age	Ma	GSSP							
								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	↗	
									Lower	Cenomanian		99.6 ± 0.9	↗	
										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	↗											

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

Phanerozoic	Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP							
								Paleozoic						
Phanerozoic	Eon	Era	Period	Epoch	Age	Ma	GSSP							
								Paleozoic	Devonian	Upper	Famennian		359.2 ± 2.5	↗
											Frasnian		374.5 ± 2.6	↗
										Middle	Givetian		385.3 ± 2.6	↗
											Eifelian		391.8 ± 2.7	↗
											Emsian		397.5 ± 2.7	↗
									Lower	Pragian		407.0 ± 2.8	↗	
										Lochkovian		411.2 ± 2.8	↗	
									Silurian	Pridoli			416.0 ± 2.8	↗
													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	↗										
	Hirnantian		445.6 ± 1.5	↗										
Ordovician	Upper	Katian		455.8 ± 1.6	↗									
		Sandbian		460.9 ± 1.6	↗									
		Darriwilian		468.1 ± 1.6	↗									
Middle	Dapingian		471.8 ± 1.6	↗										
	Floian		478.6 ± 1.7	↗										
Lower	Tremadocian		488.3 ± 1.7	↗										
	Furongian		~ 492 *	↗										
Cambrian	Eon	Era	Period	Epoch	Age	Ma	GSSP							
								Series 1	Stage 10		~ 496 *	↗		
									Stage 9		~ 499	↗		
								Series 2	Paibian		~ 503	↗		
									Guzhangian		~ 506.5	↗		
Terreneuvian	Drumian		~ 510 *	↗										
	Stage 5		~ 515 *	↗										
Fortunian	Stage 4		~ 521 *	↗										
	Stage 3		~ 528 *	↗										
Stage 2		542.0 ± 1.0	↗											

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

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

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LES ALPES FRANCO-ITALIENNES

Introduction : Les Alpes au sein des chaînes téthysiennes

I. Les Alpes franco-italiennes : une chaîne de subduction-collision

- A. Les unités structurales: nature, origine, mise en place
 - 1. Le domaine dauphinois et les chaînes plissées de l'avant-pays alpin : un prisme d'accrétion Oligo-Miocène
 - 2. Les unités Briançonnaises et piémontaises : un prisme d'accrétion Eocène
 - 3. Les unités liguro-piémontaises : un prisme d'accrétion Crétacé supérieur - Paléocène
 - Les nappes ophiolitiques
 - Les nappes de flyschs à Helminthoïdes
 - 4. La Corse alpine
- B. La structure profonde vue par la géophysique
- C. Le métamorphisme alpin et les contraintes thermo-barométriques sur l'édification du prisme orogénique
- D. Une absence quasi-totale de magmatisme

II. Les Alpes franco-italiennes : une structure impliquant la fermeture d'un océan lent et l'inversion d'une paléomarge passive

- A. La superposition des nappes de charriage implique l'existence d'un ou plusieurs domaines océaniques alpins d'âges différents
- B. Les océans « alpins », liguro-piémontais et valaisan
 - 1. Les ophiolites alpines et les océans alpins
 - 2. L'océan liguro-piémontais : des fonds océaniques étroits de type Atlantique
- C. La marge européenne de l'océan ligure
 - 1. Les séries sédimentaires et les grands domaines paléogéographiques
 - 2. Le rifting « ligure »
 - * La tectonique de blocs basculés : observations directes et reconstitutions
 - * Reconstitution de la géométrie de la marge européenne
 - 3. L'évolution post-rift de la marge européenne
- D. Essai de reconstitution paléogéographique d'ensemble

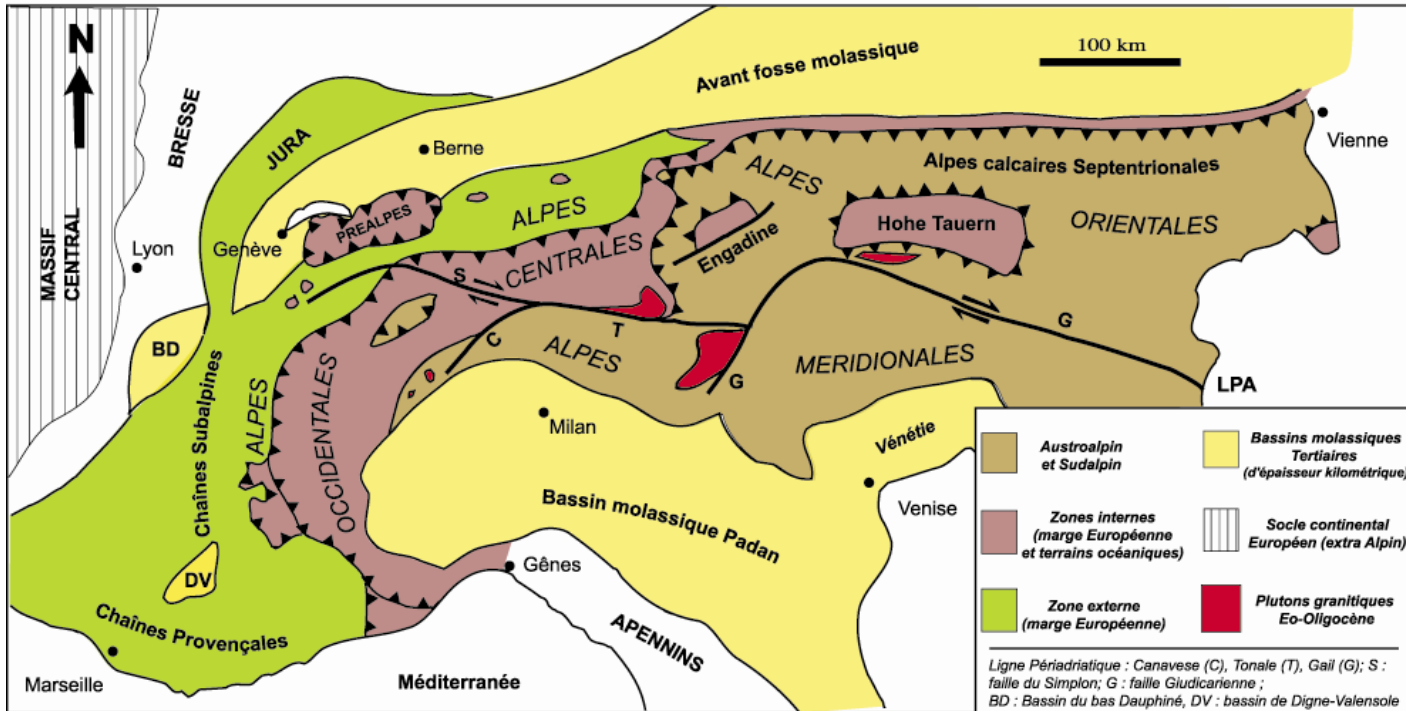
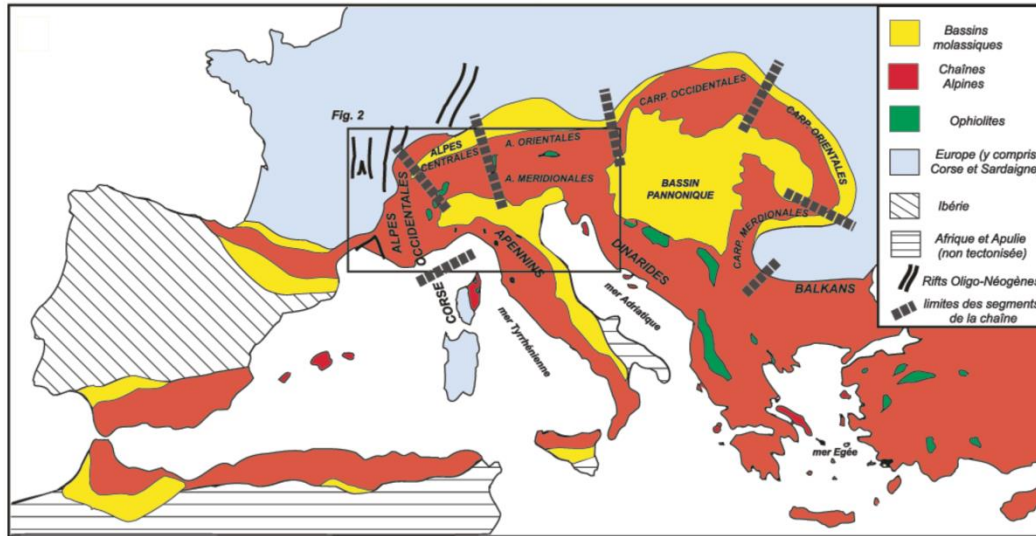
III. Calendrier et modèle d'évolution des Alpes franco-italiennes; évolution récente; réflexion sur la structure

- A. Calendrier et modèle d'évolution
- B. Evolution récente à actuelle
- C. Une structure résultant d'un poinçonnement mantellique et de l'emboîtement de 3 prismes d'accrétion dans le temps et dans l'espace

BIBLIOGRAPHIE

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- Dercourt : "Géologie et Géodynamique de la France, Dunod
- Agard et Lemoine : "Visages des Alpes : structure et évolution géodynamique", CCGM
- Debelmas et Masclé : "Les grandes structures géologiques", Masson
- Lallemand, Jolivet, Huchon, Prouteau : « Convergence lithosphérique », Vuibert

(Agard et Lemoine, 2003)

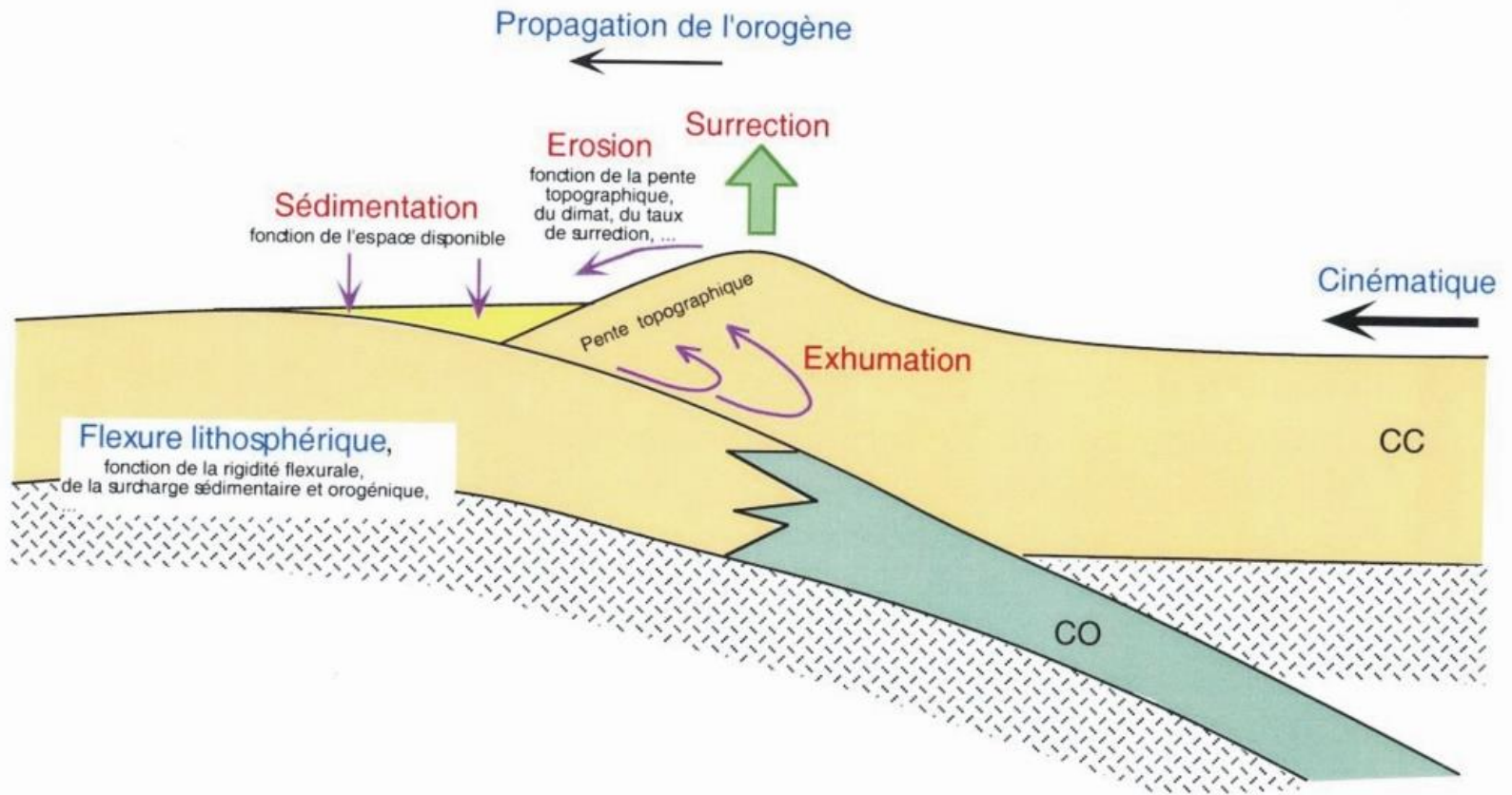


I. Les Alpes franco-italiennes : une chaîne de subduction-collision

I. Les Alpes franco-italiennes : une chaîne de subduction-collision

A. Les unités structurales

Le domaine dauphinois
et les chaînes de l'avant-pays alpin :
Un « prisme d'accrétion » oligo-miocène



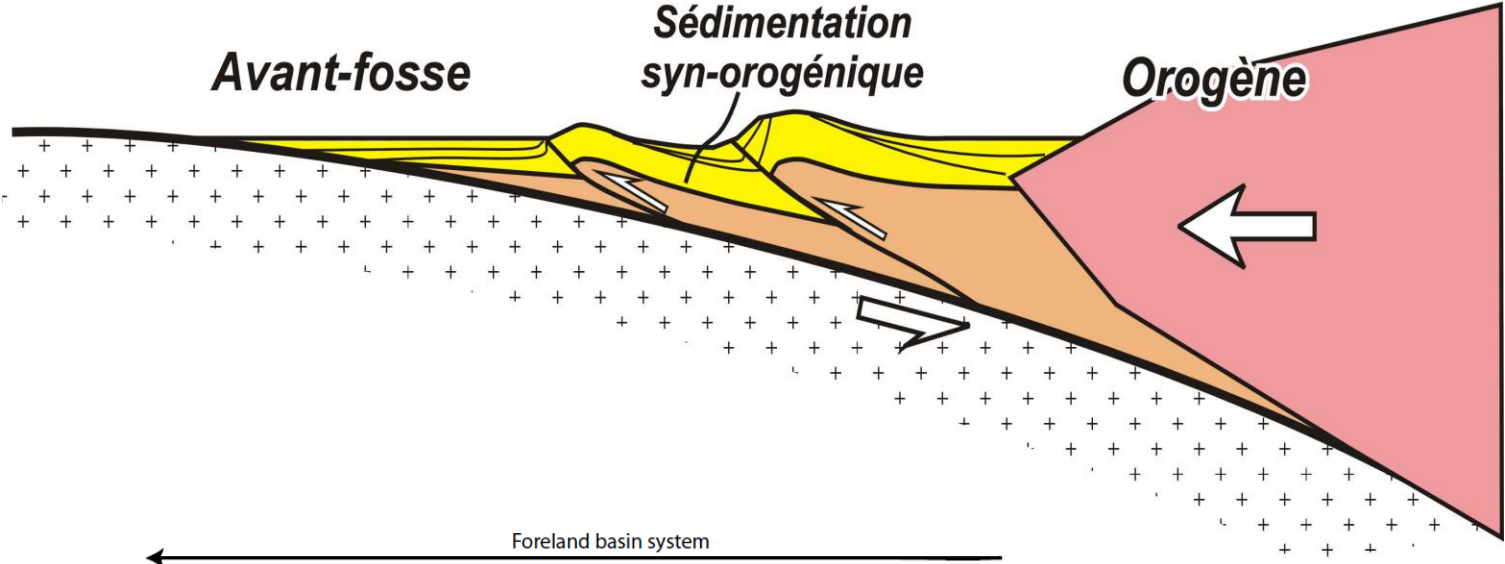
Prisme orogénique

Bassin d'avant-pays

Avant-fosse

**Sédimentation
syn-orogénique**

Orogène



Orogenic wedge

Foreland basin system

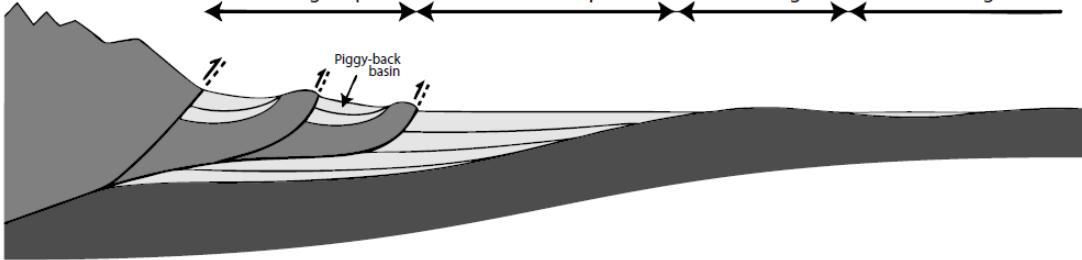
Wedge top

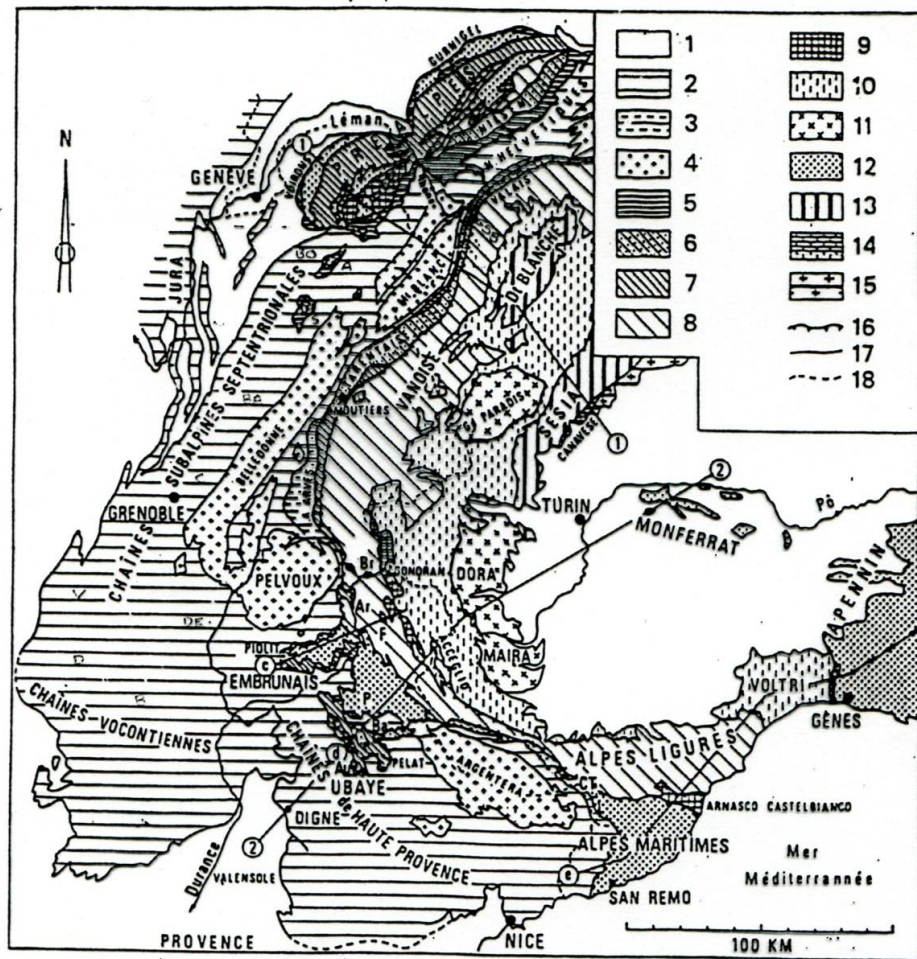
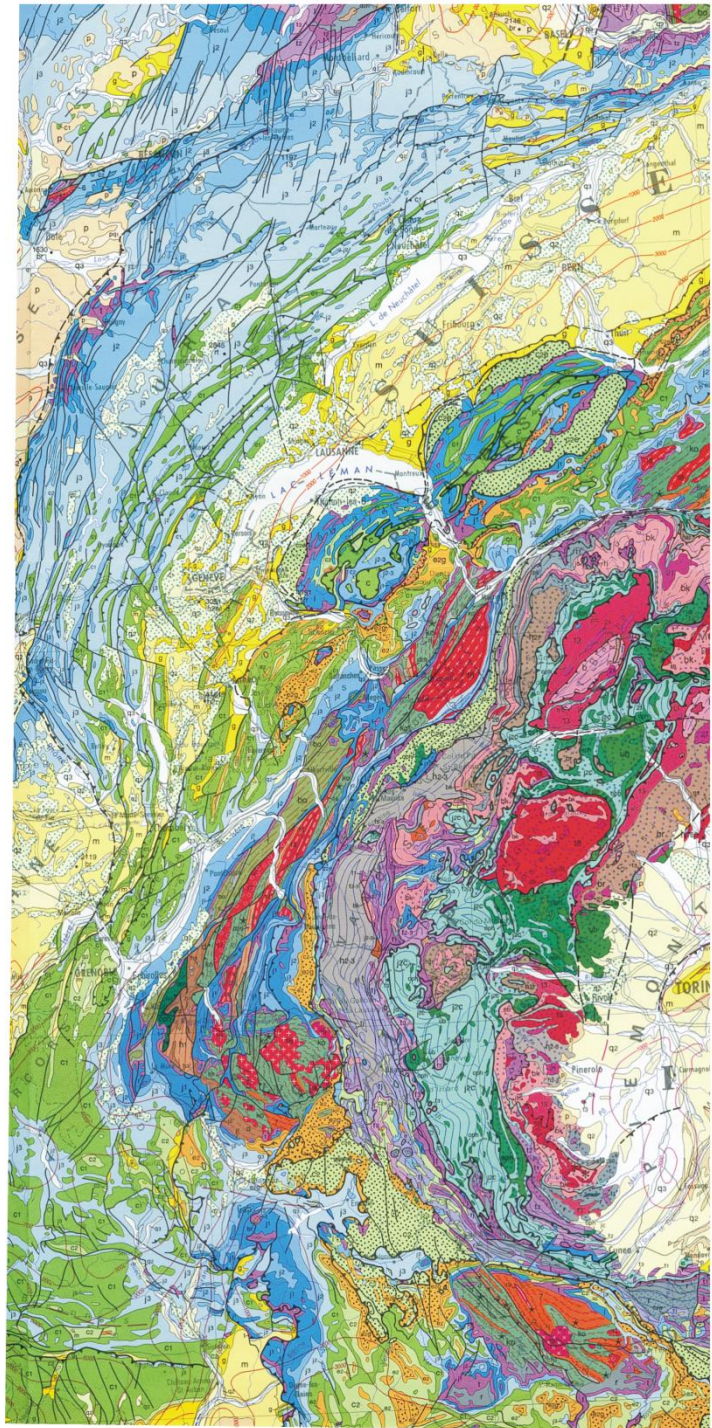
Foredeep

Forebulge

Backbulge

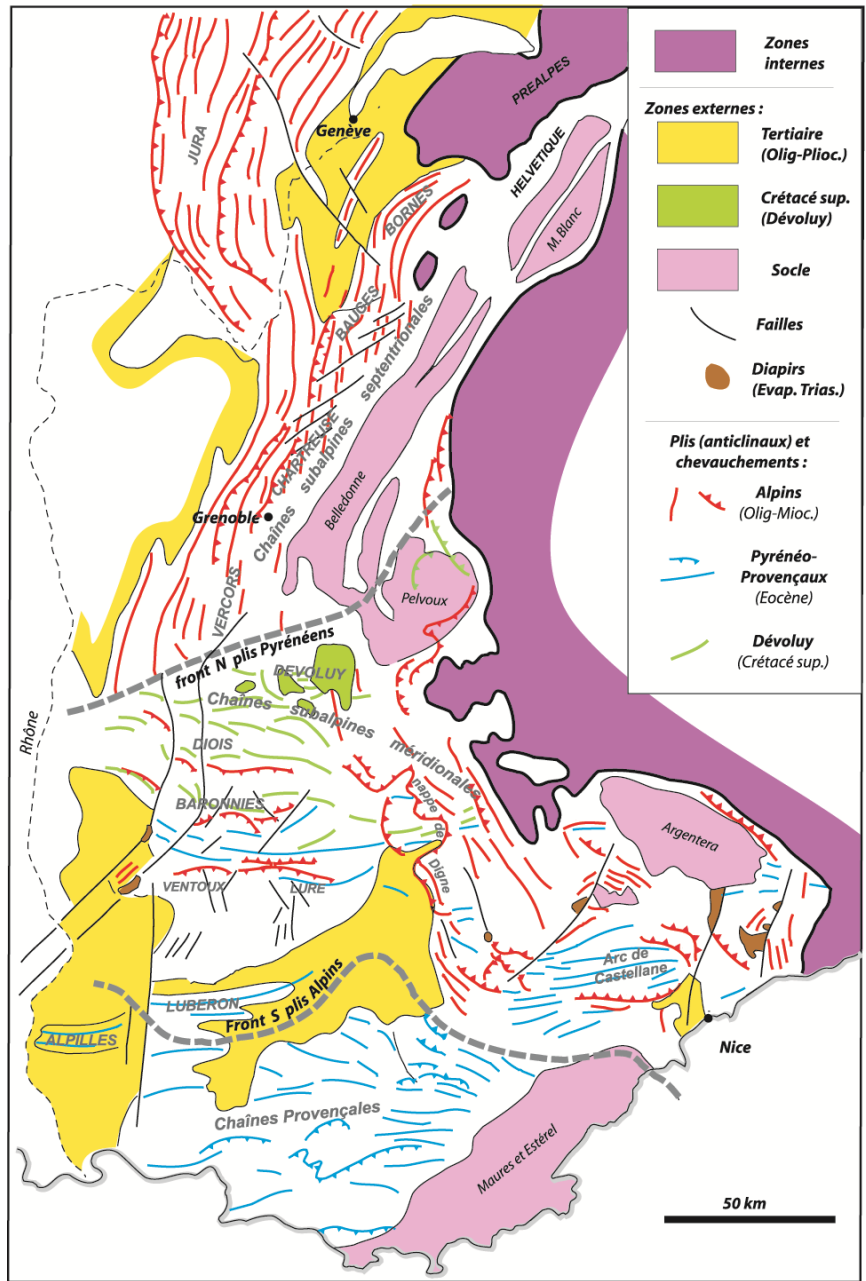
Piggy-back basin





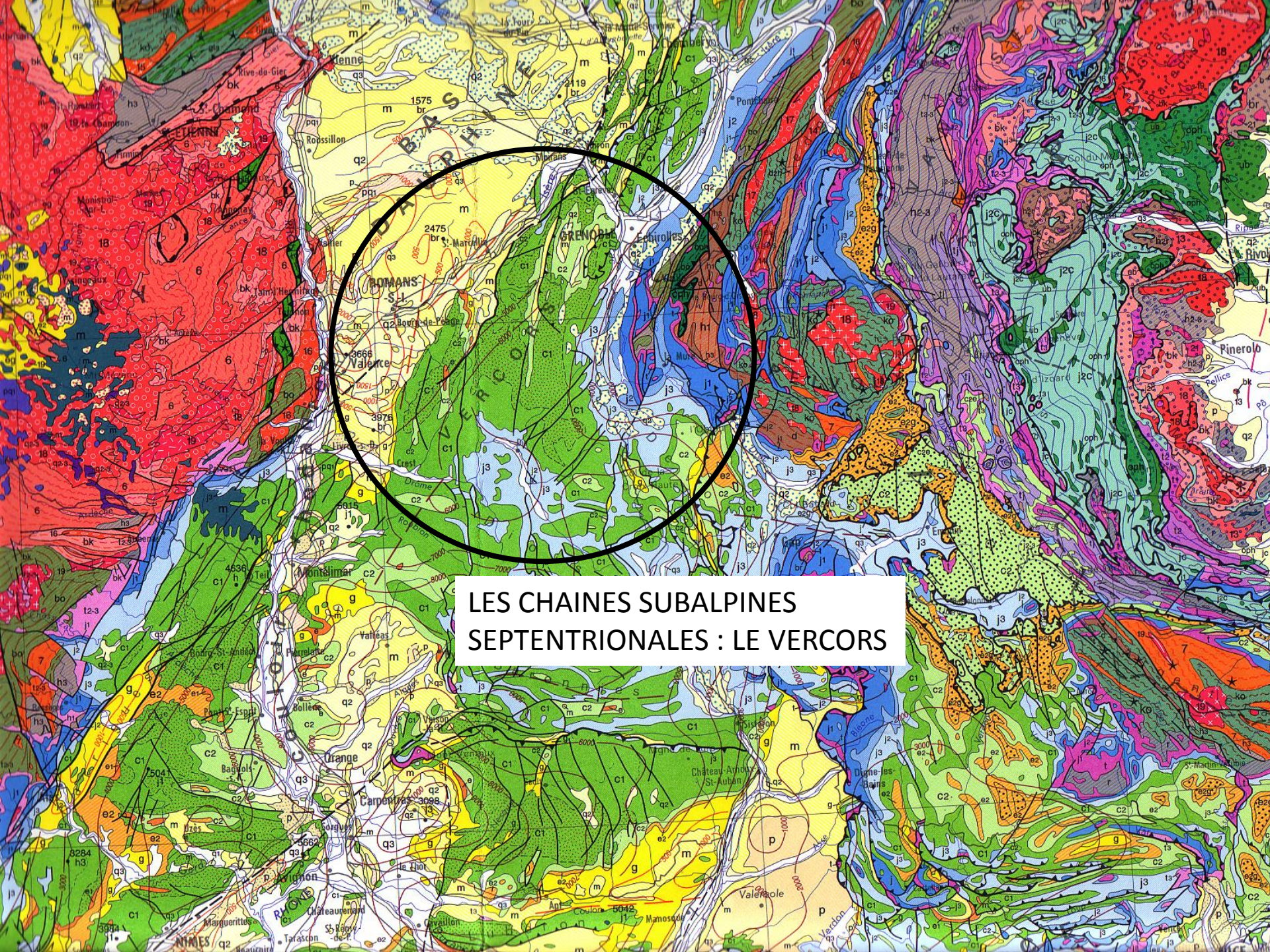
Esquisse structurale des Alpes occidentales, des Préalpes à l'Apennin septentrional.

1. Bassins tertiaires et quaternaires péri-alpins ; 2. Couverture sédimentaire mésozoïque et cénozoïque de la zone externe ; 3. Unités parautochtones orientales majeures de la zone externe ; 4. Massifs cristallins externes et leur tégument permo-carbonifère ; 5. Nappes ultrahelvétiques (Préalpes inférieures) ; 6. Zone valaisanne (et nappe du Niesen des Préalpes) ; 7. Zone subbriançonnaise (et Préalpes médianes "plastiques") ; 8. Zone briangonnaise (et Préalpes médianes "rigides") ; 9. Unités prépiémontaises (et nappe de la Brèche des Préalpes) ; 10. Zone piémontaise ("Pays des Schistes lustrés") ; 11. Massifs cristallins internes sous la zone piémontaise ; 12. Flyschs alloctones et nappes ligures de l'Apennin ; 13. Unités ? austroalpines ? ; 14. Zone du Canavese ; 15. Cristallin insubrien (sud-alpin) ; 16. Chevauchement majeur ; 17. Limite d'unité tectonique ; 18. Frontière franco-italienne et franco-suisse ;
 Ba. Barcelonnette (fenêtre de) ; Br. Briançon ; C.T. Col de Tende (unité parautochtone du) ; F. Furfande (klippe de Nisch de) ; P. Parpaillon (massif du) ;

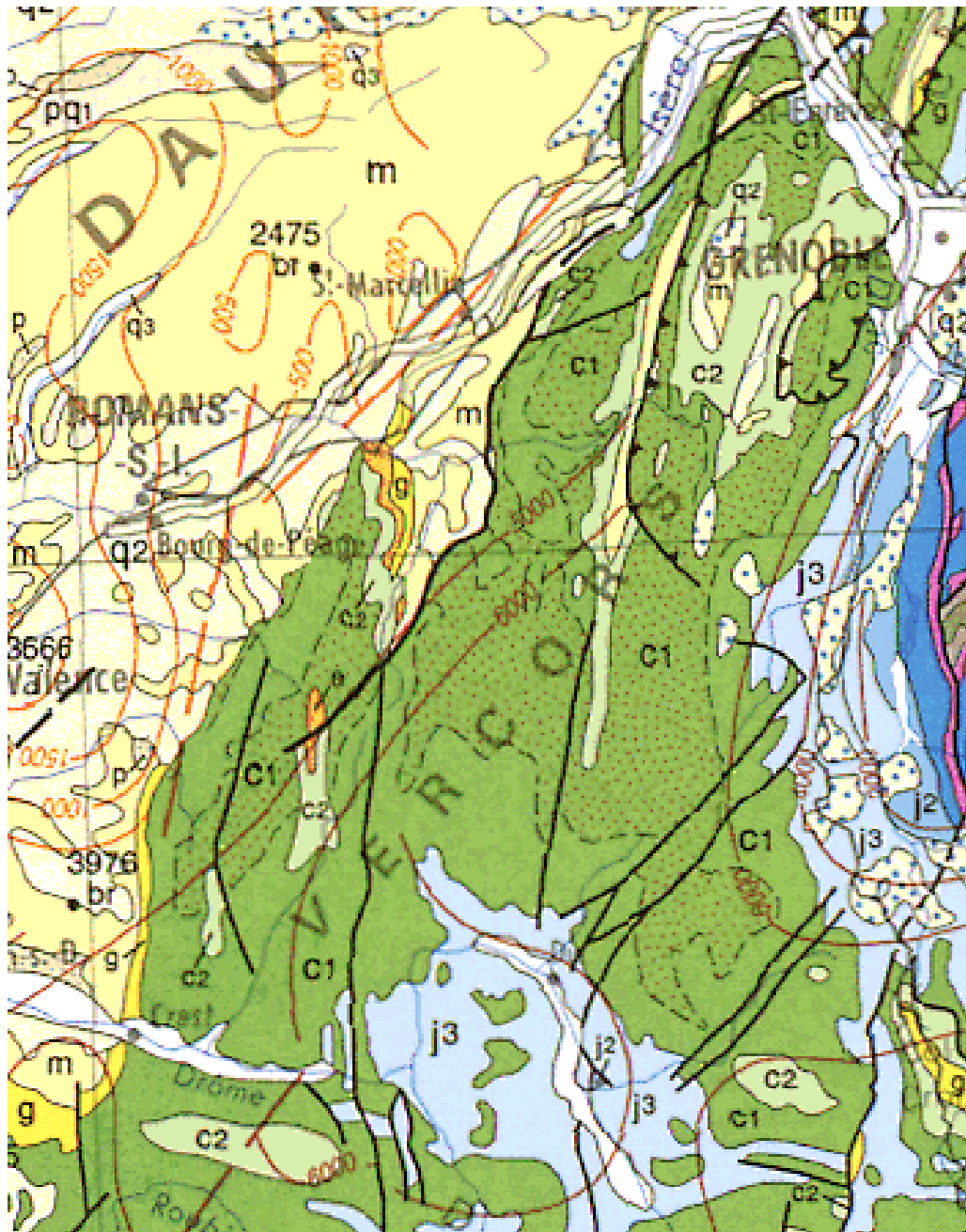


(Agard et Lemoine, 2003)

Un exemple de chaîne subalpine :
La chaîne plissée d'avant-pays du Vercors



LES CHAINES SUBALPINES
SEPTENTRIONALES : LE VERCORS

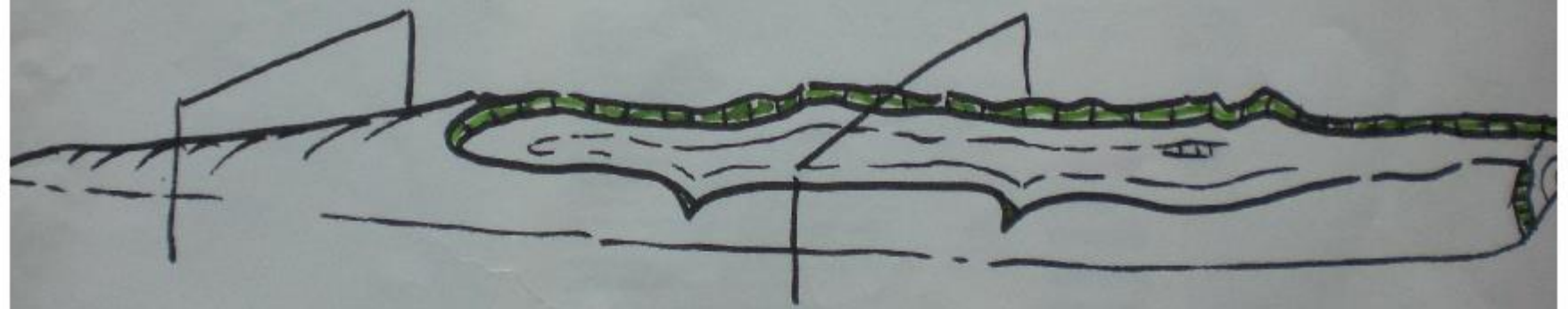


Vue depuis l'Ouest de l'anticlinal de Saint Nazaire en Royans



N

S



n

h



Front de l'anticlinal de Pont-en-Royans

Front de chevauchement du Vercors sur les molasses

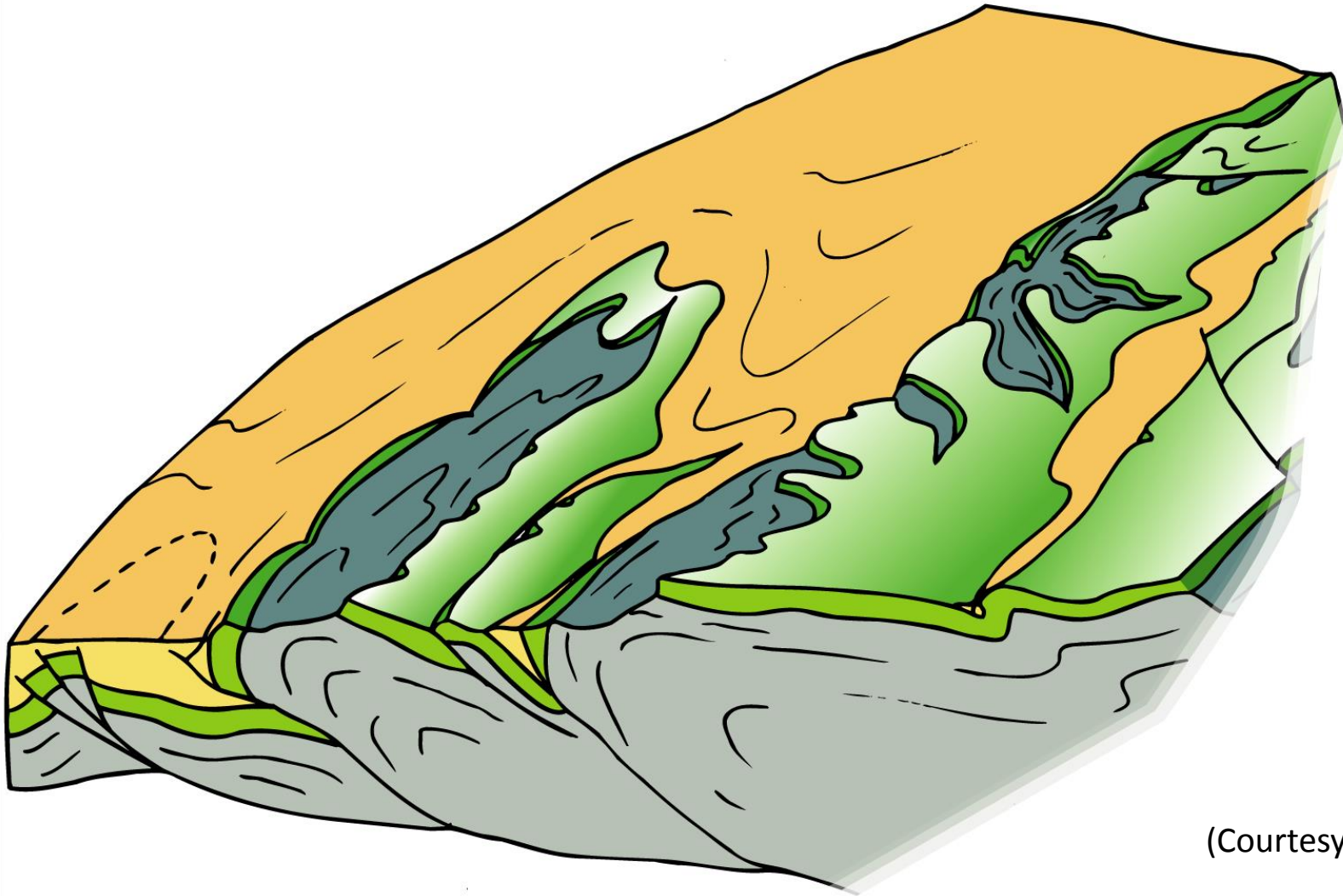


Le synclinal à cœur de Miocène de Rencurel

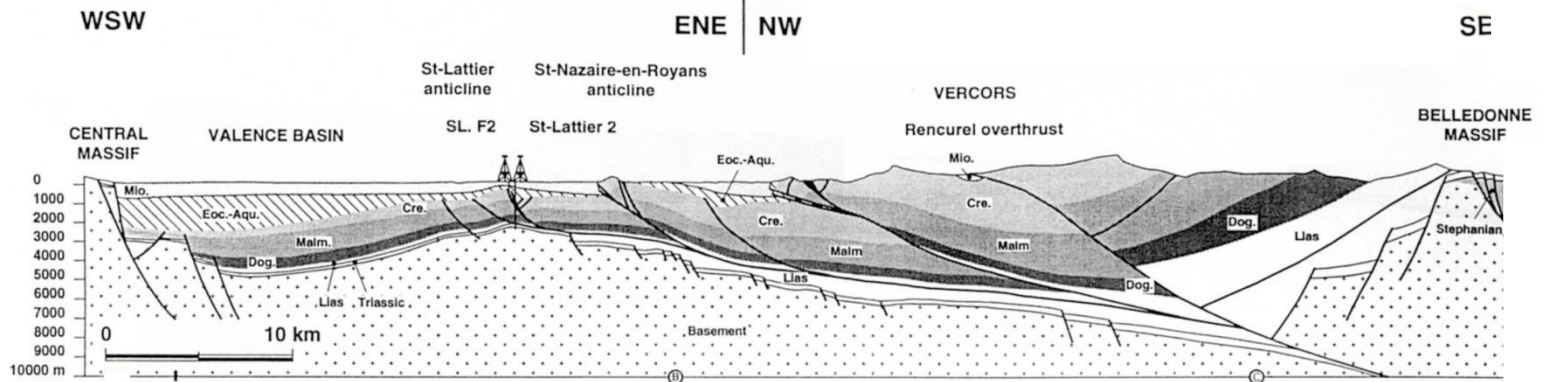




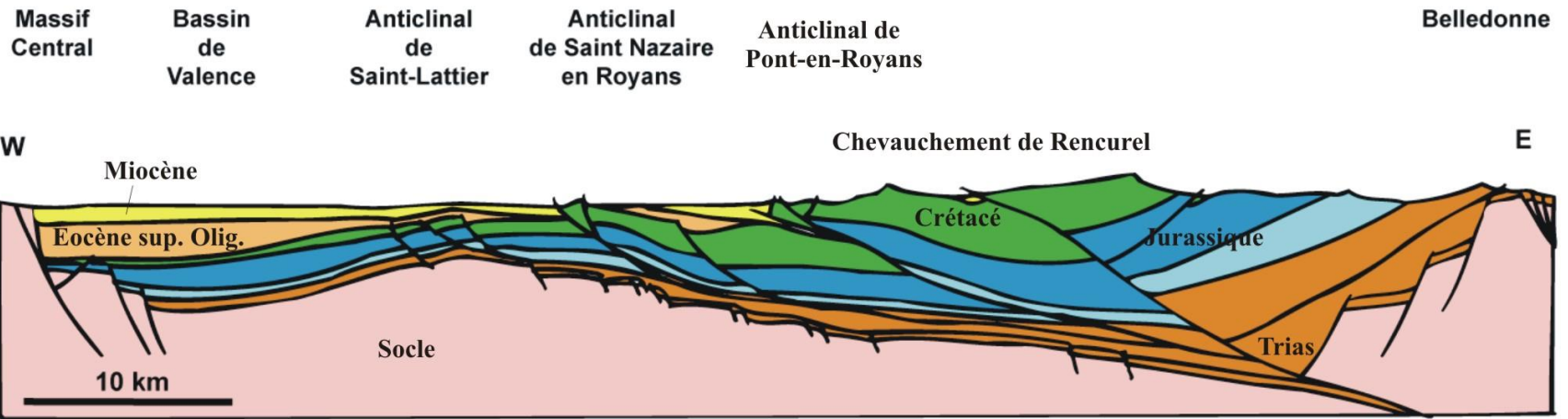
Le style tectonique du Vercors



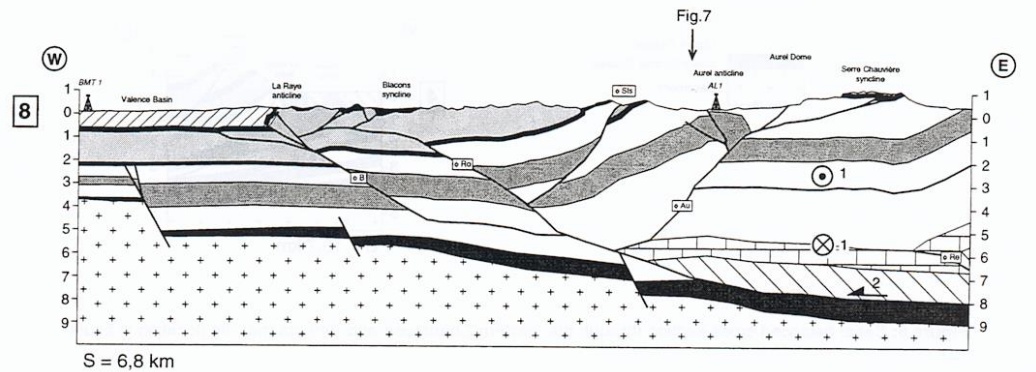
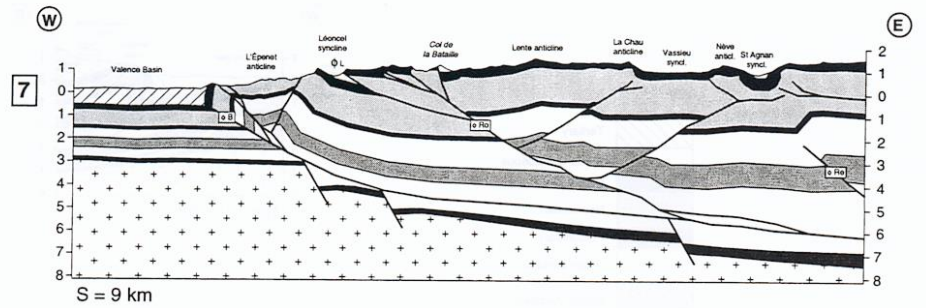
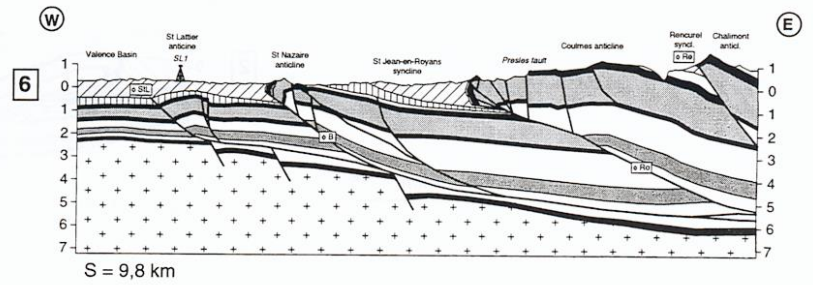
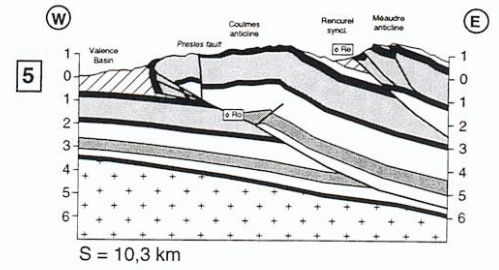
(Courtesy of L. Jolivet)



VERCORS



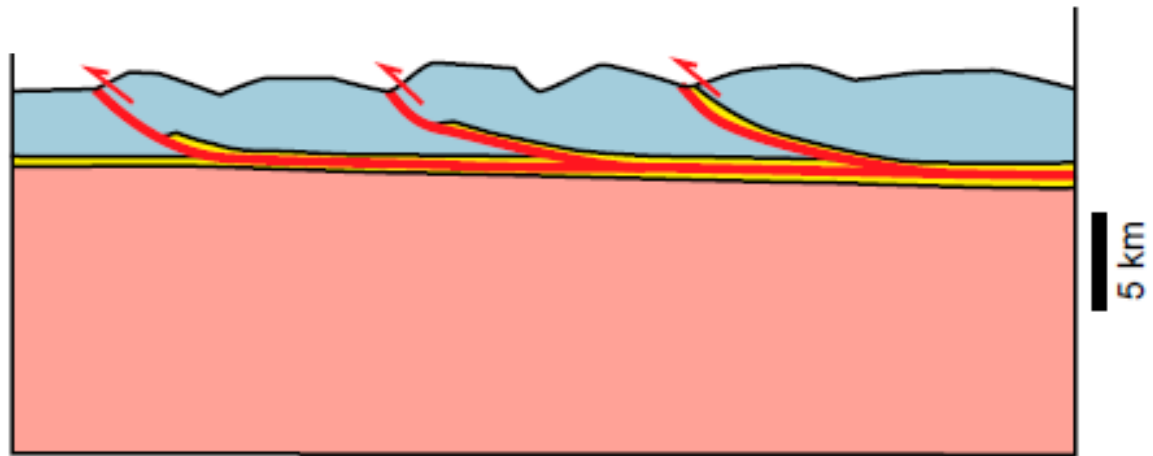
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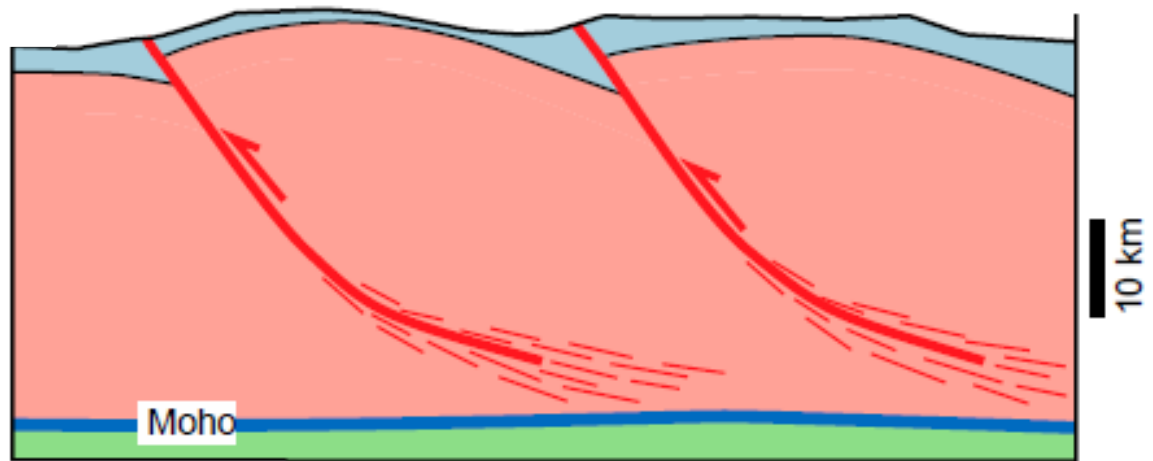
(Philippe, 1995)

(Pfiffner, 2017)

Thin-skinned style

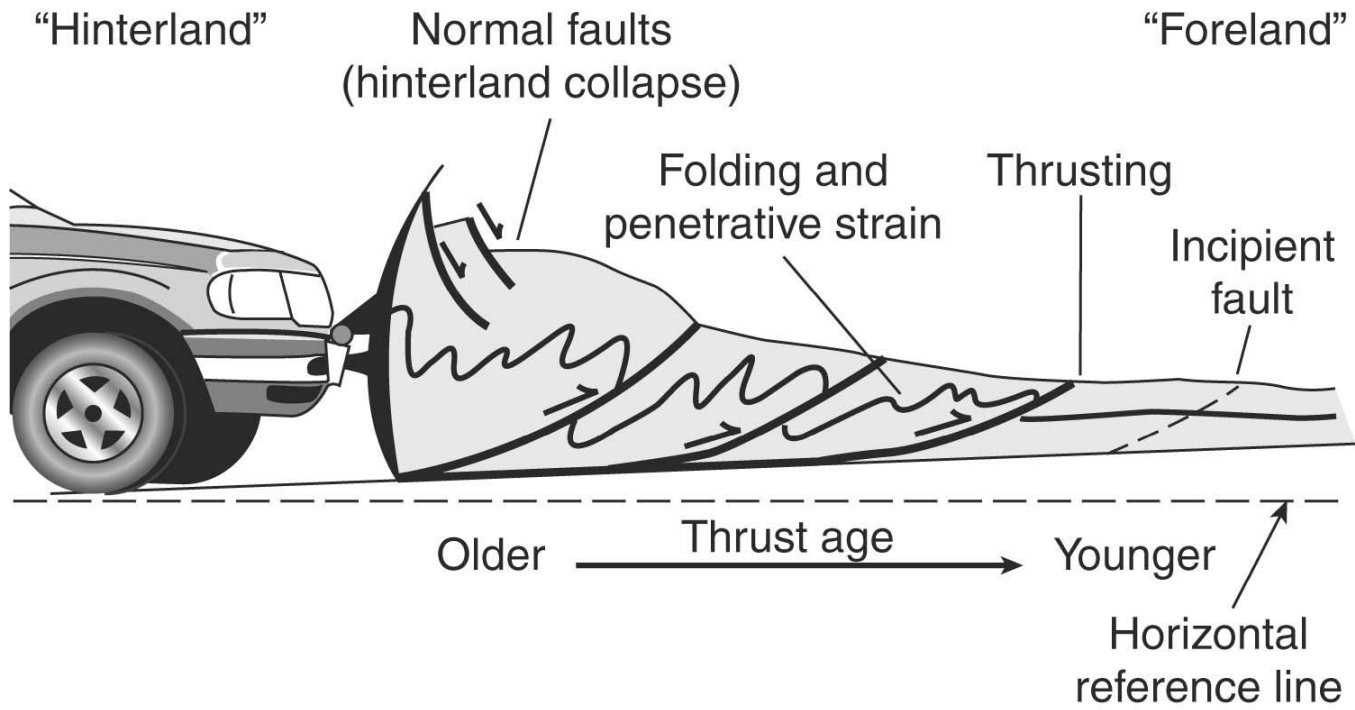


Thick-skinned style

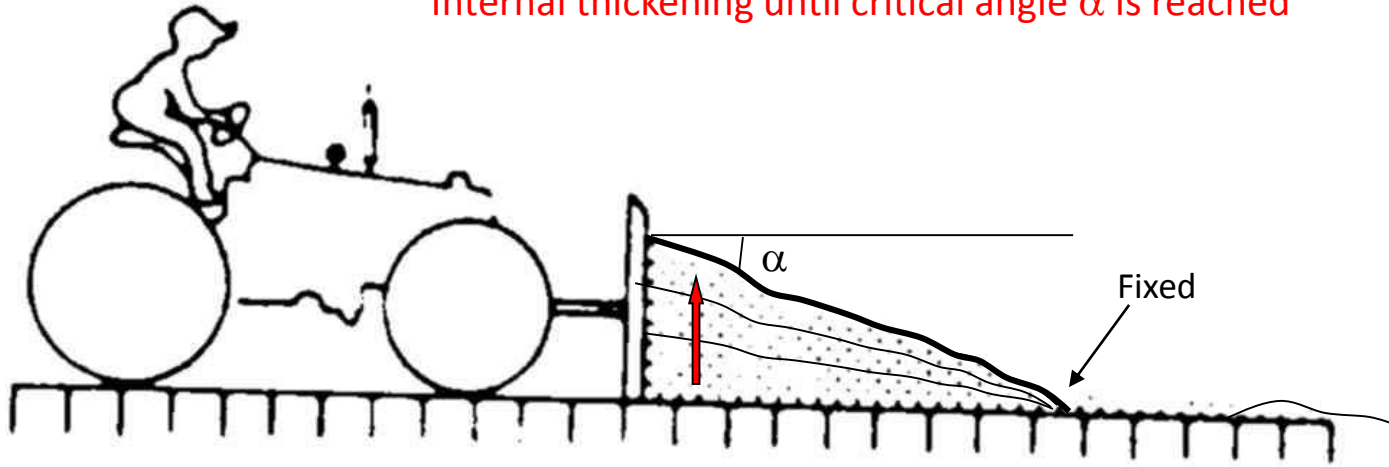


Le Vercors :
une chaîne de couverture Mio-Pliocène
décollée au niveau du Lias...

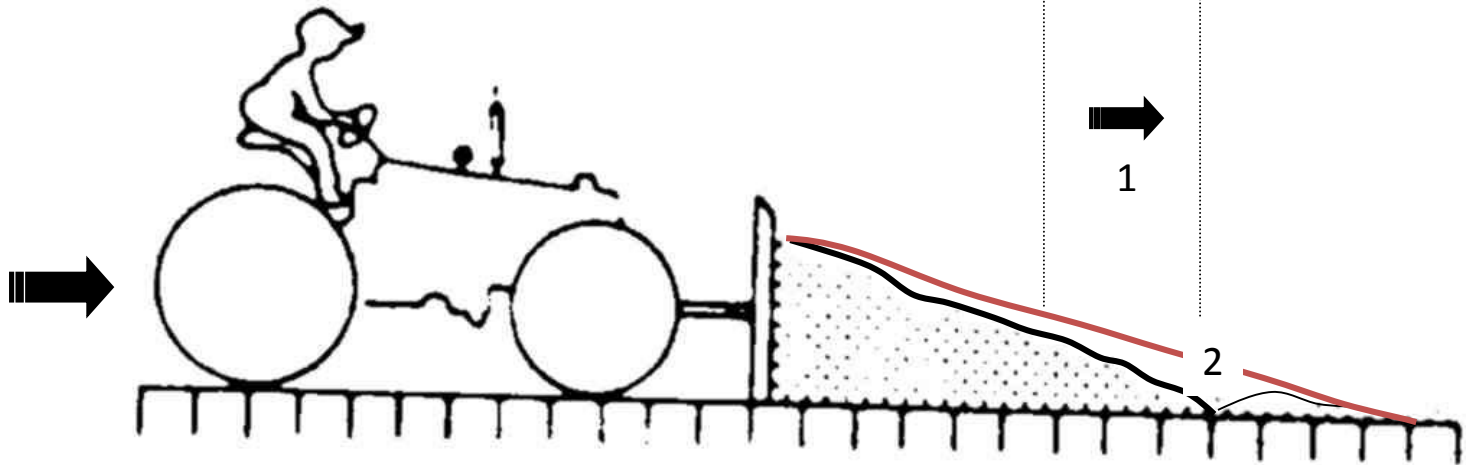
... analogue à un prisme d'accrétion
sédimentaire des zones de subduction ...



Internal thickening until critical angle α is reached



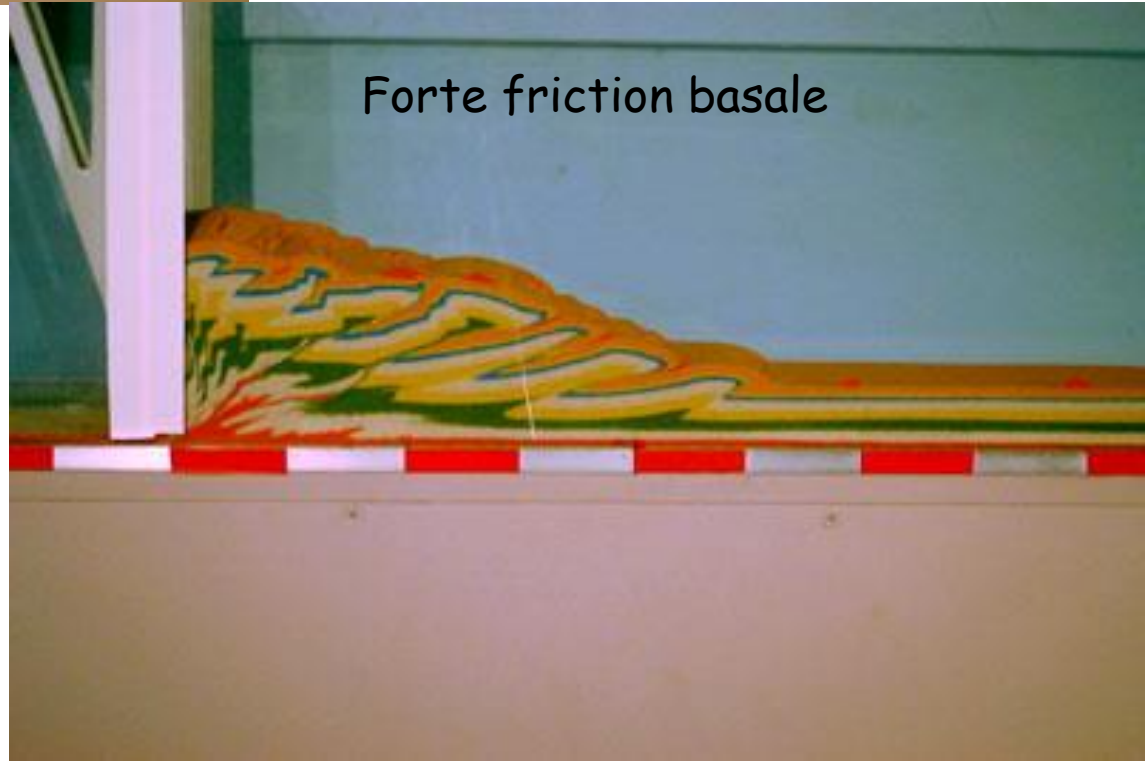
1. Basal sliding without internal thickening, then
2. New snow is incorporated in the wedge, α is lowered, then
3. The wedge will deform internally until α is reached again, and so on



Faible friction basale



Forte friction basale





| B

| A

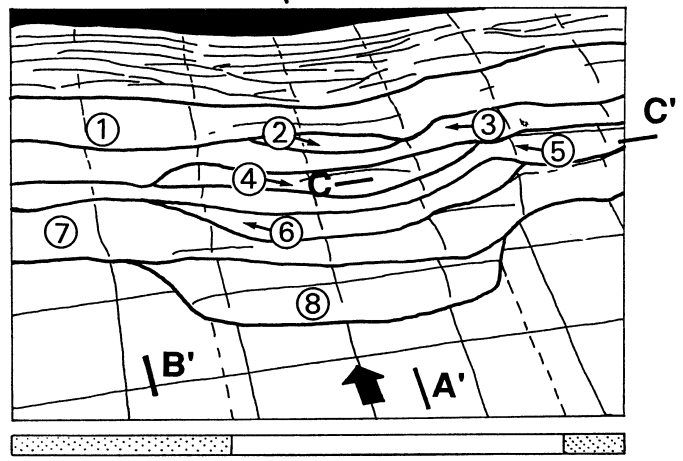
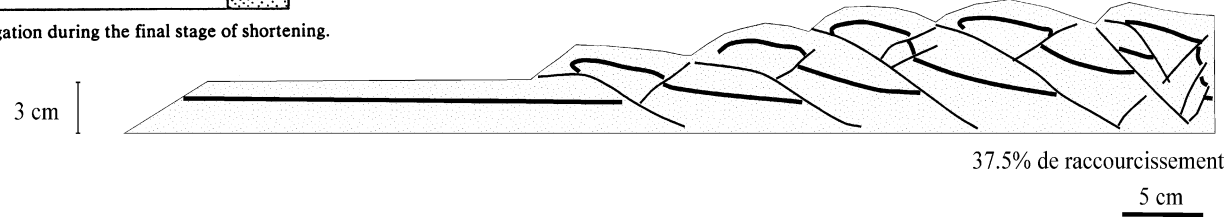
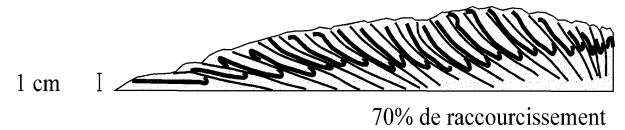
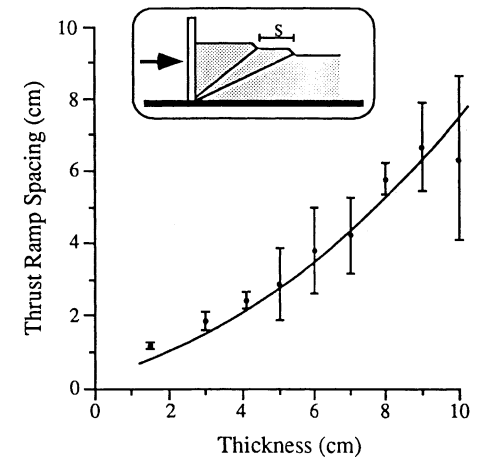
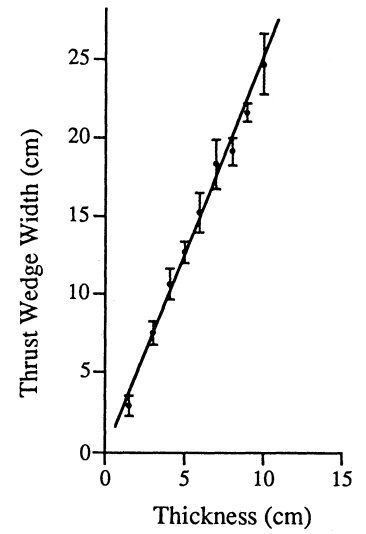
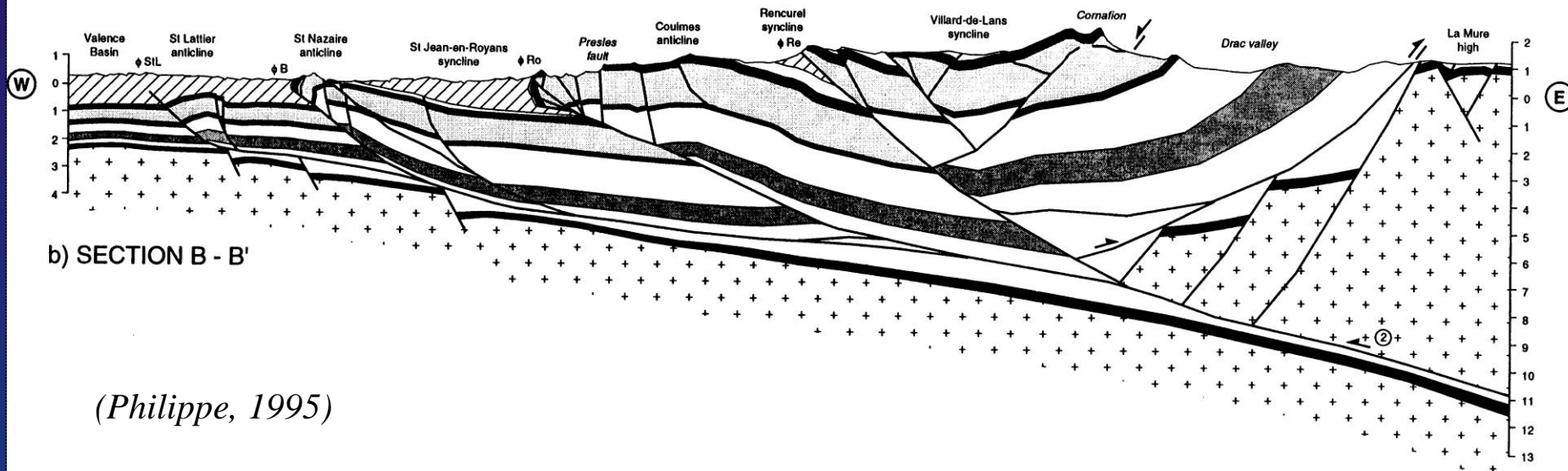
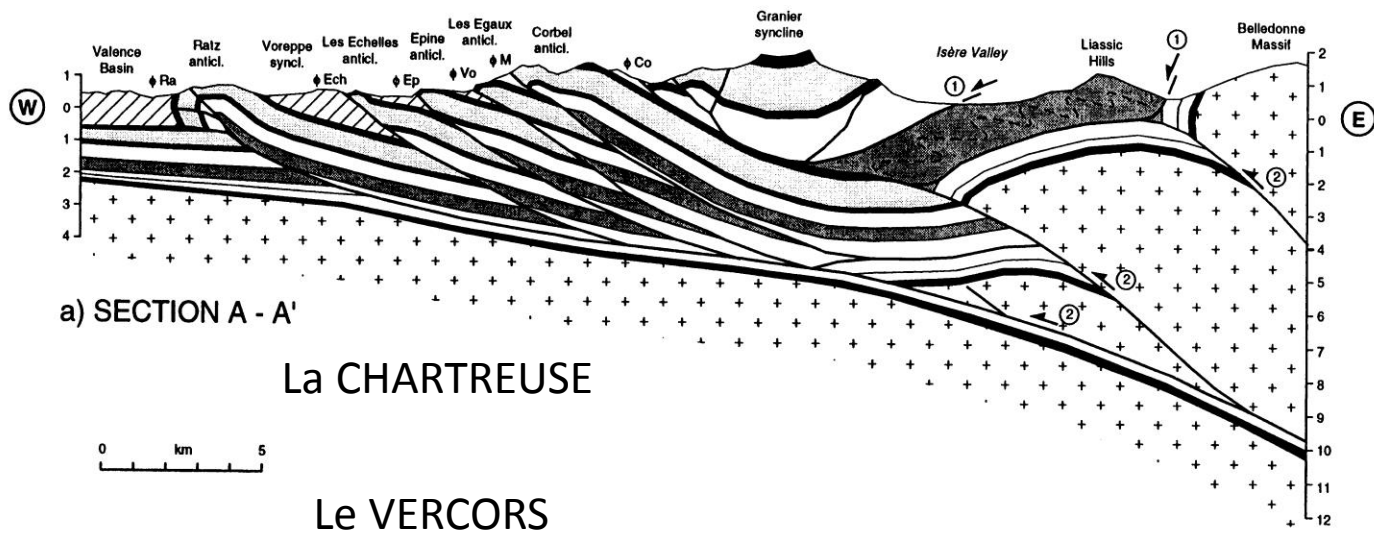
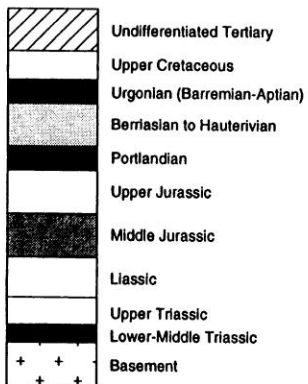


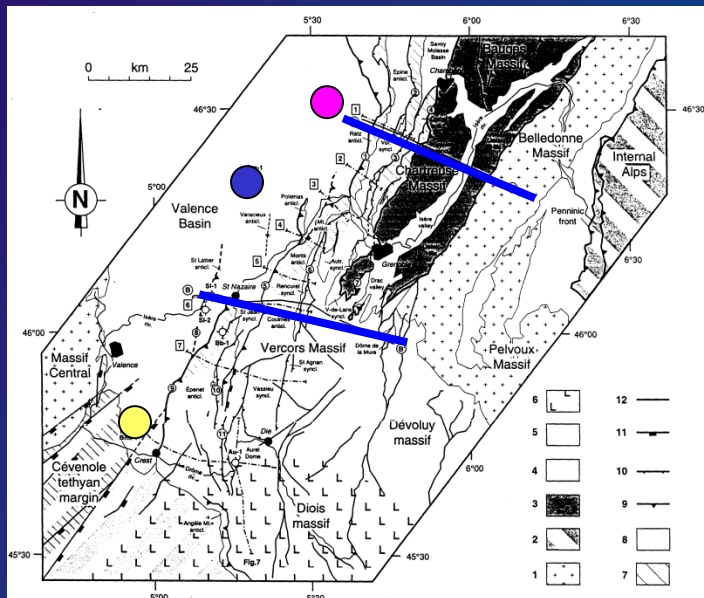
Fig. 12. The kinematics of thrust propagation during the final stage of shortening.



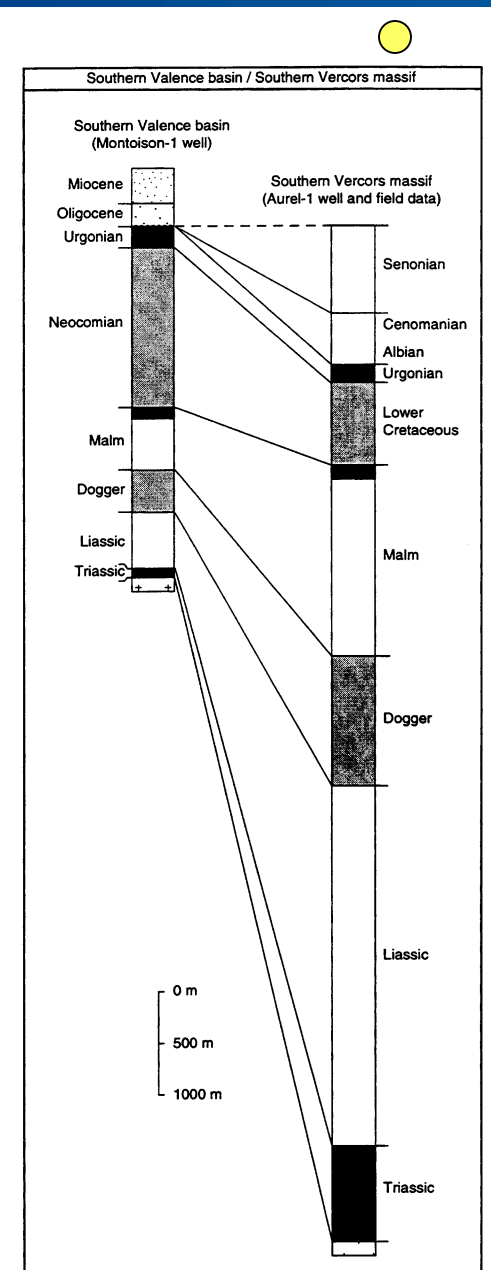
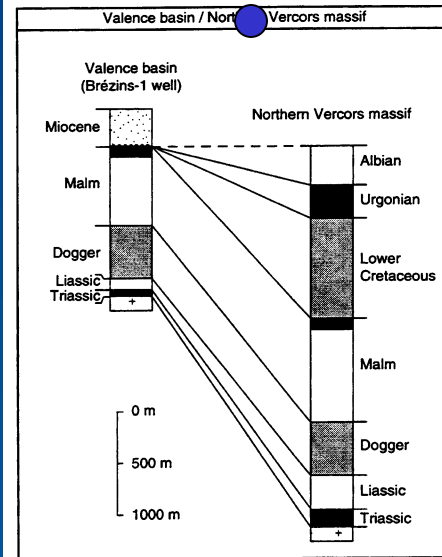
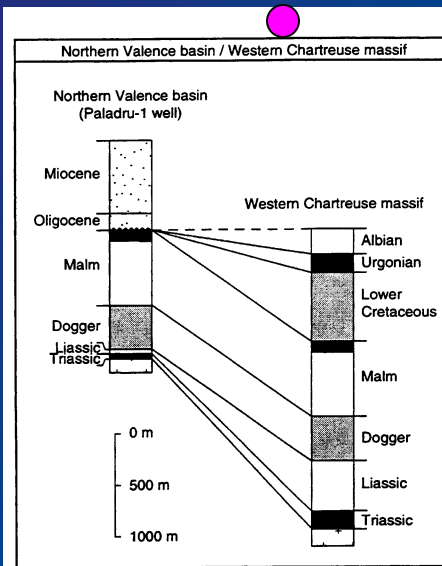


(Philippe, 1995)

Epaisseur de la couverture sédimentaire de la Chartreuse au Vercors



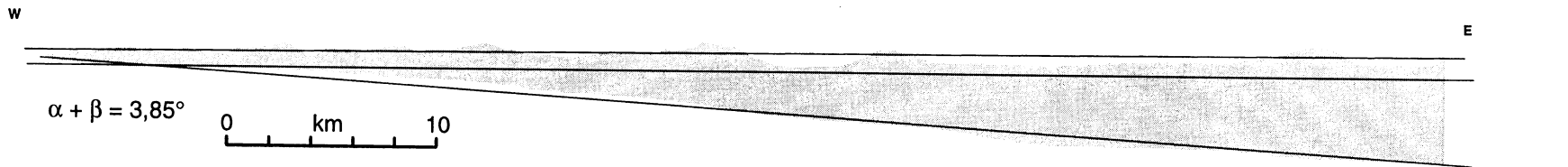
(Philippe, 1995)



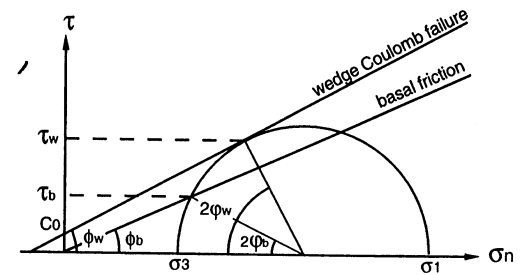
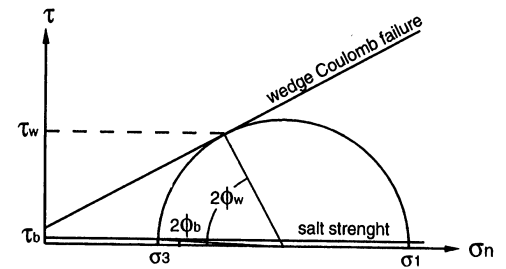
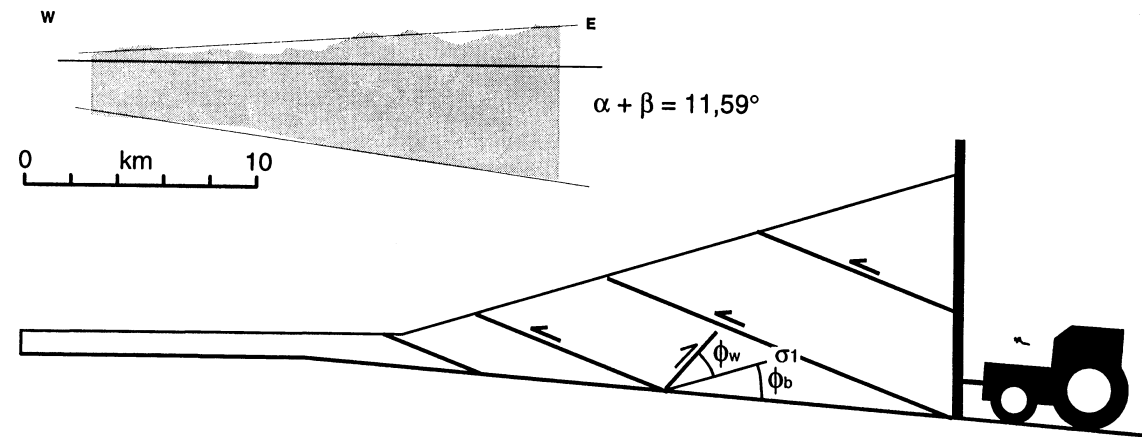
Interprétation Jura (ou Vercors)/Chartreuse en termes de prisme critique (rôle de la friction basale)

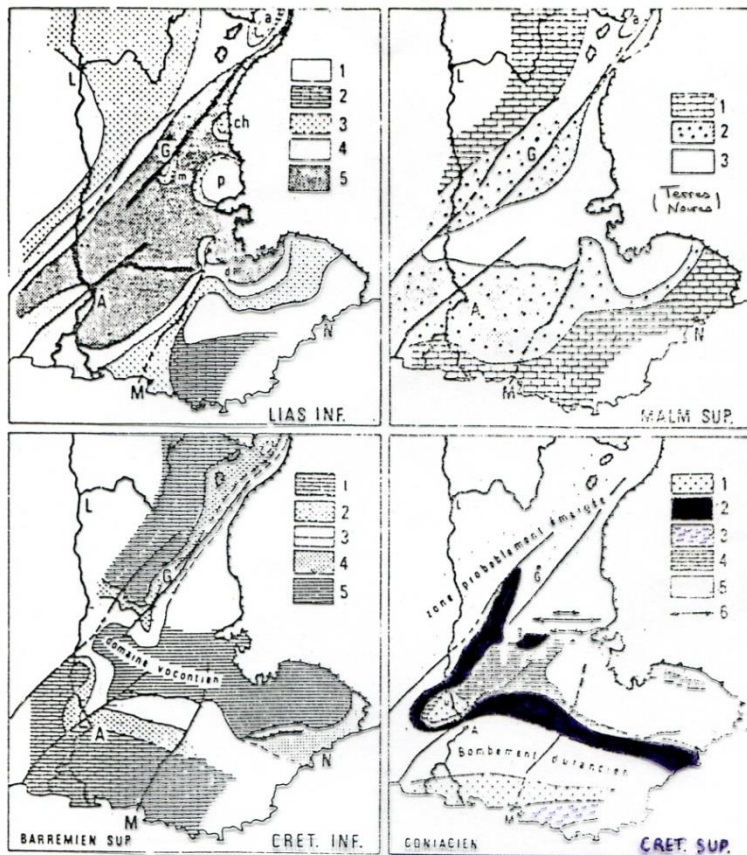
(a) Jura fold-and-thrust belt and Molasse Basin: / Vercors

(Philippe, 1995)



(b) Chartreuse fold-and-thrust belt:





Cartes paléogéographiques simplifiées au Sud-Est de la France.

Sur toutes les cartes, on a indiqué un certain nombre de grandes failles qui ont commandé la paléogéographie pendant tout le Mésozoïque et ont, localement au moins, rejoué au moment du plissement alpin. Ce sont, du NW au SE, la faille d'Alès-Marsanne, la faille de la Cléry et du synclinal médian de Belledonne, la faille de Nîmes, et la faille de la Basse-Durance (ou d'Aix-en-Provence).

En outre ont été indiqués, à titre de repère topographique et parce qu'ils raccourcissent l'aire paléogéographique, les chevauchements de Ventoux-Lure (à gauche) et de Castellane (à droite).

A : Avignon, G : Grenoble, L : Lyon, M : Marseille, N : Nice.

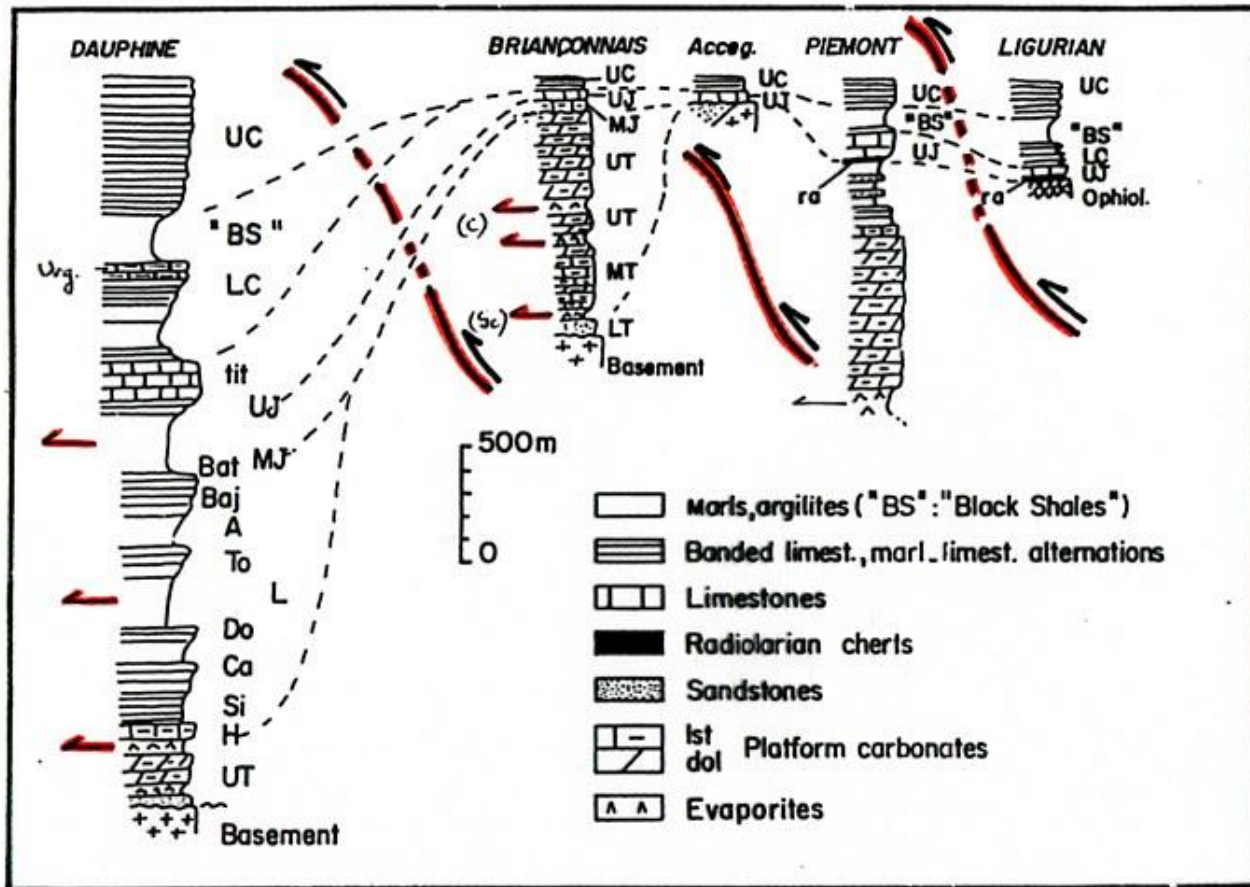
Lias inférieur : 1. Zones émergées; 2. Dolomies intertidales à supratidales; 3. Faciès zongènes peu épais; 4. Faciès calcaréo-marneux à Céphalopodes et Gryphées (Digne); épaisseur moyenne à faible; 5. Faciès calcaréo-marneux à Céphalopodes; épaisseur forte.

Malm supérieur : 1. Portlandien récifal, souvent dolomitisé; 2. Tithonique pélagique; 3. Id. mais faciès plus profond.

Crétacé inférieur (Barremien supérieur) : 1, 2. Faciès urgonien (1. Calcaires à Rudistes; 2. Calcaires à débris); 3. Marnes et calcaires à spicules de Spongiaires; 4. séries minces : calcaires micritiques à Céphalopodes, glauconie, galets phosphatés et niveaux de condensation; 5. Calcaires et marnes à ammonites (faciès vocontien s.str.).

Crétacé supérieur (Coniacien) : 1. Calcaires à Rudistes (u. Uchaux); 2. Sables glauconieux souvent rubéfiés, et conglomérats (g. congl. des Cds, près Châtillon-en-Diois); 3. marnes gréseuses à brèches sédimentaires du sillon provençal; 4. Calcaires gréseux; 5. Calcaires pélagiques à Foraminifères, Céphalopodes et Inocérames; 6. Plis (Diois, Devoluy).

Le Lias d'après R. Mouterde; le Malm d'après Baudrimont et Dubois; le Crétacé inférieur d'après H. Arnaud; le crétacé supérieur d'après H. Arnaud, J. Philip et B. Porthault.

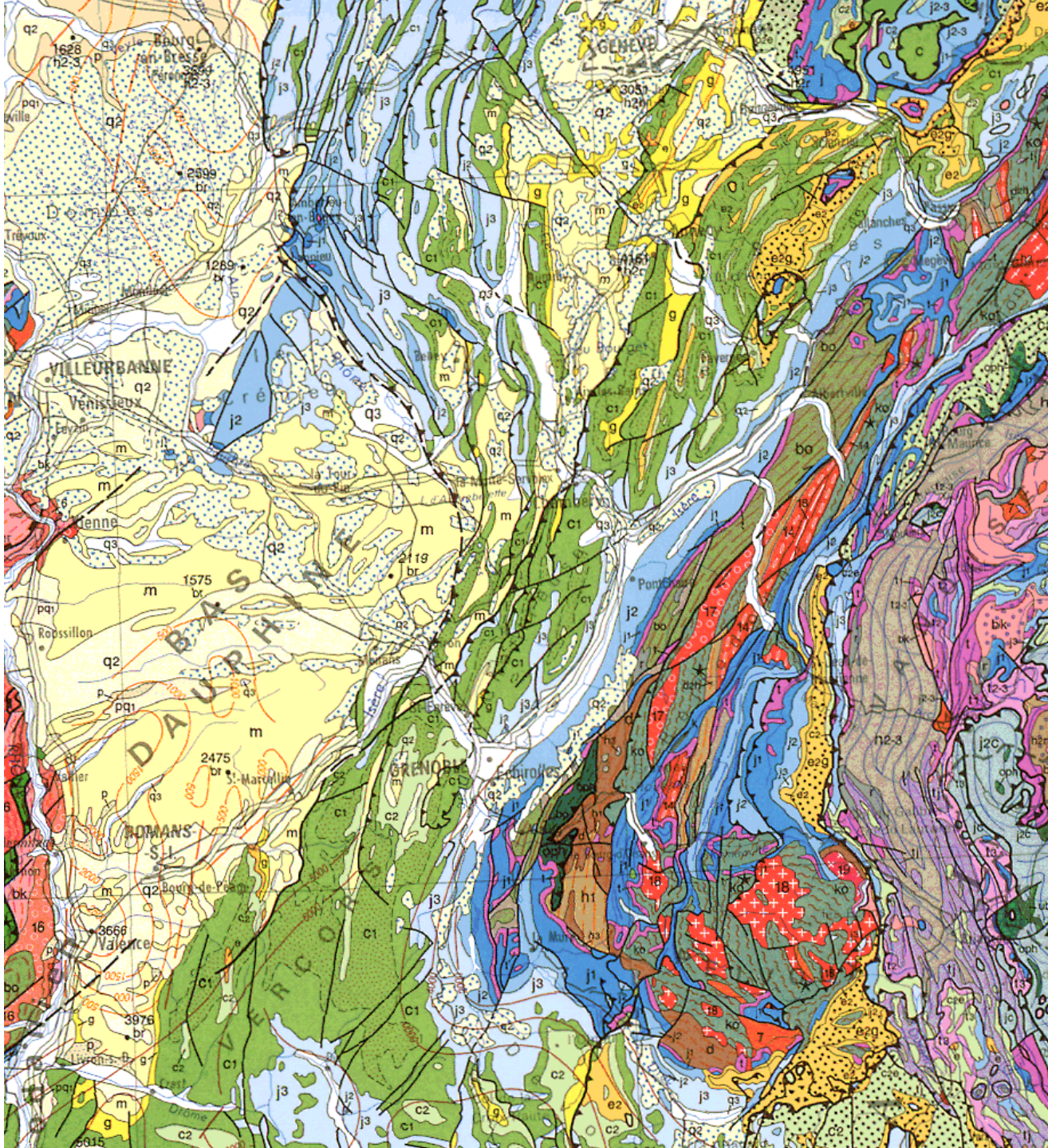


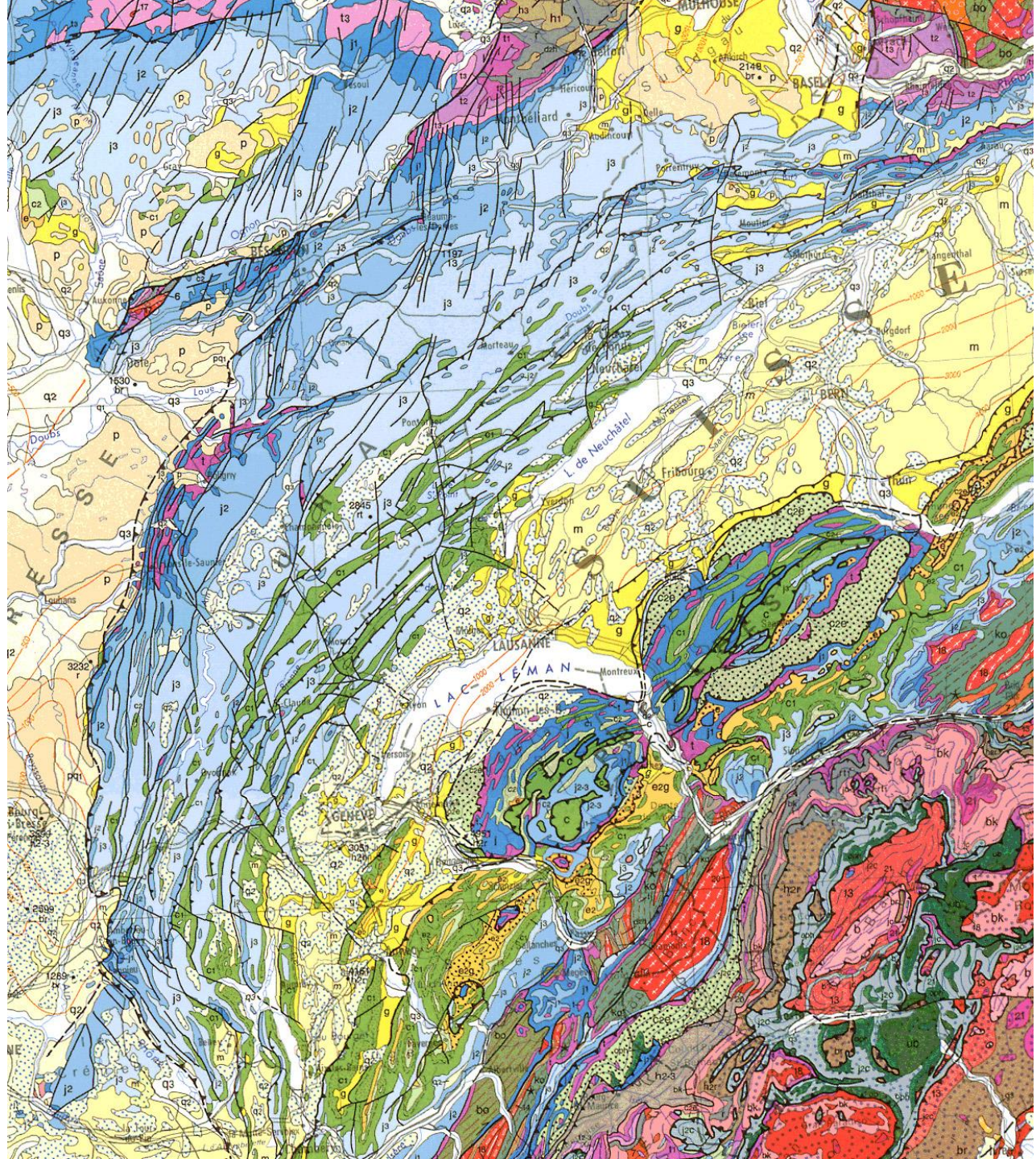
Simplified stratigraphic columns of the main types of sedimentary series in the Western Alps.

= Méozoïque

(Lemoine et al., 2006)

Le Jura







Jura externe =
Jura des Plateaux

Jura interne = Jura plisse

NEUCHÂTEL

LAUSANNE

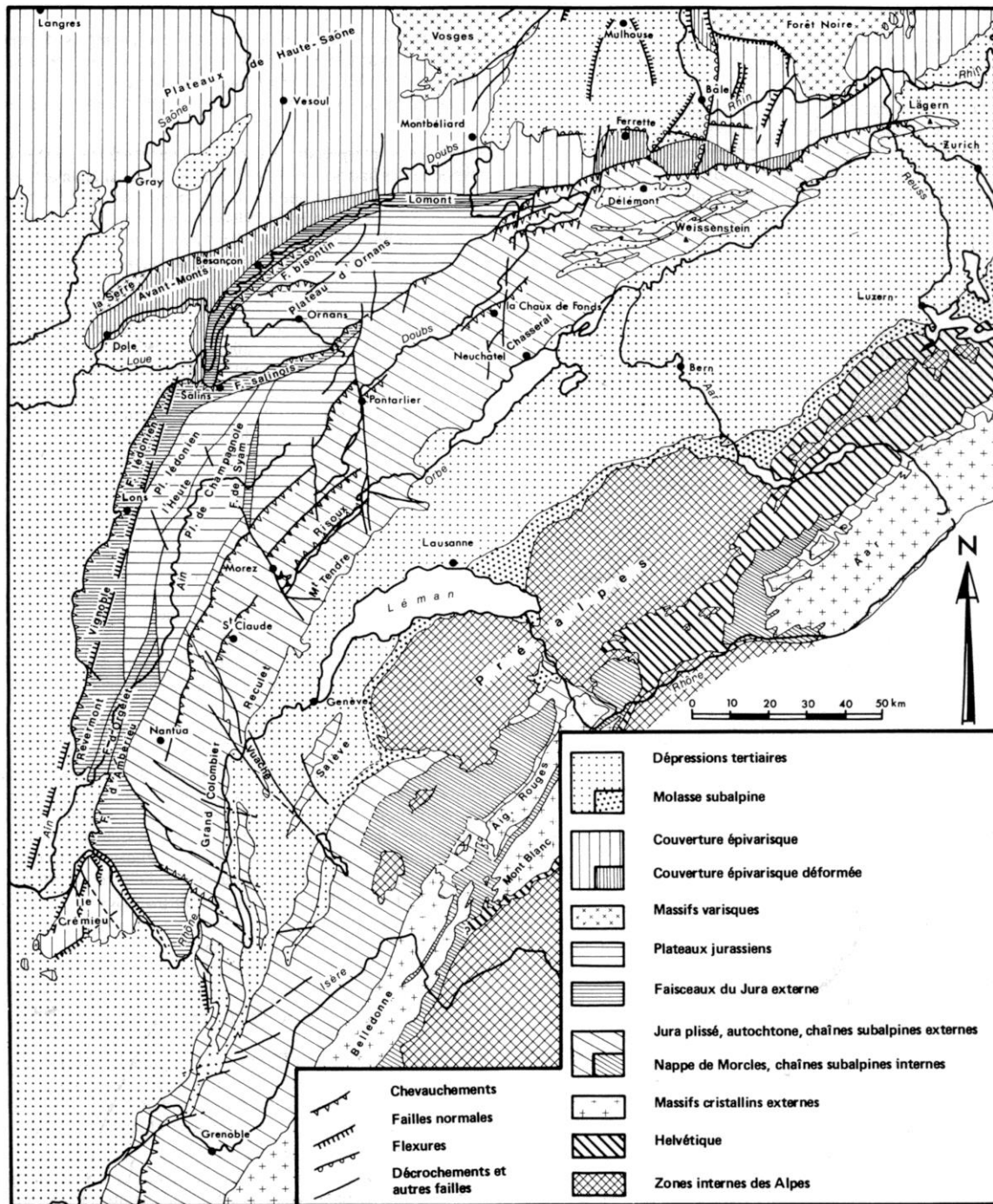
GENÈVE

S O I L

LEMAN

BERN

BASEL



Langres

Haute-Saône

Vosges

Mulhouse

Forêt Noire

Bâle

Läger

Zurich

Vesoul

Montbéliard

Doubs

Ferrette

Delémont

Weissenstein

Gray

Lamont

Avant-Monts

Plateau d'Ornans

Dole

Ornans

Doubs

Chaux de Fonds

Neuchâtel

Chassera

Bern

Luzern

la Serris

Basancion

Disant

Plateau d'Ornans

Dole

Loup

Salins

F. salins

Pontarlier

Ornans

Doubs

Chassera

la Serris

Avant-Monts

Disant

Plateau d'Ornans

Dole

Loup

Salins

F. salins

Pontarlier

Ornans

Doubs

Chassera

la Serris

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Pontarlier

Ornans

Doubs

Chassera

la Serris

Avant-Monts

Disant

Plateau d'Ornans

Dole

Loup

Salins

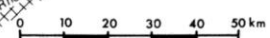
F. salins

Pontarlier

Ornans

Doubs

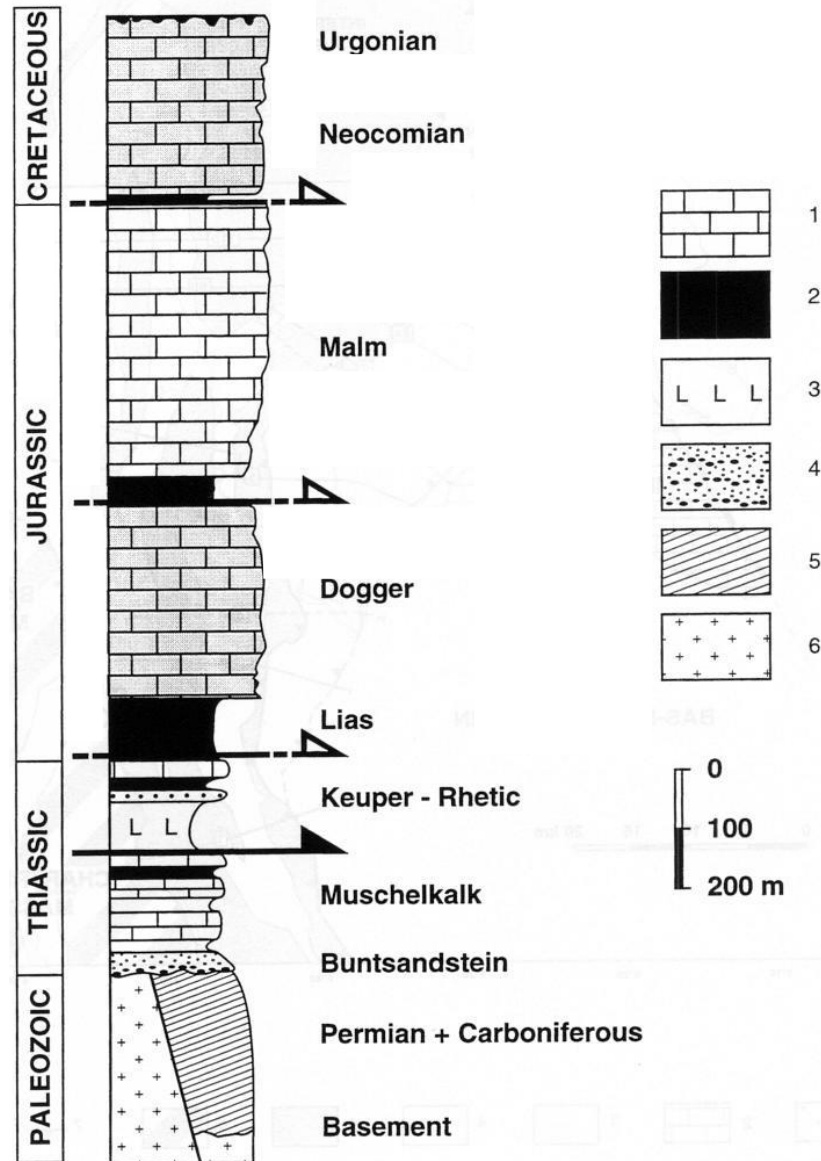
Chassera

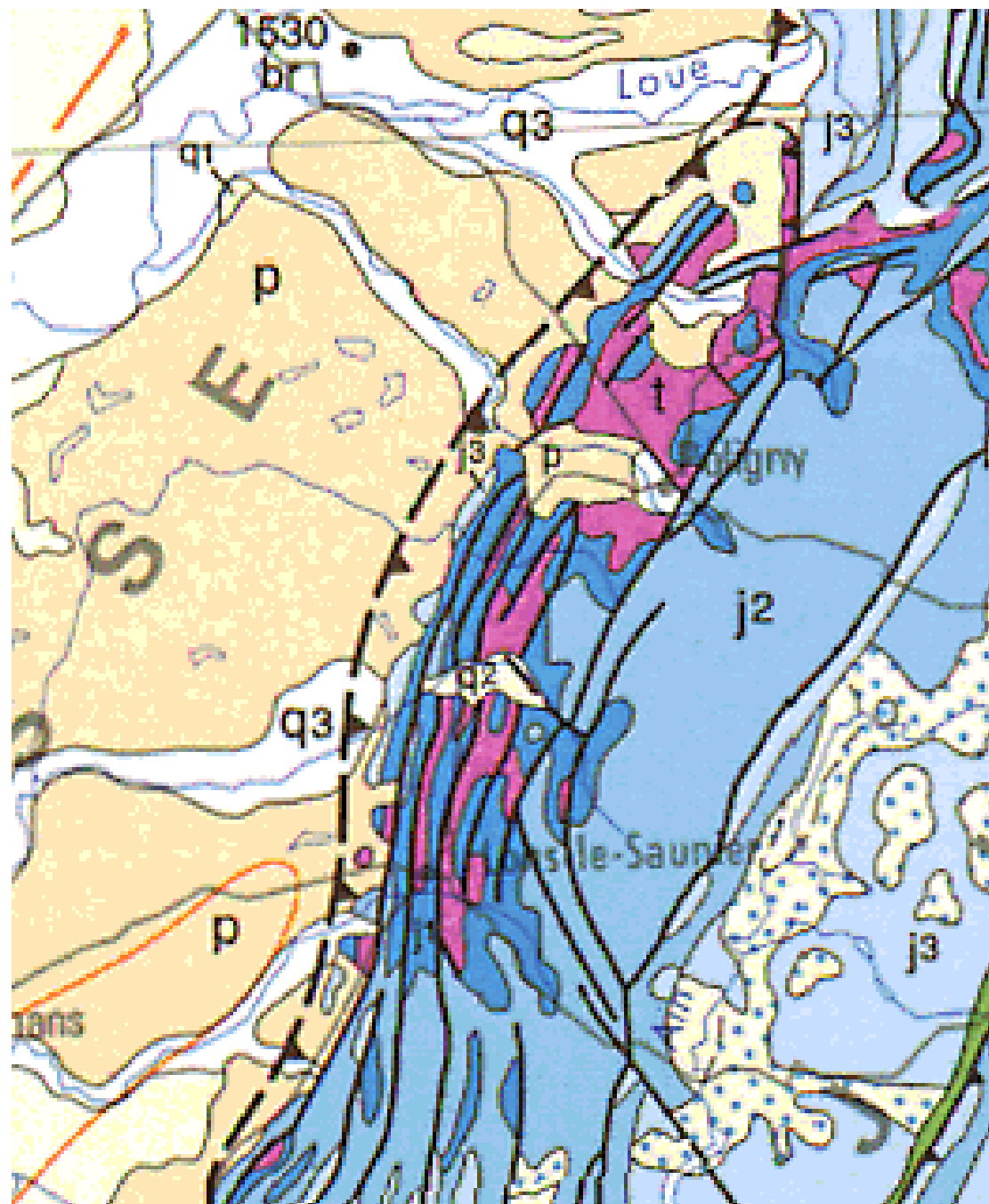


- Dépressions tertiaires
- Molasse subalpine
- Couverture épivarisque
- Couverture épivarisque déformée
- Massifs varisques
- Plateaux jurassiens
- Faisceaux du Jura externe
- Jura plissé, autochtone, chaînes subalpines externes
- Nappe de Morcles, chaînes subalpines internes
- Massifs cristallins externes
- Helvétique
- Zones internes des Alpes

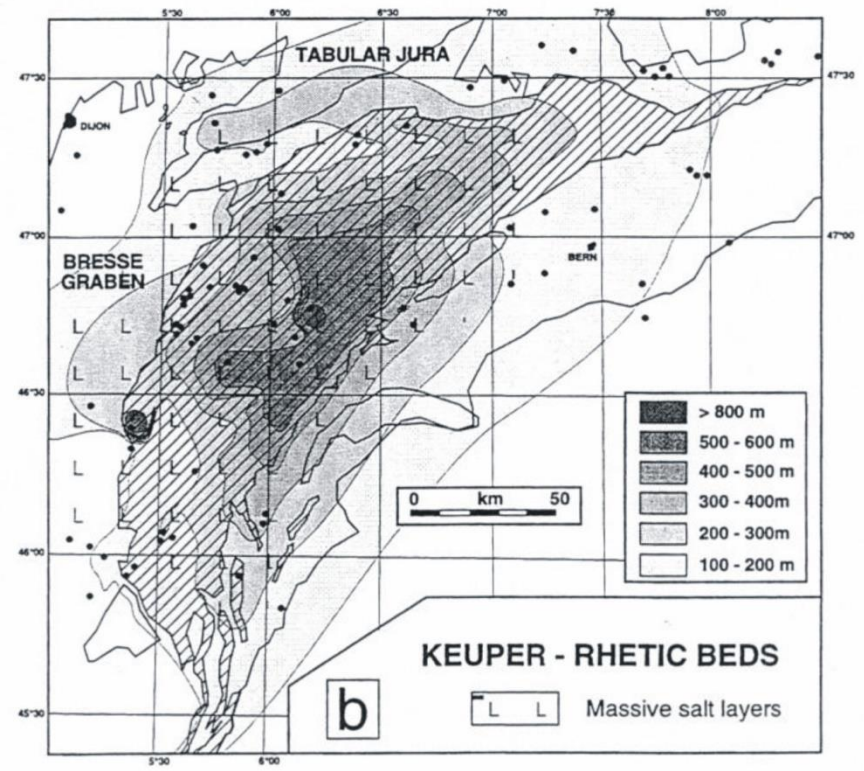
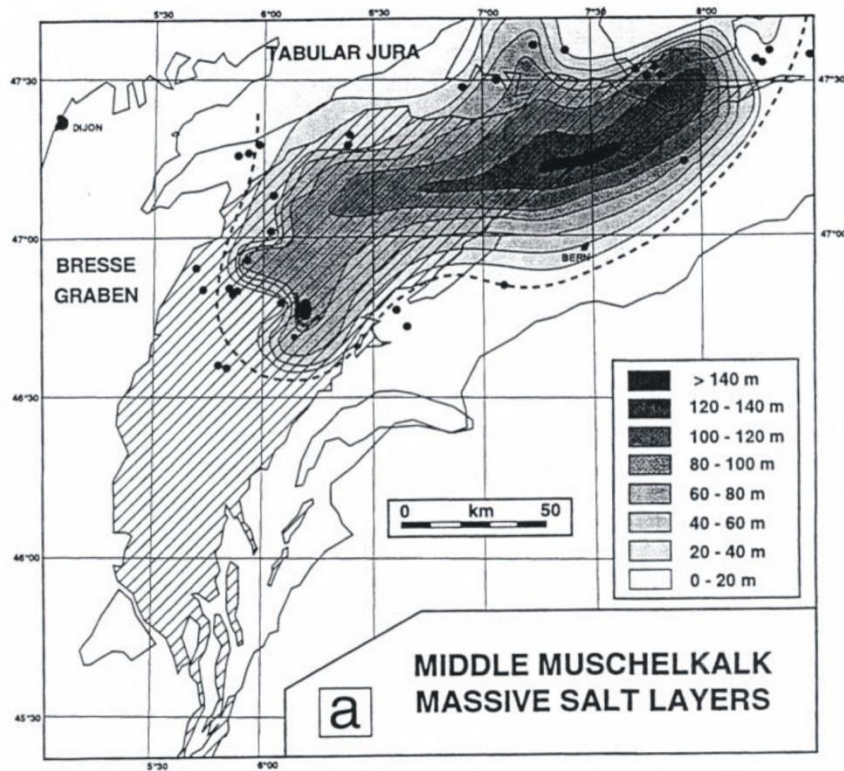
- Chevauchements
- Failles normales
- Flexures
- Décrochements et autres failles

**Décollement majeur
dans le Trias**



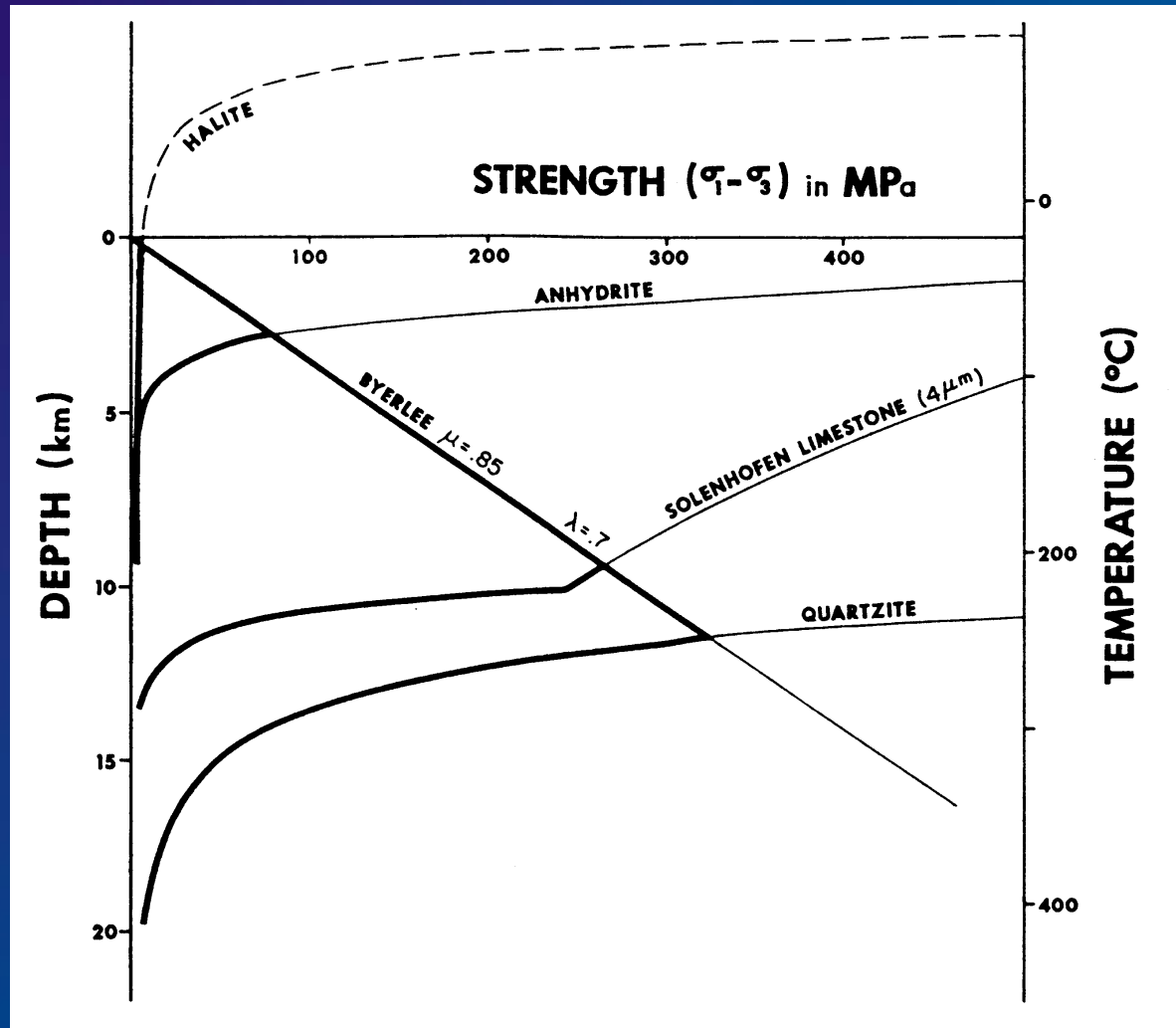


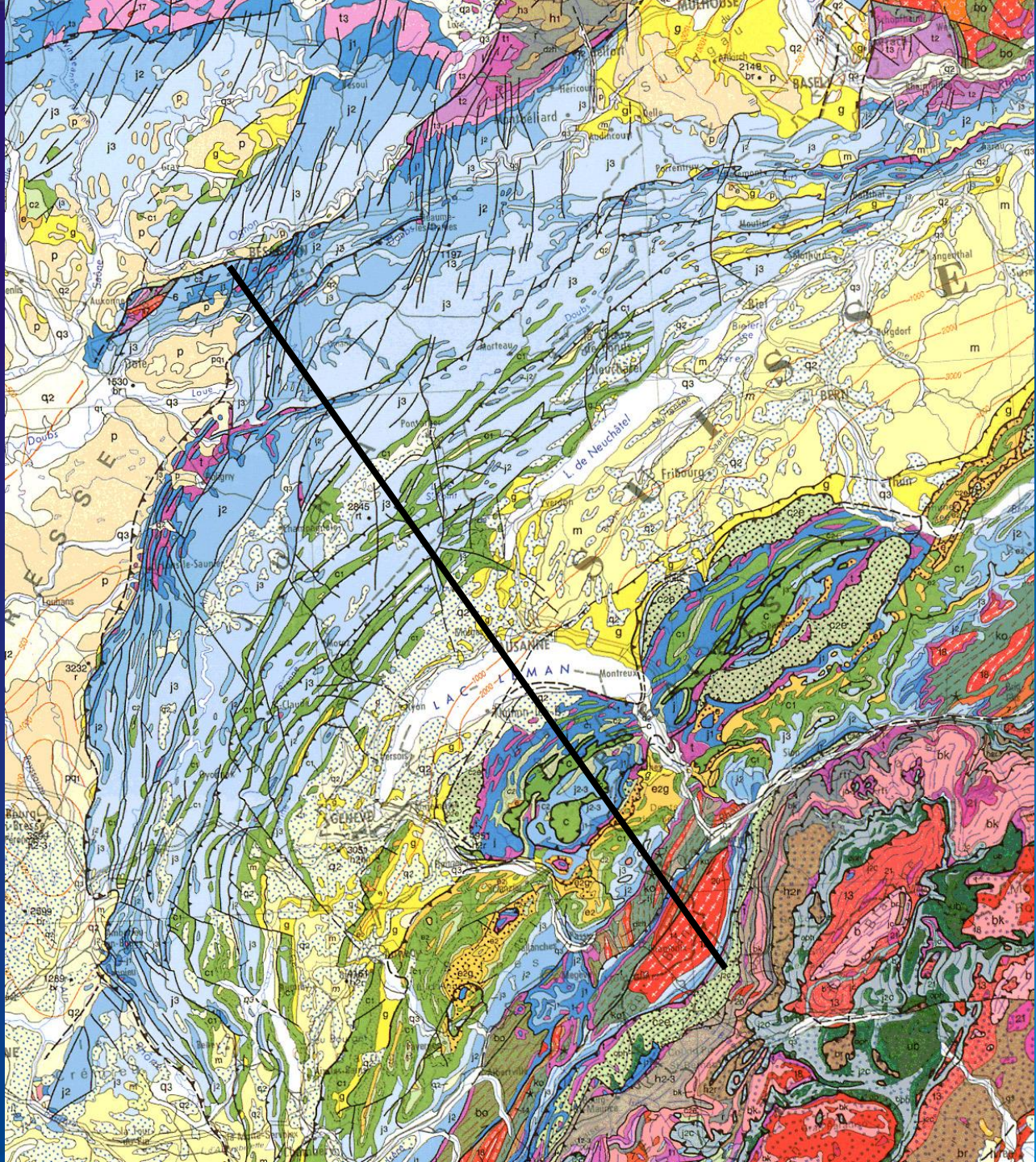
Répartition des évaporites du Trias sous le Jura



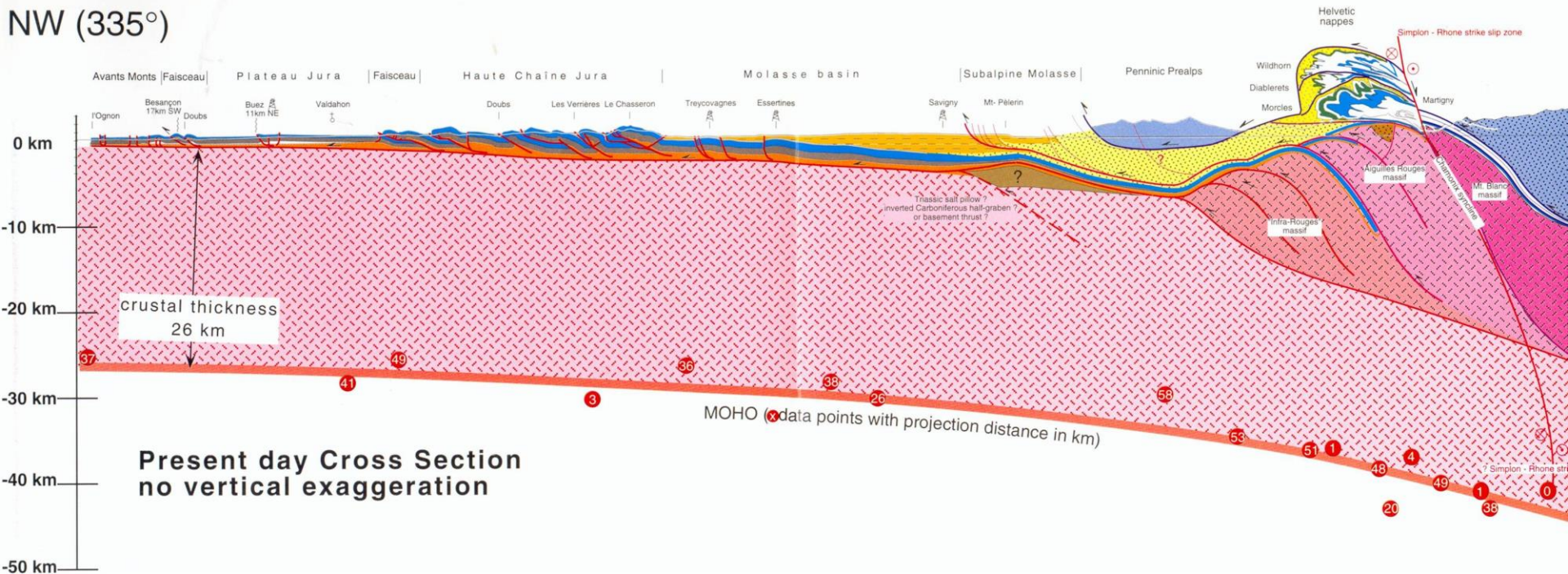
(Lienhard, 1984)

Comportement mécanique des évaporites du Trias





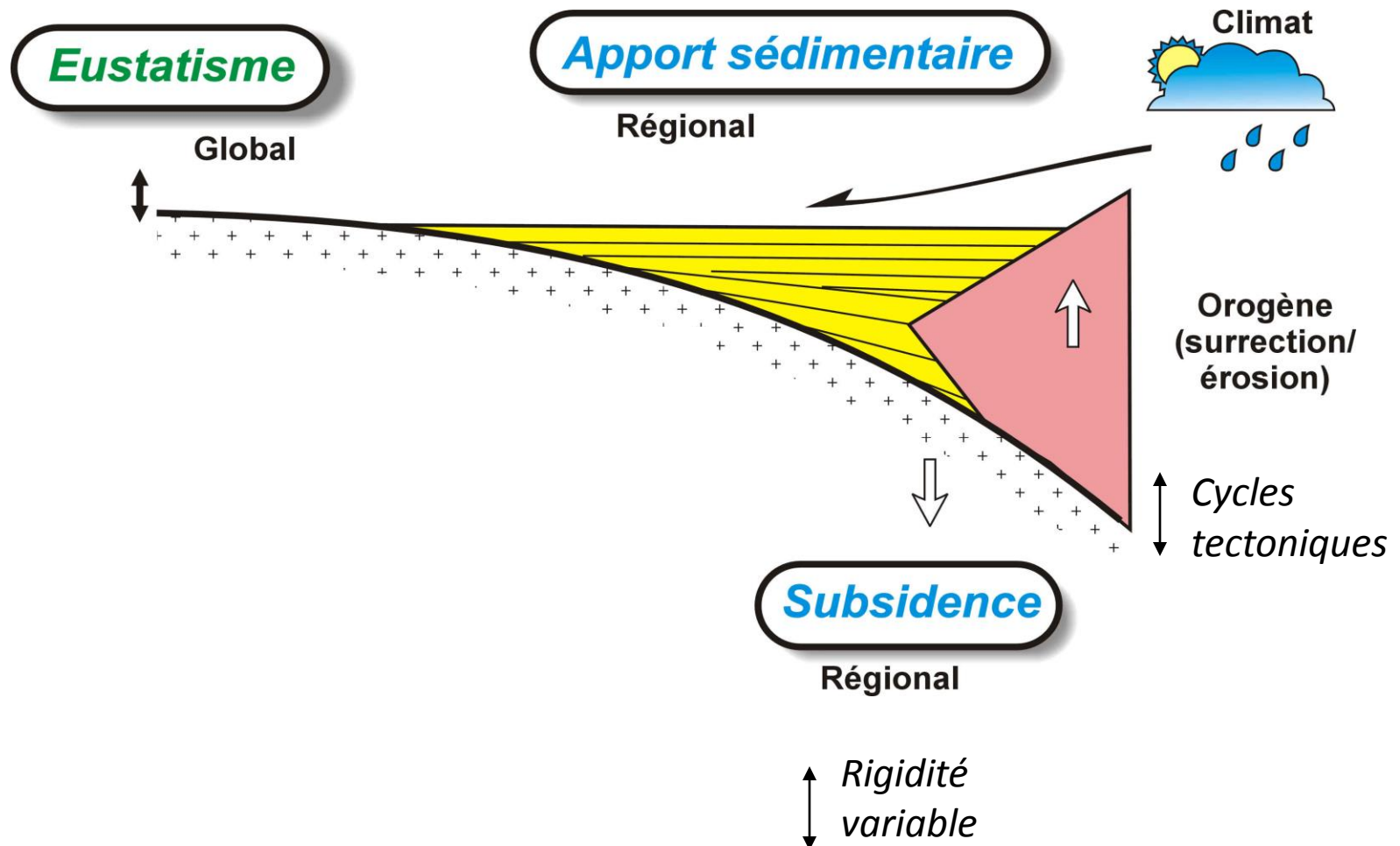
NW (335°)



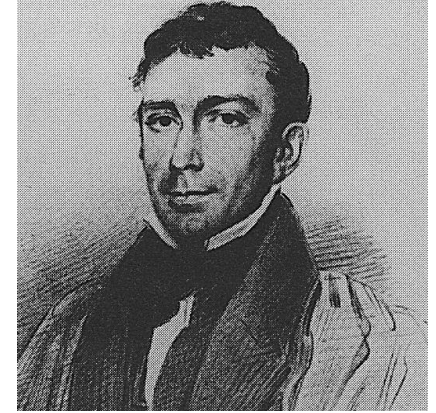
(Burkhard et Sommaruga, 1998)

Le bassin d'avant-pays

L'enregistrement sédimentaire est le résultat de l'interaction de facteurs tectoniques et eustatiques

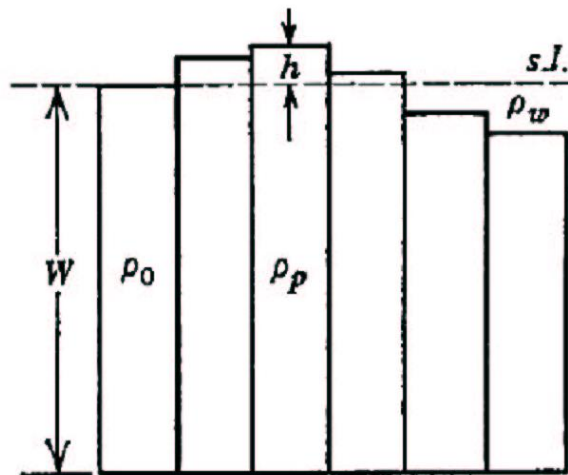


Isostasie



Pratt (1854)

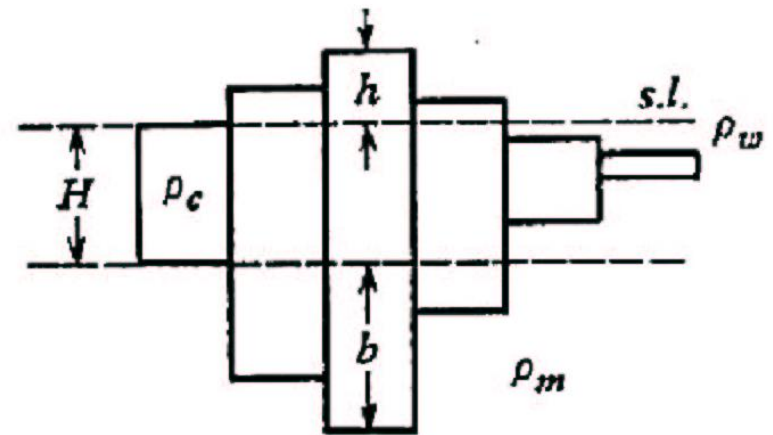
- ρ diminue si h augmente
- profondeur de compensation constante



Exemple: dorsales océaniques

Airy (1855)

- ρ constant
- profondeur de compensation augmente si h augmente

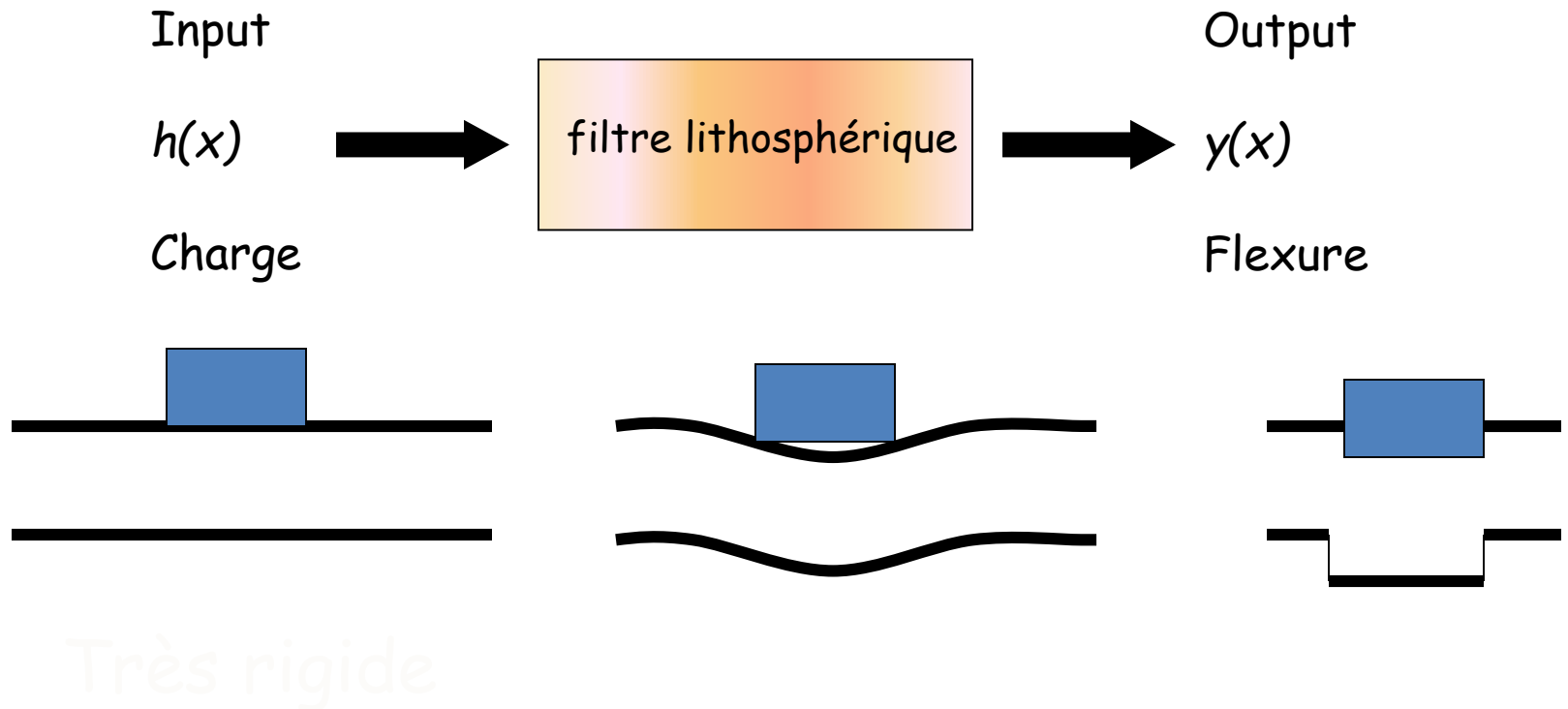


Exemple: Chaînes de montagnes

Isostasie

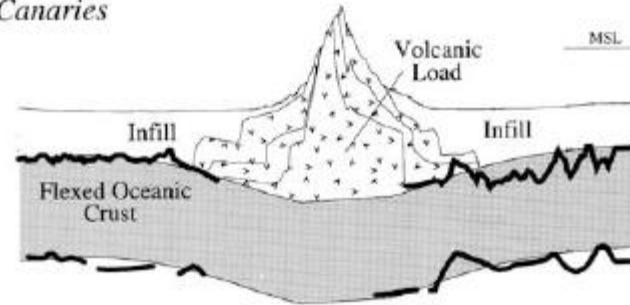
- Isostasie régionale

- Dépend de la rigidité de la lithosphère
- En étudiant le signal gravimétrique, on détermine le comportement mécanique de la lithosphère

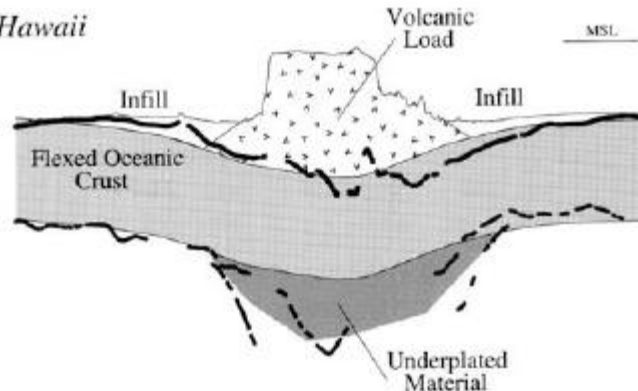


4.3 Seamounts and Oceanic Islands

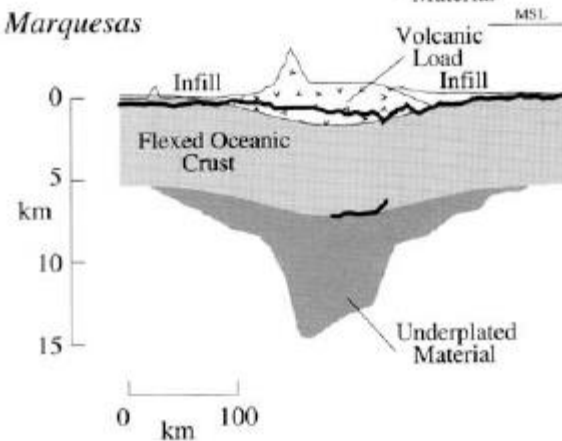
Canaries



Hawaii



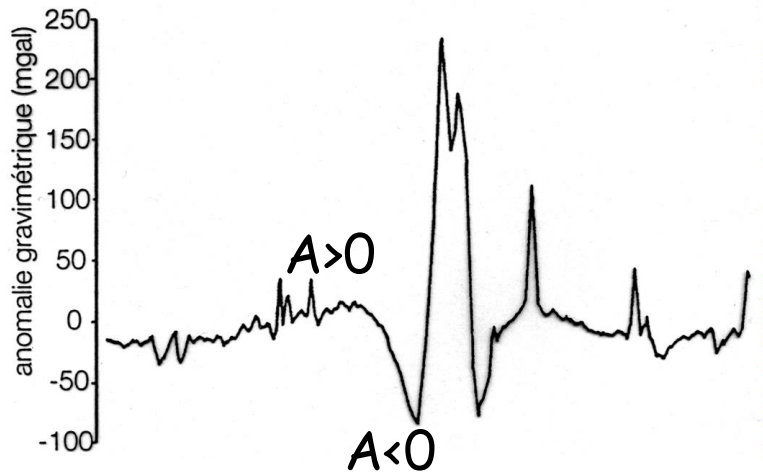
Marquesas



Plaque continue

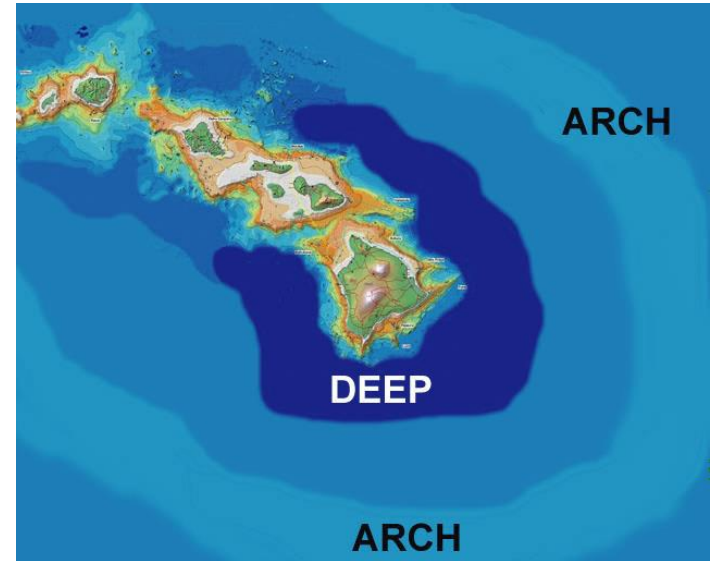
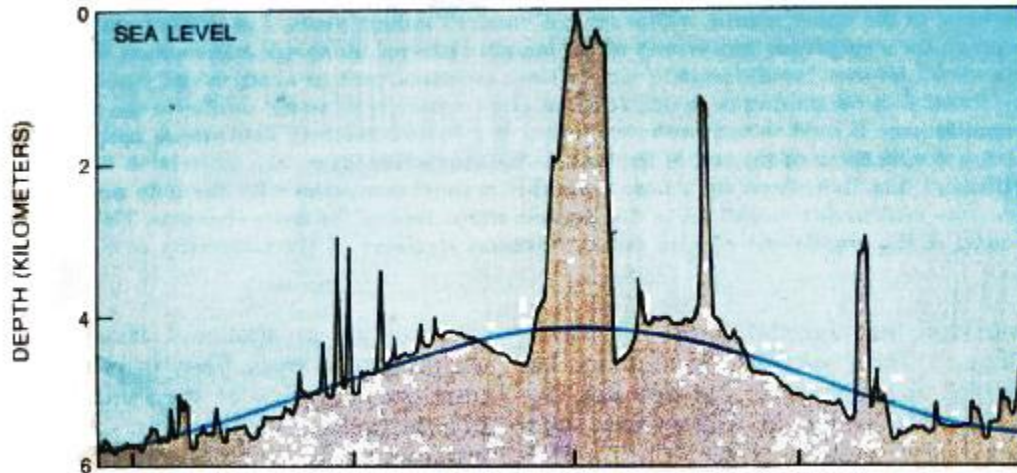
Les « Seamounts »

(D'après Watts)



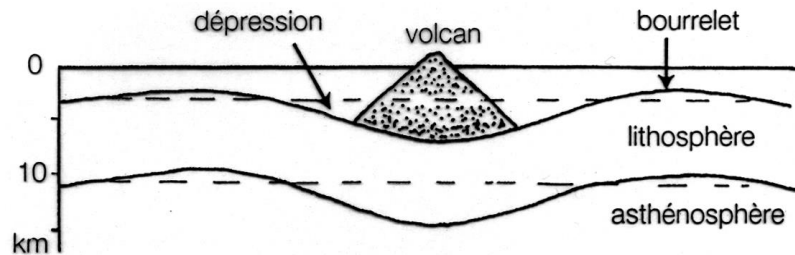
$A > 0$ excès de masse

$A < 0$ défaut de masse

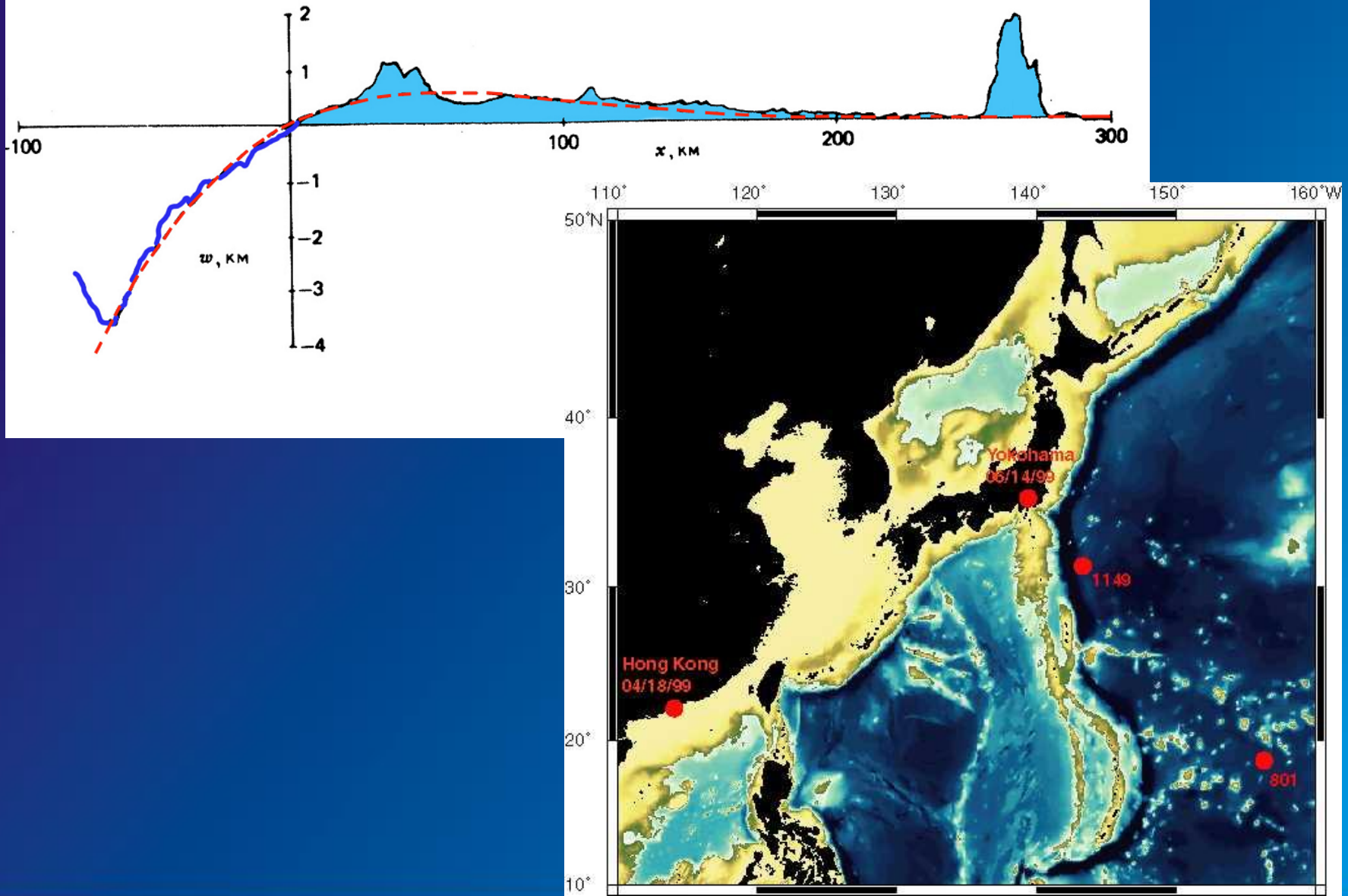


Flexure de la lithosphère

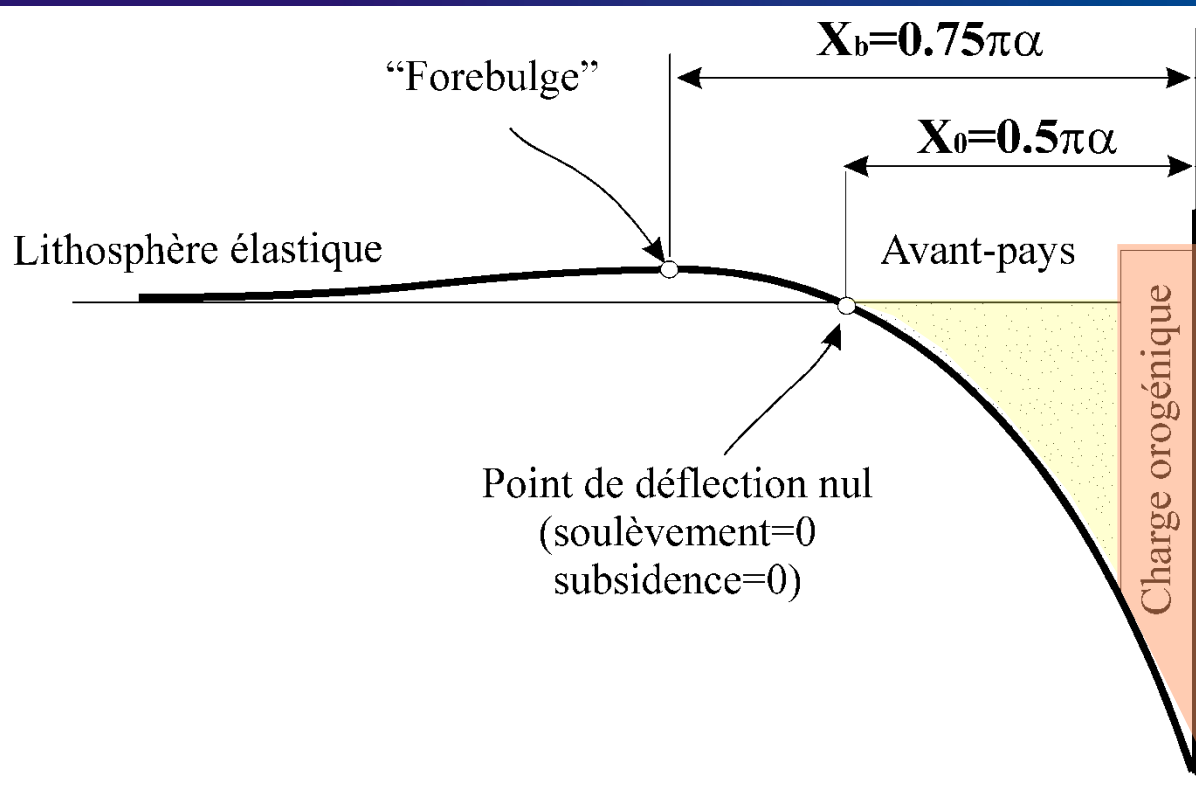
Compensation régionale



Mariana Trench



Déflexion d'une lithosphère élastique (continentale ou océanique)



Rigidité et épaisseur élastique équivalente d'une lithosphère

Paramètre flexural

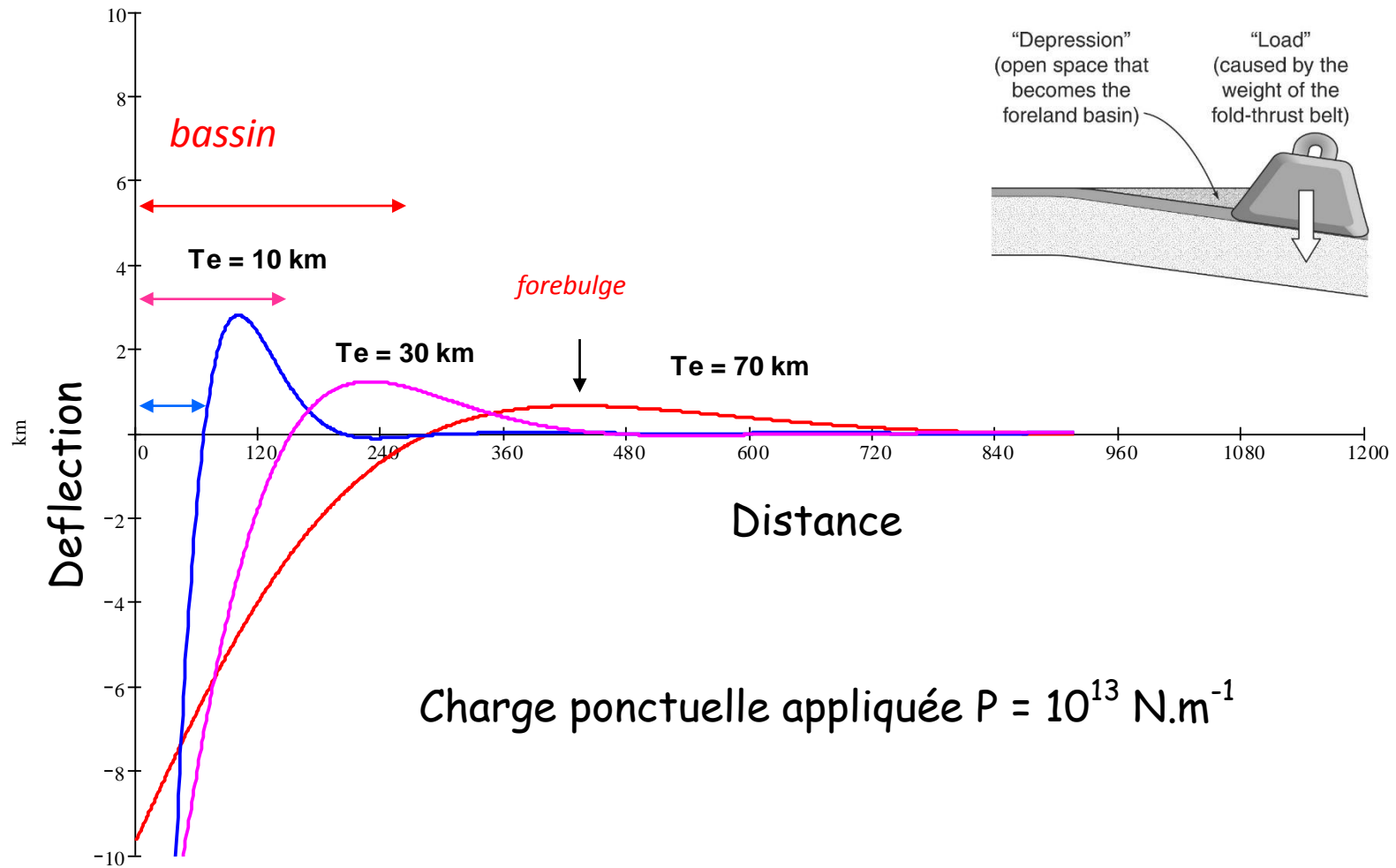
$$\alpha = \left(\frac{4D}{g(\rho_m - \rho_w / sed)} \right)^{1/4}$$

$$D = \frac{ET_e^3}{12(1-\nu^2)}$$

Te (km)
D (Nm)

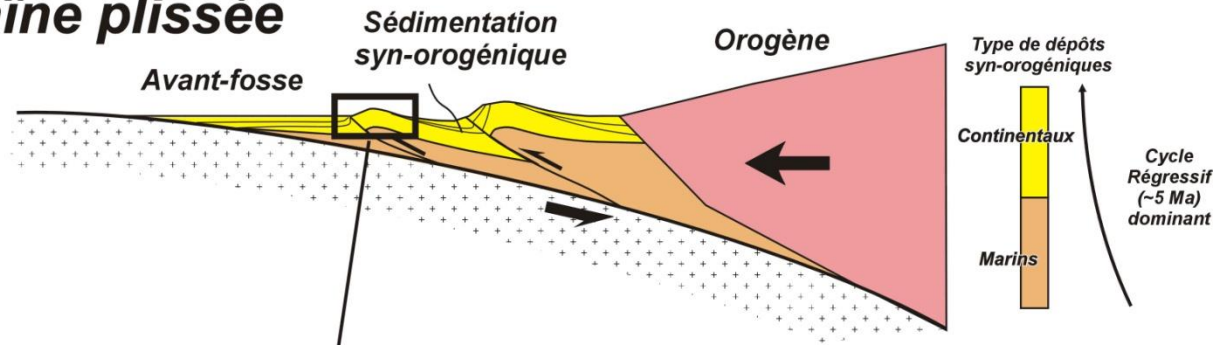
La subsidence est liée à la compensation isostatique régionale (flexurale) et non locale (Airy) de la surcharge tectonique et sédimentaire

Plaque cassée

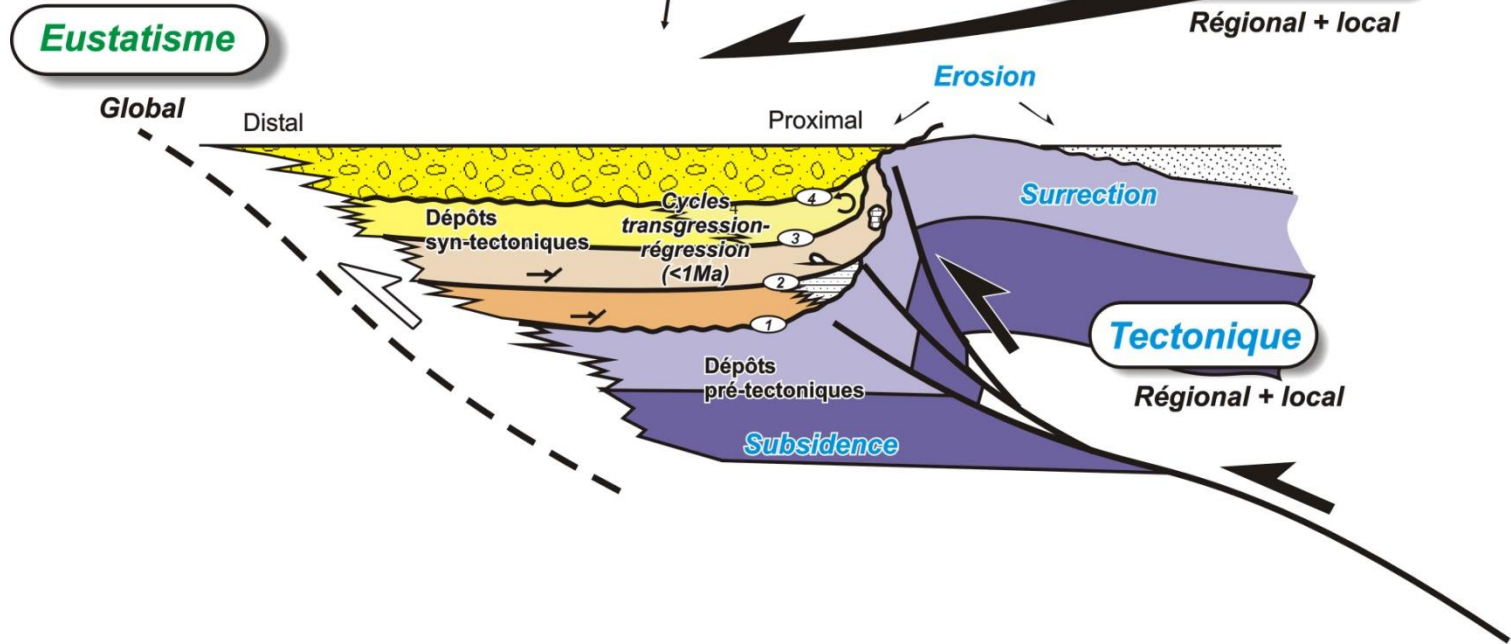


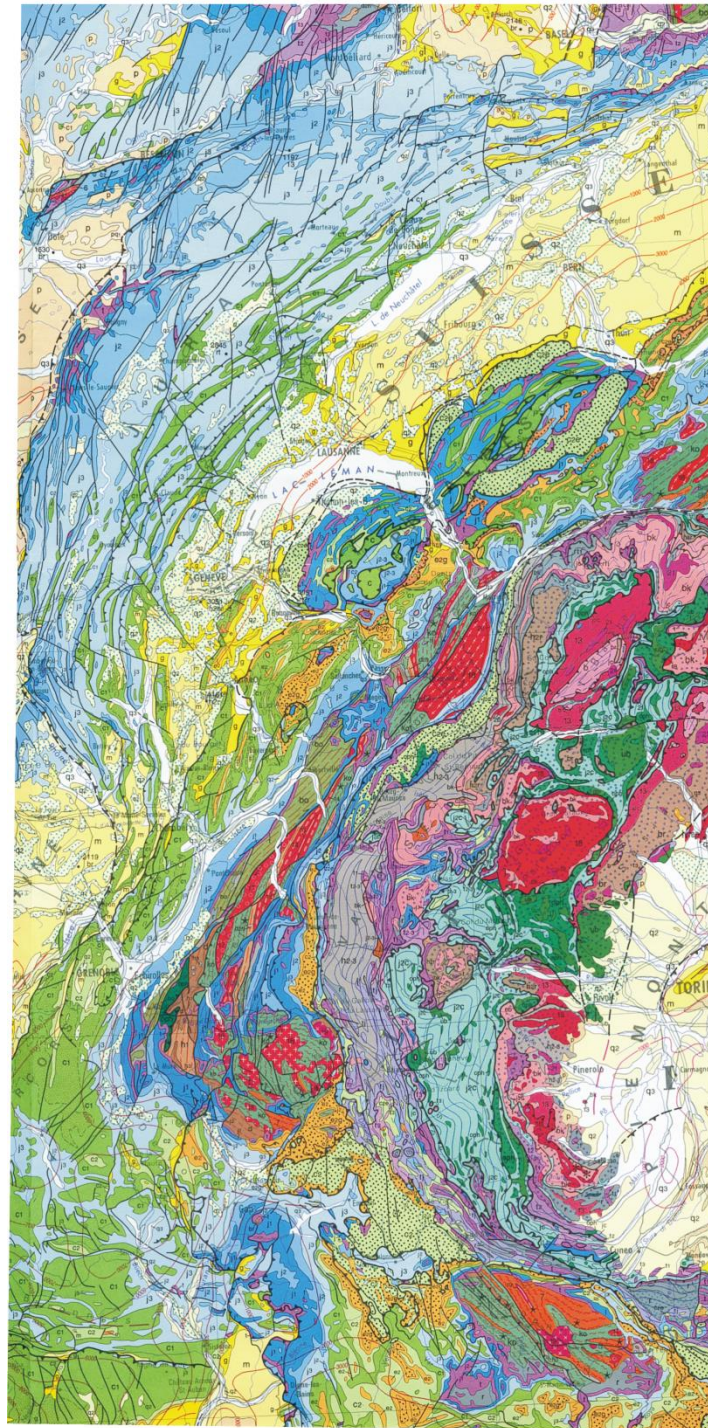
Charge ponctuelle appliquée $P = 10^{13} \text{ N.m}^{-1}$

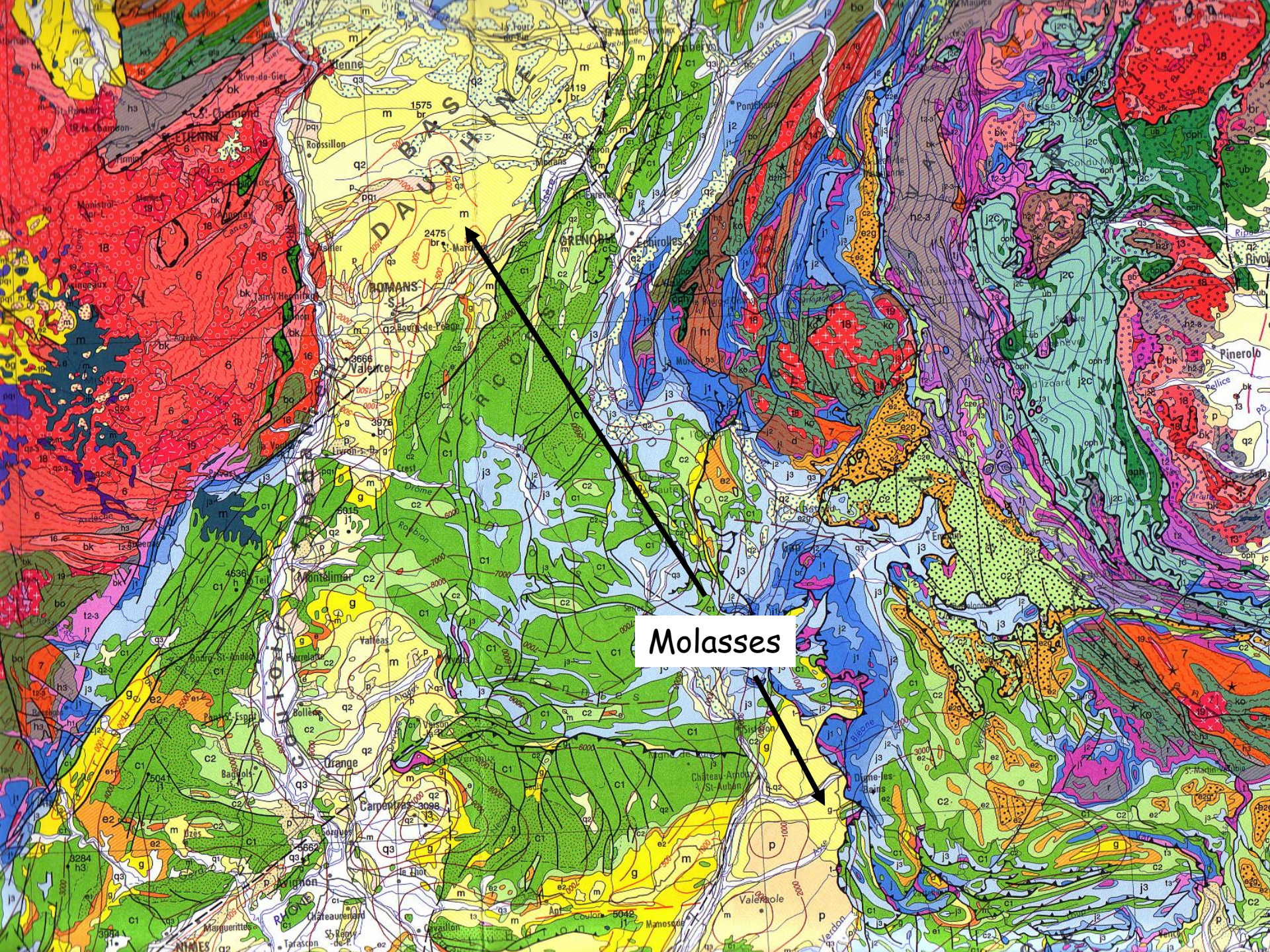
La chaîne plissée



L'unité chevauchante







DAUPHINÉ

ROMANS

GRENOBLE

Montlamar

Orange

Carpenas

Molasses

Valepsole

Pinerolo

Molasses sableuses, Langhien, Bassin de Valence (Châteauneuf sur Isère)





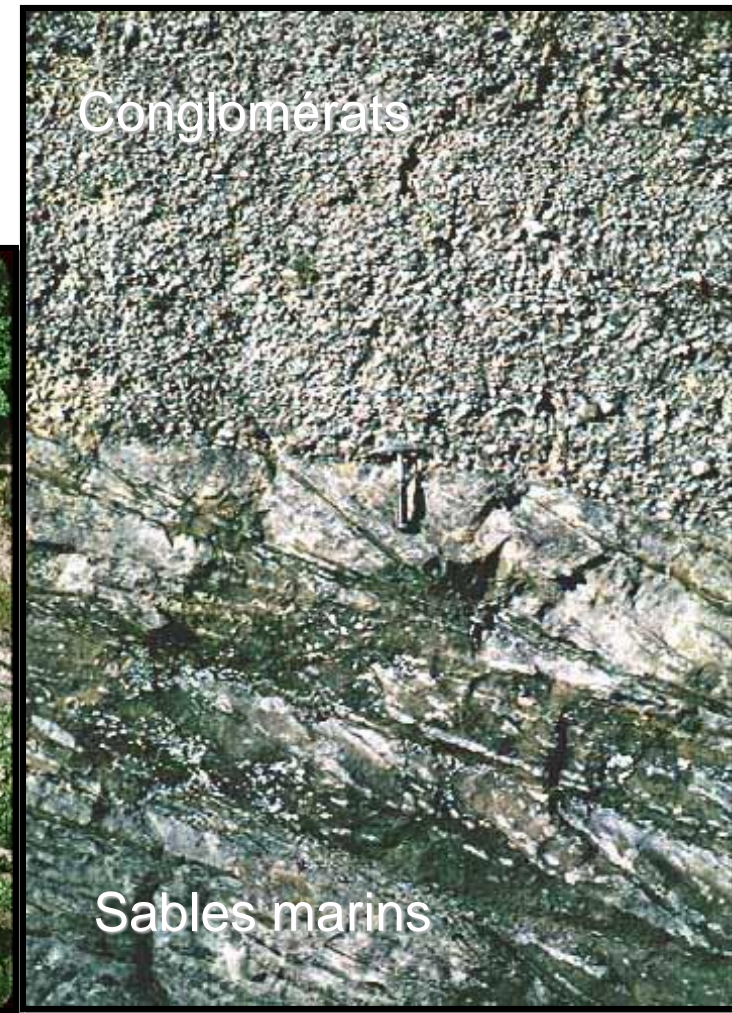
*Molasse marine conglomératique
Langhienne, Croix de Lichou*



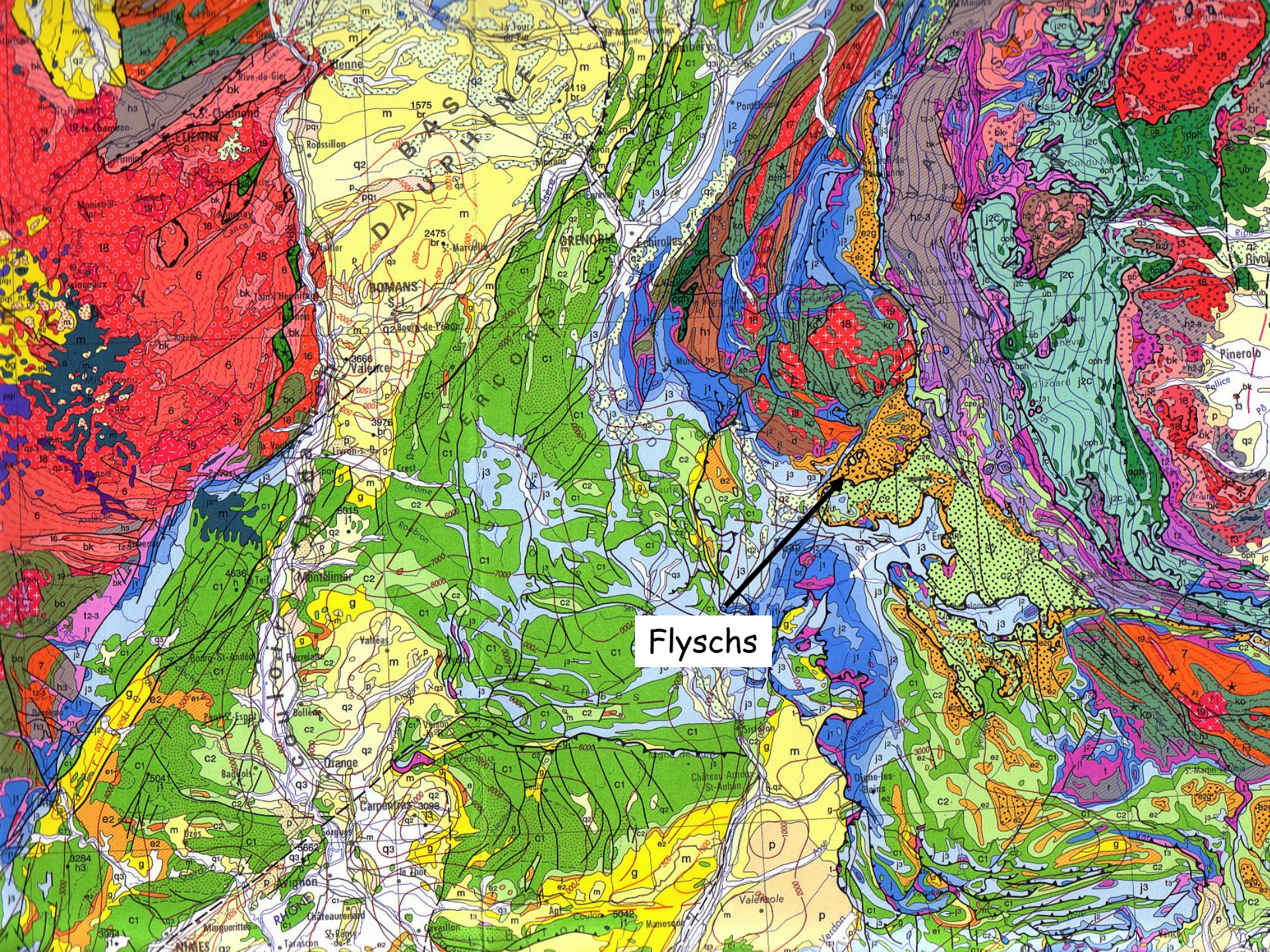


Molasse Alpine

Dépôts fluvio-marins miocènes
contemporains de la croissance de la chaîne



Dépôts d'avant-pays proximaux (source d'apport proche)



Flyschs

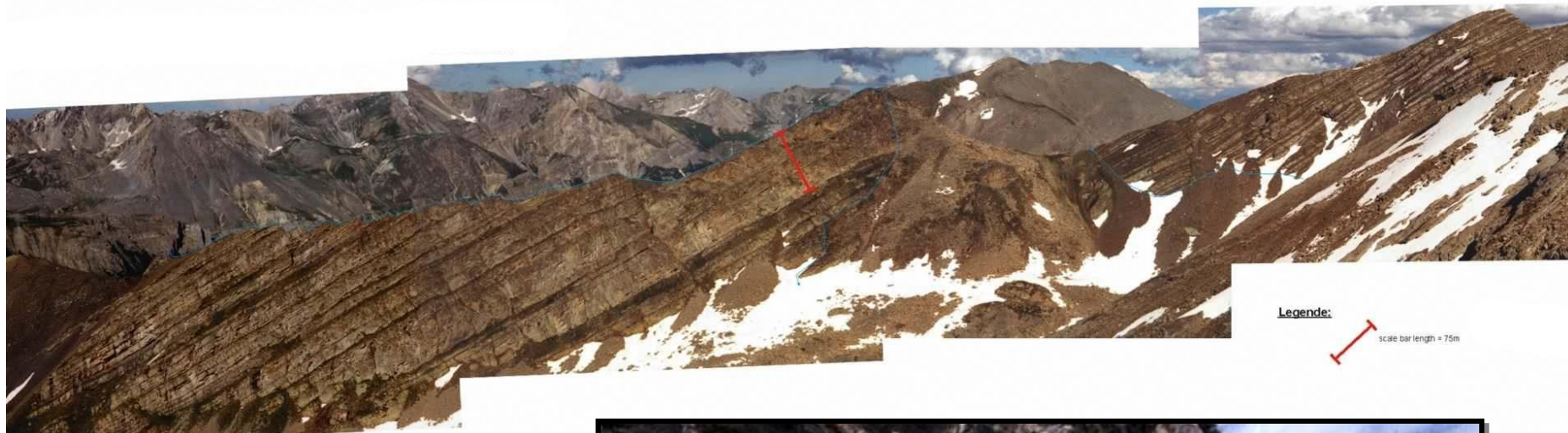


Grès turbiditiques du Champsaur
(Eo-Oligocène)

Marnes bleues

Conglomérats de base

« *Flyschs* » *Eocène alpins* : les grès d'Annot



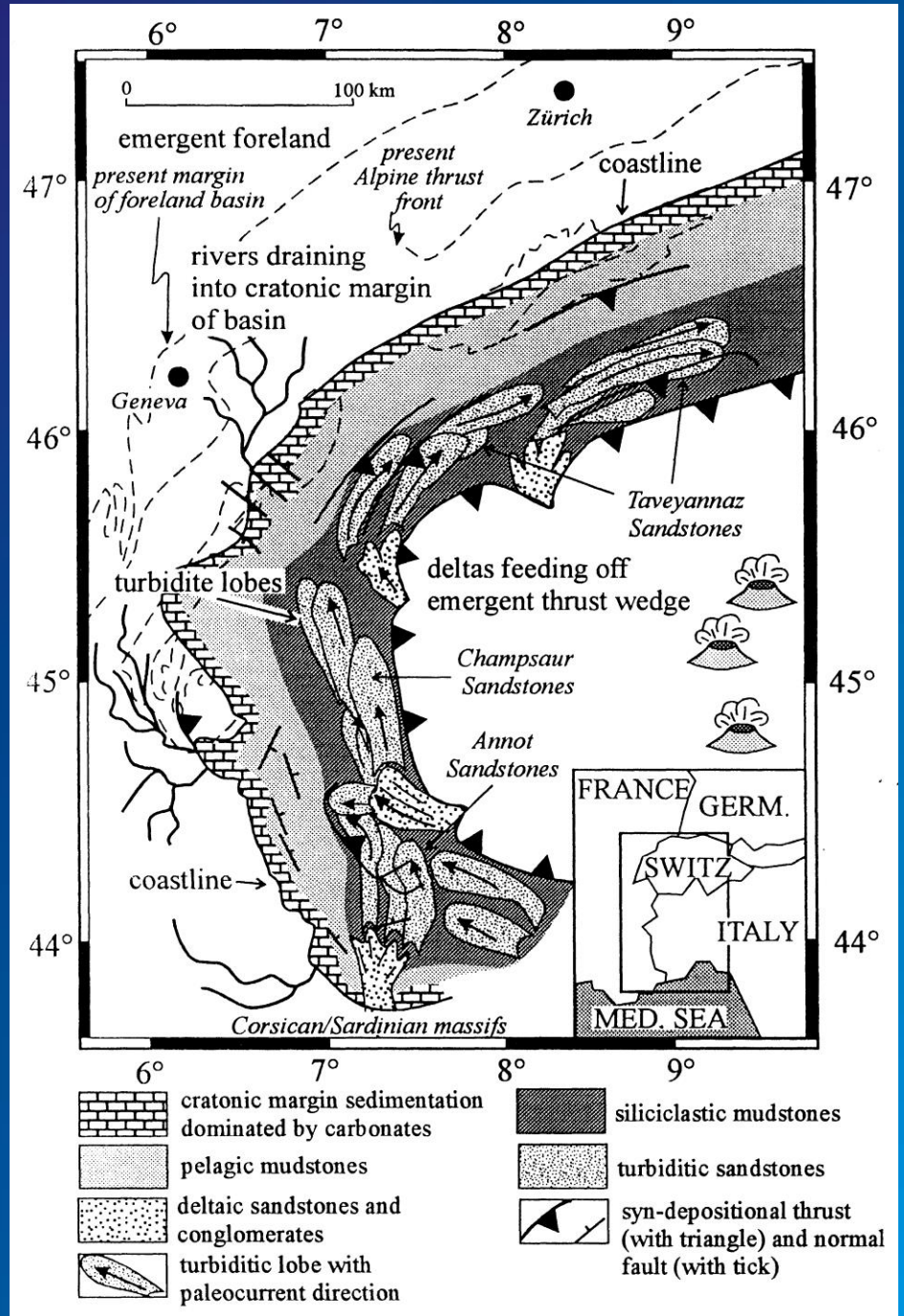
Dépôts marins profonds
turbiditiques éocènes
(Priabonien)

Souligne l'initiation du
bassin flexural

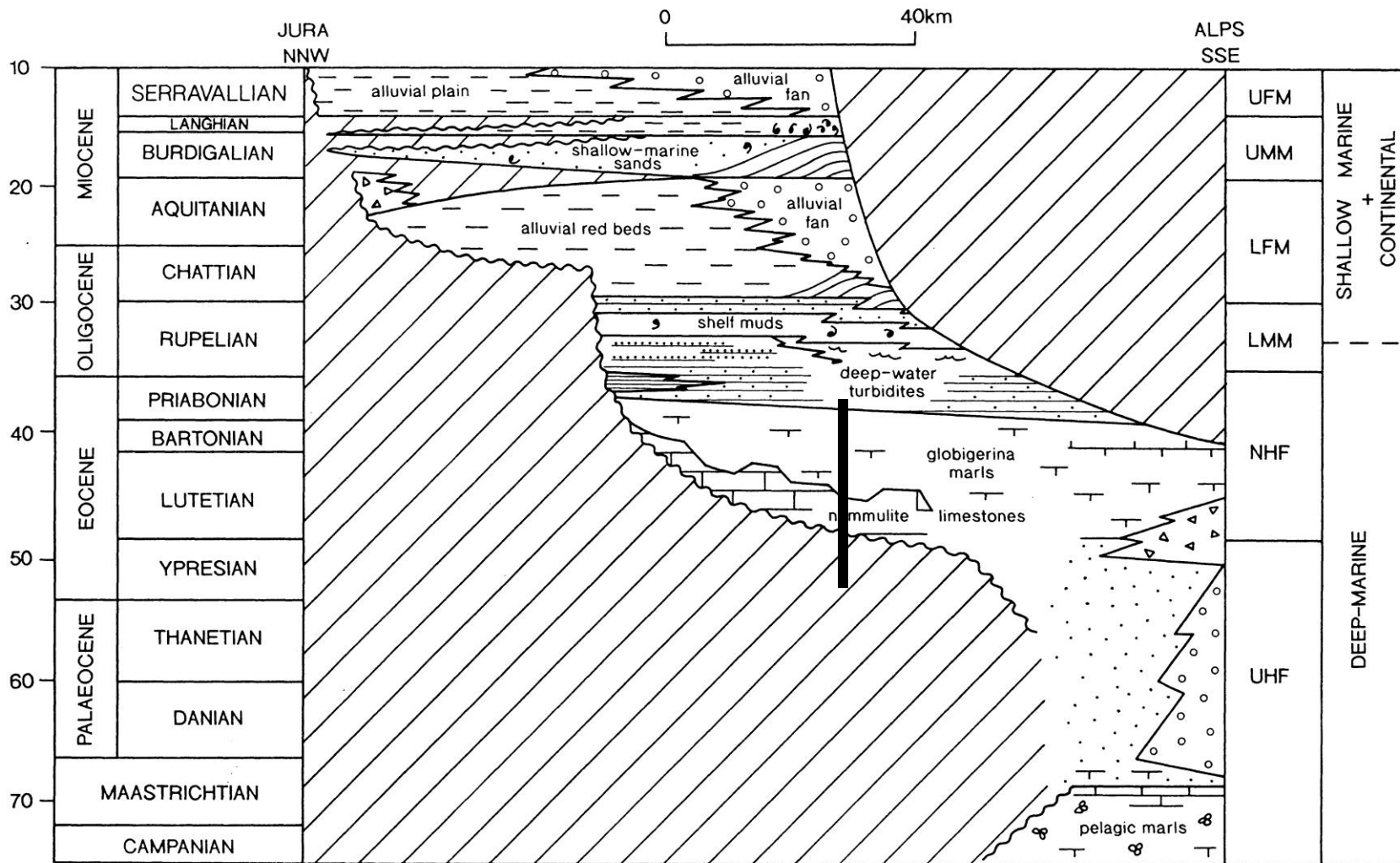


L'avant-pays alpin à l'Eocène

La trilogie calcaire/
marnes/flyschs
souligne la géométrie
initiale du bassin



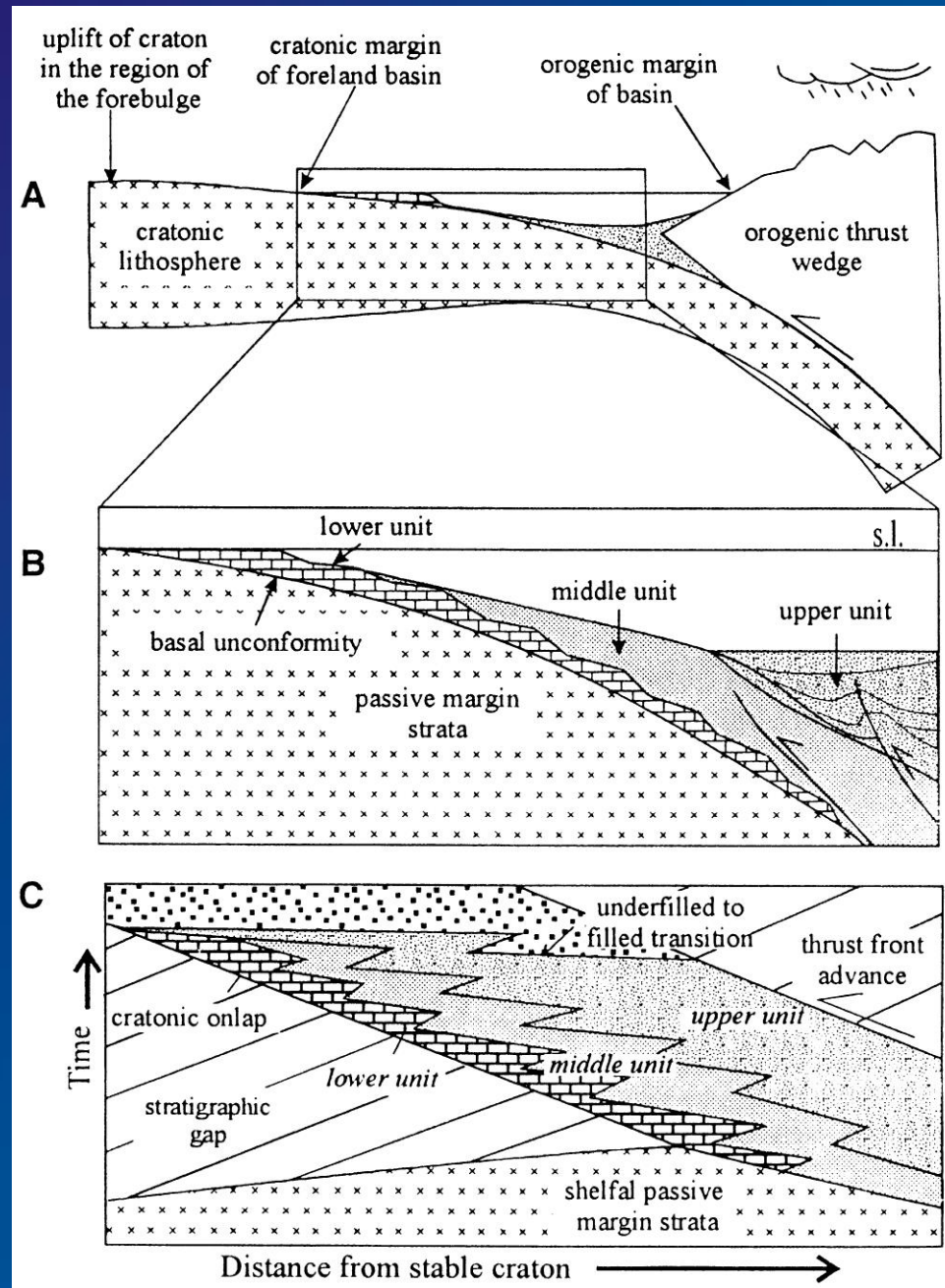
Coupe stratigraphique reconstituée du bassin flexural alpin



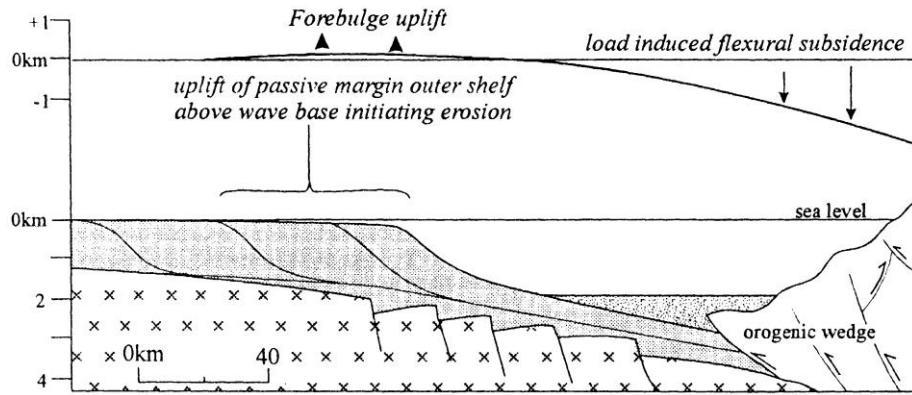
*Début du développement
du bassin et migration
sur la marge à l'Eocène*

*Reconstitution
du bassin
au Priabonien*

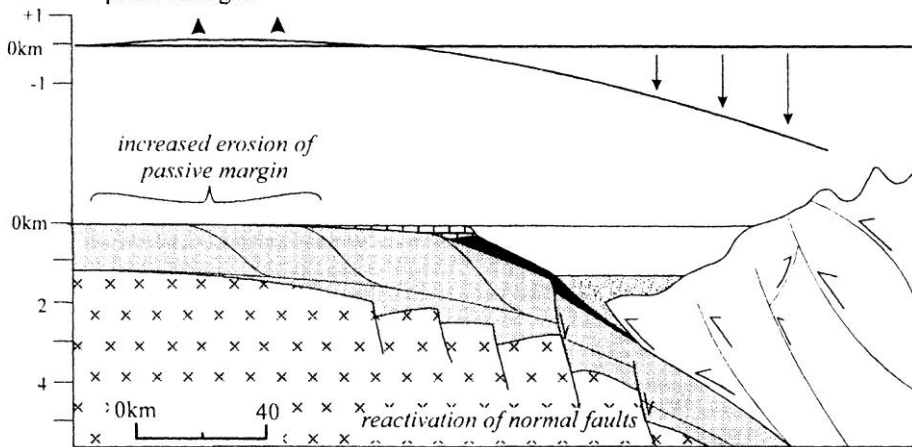
Stratigraphie



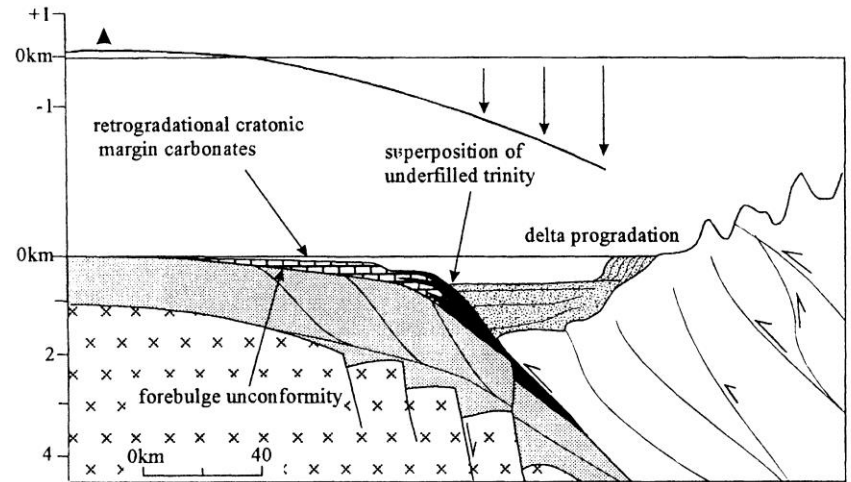
Stage 1. Initial loading of outer passive margin, eg., present day Taiwan, Timor and Papua New Guinea. Paleocene in the Alps.



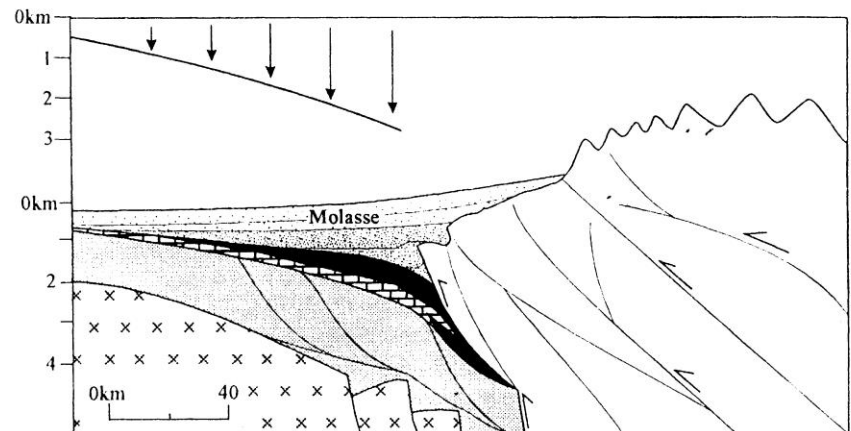
Stage 2. Development of underfilled trinity as flexural profile passes over passive margin.

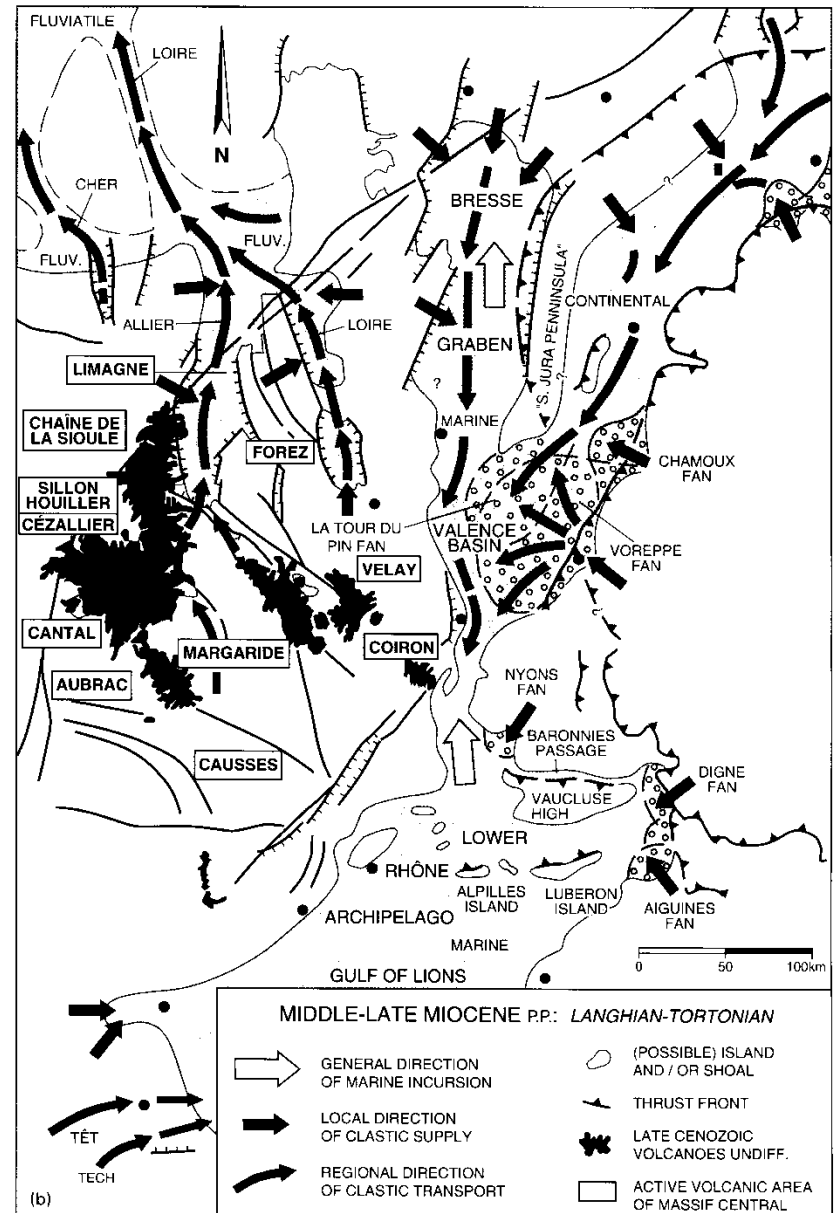
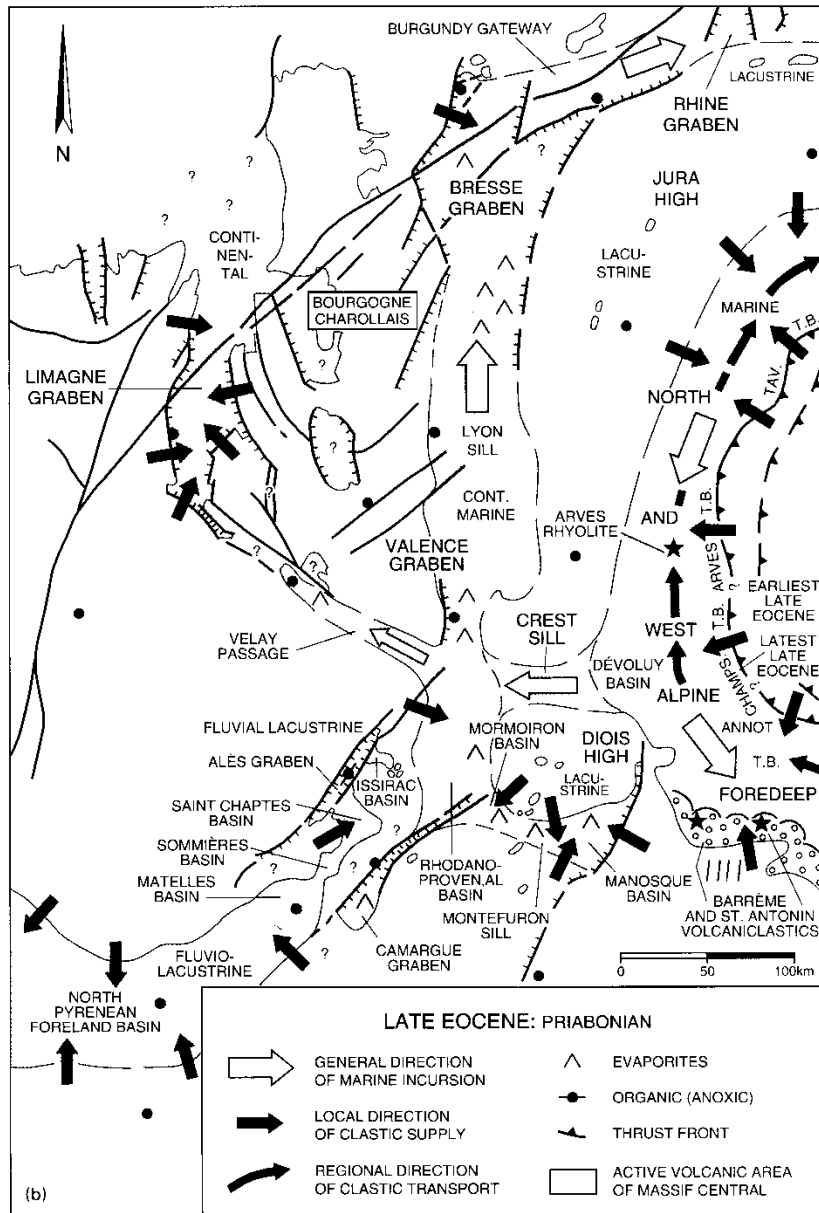


Stage 3. Steady state migration of the underfilled trinity over the craton i.e., rate of thrust front advance equals rate of cratonic onlap



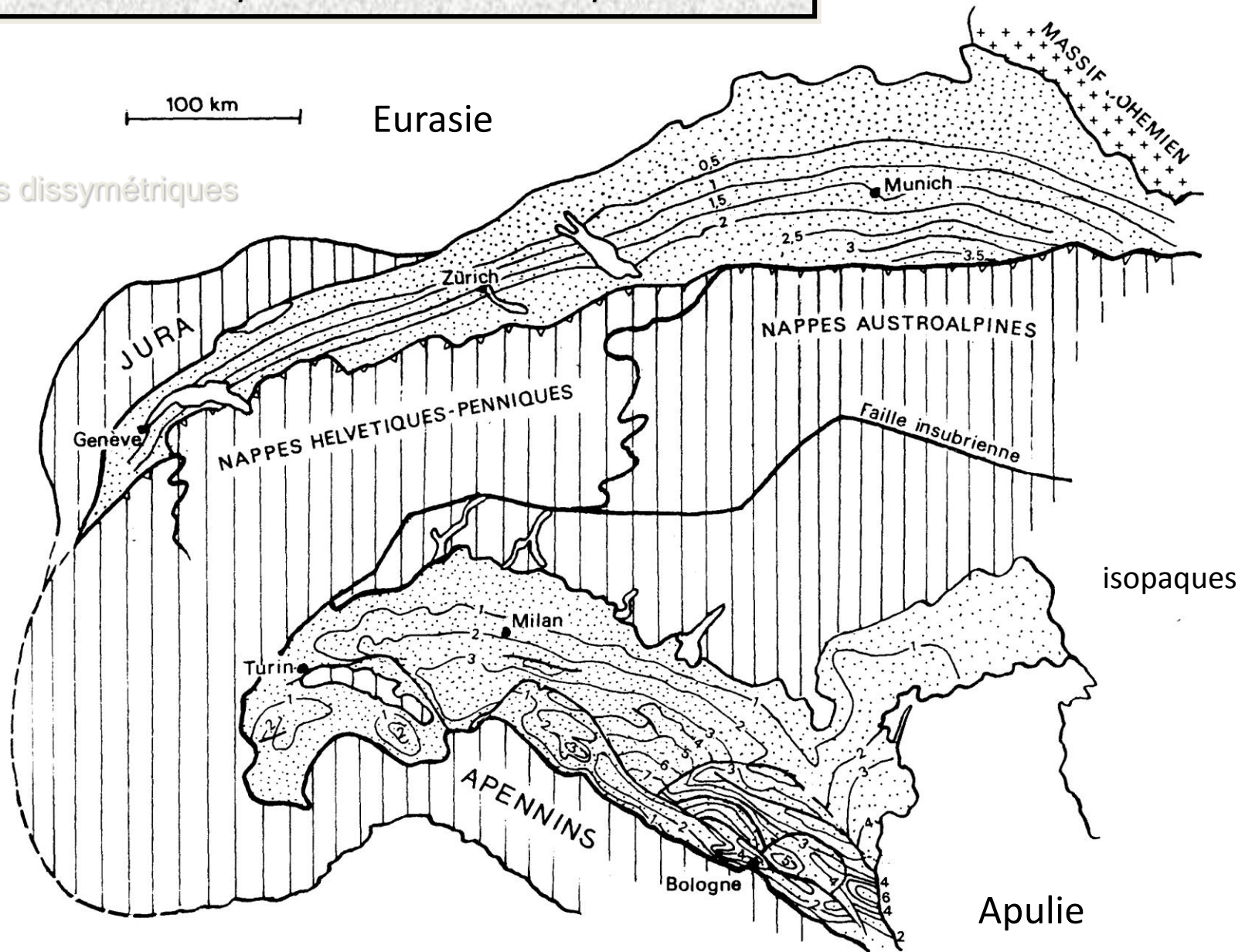
Stage 4. Transition of foreland basin from an underfilled to a filled depositional state. Siliciclastics from orogen fill the basin, smothering the underfilled stratigraphy.



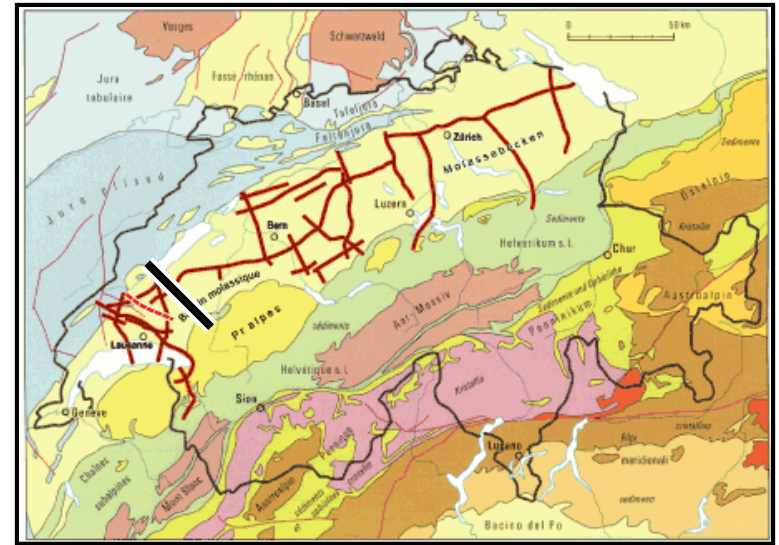
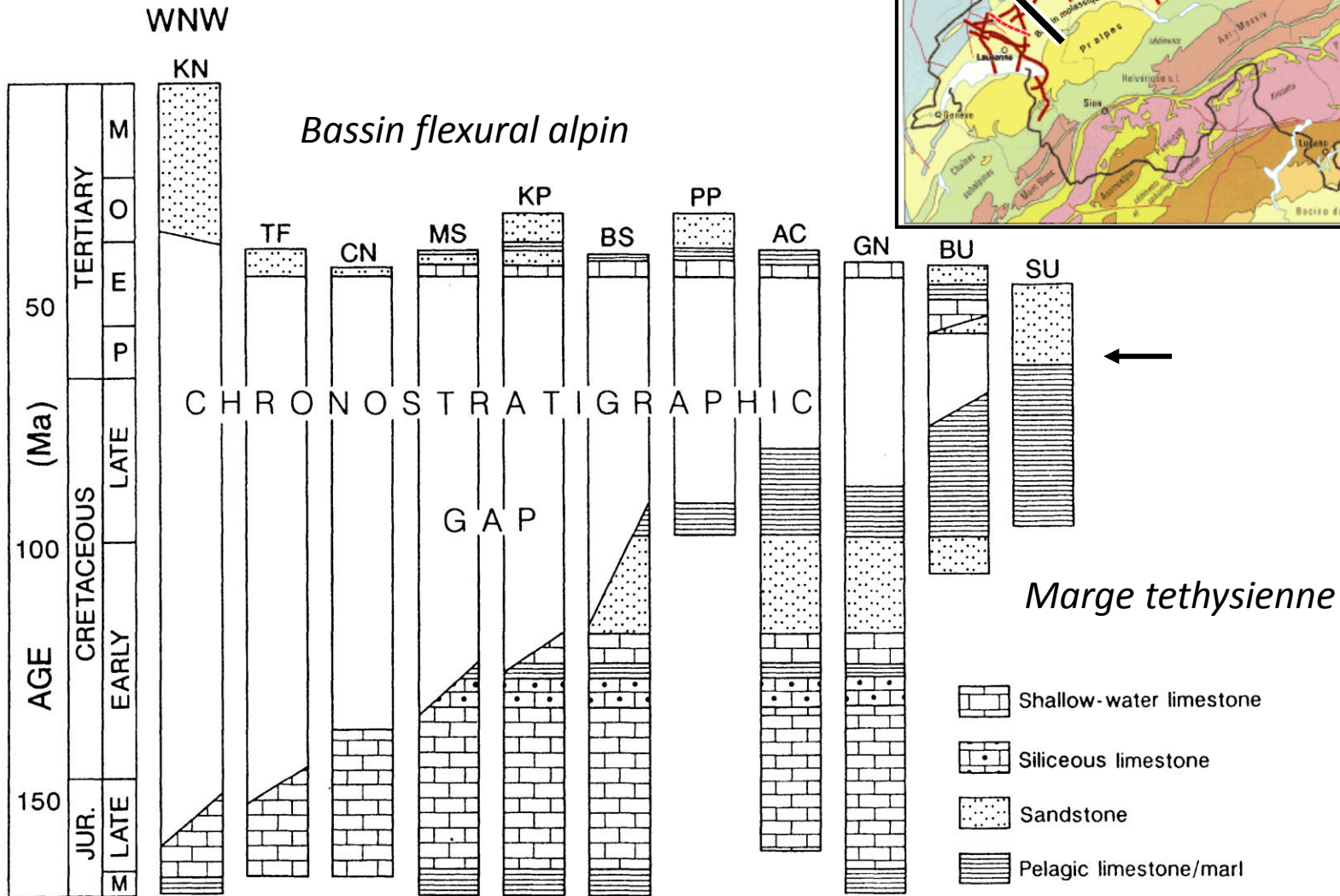


Bassin molassique suisse et bassin padan

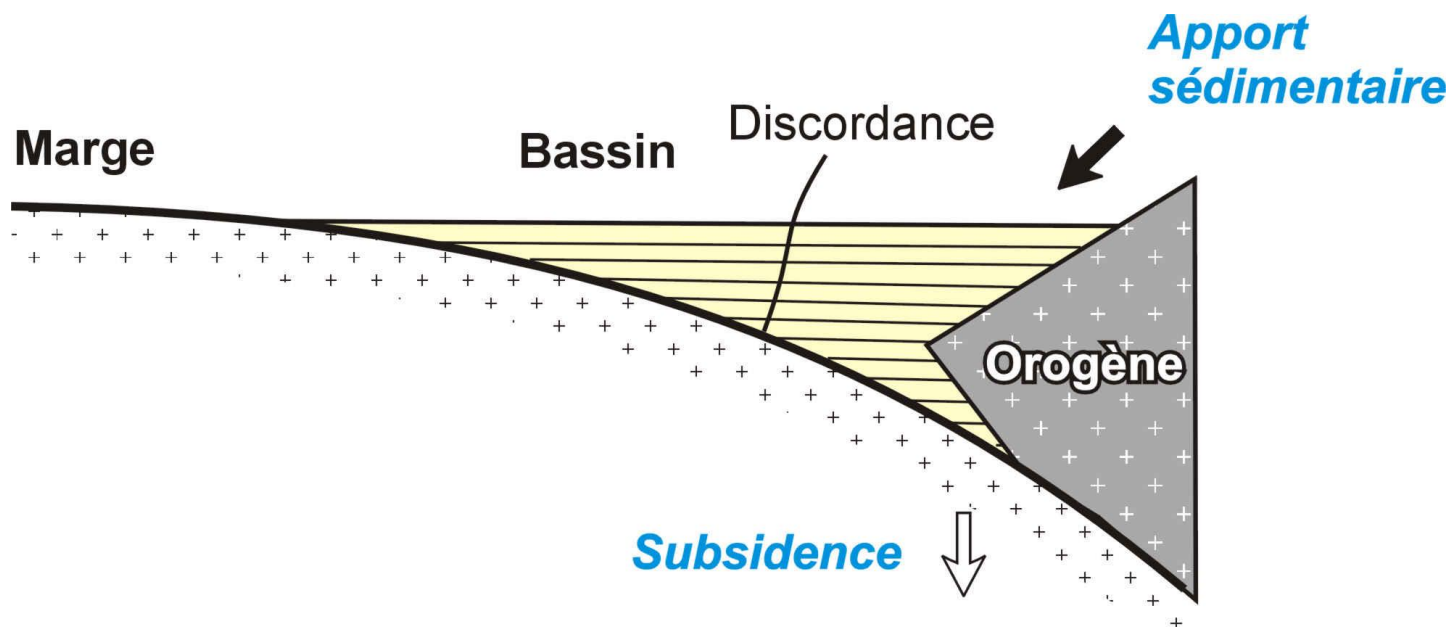
Bassins dissymétriques



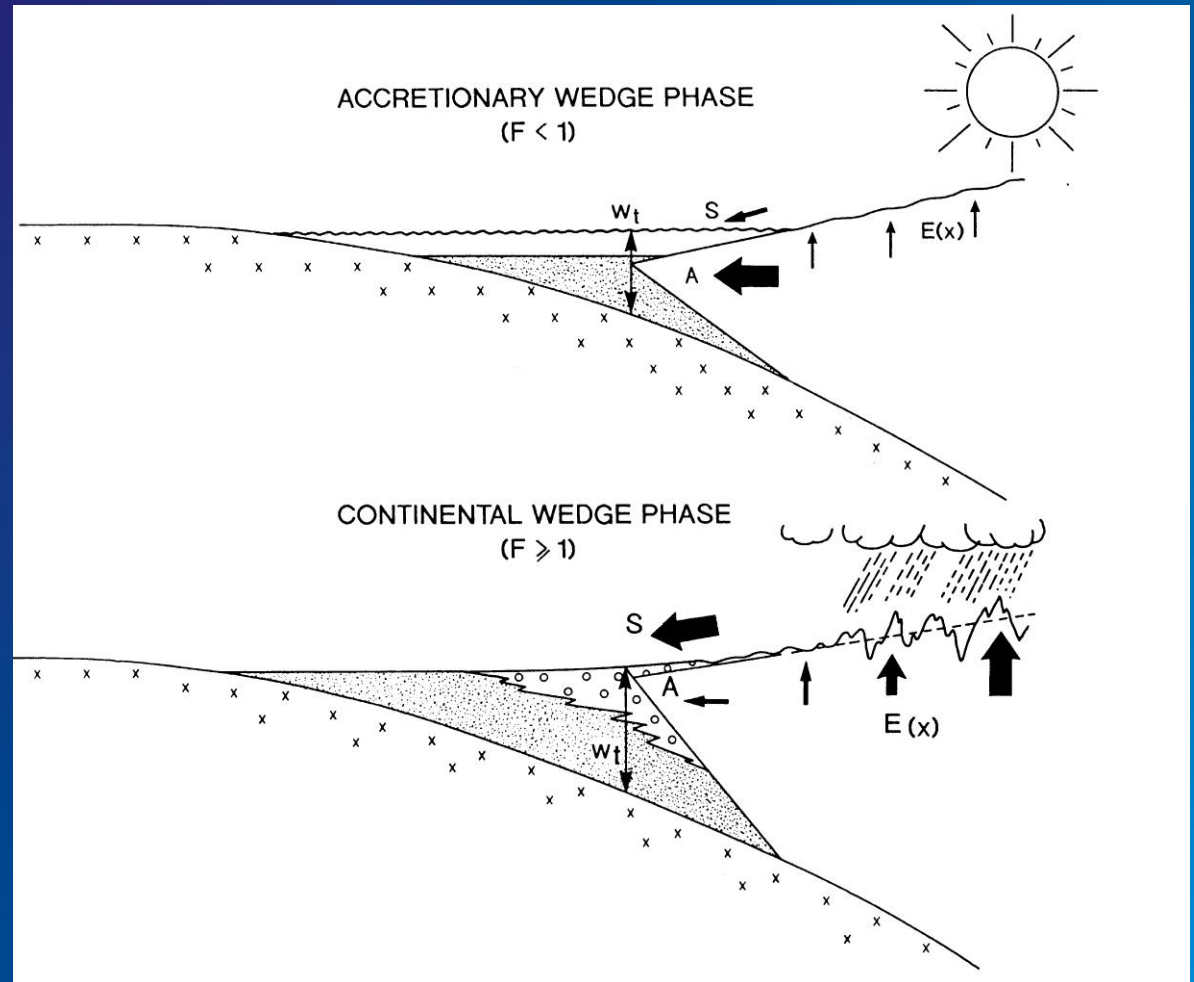
Stratigraphie et géométrie du bassin molassique



Remplissage sédimentaire discordant en onlaps sur la marge



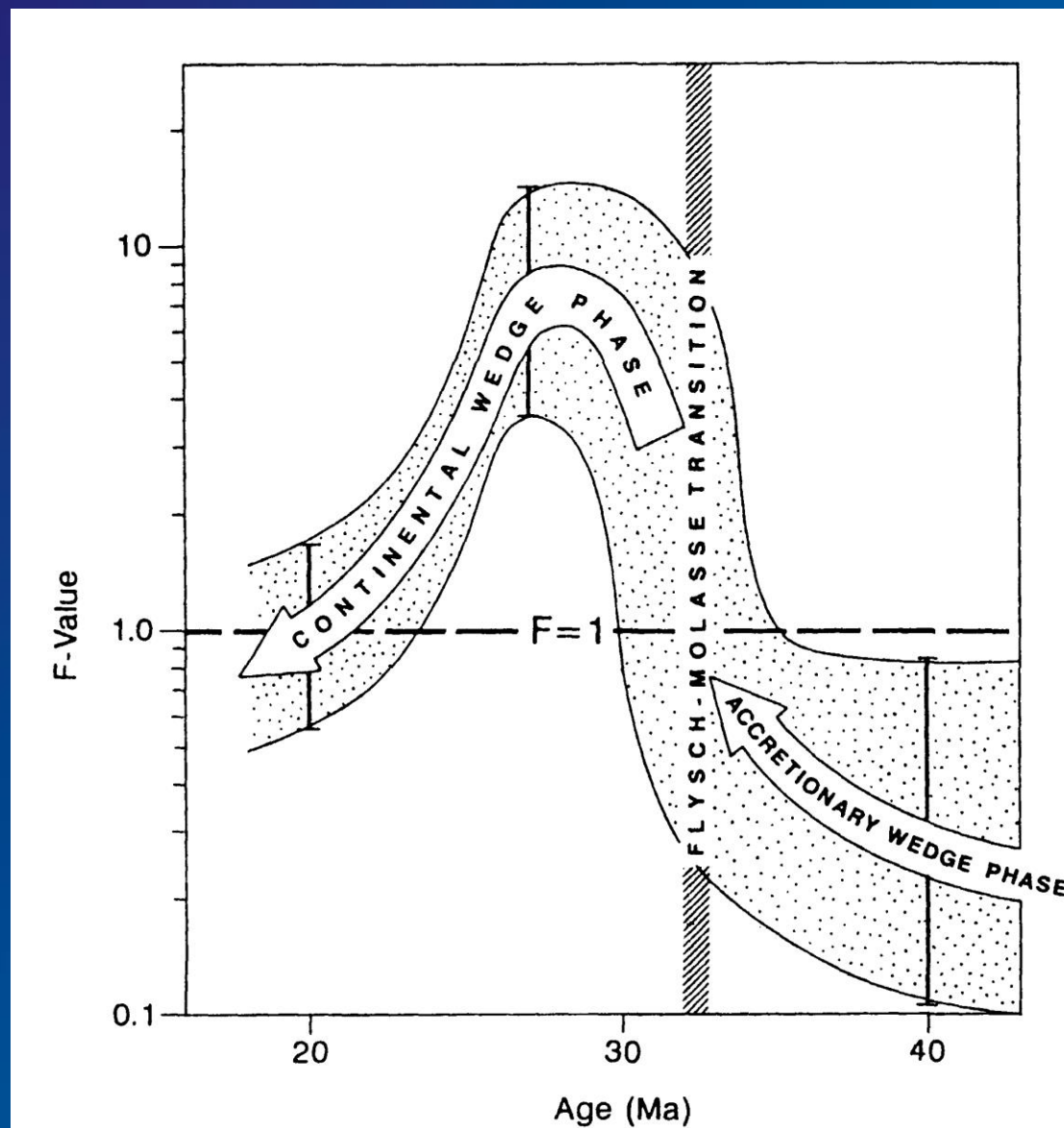
Bassin sous-alimenté
stade « océanique »



Bassin sur-alimenté
stade « continental »

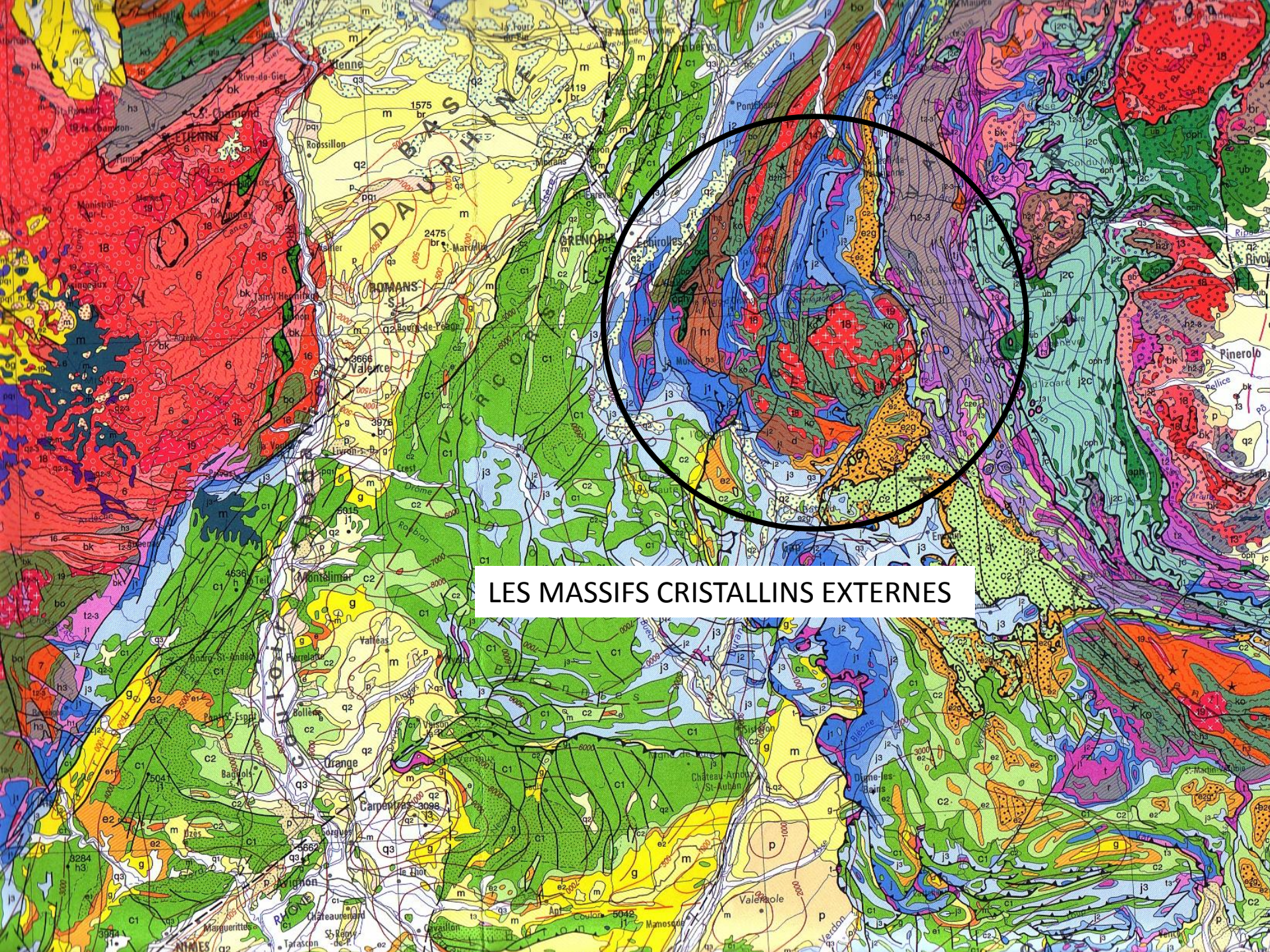
(d'après Sinclair)

Modèle d'accommodation



(d'après Sinclair)

Les Massifs Cristallins Externes



LES MASSIFS CRISTALLINS EXTERNES



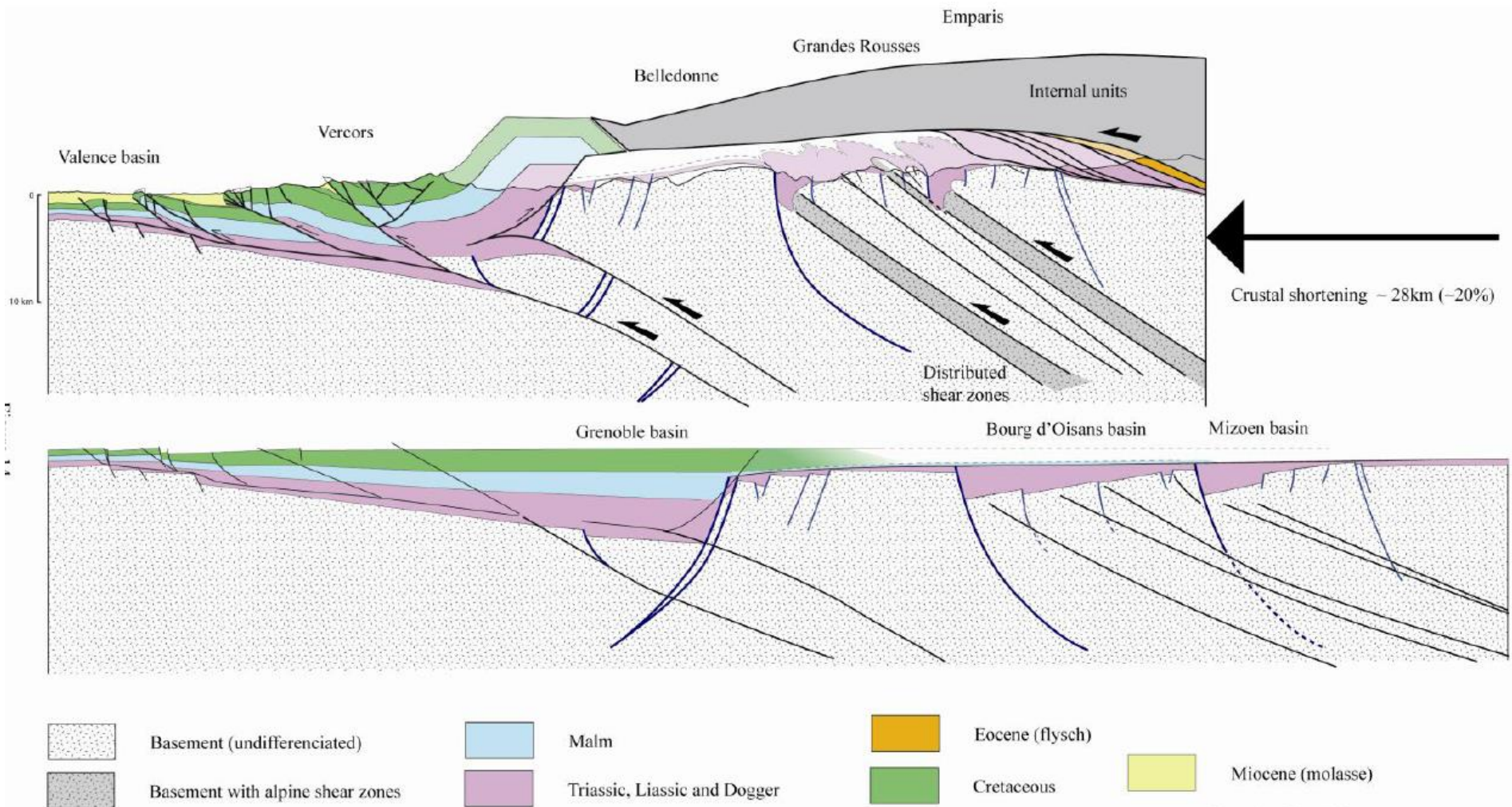
LA MEIJE
3983 m



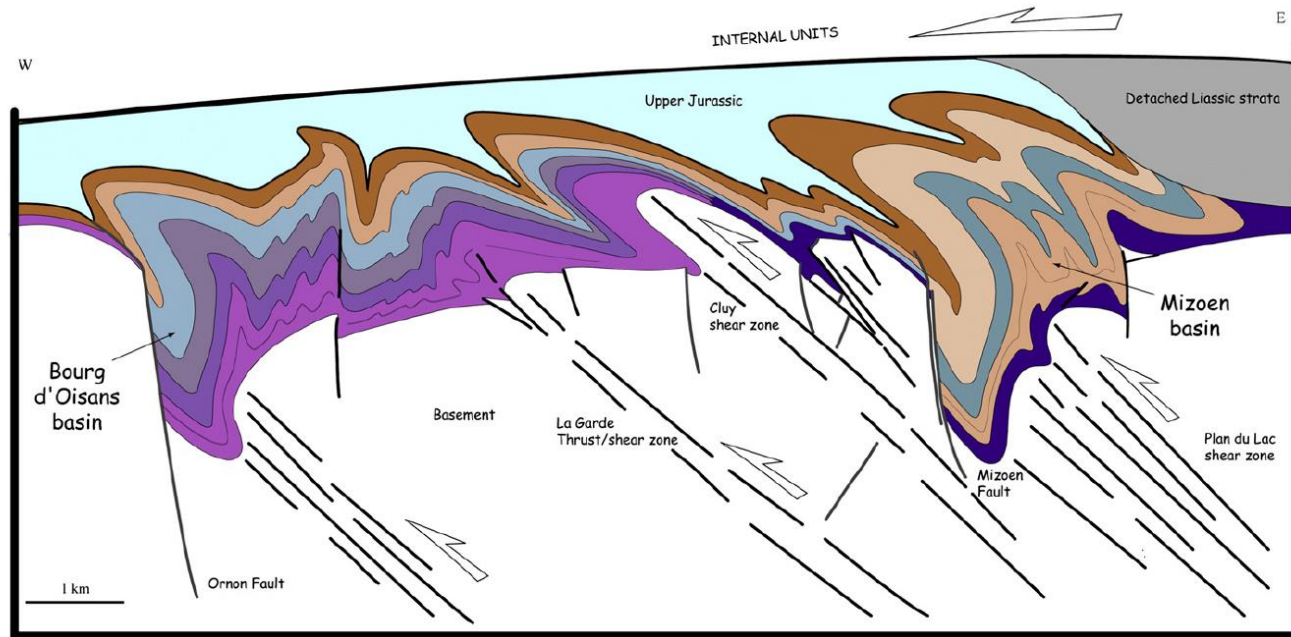




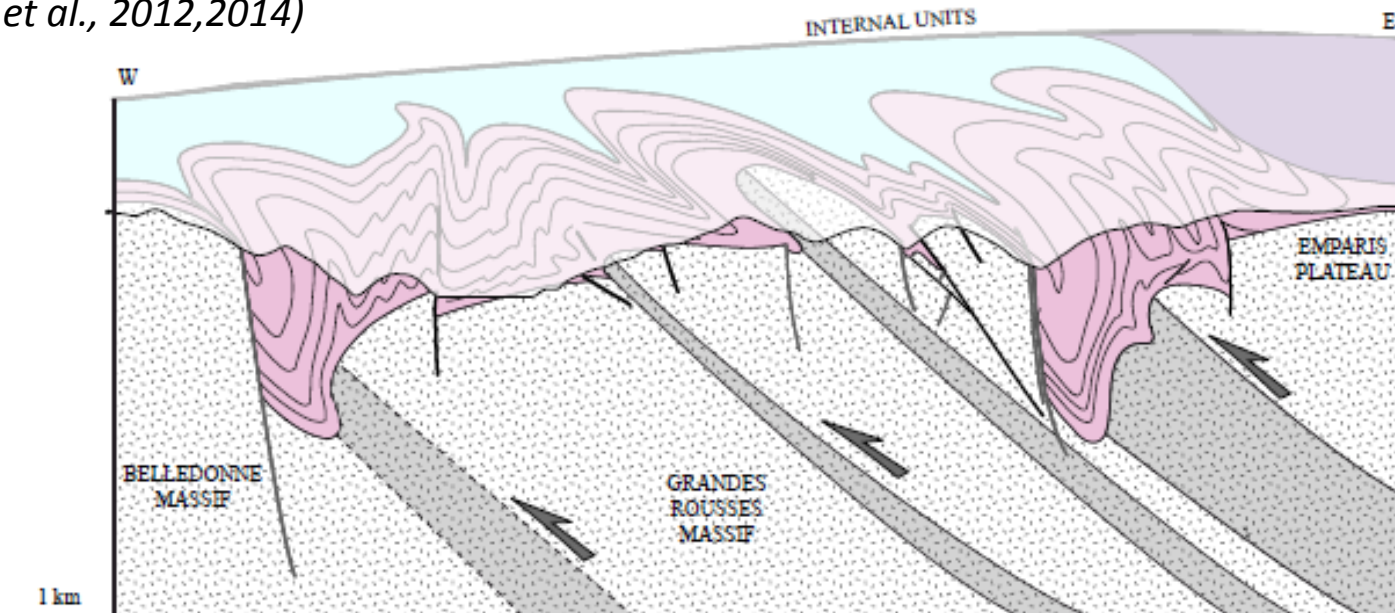




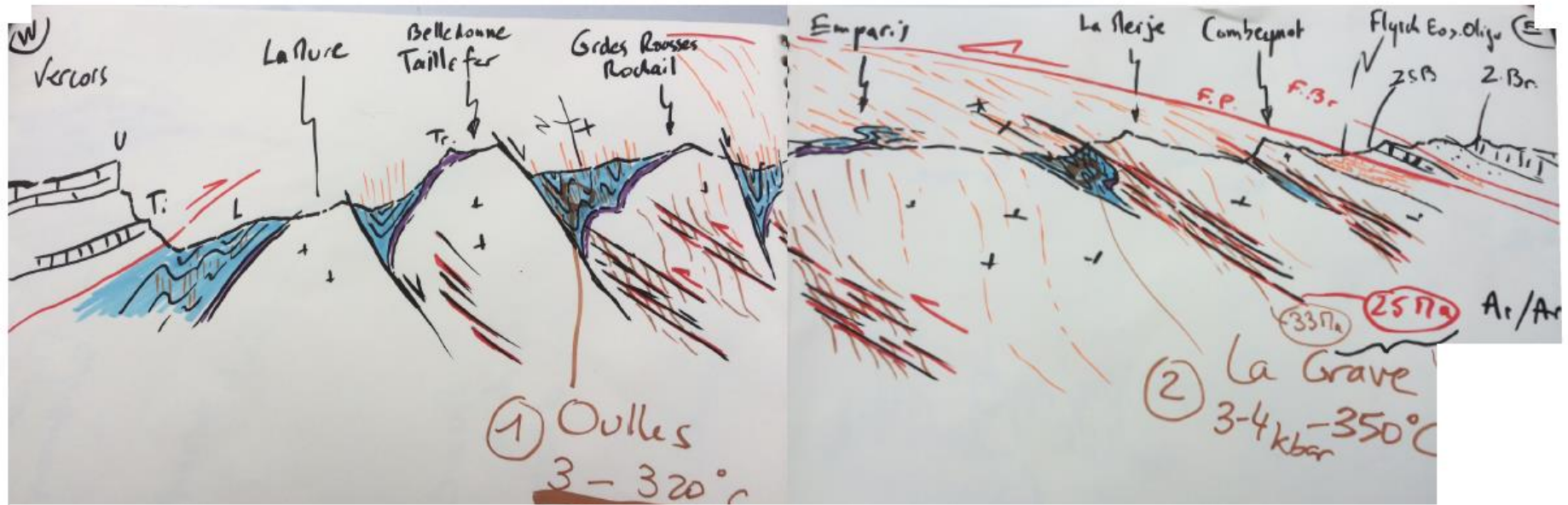
(Bellahsen et al., 2012)



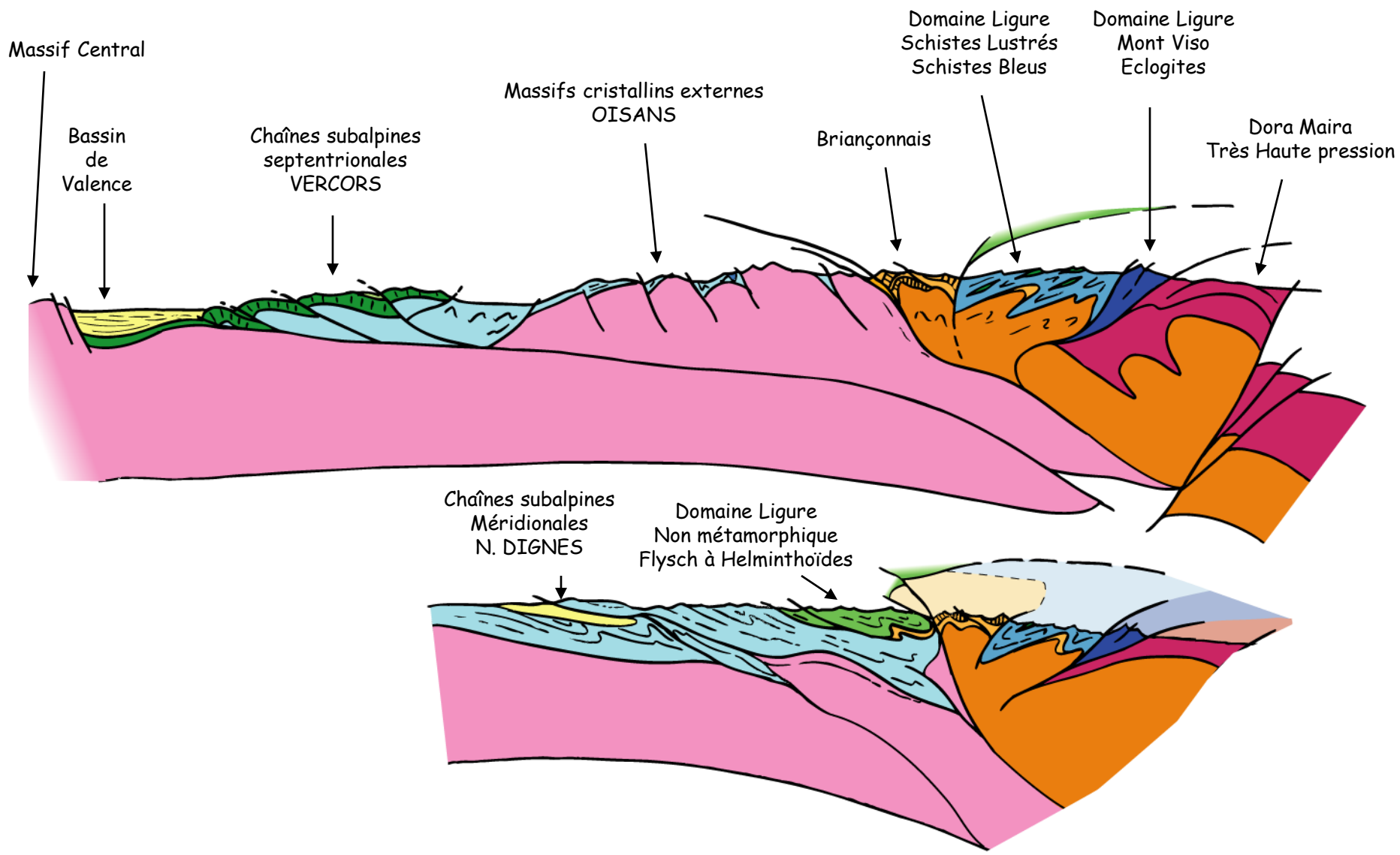
(Bellahsen et al., 2012,2014)



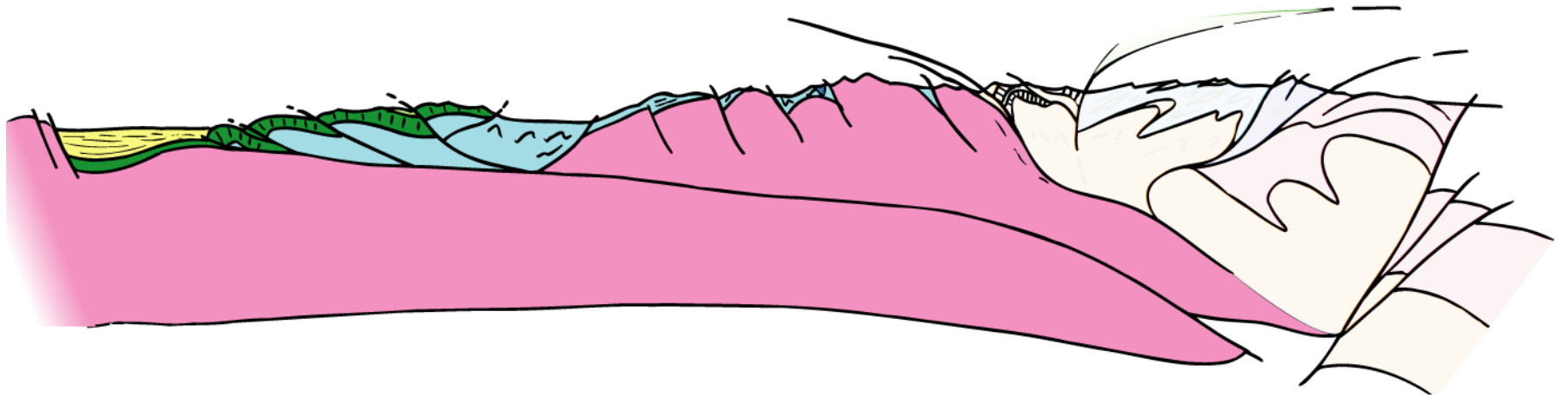




(Courtesy of L. Jolivet)



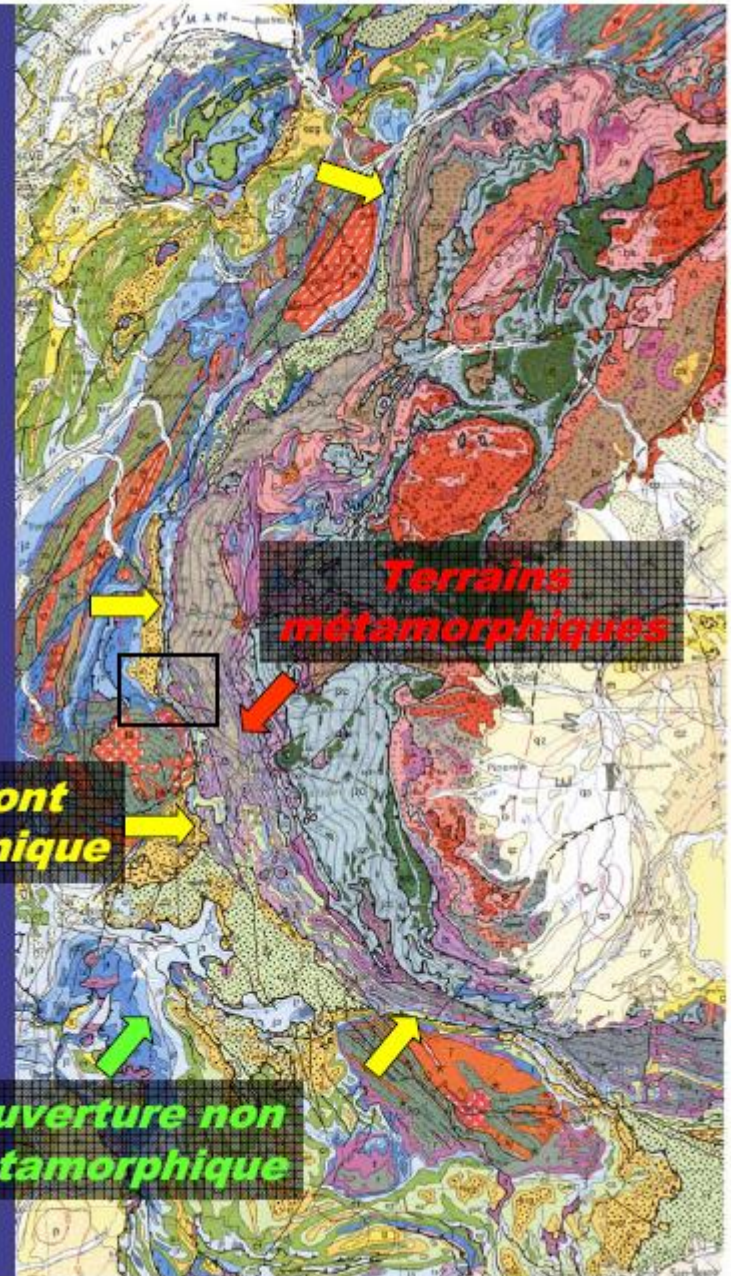
Le domaine dauphinois:
un prisme d'accrétion Oligo-Miocène



Les unités Briançonnaises et piémontaises :
Un « prisme d'accrétion » éocène

Front pennique
Structure majeure
à l'échelle de l'arc alpin

Limite tectonique:
chevauchement des zones
métamorphiques sur
l'avant-pays européen

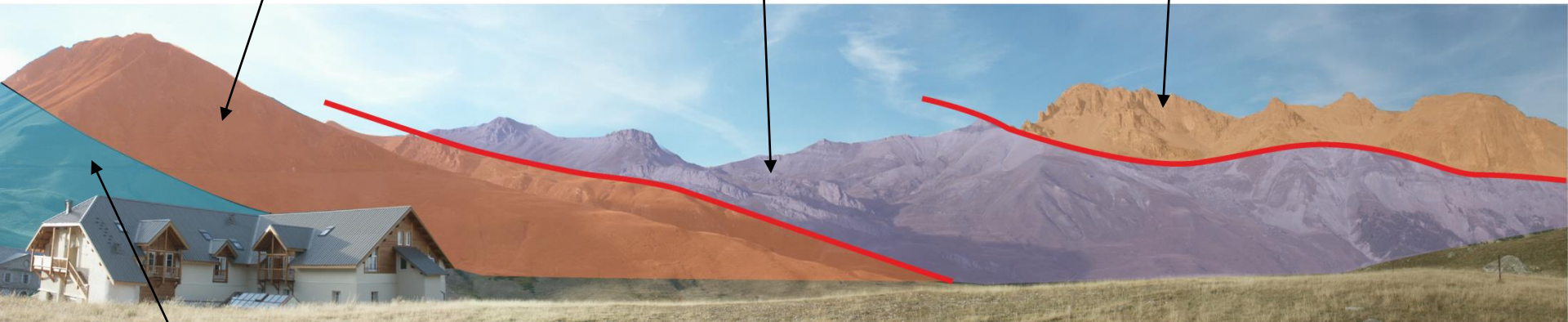


Panorama du Col du Lautaret

Flysch dauphinois

Sub-Briançonnais

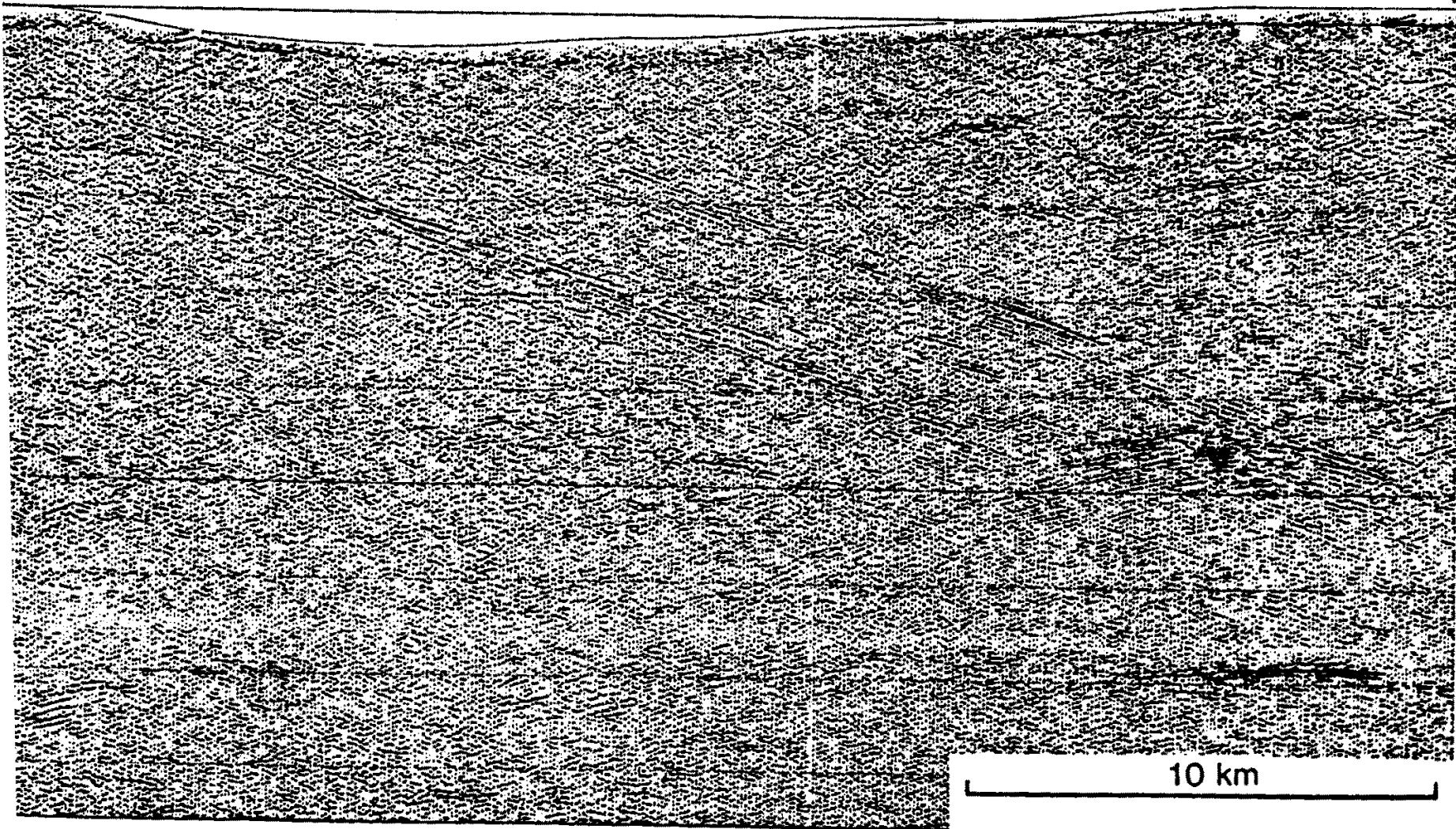
Briançonnais



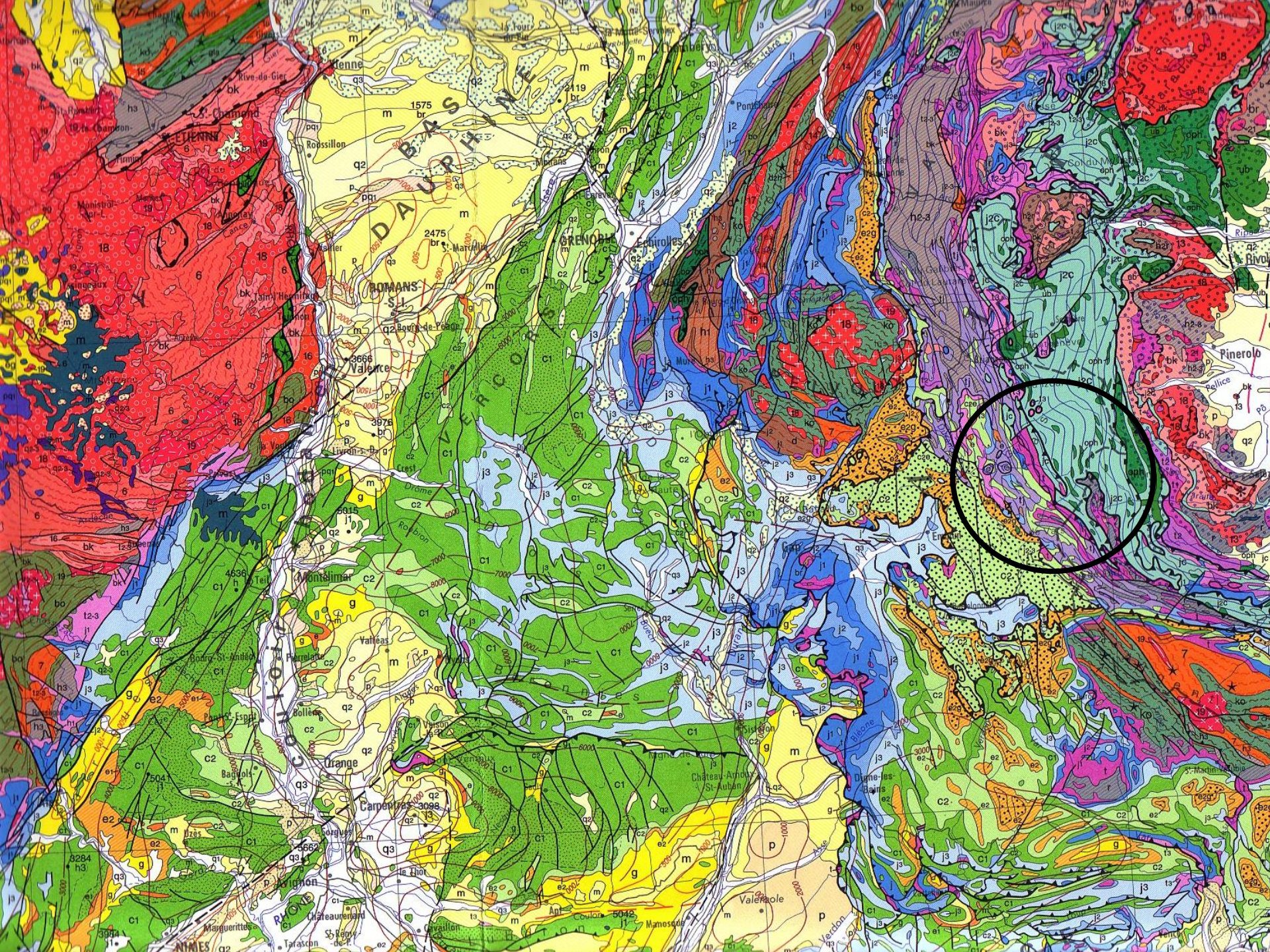
Lias dauphinois

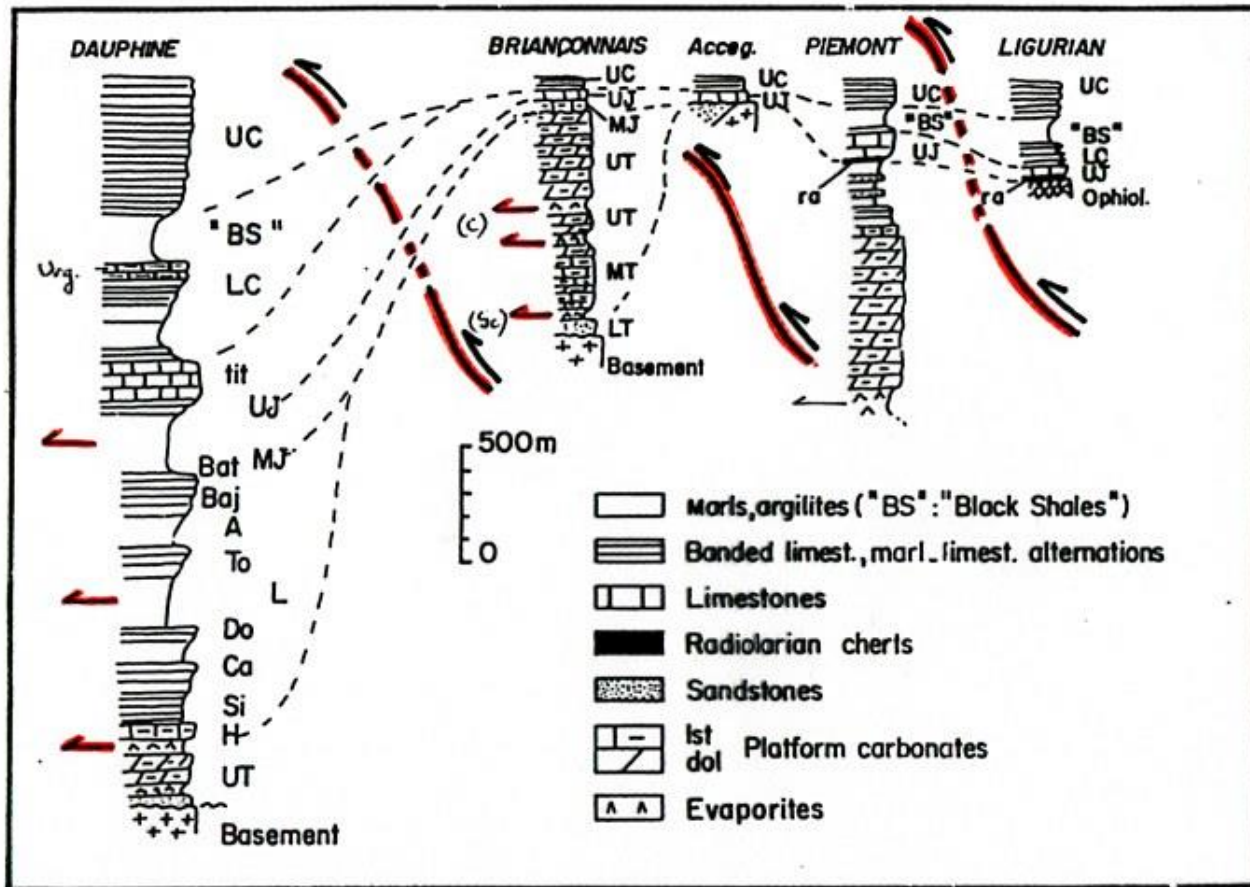
BOURG SAINT MAURICE

SE
VAL D'ISERE



Réflecteur(s) du Front Pennique





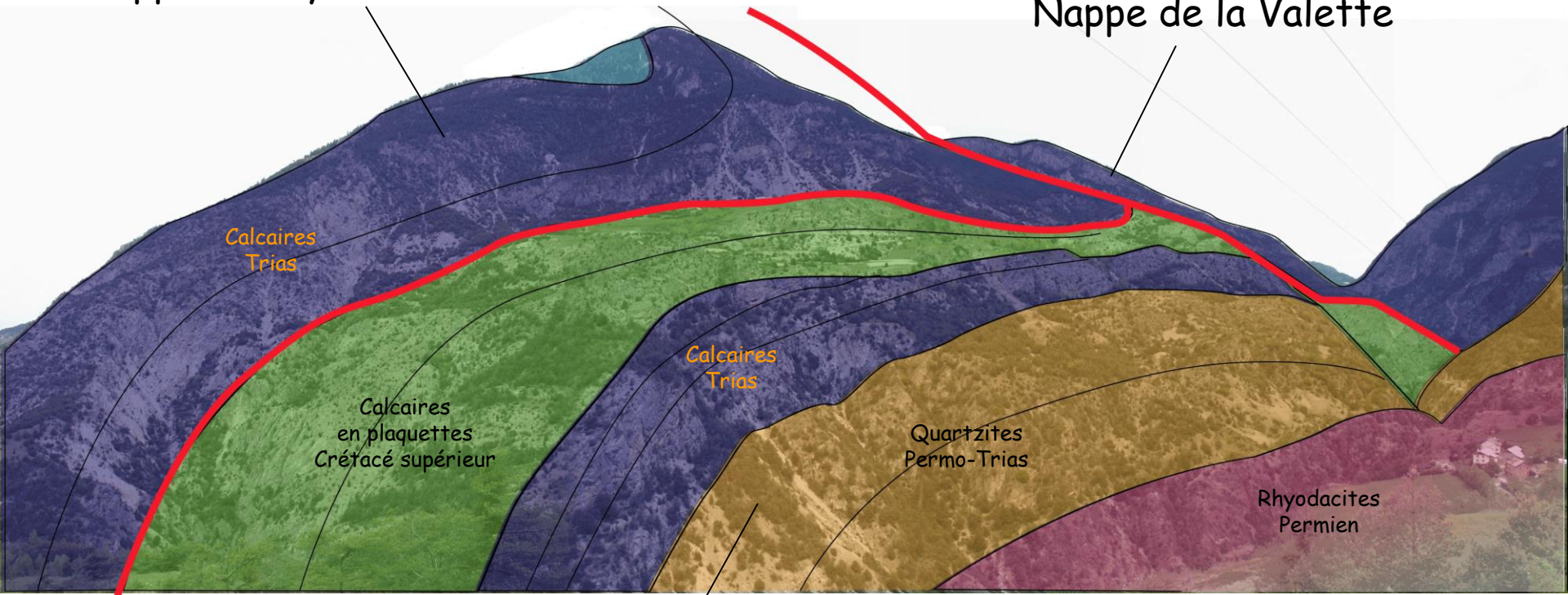
Simplified stratigraphic columns of the main types of sedimentary series in the Western Alps.

= Méozoïque

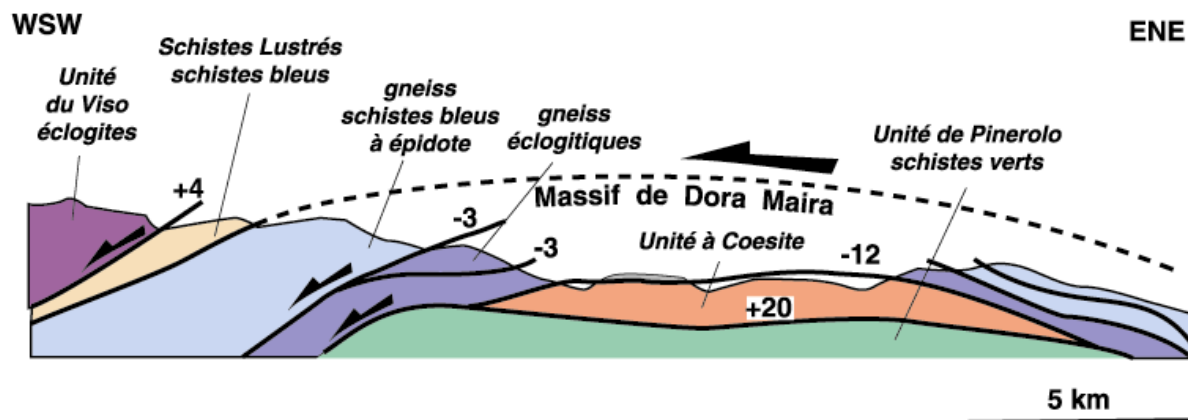
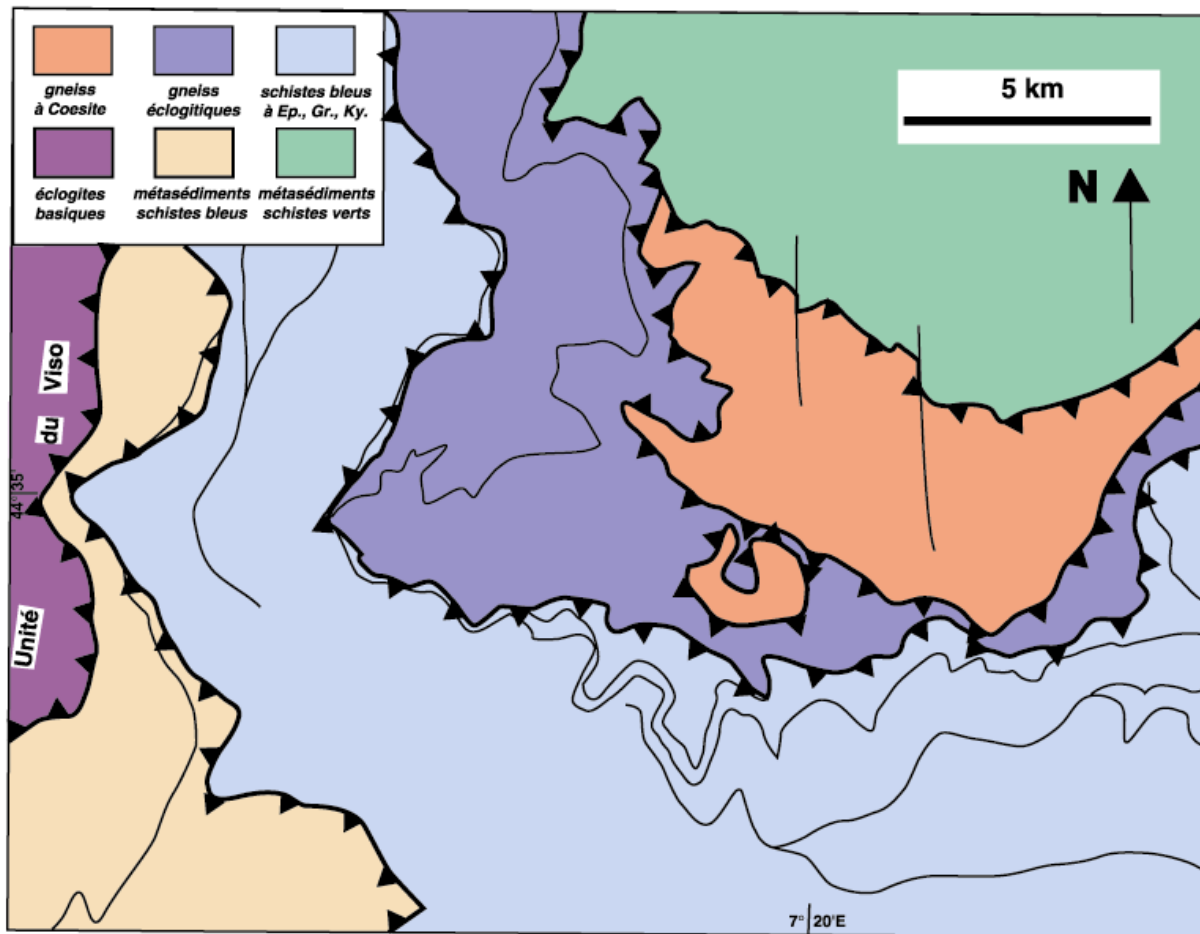


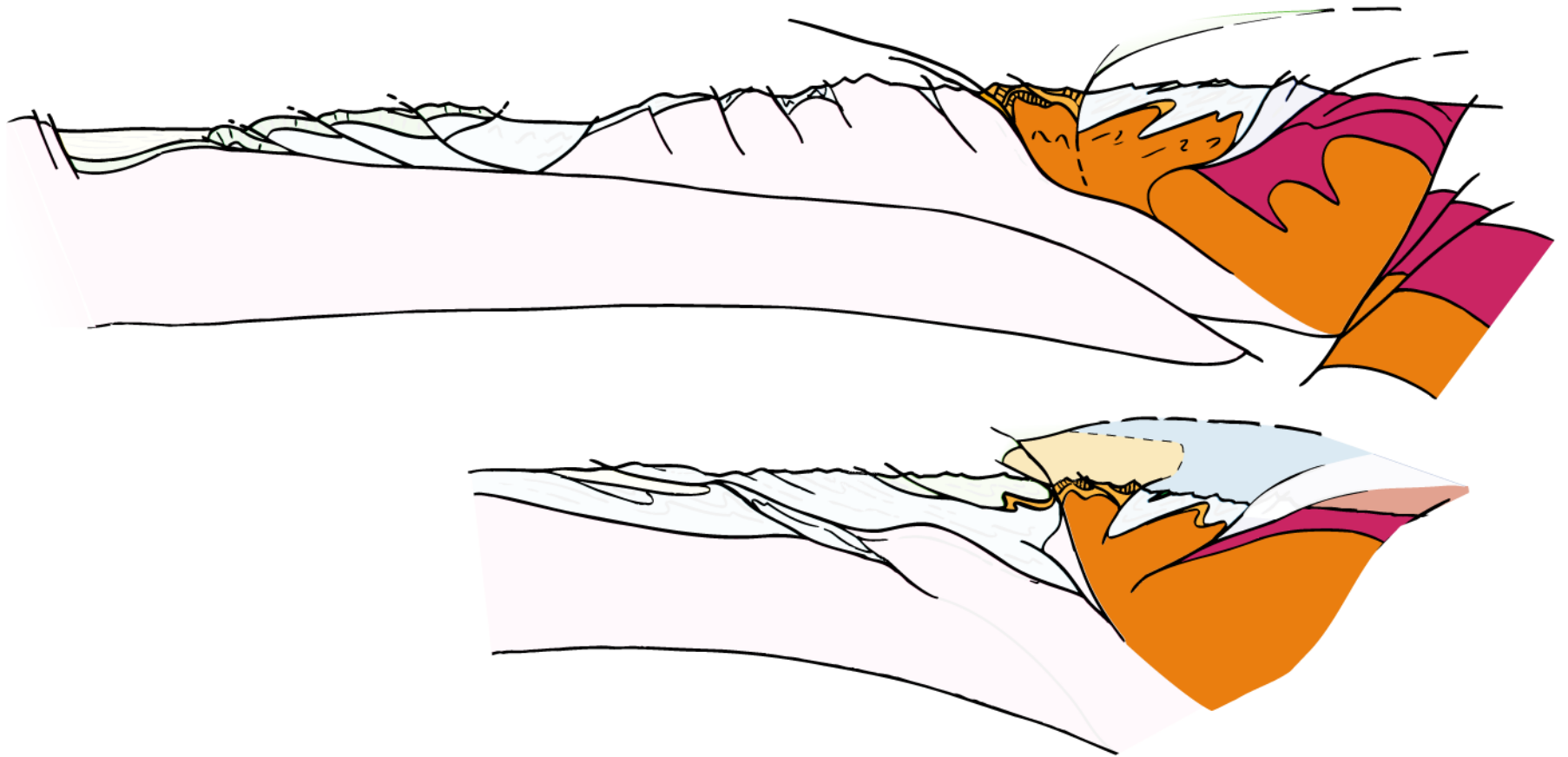
Nappe de Peyre-Haute

Nappe de la Valette

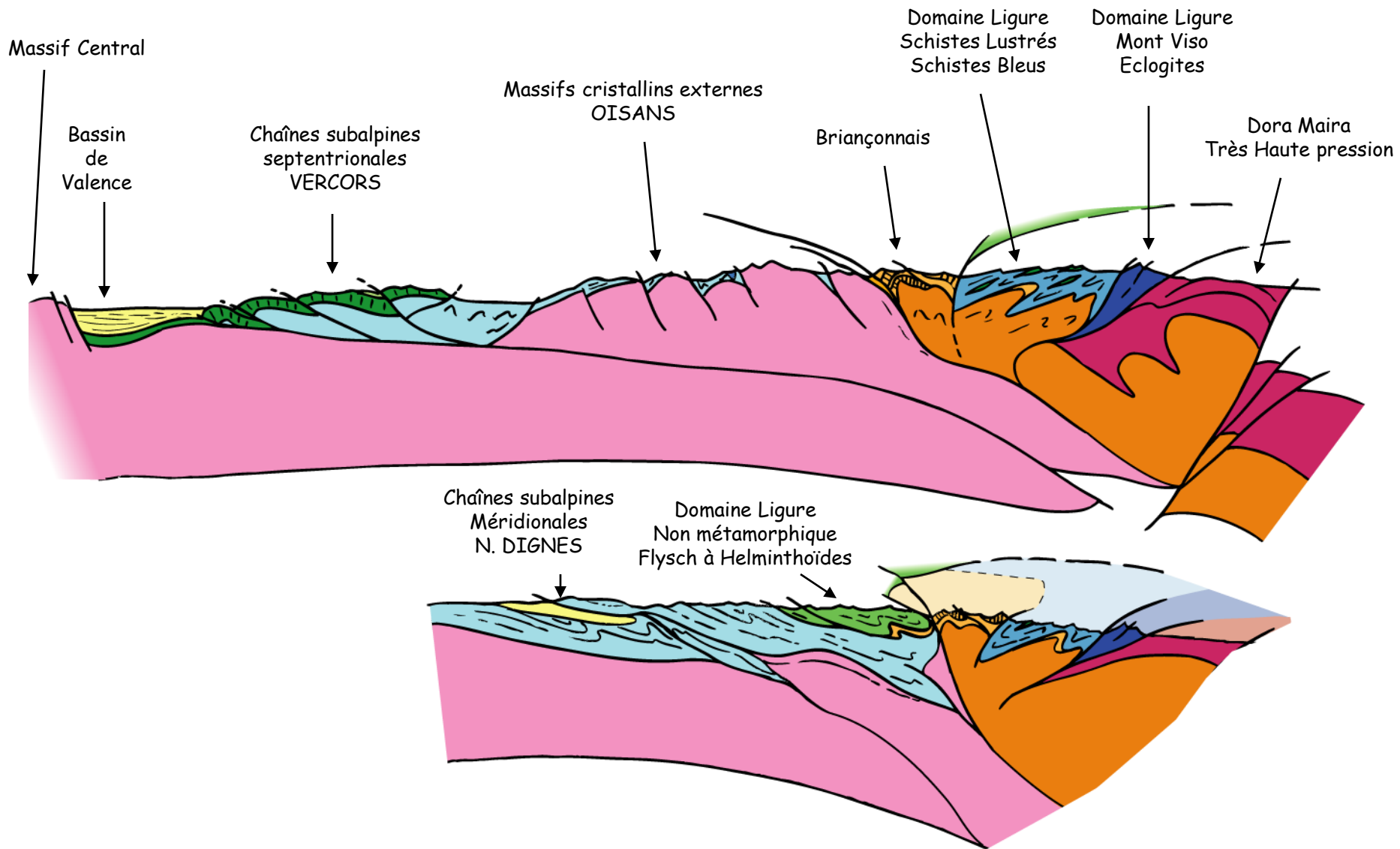


Nappe de Champcella





Prisme d'accrétion Briançonnais



La limite entre zone externe / zones internes

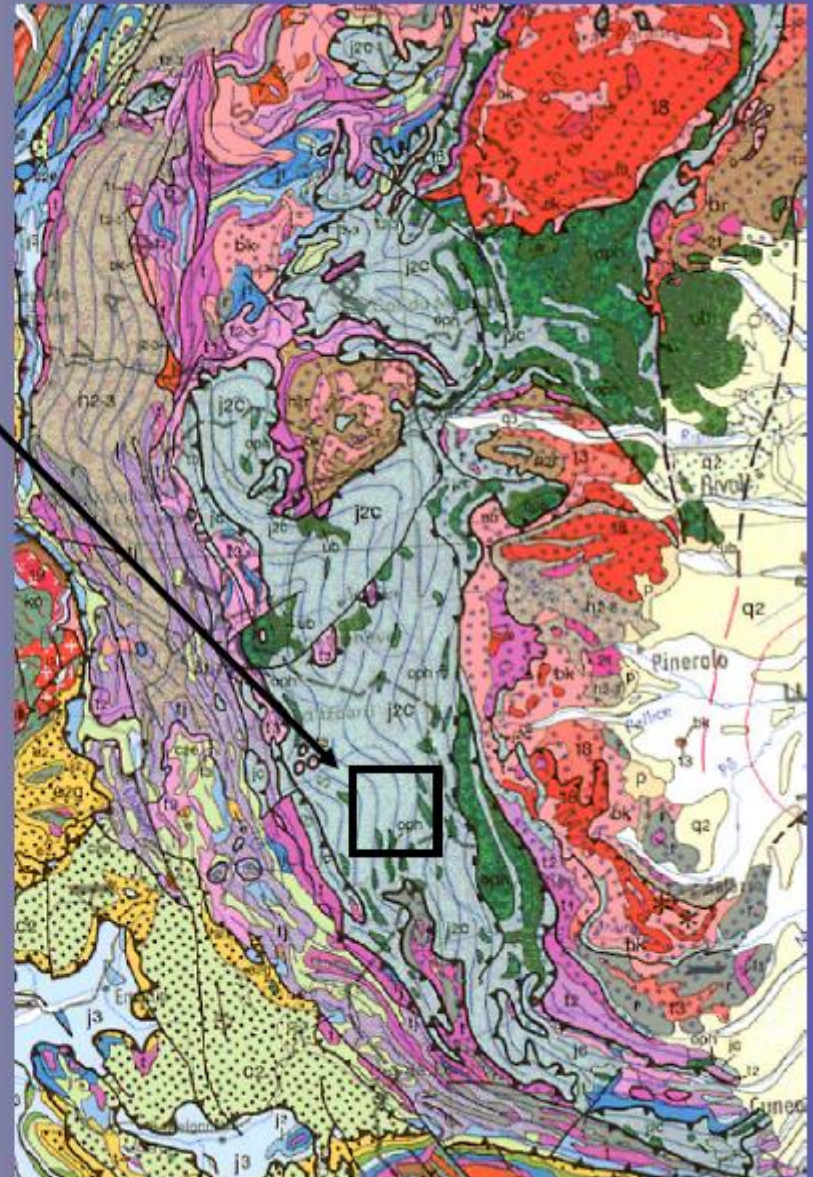
Les unités liguro-piémontaises :
Un « prisme d'accrétion » crétacé sup.-paléocène



Association :

- sédiments**
- gabbros**
- basaltes**
- péridotites serpentinisées**

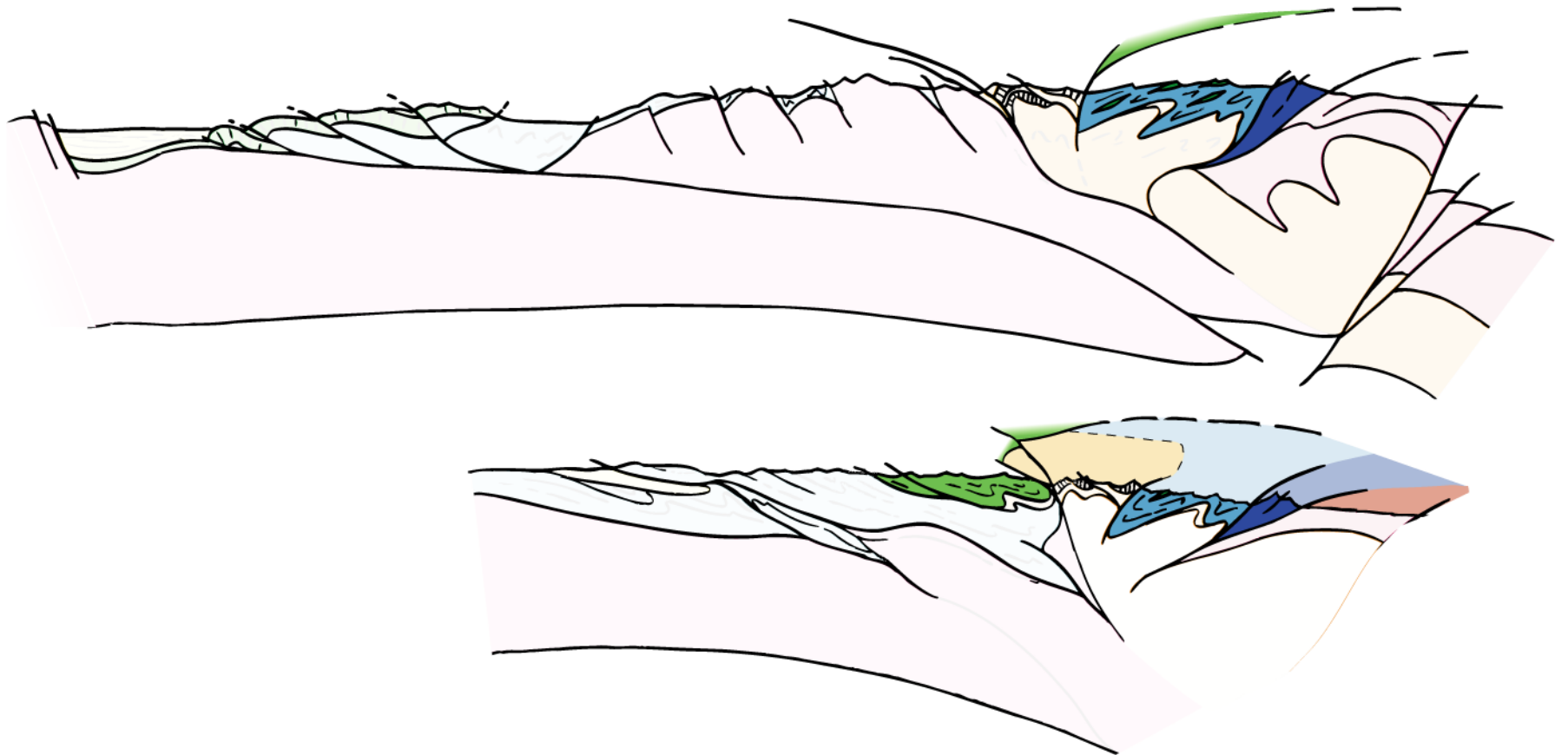
➔ Fragments de lithosphère océanique emballés dans des sédiments le tout métamorphisé



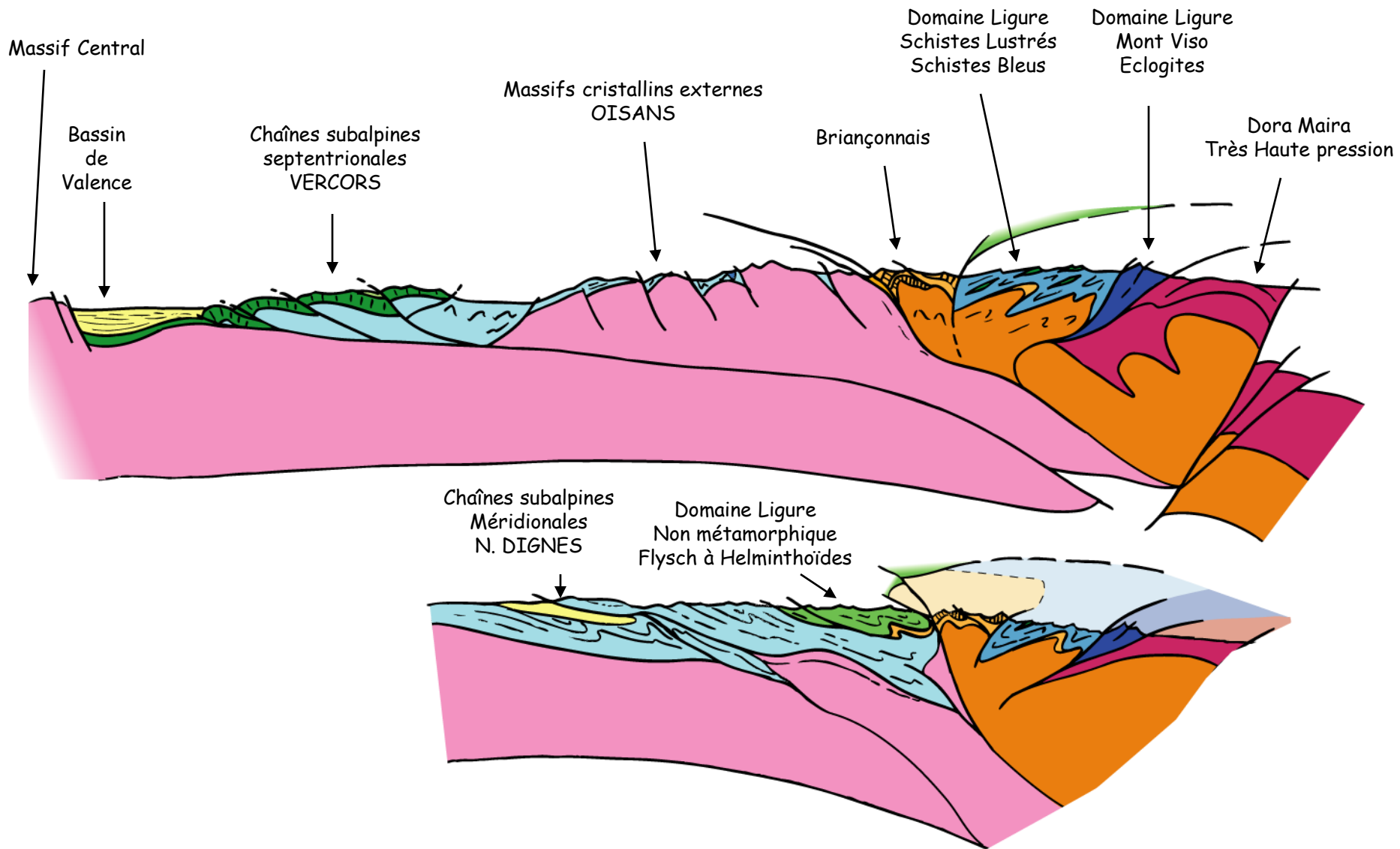




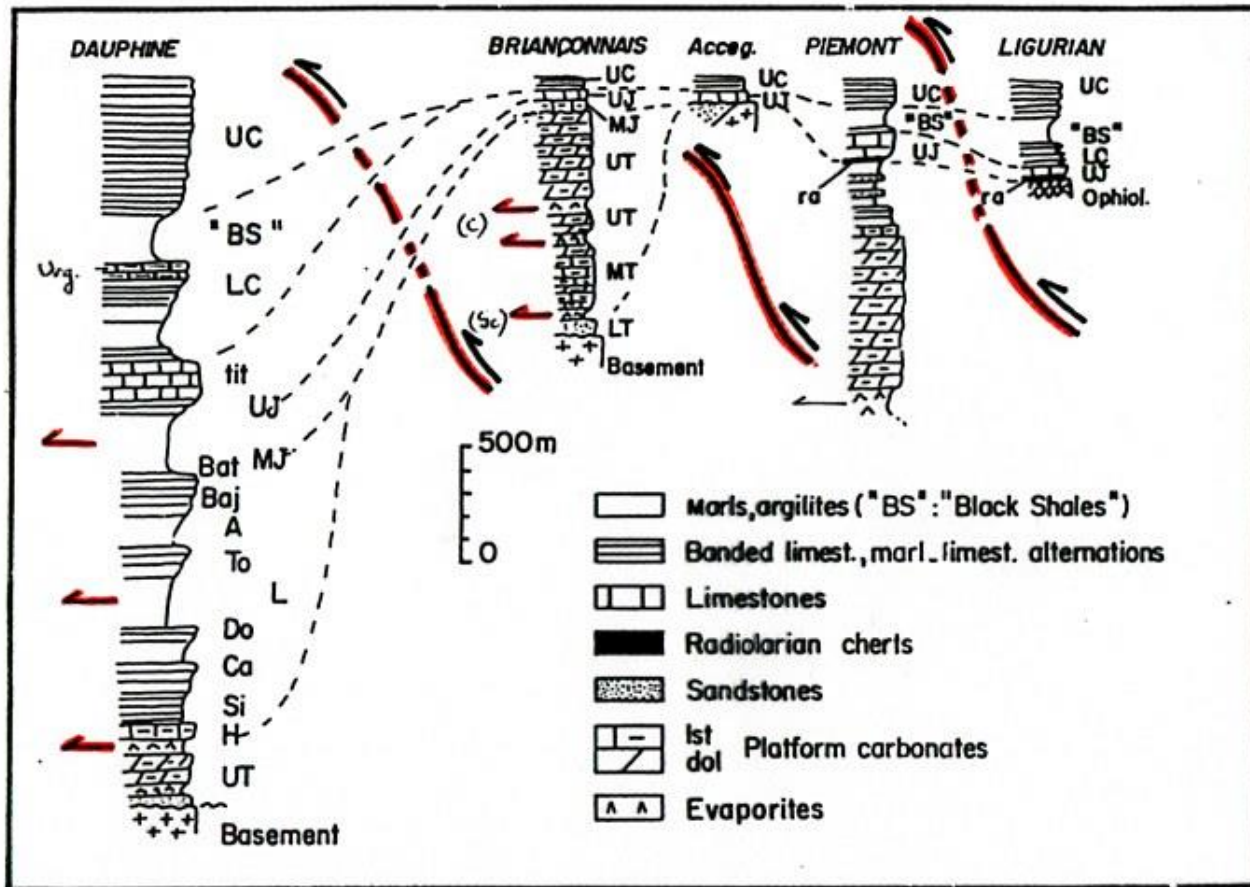




Prisme d'accrétion ligure



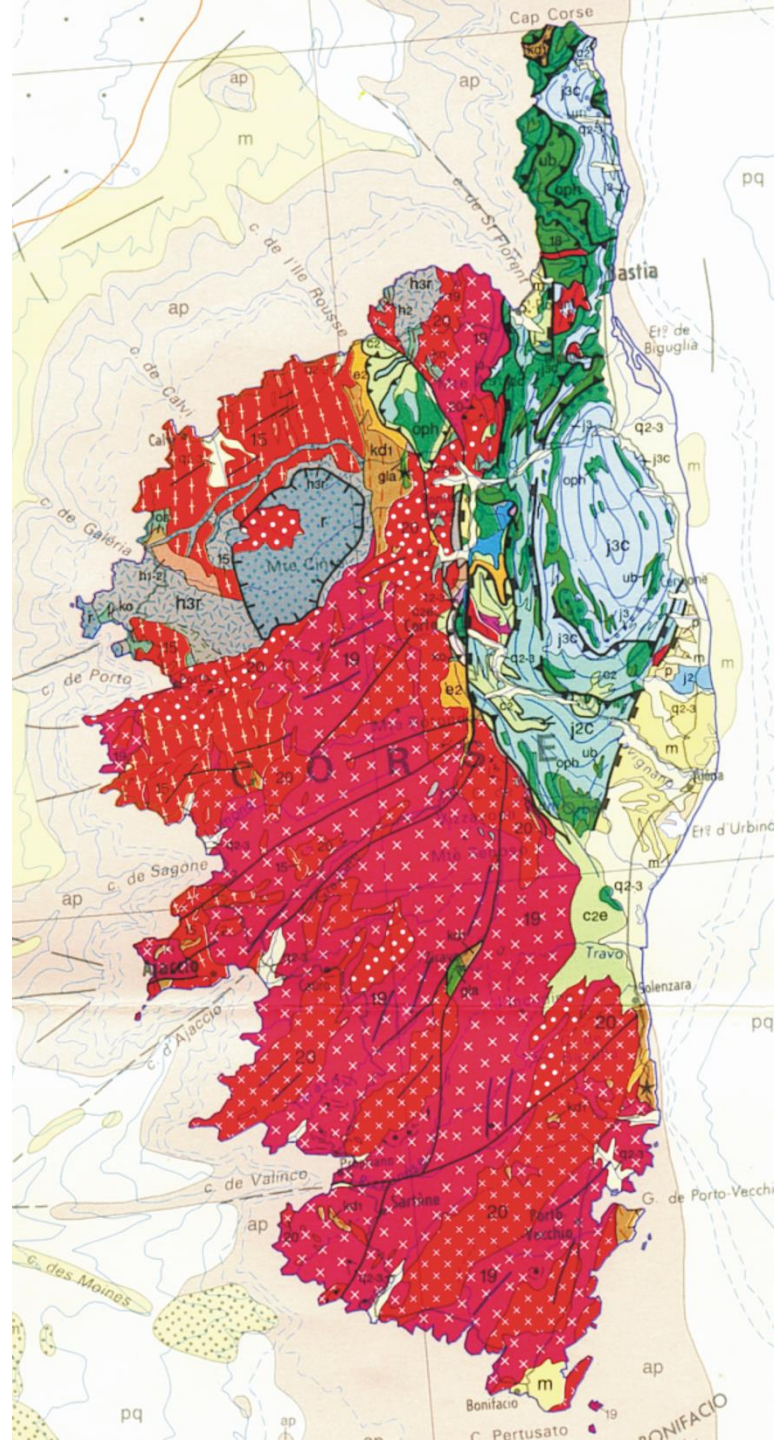
La limite entre zone externe / zones internes



Simplified stratigraphic columns of the main types of sedimentary series in the Western Alps.

= Méozoïque

La Corse alpine



Nappe de Balagne s.l.

1-3
Nappe des Schistes Lustrés

- Calcschistes
- Metagabbros et péridotites
- Orthogneiss
- Eclogites

Chev.

Chev. repris en dét.

FN ou dét.

10 km

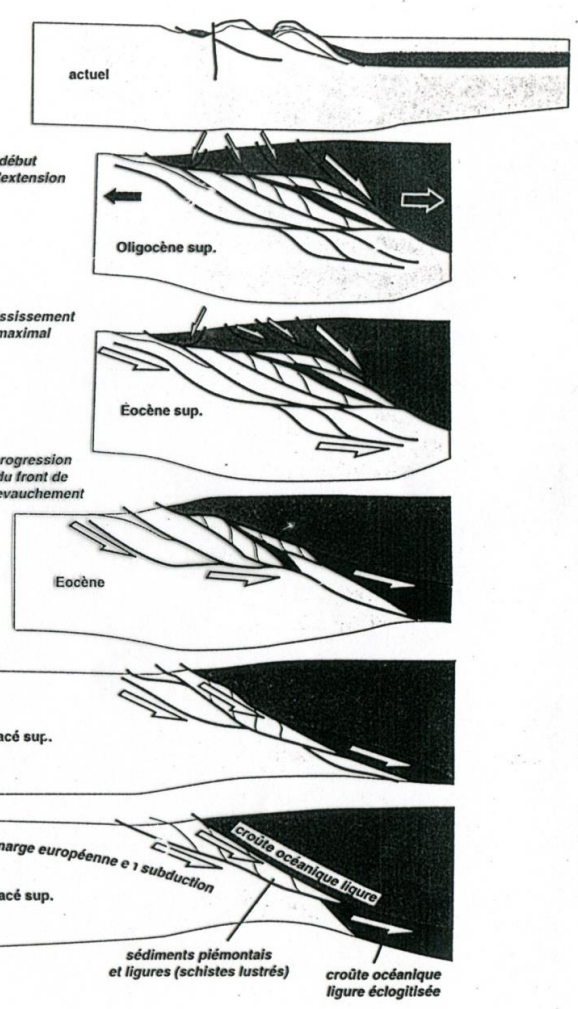
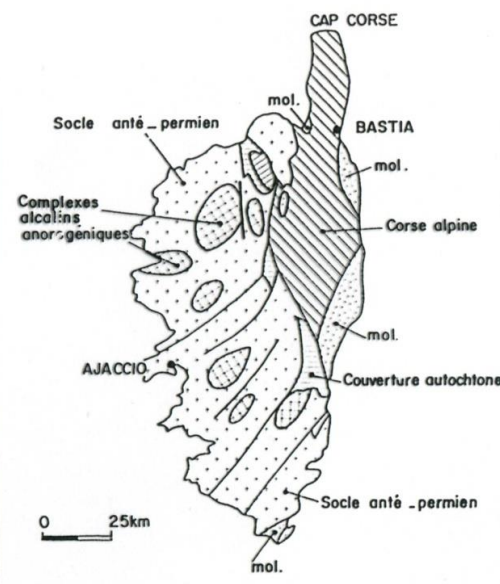
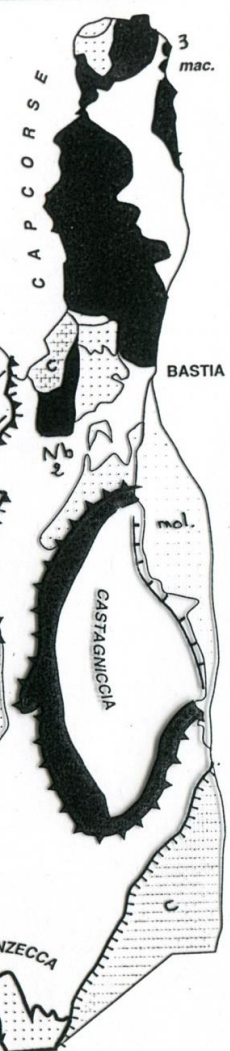
Ecailles de Corte et Massif du Tendr.

Socle et couverture

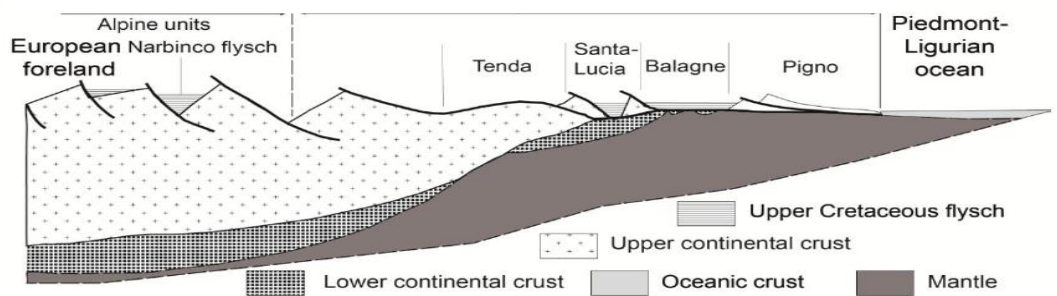
Corse occidentale
 socle granitique paléozoïque

Bassins sédimentaires
 Calcaires burdigalien

NW

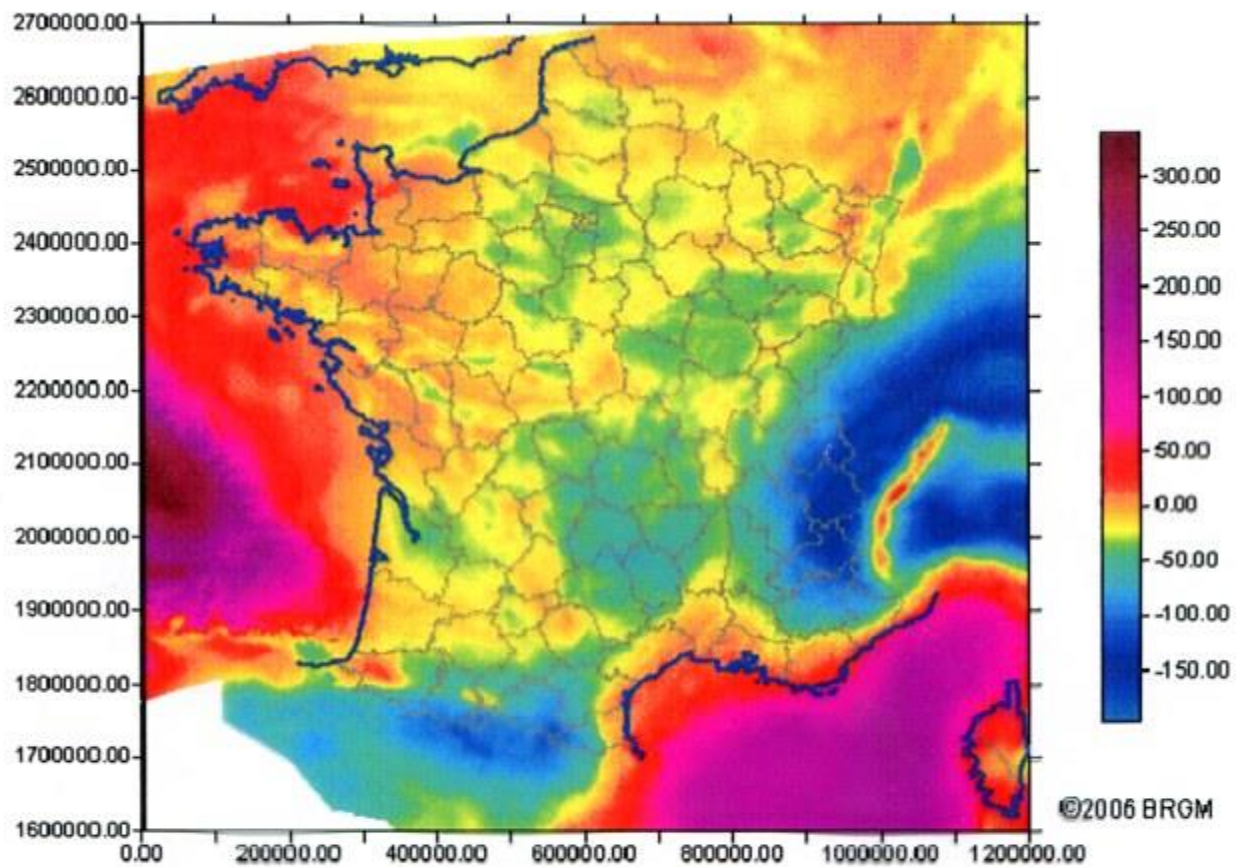


SE



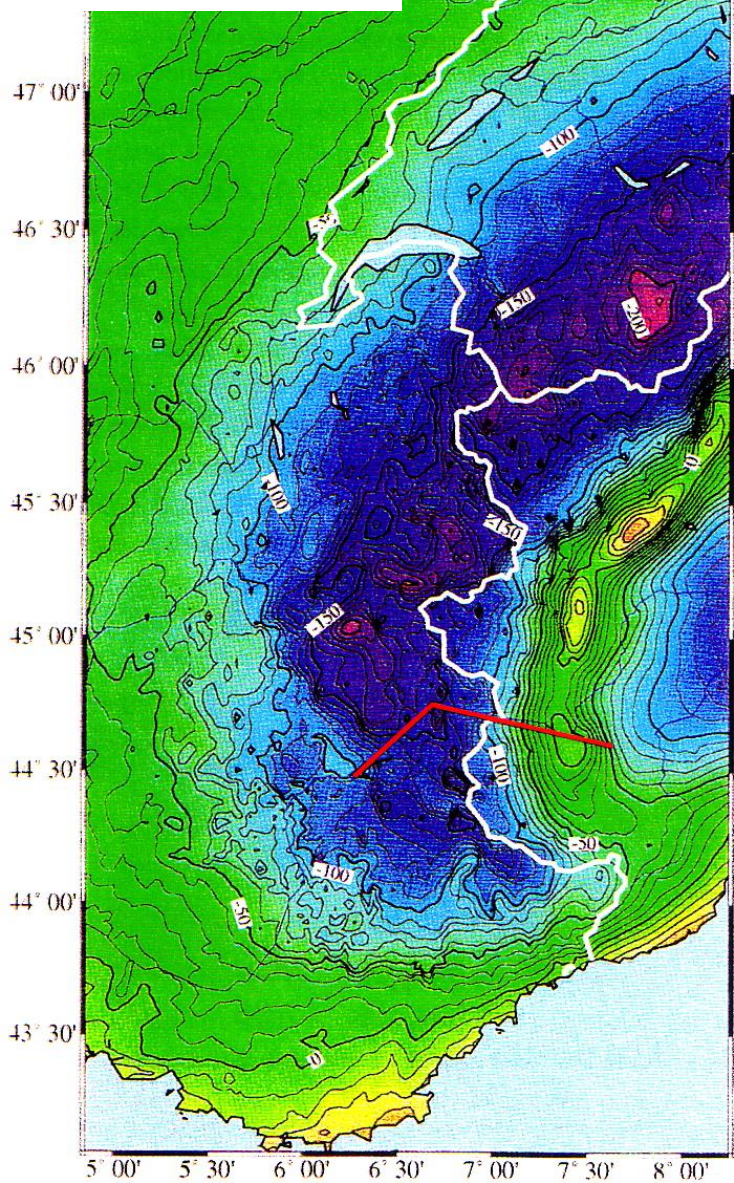
I. Les Alpes franco-italiennes :
une chaîne de subduction-collision

B. La structure profonde vue par la géophysique

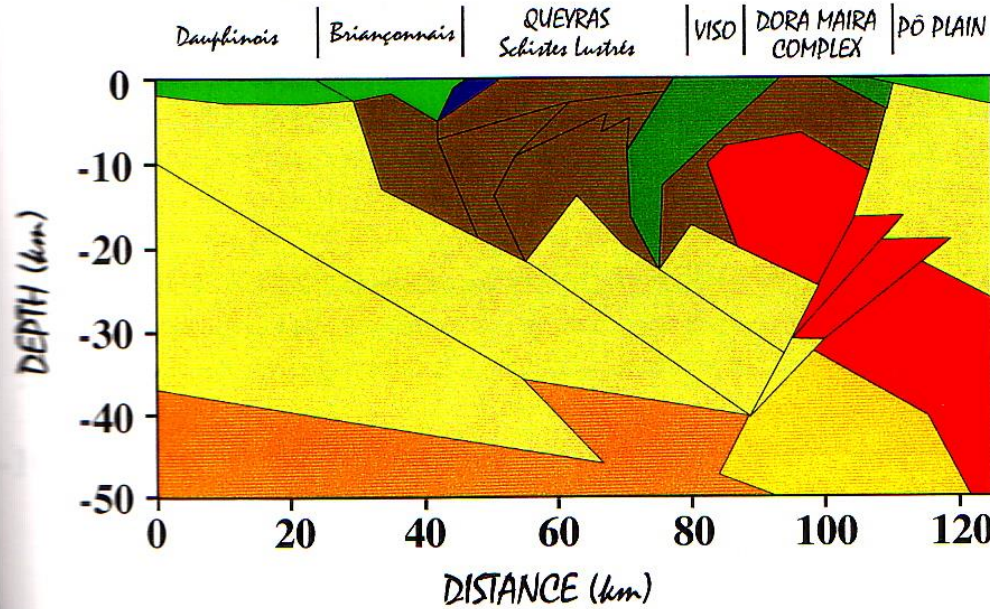
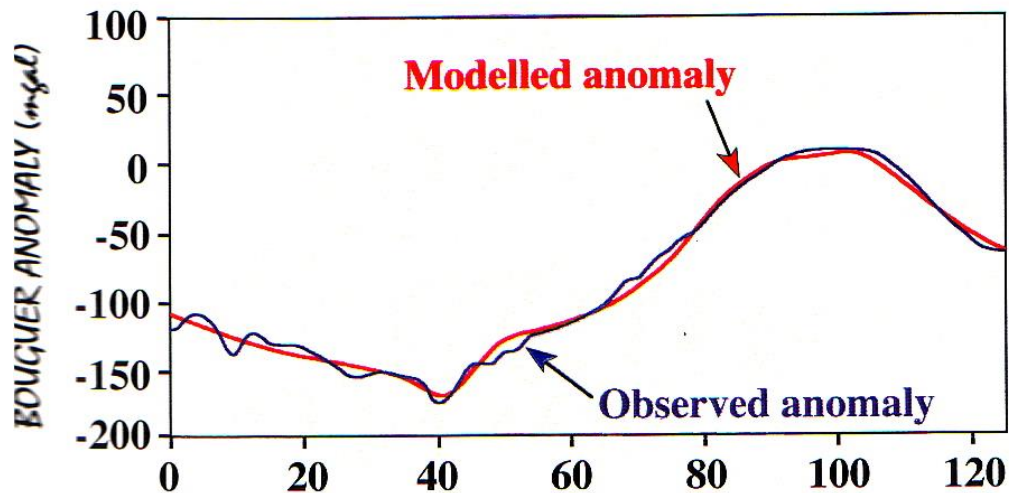


Anomalie de Bouguer (en 10^{-5} m/s^2) cartographiée à partir d'une grille de maille 4 x 4 km.
(d'après Grandjean et al, 1998)

Gravimétrie



-220 -180 -140 -100 -60 -20 20 60 100
Anomalie de Bouguer en mgal



2.40	2.75	2.85	3.20
2.60	2.80	3.15	3.30

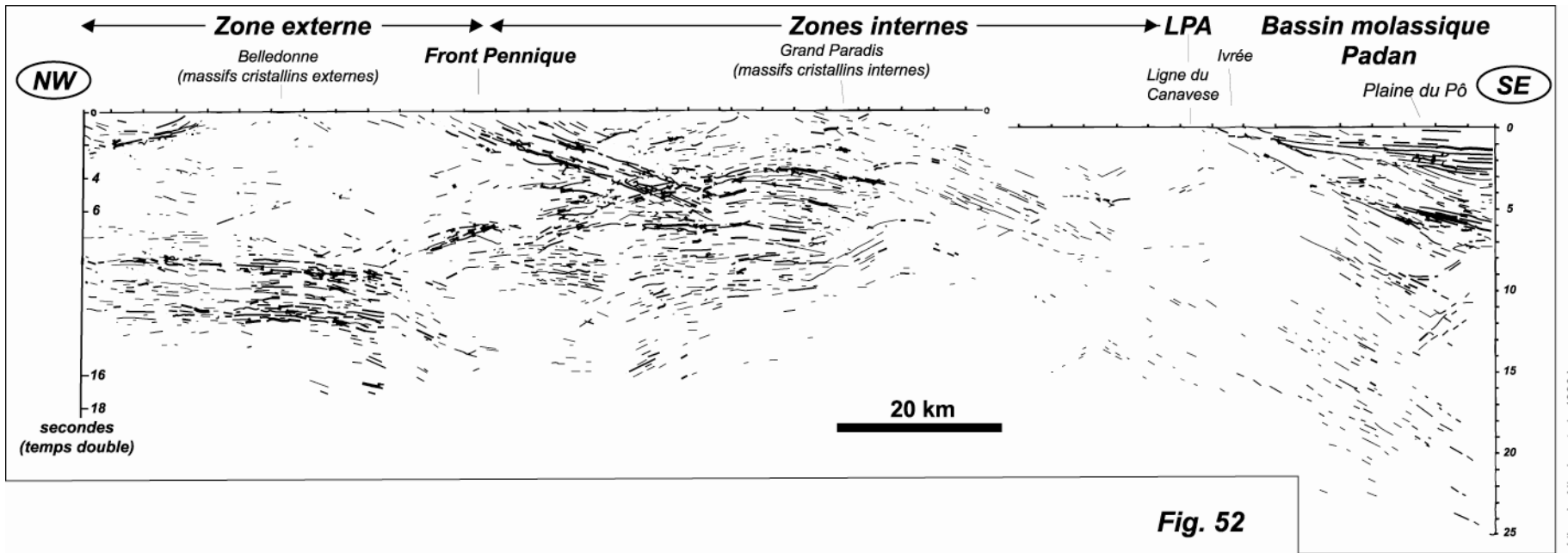
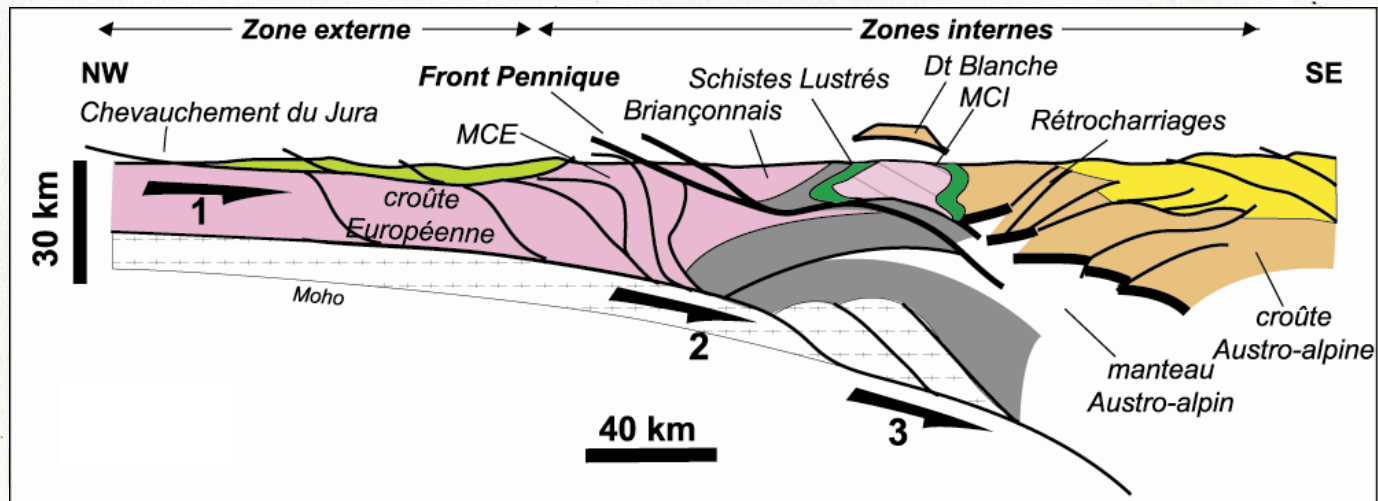
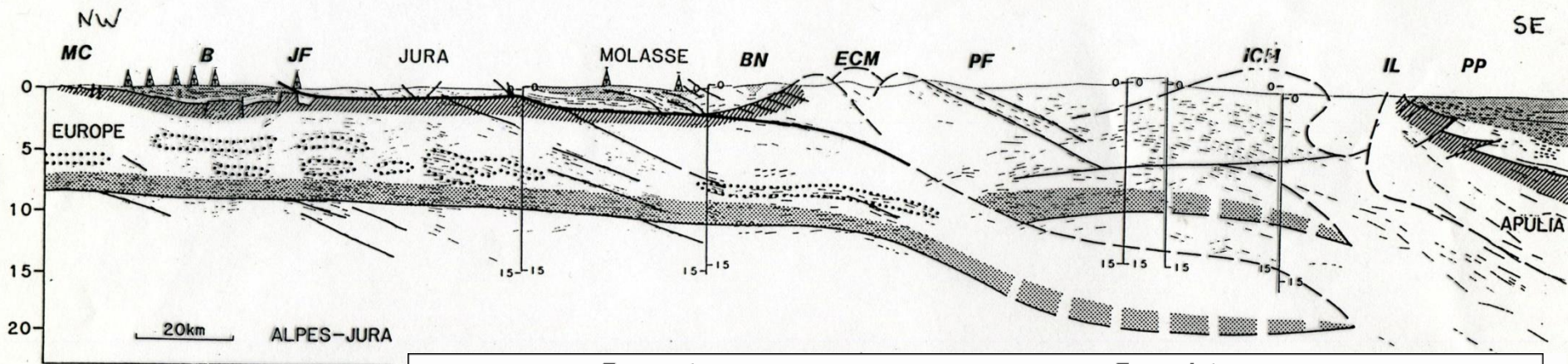
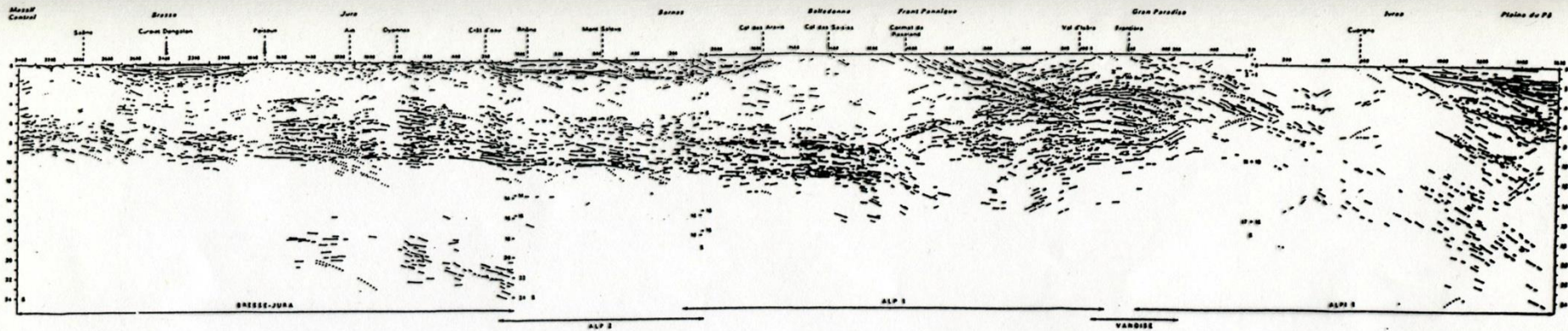


Fig. 52

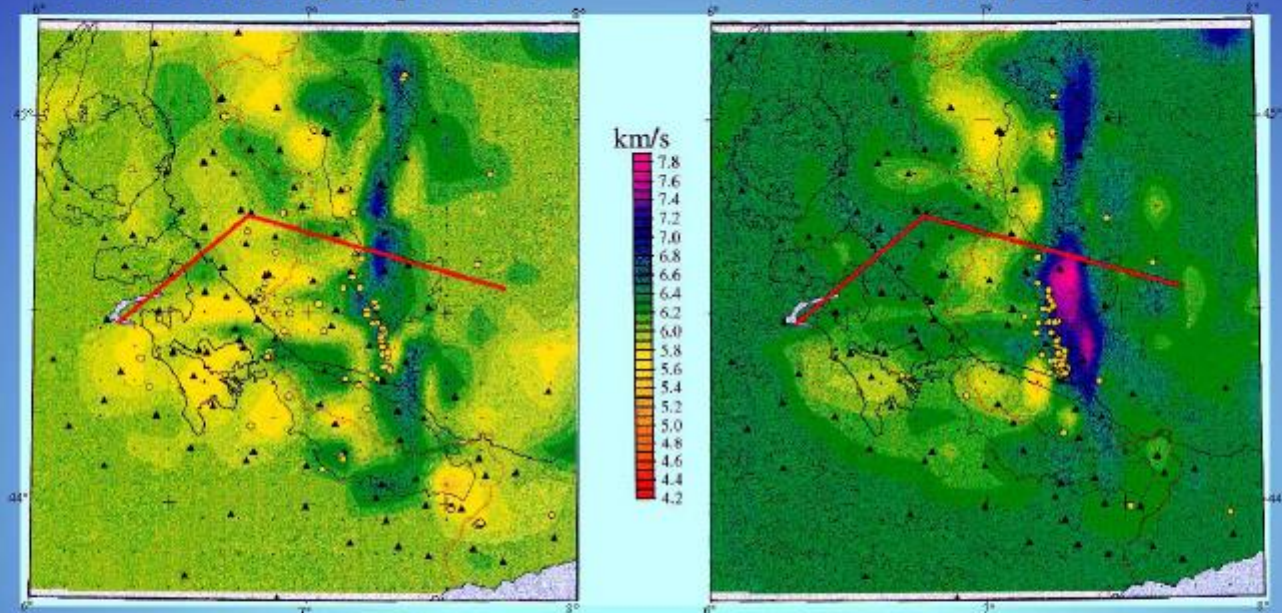


D'après Bois, Roure)

RESULTATS TOMOGRAPHIQUES

P-wave velocity-Depth 8km

P-wave velocity-Depth 12km



SW

NE/NW

SE

Dauphinois

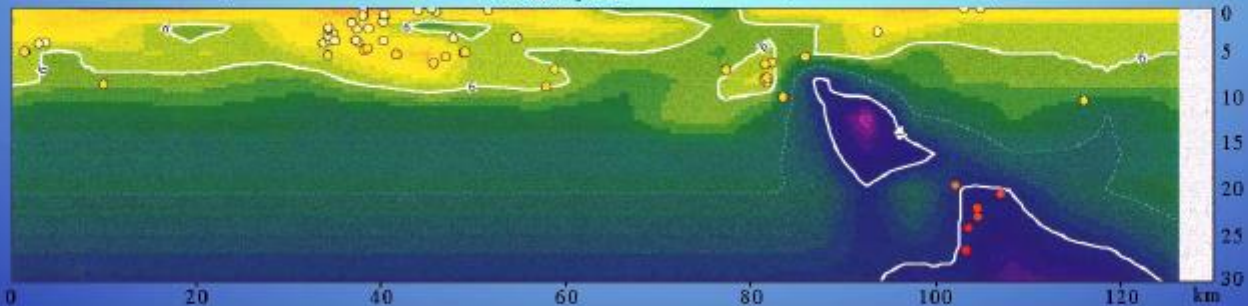
Briançonnais

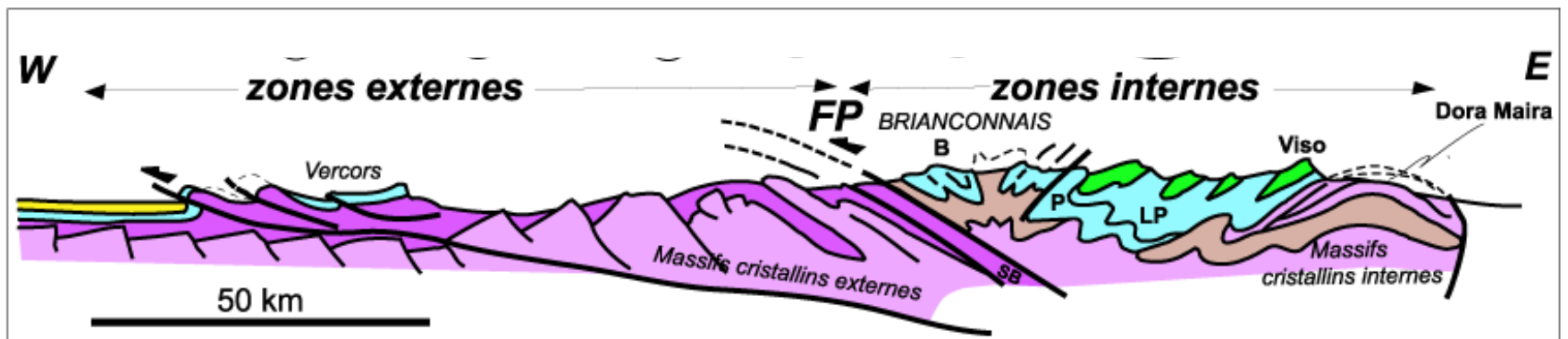
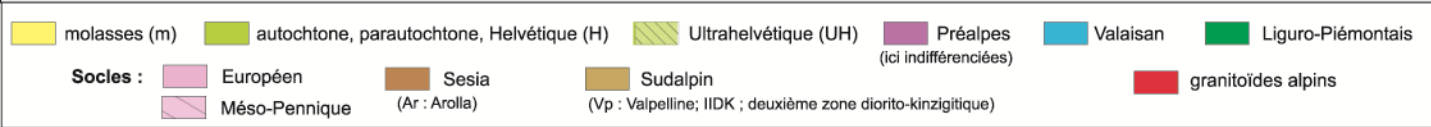
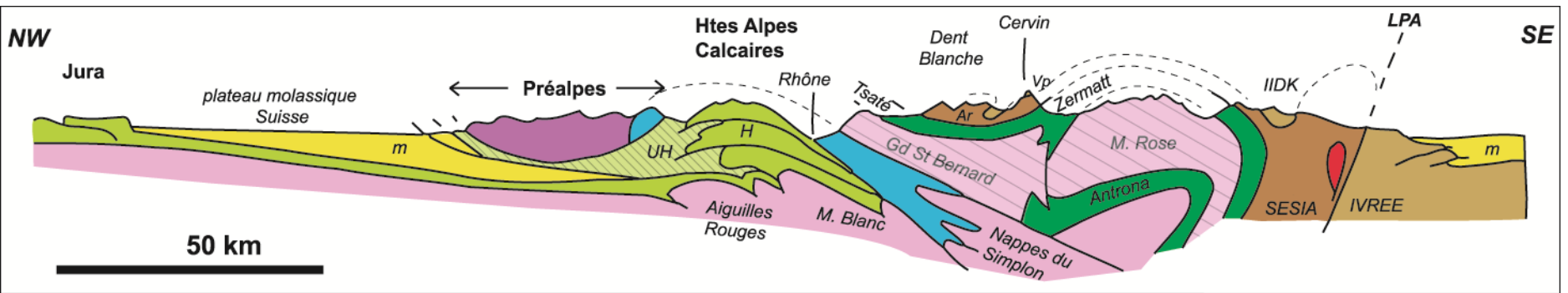
Schistes lustrés
du Queyras

Viso

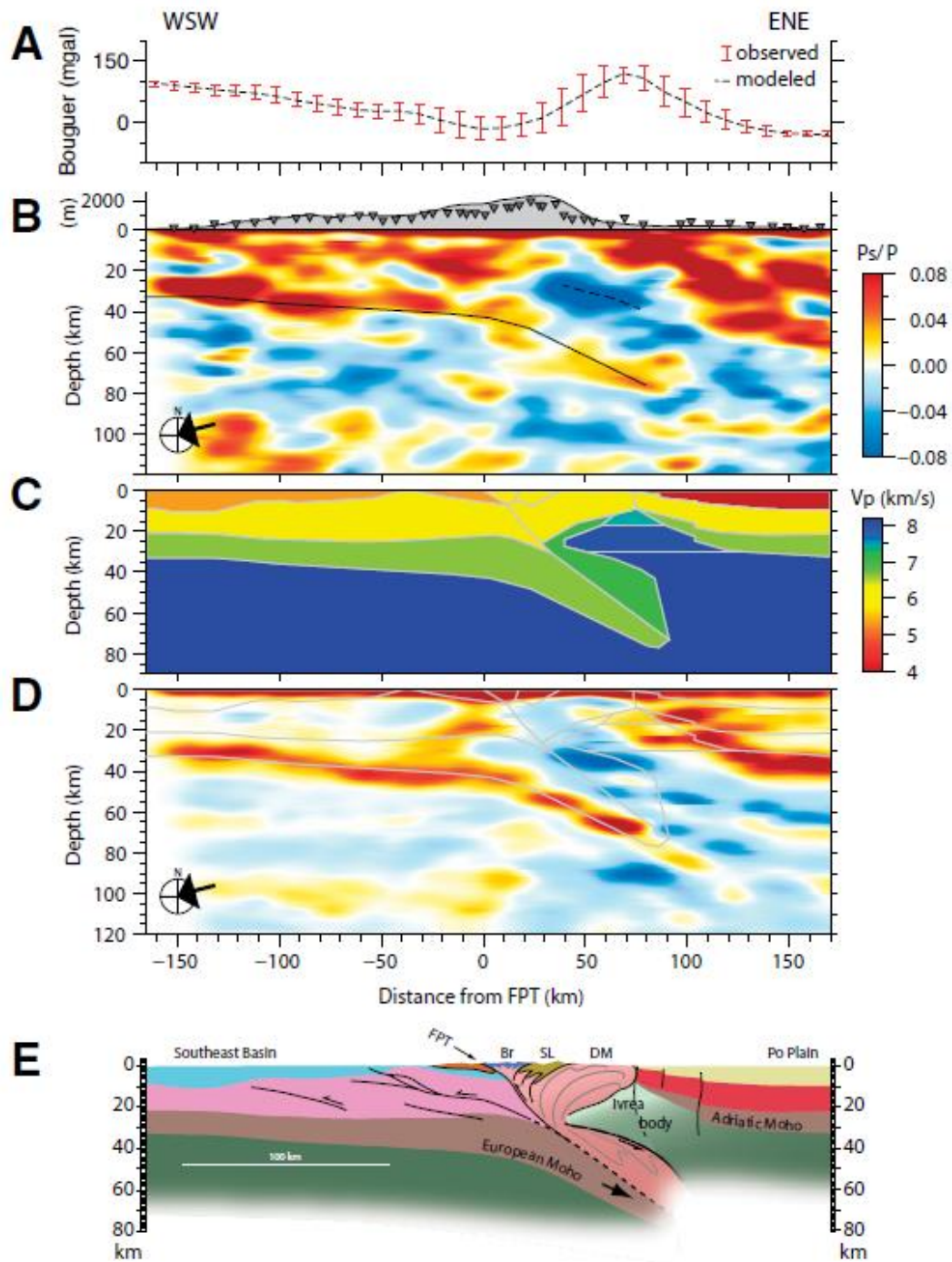
Dora Maira

Zone Sud-alpine

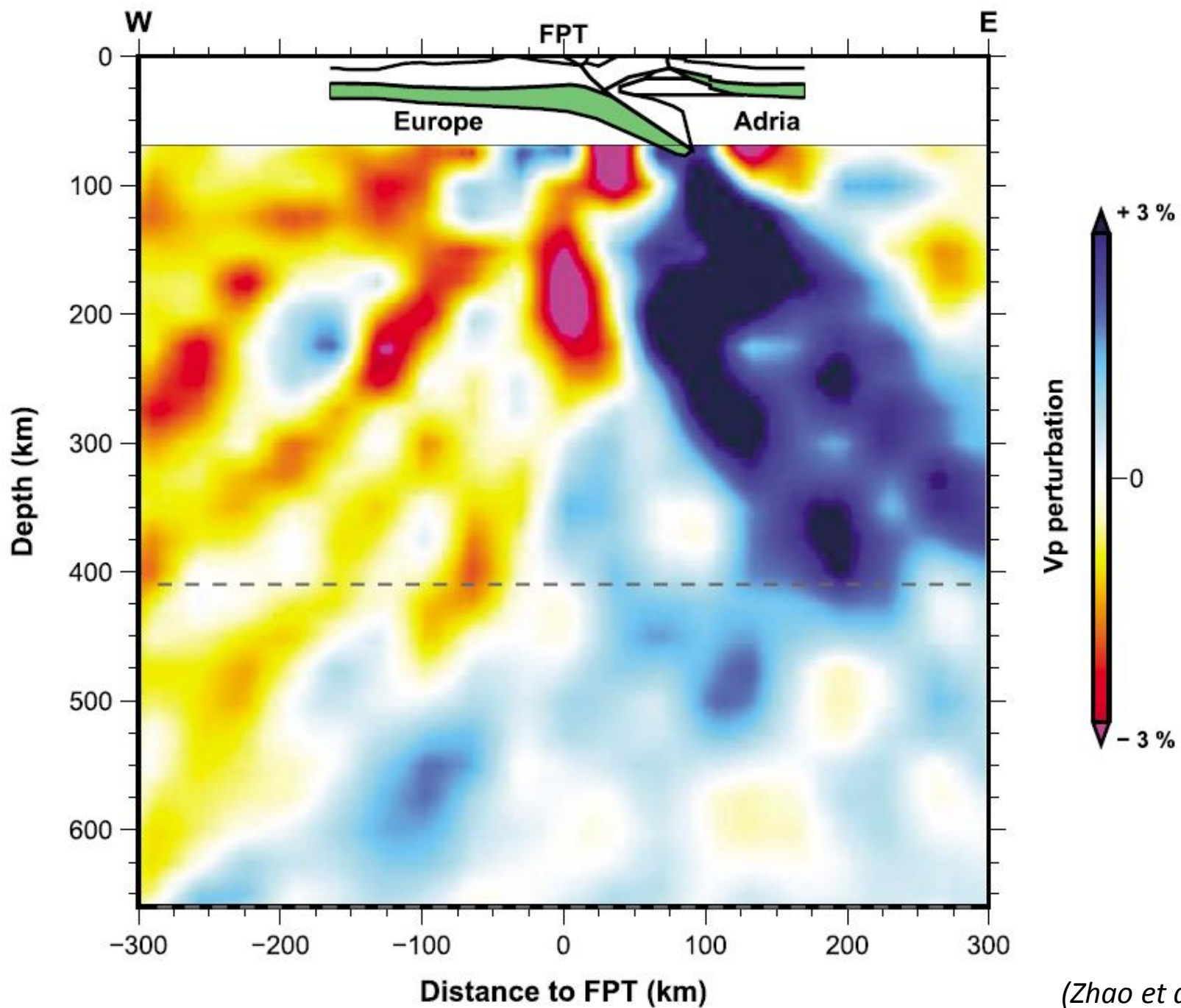




(Agard et Lemoine, 2003)



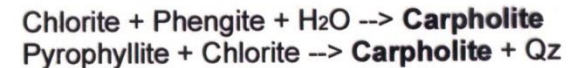
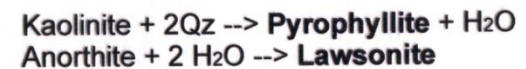
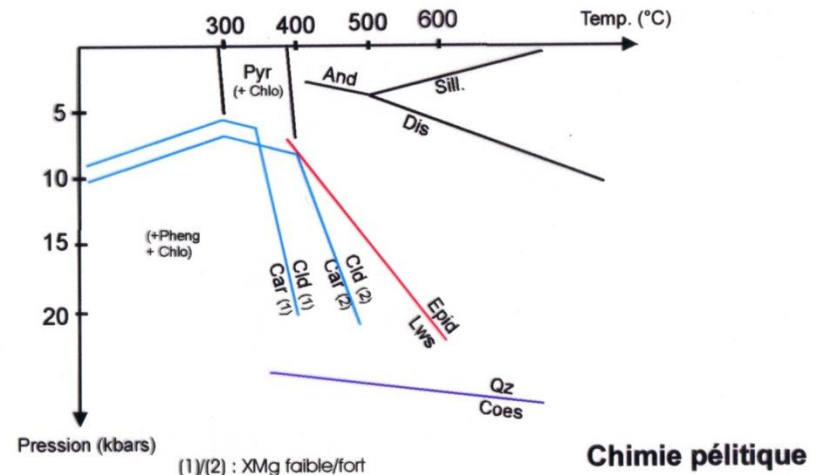
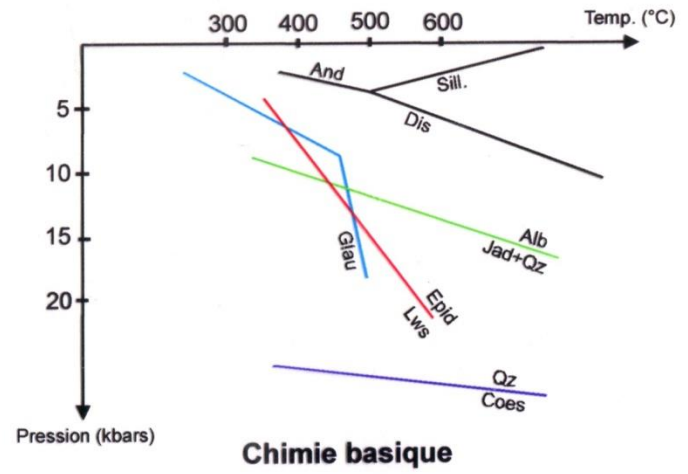
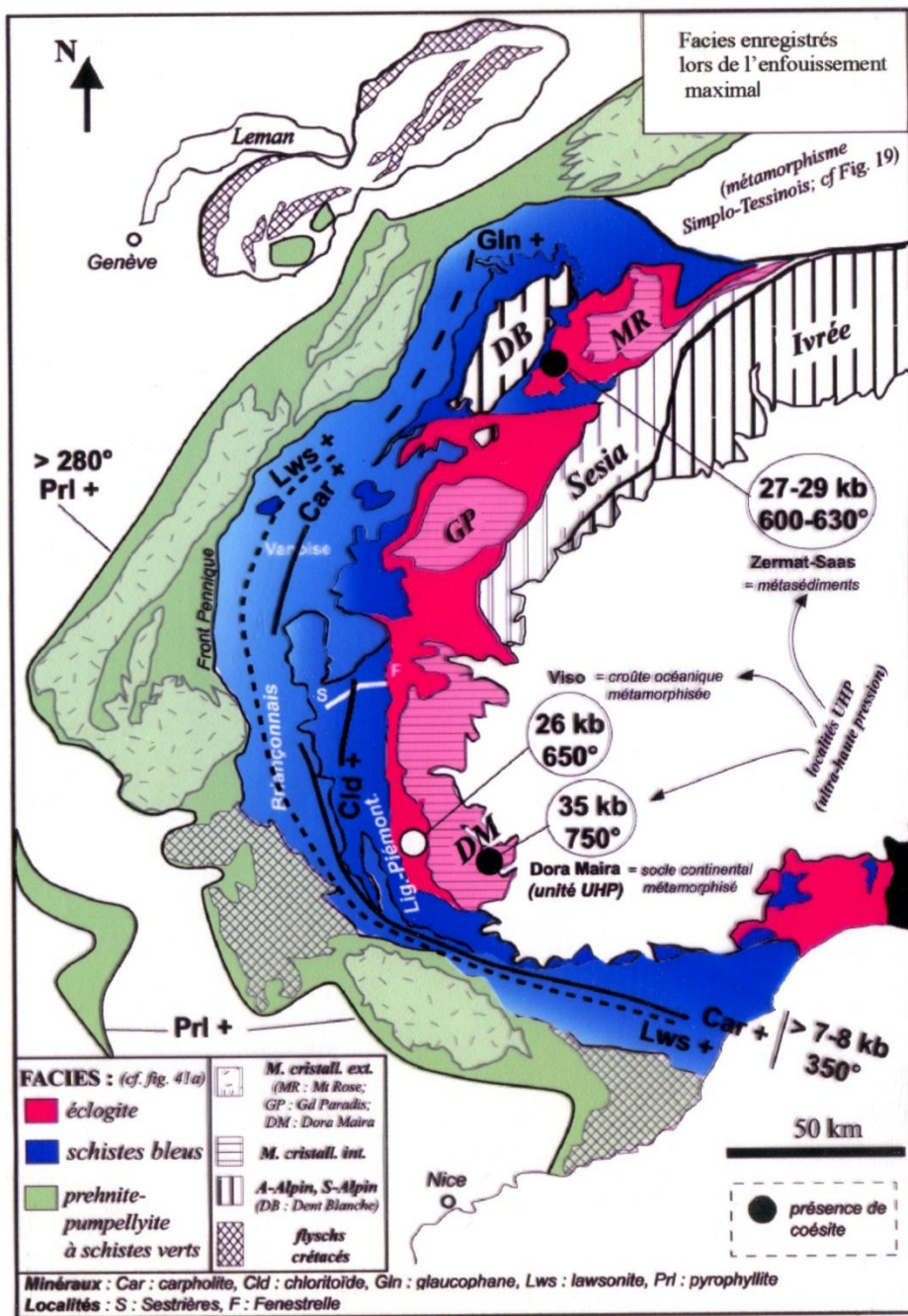
(Zhao et al., 2015)

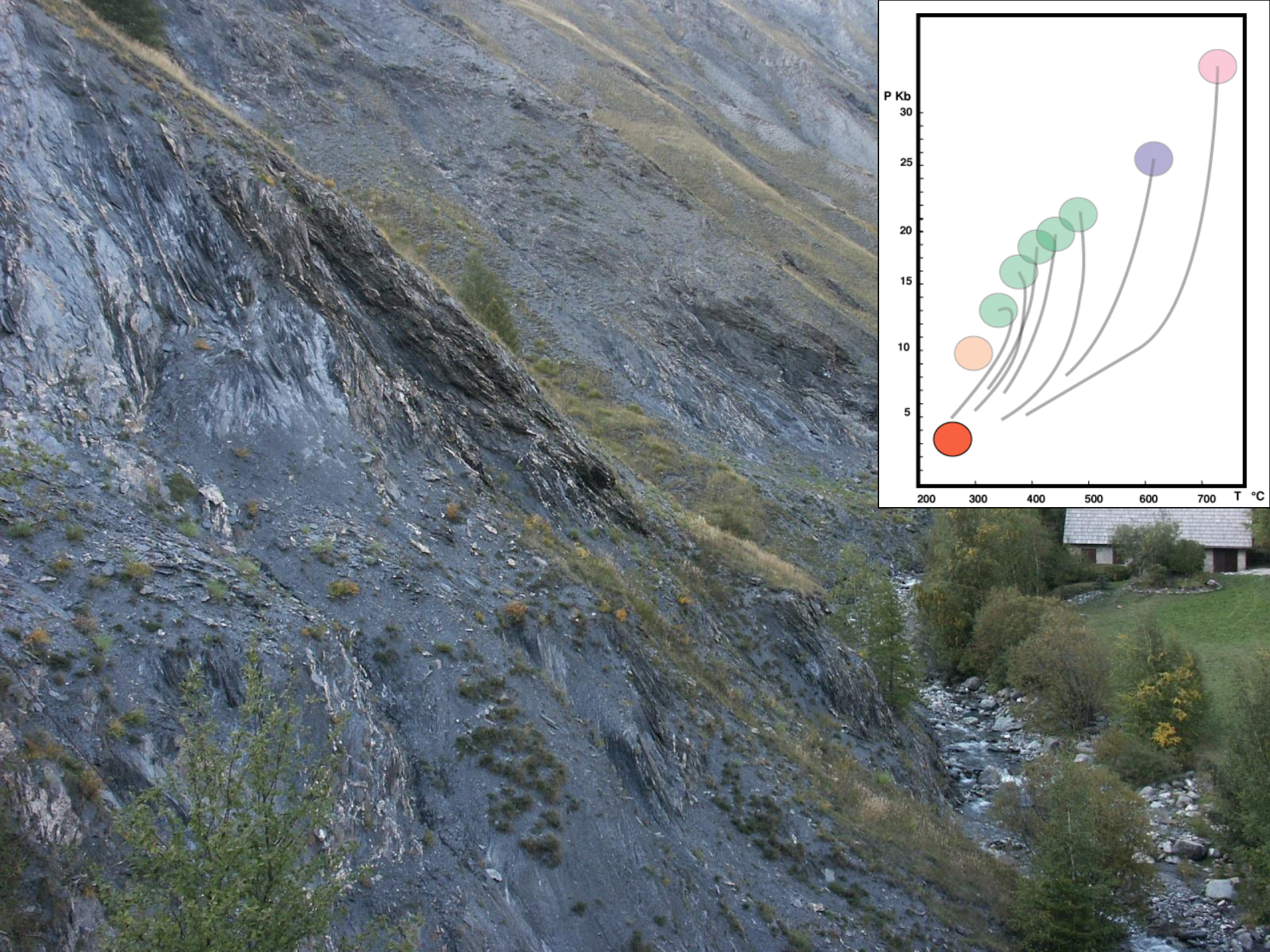


(Zhao et al., 2016)

I. Les Alpes franco-italiennes : une chaîne de subduction-collision

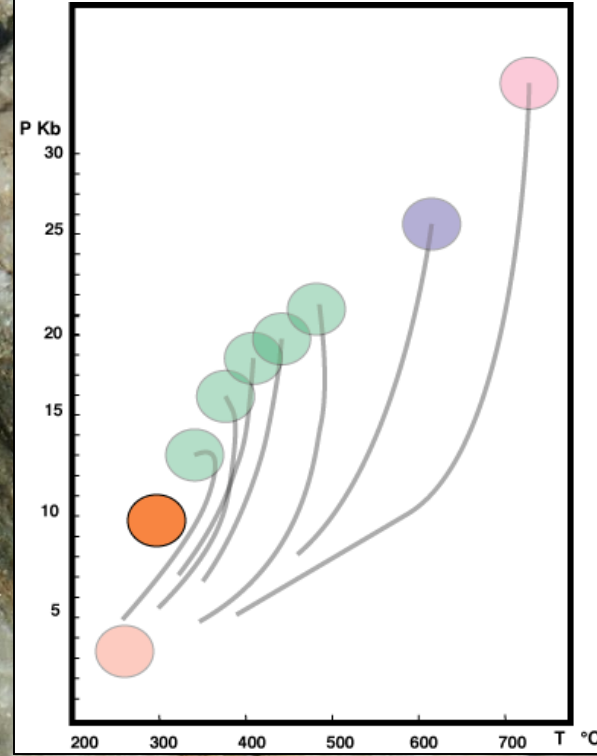
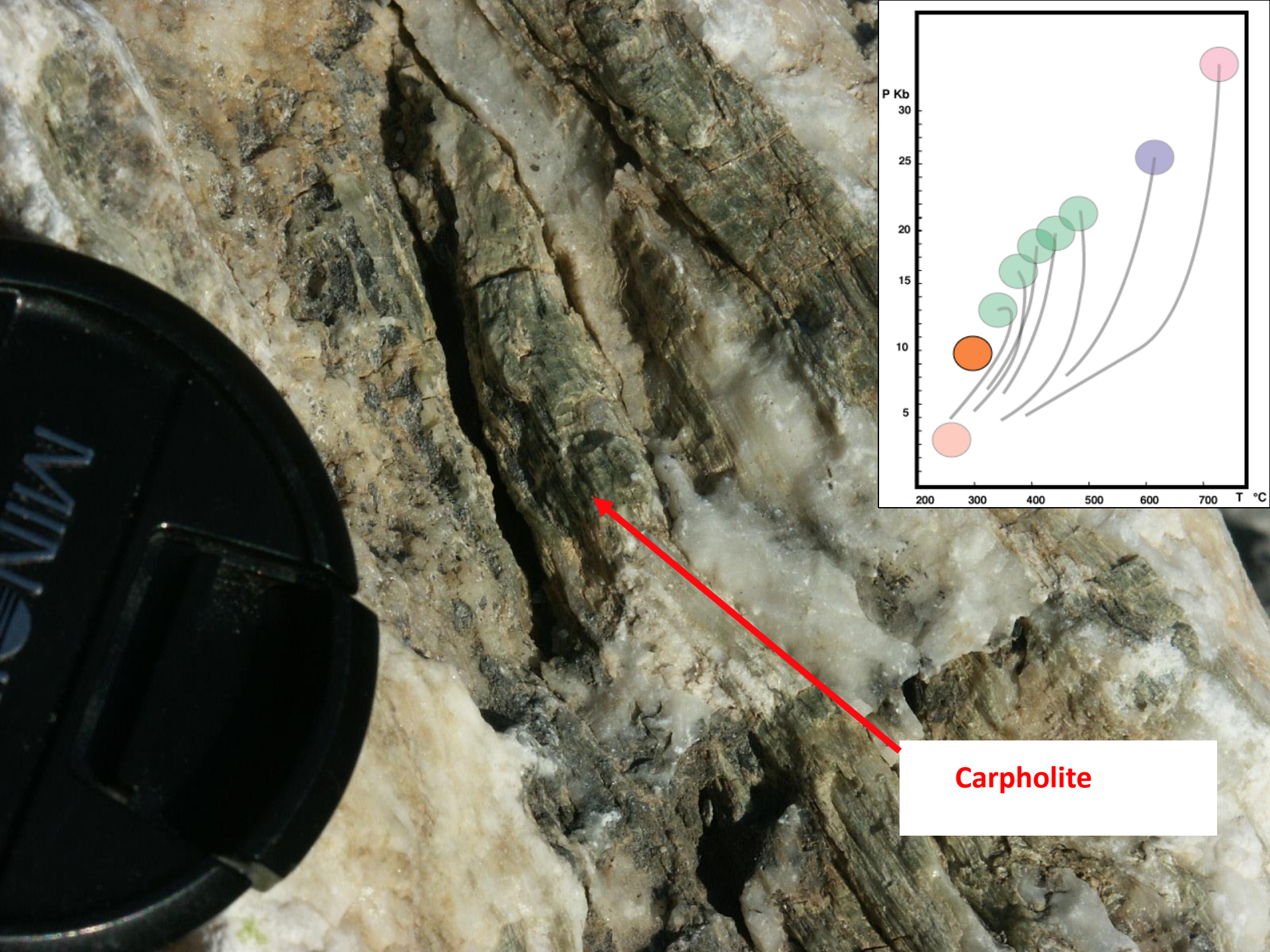
C. Le métamorphisme alpin
et les contraintes thermo-barométriques
sur l'édification du prisme orogénique



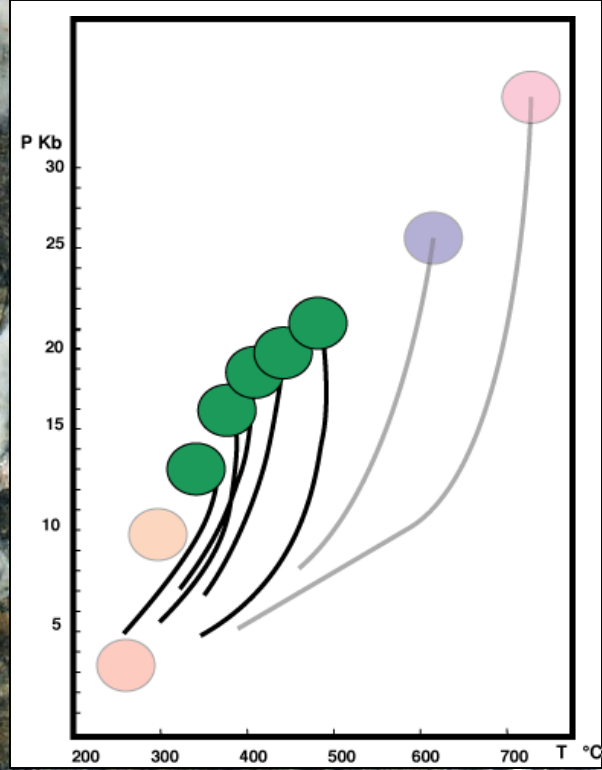
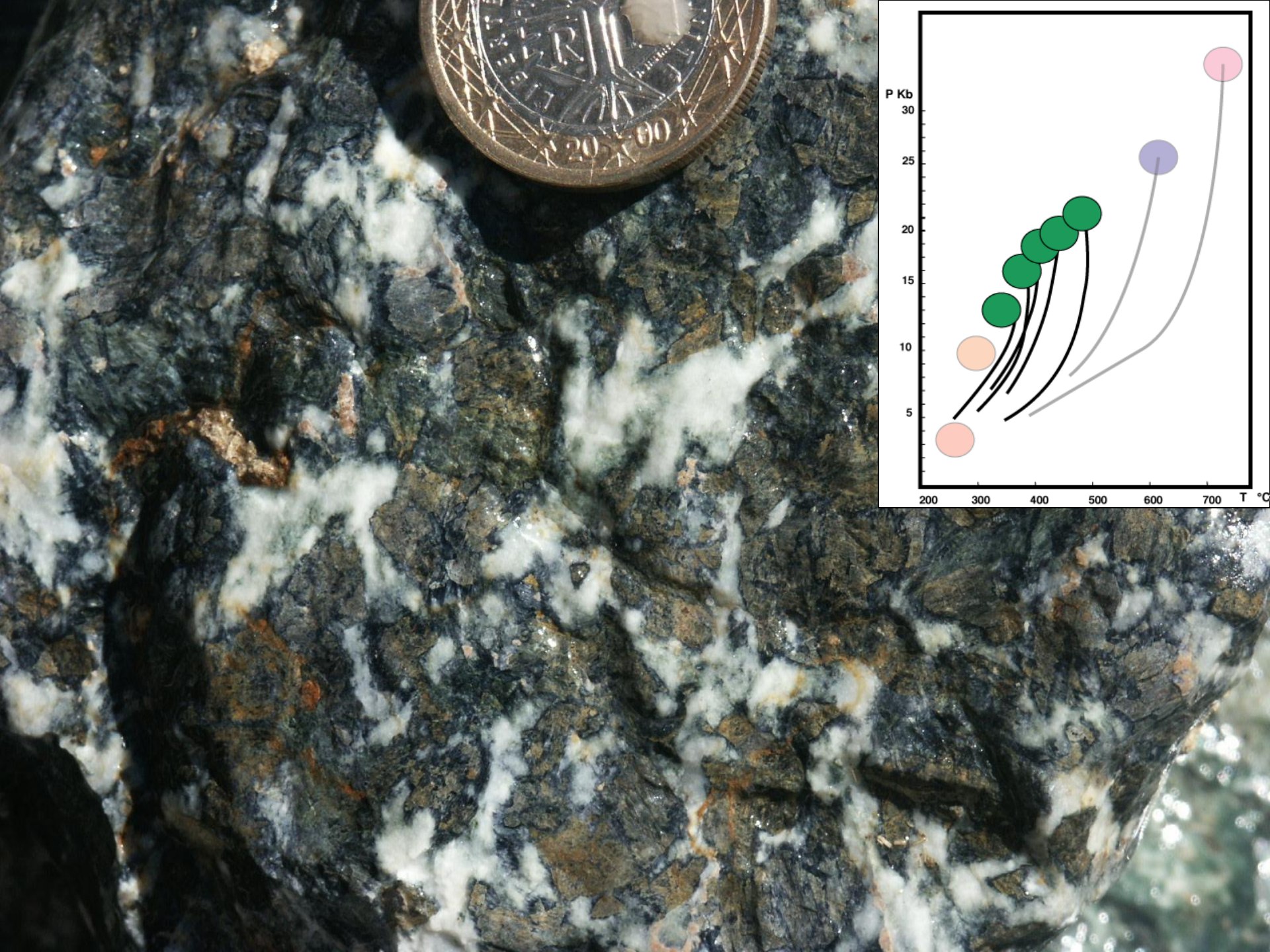




Lawsonite



Carpholite

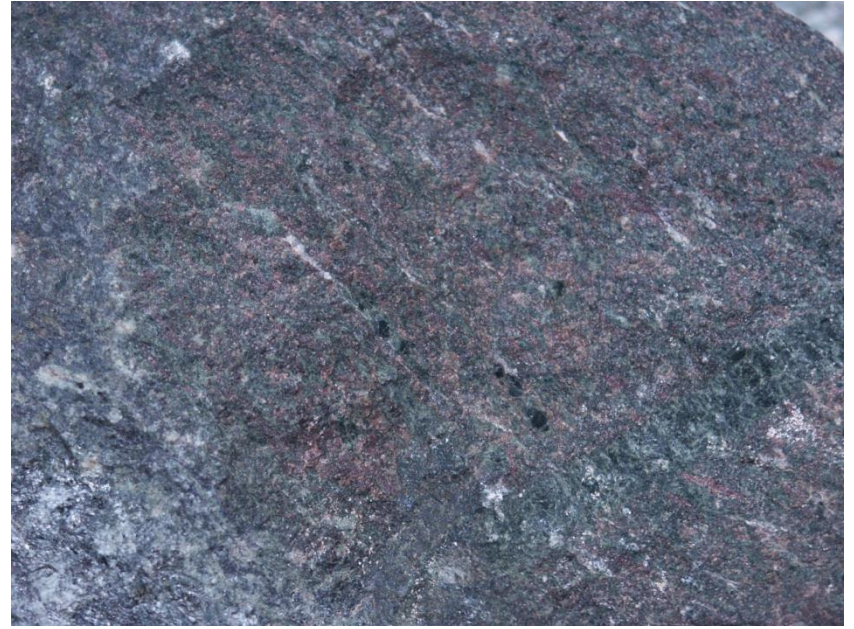


Le Viso

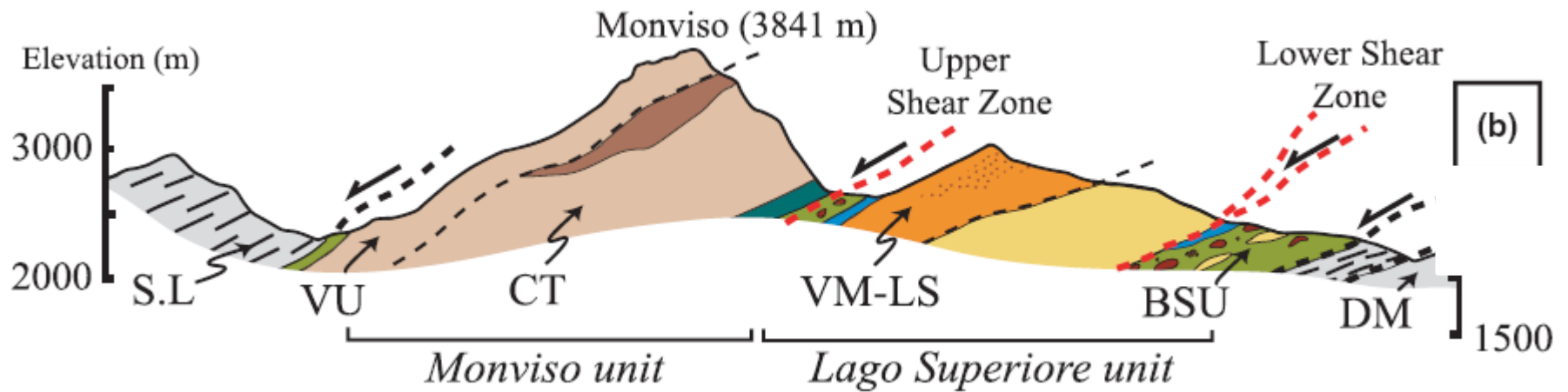




métagabbro Mg éclogitique

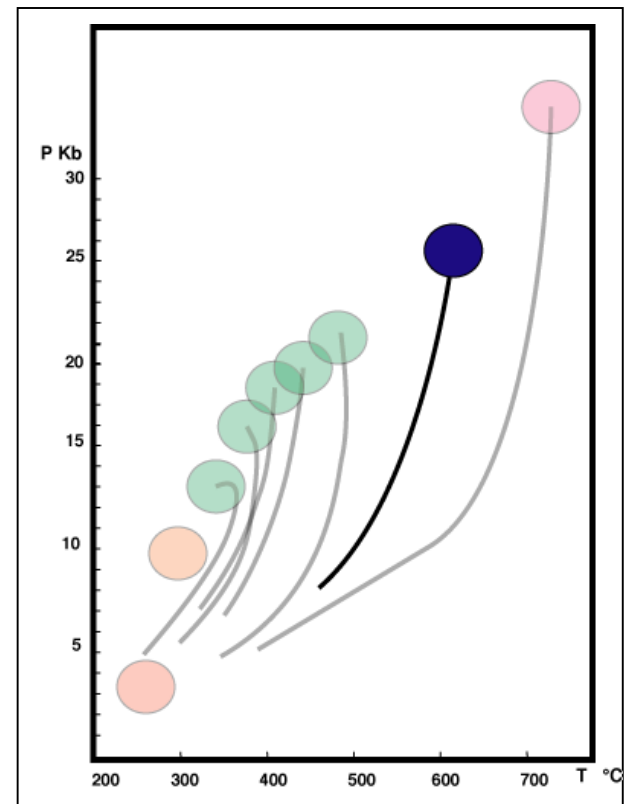
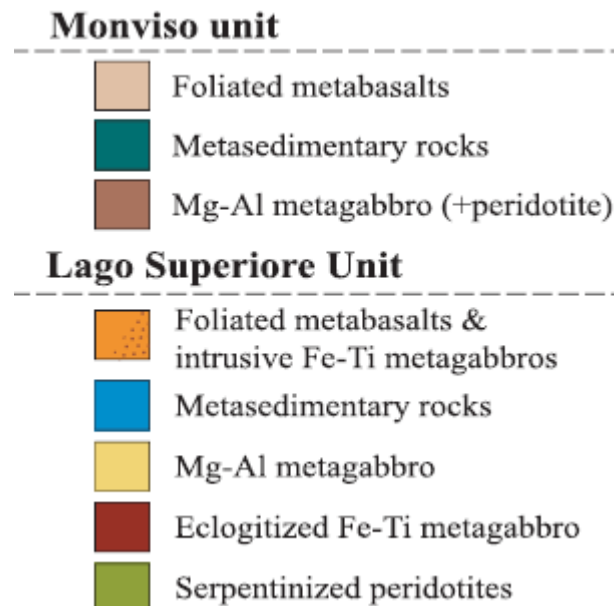


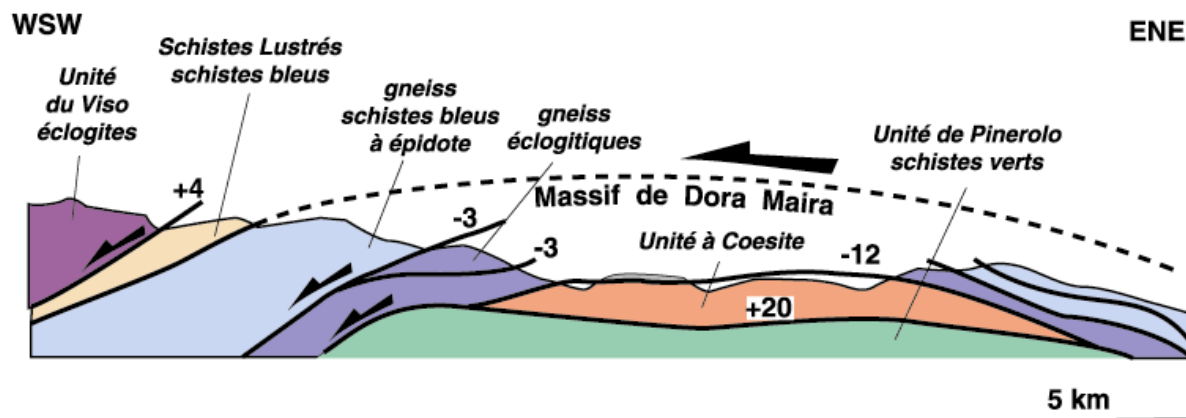
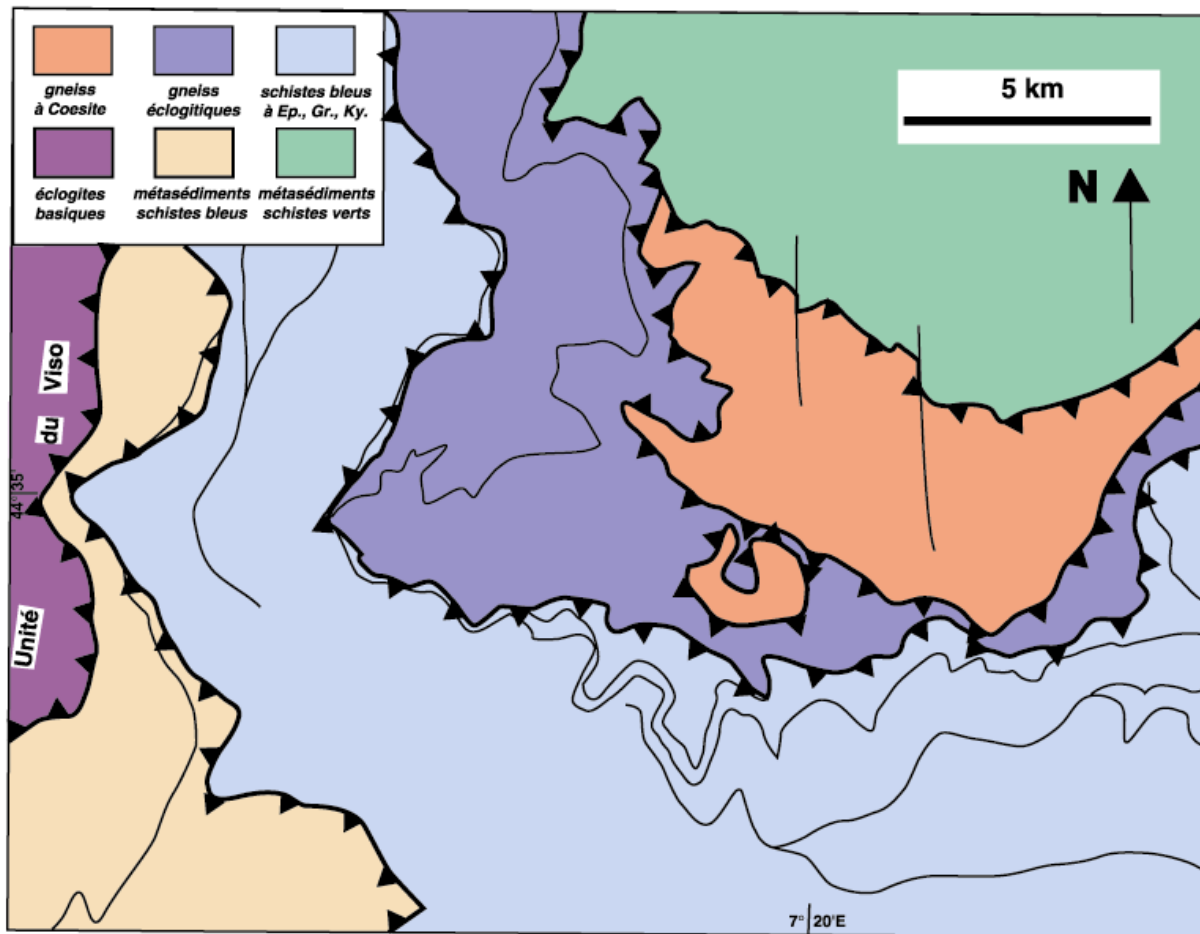
métagabbro Fe-Ti éclogitique



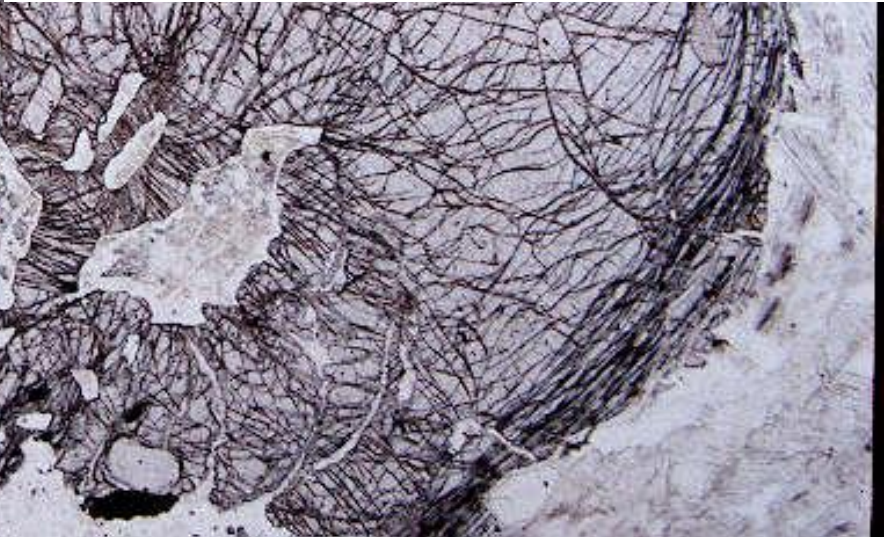
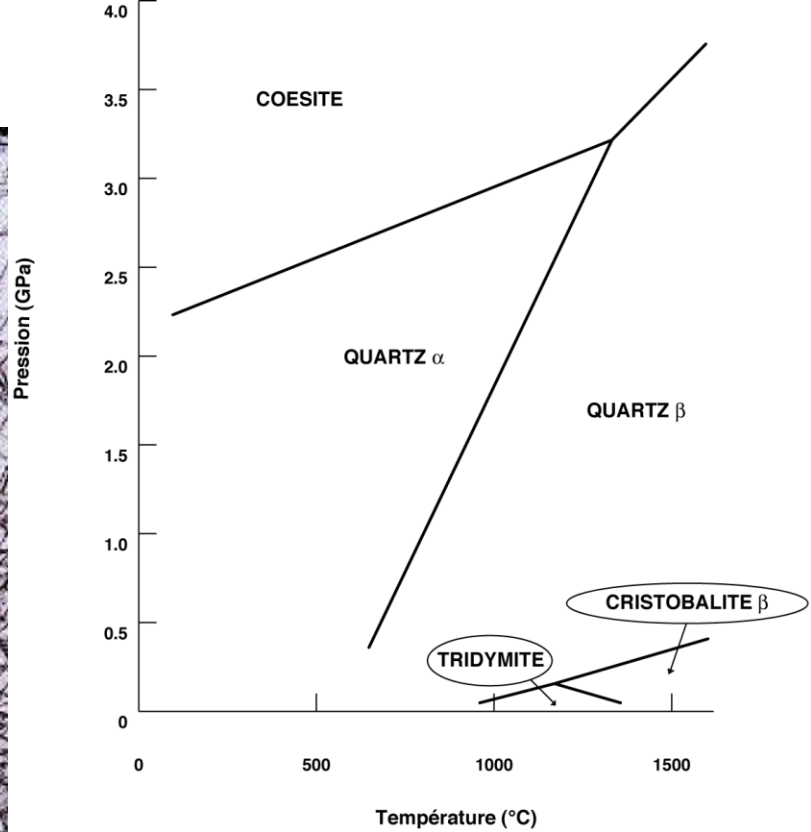
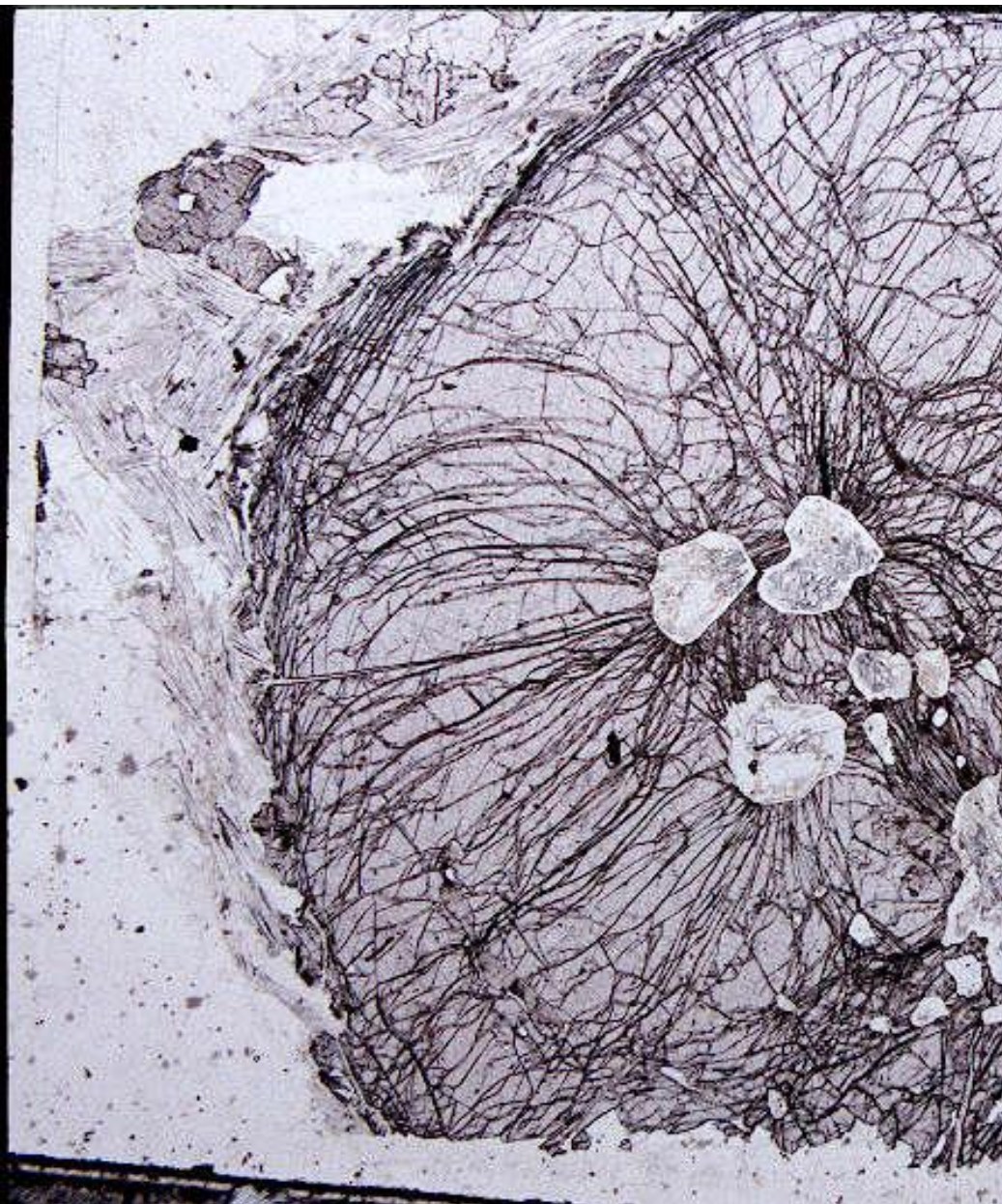
VU (Vallanta Unit), CT (Costa Ticino unit), VM-LS (Viso Mozzo, Lago Superiore units), BSU (Basal Serpentinite Unit) and DM (Dora Maira)

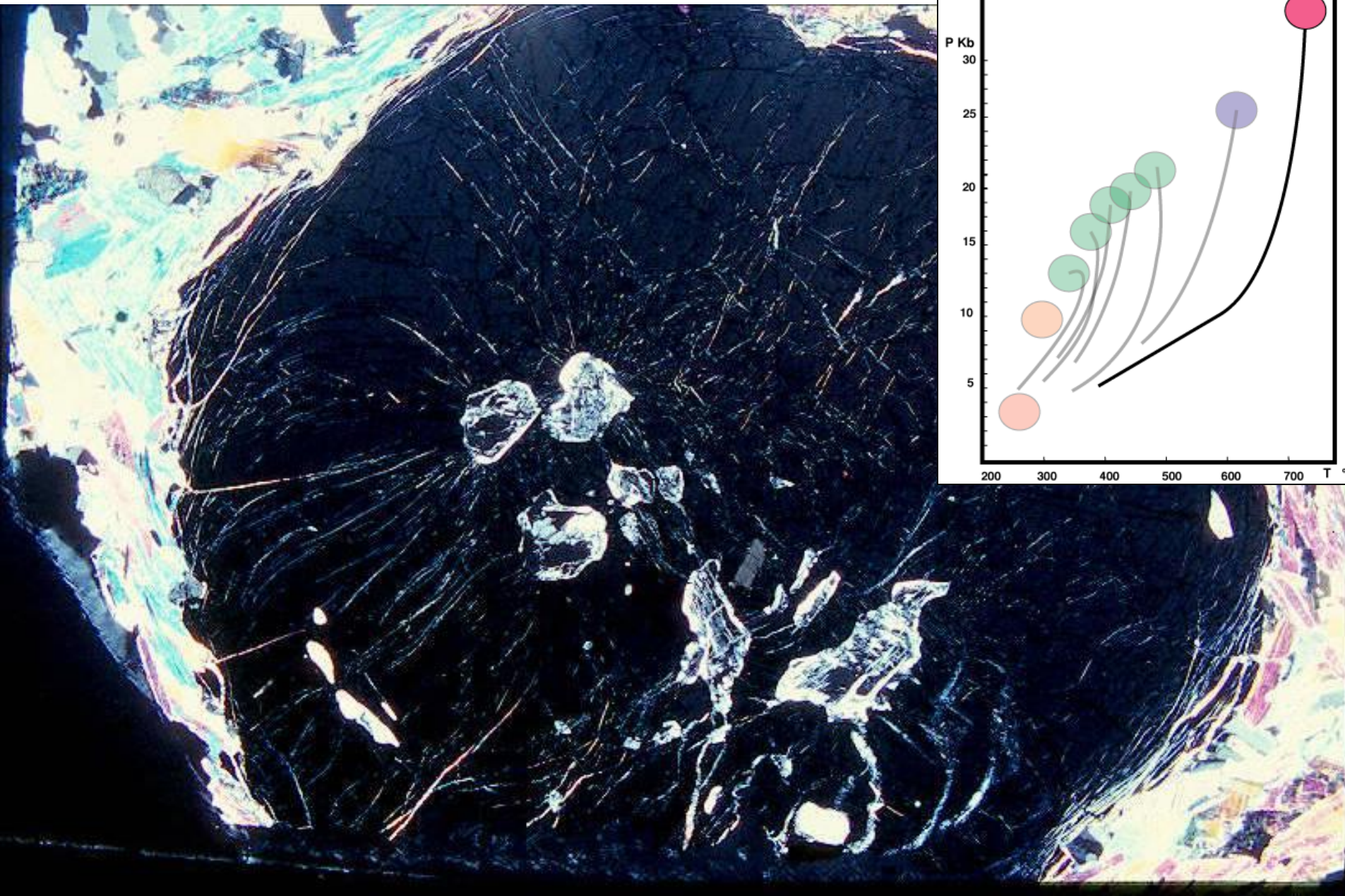
(Angiboust et al., 2011)



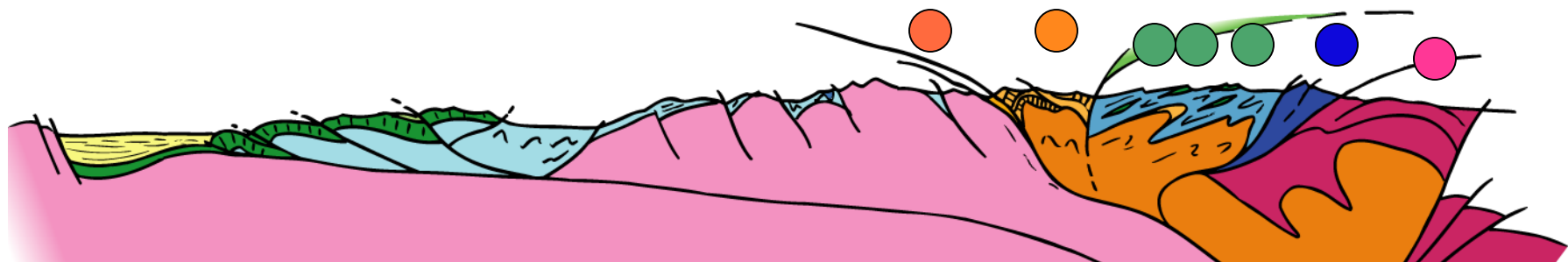
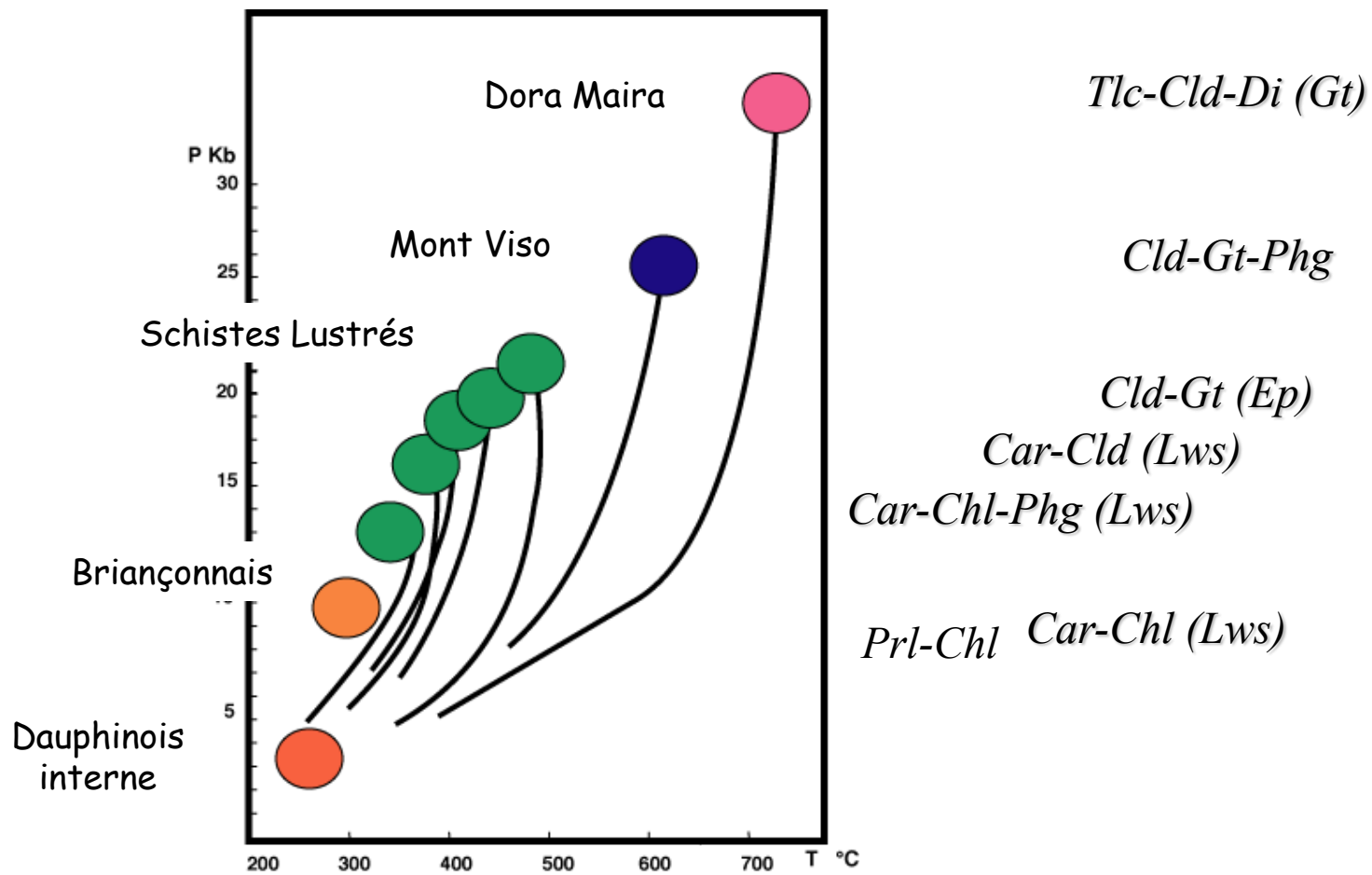




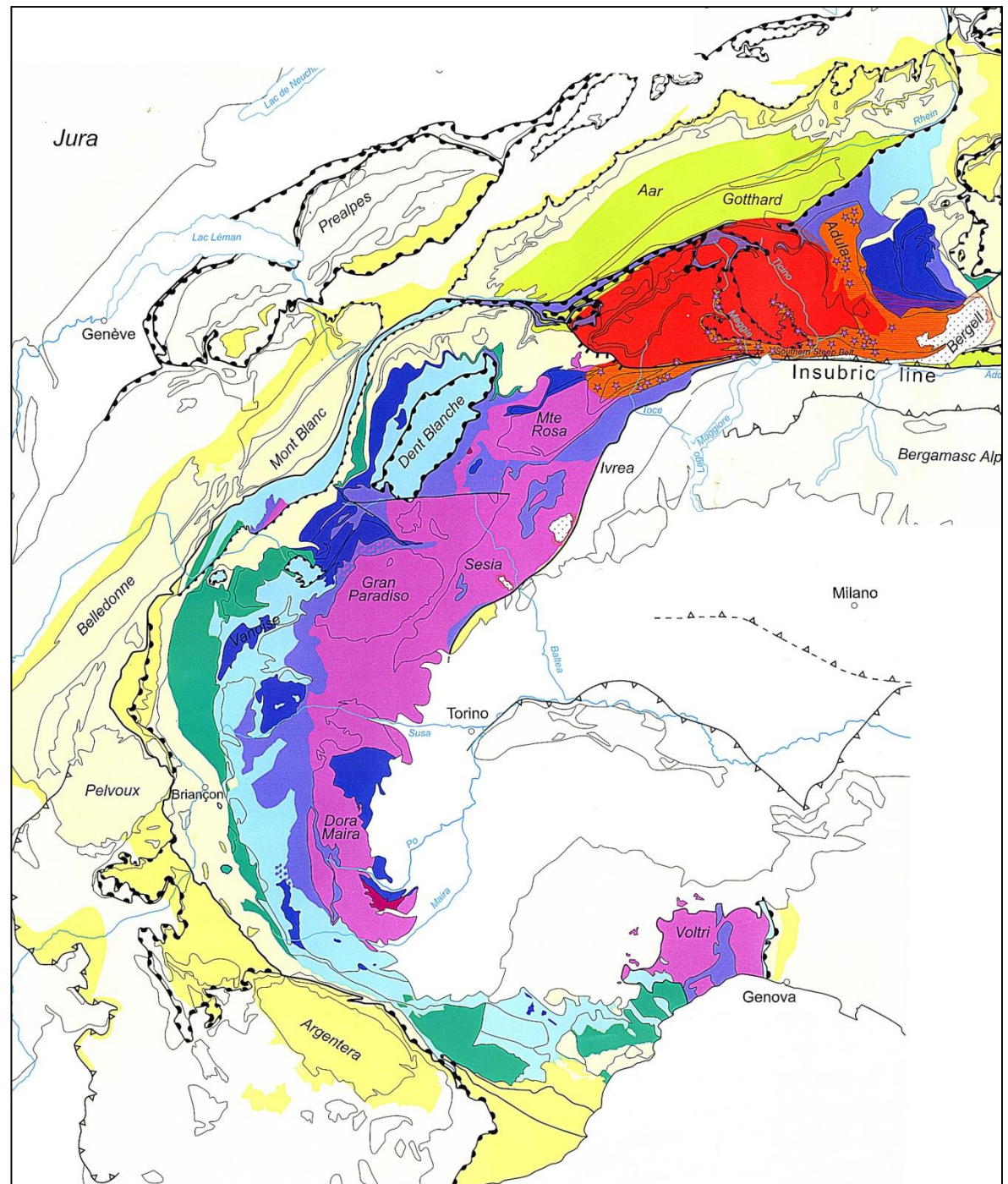


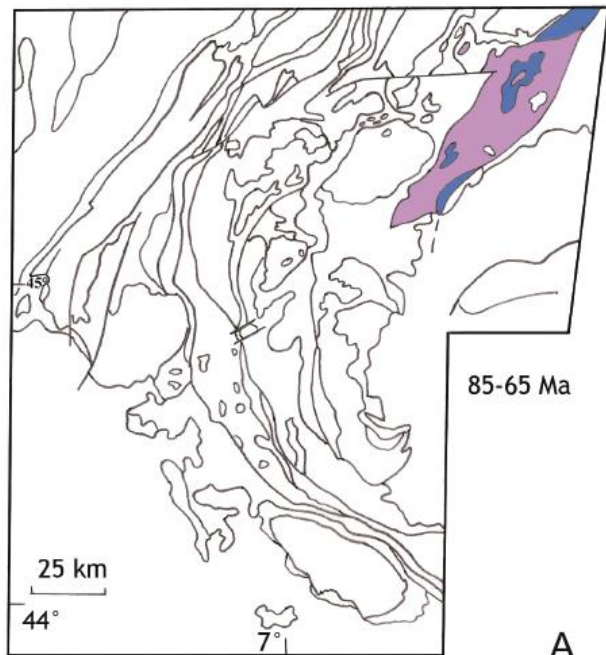


Évolution des conditions P-T sur un transect

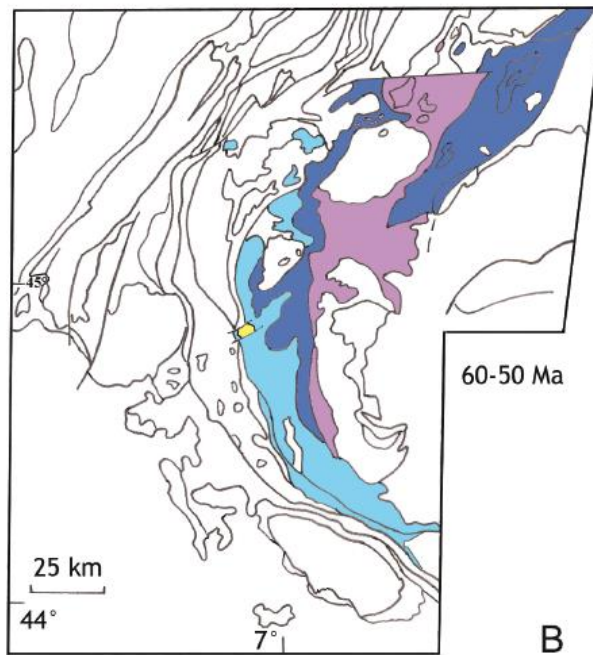


... et une vision plus rigoureuse

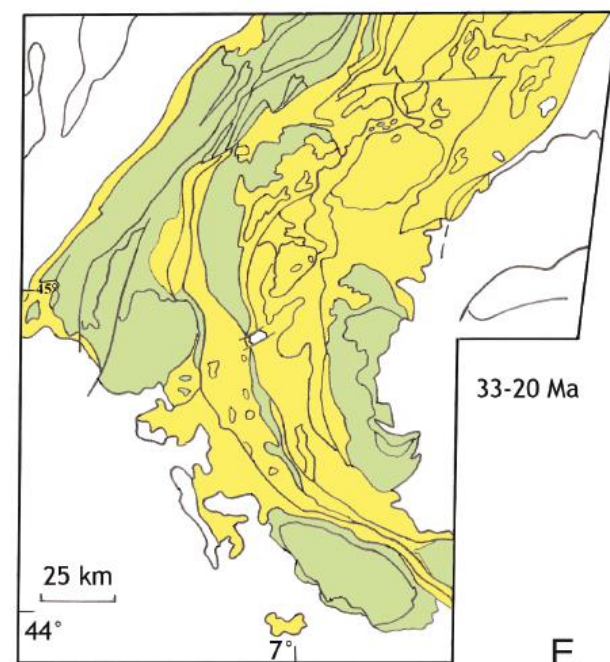




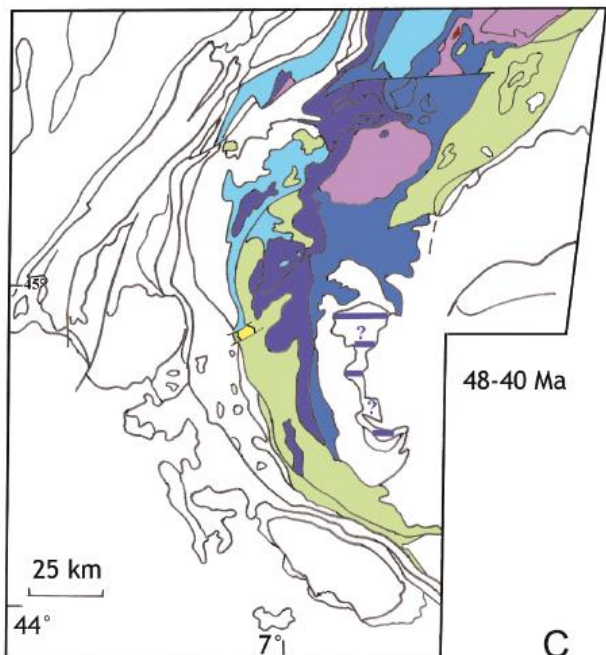
A



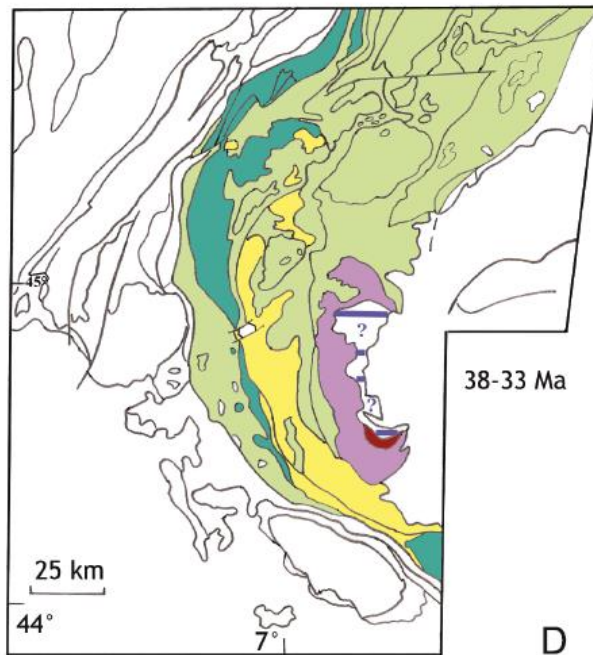
B



E



C

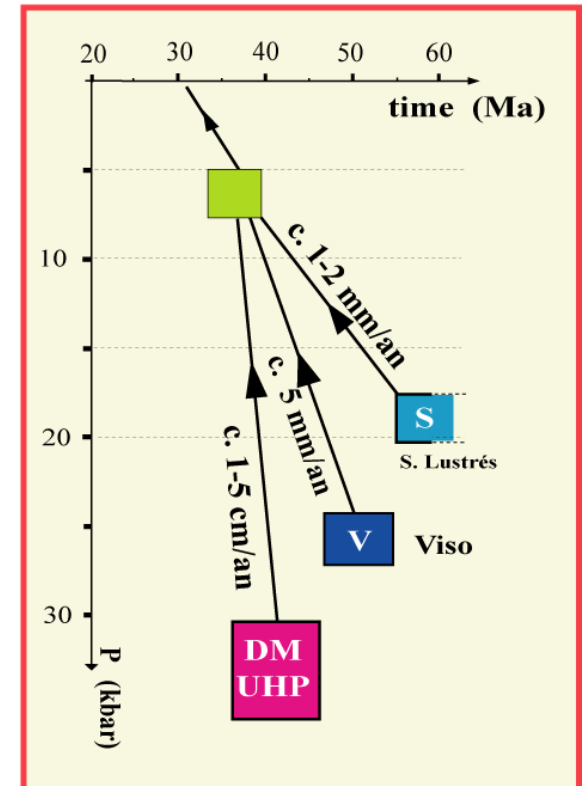
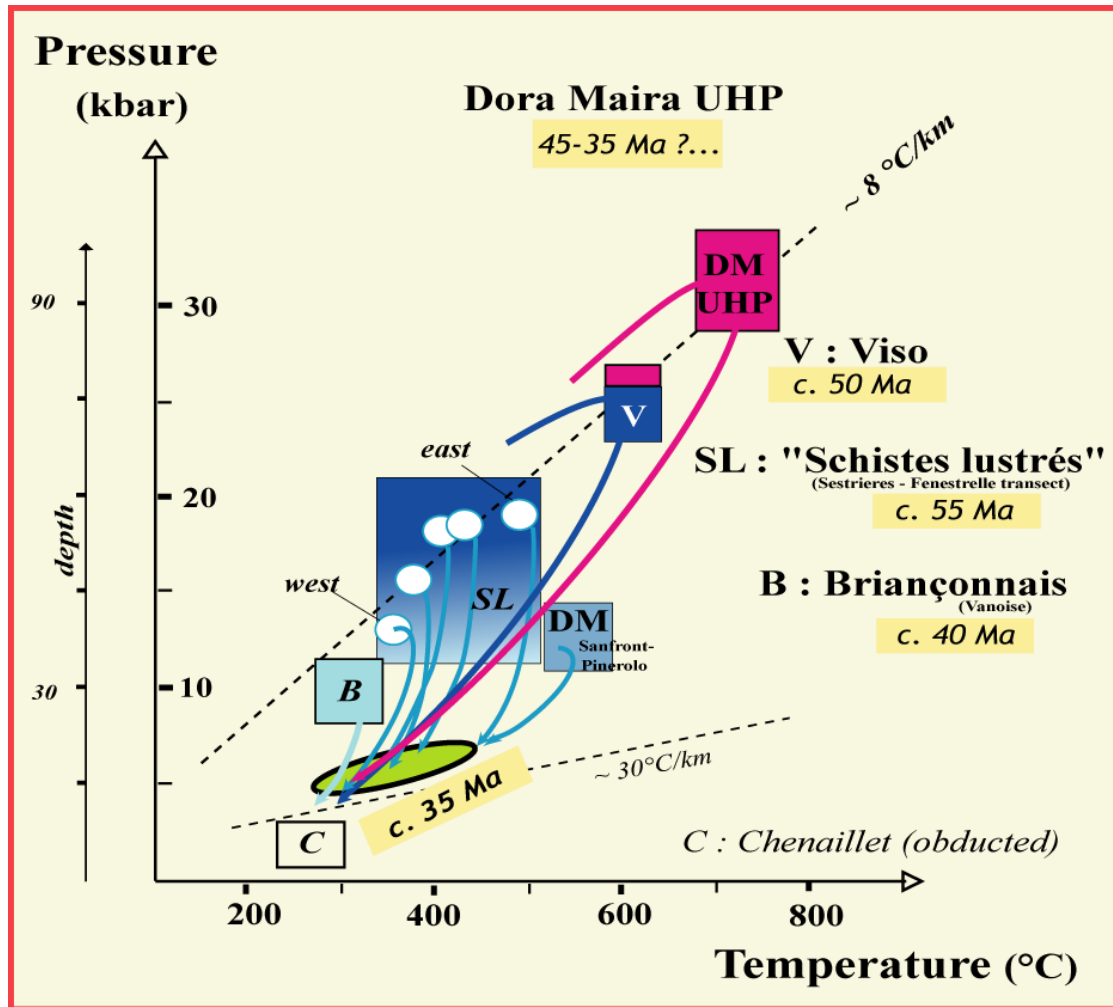


D

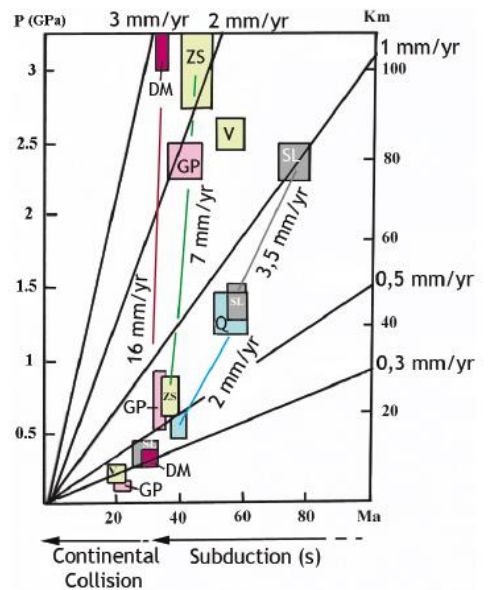
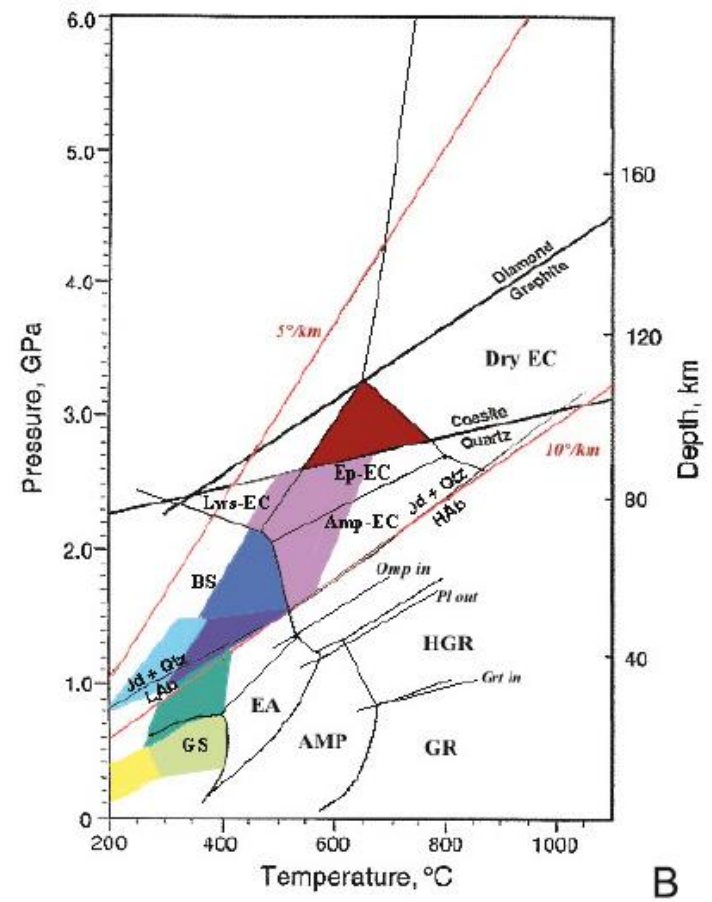
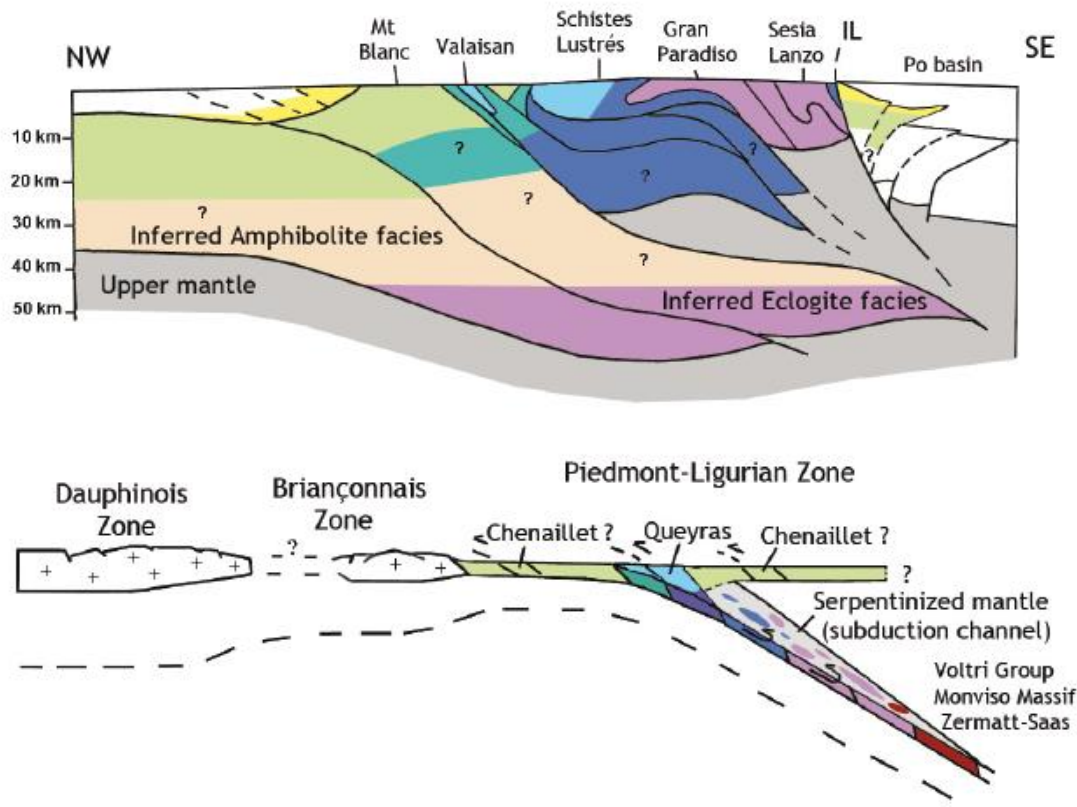
- Quartz-Eclogite
- Blueschist/Eclogite transition
- HT Blueschist
- LT Blueschist
- HP Greenschist
- Greenschist
- Anchizone sub-Greenschist

(Lardeaux, 2014)

Bilan provisoire sur l'exhumation des zones internes

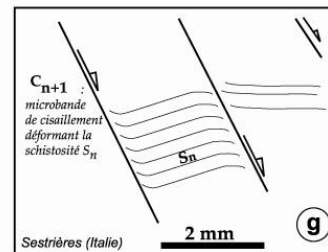
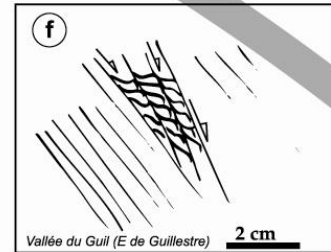
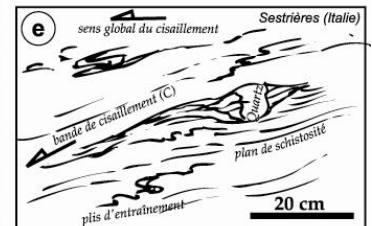
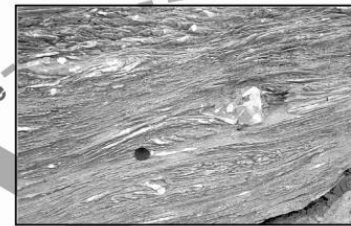
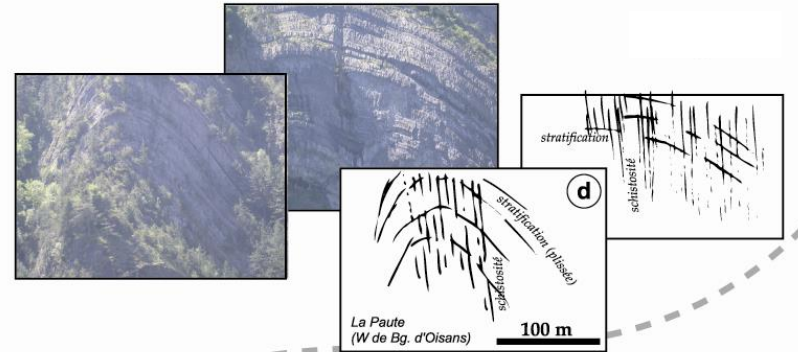
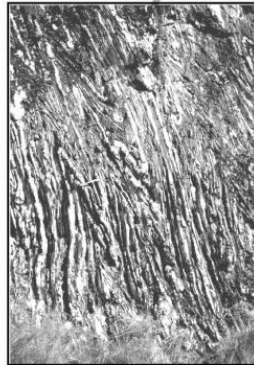
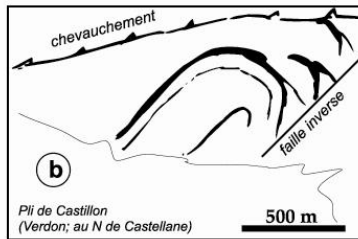
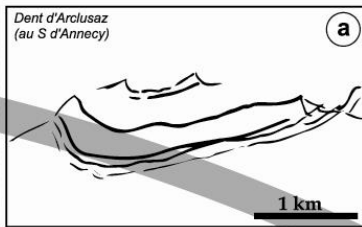
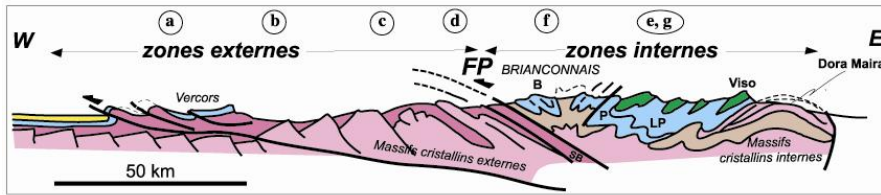


(Agard et Lemoine, 2003)



- Quartz-Eclogite
- Blueschist/Eclogite transition
- HT Blueschist
- LT Blueschist
- HP Greenschist
- Greenschist
- Anchizone sub-Greenschist

(Lardeaux, 2014)



(Agard et Lemoine, 2003)

I. Les Alpes franco-italiennes : une chaîne de subduction-collision

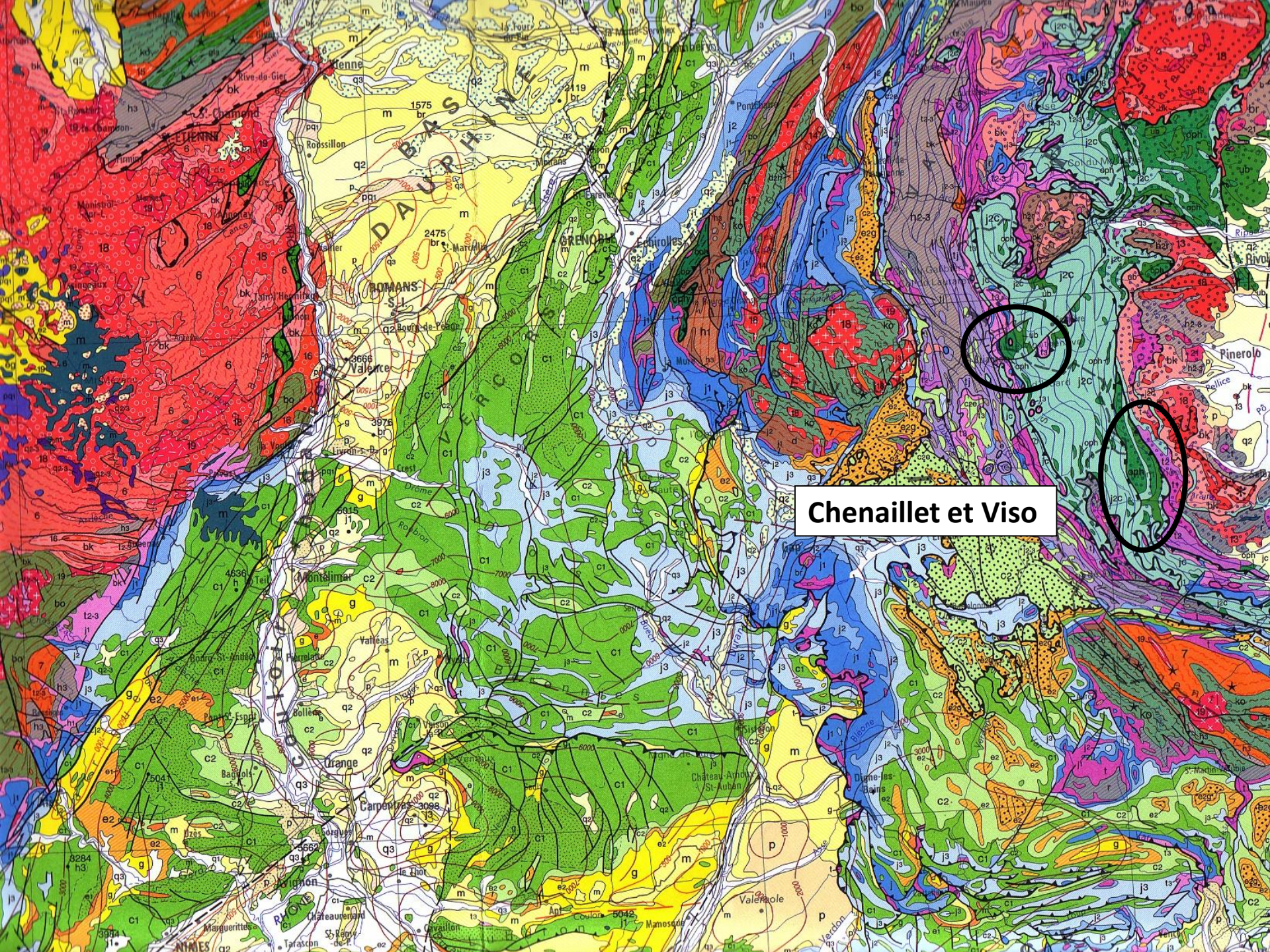
D. Une absence quasi-totale
de magmatisme orogénique

II. Les Alpes franco-italiennes :
une structure impliquant la fermeture
d'un (ou plusieurs?) océan(s) lent(s)
et l'inversion d'une paléomarge passive

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une structure impliquant la fermeture
d'un (ou plusieurs?) océan(s) lent(s)
et l'inversion d'une paléomarge passive

A. La superposition des nappes de charriage
implique l'existence d'un ou plusieurs
domaines océaniques

Les ophiolites alpines



Chenaillet et Viso

DAUPHINÉ

GRENOBLE

ROMANS

Valence

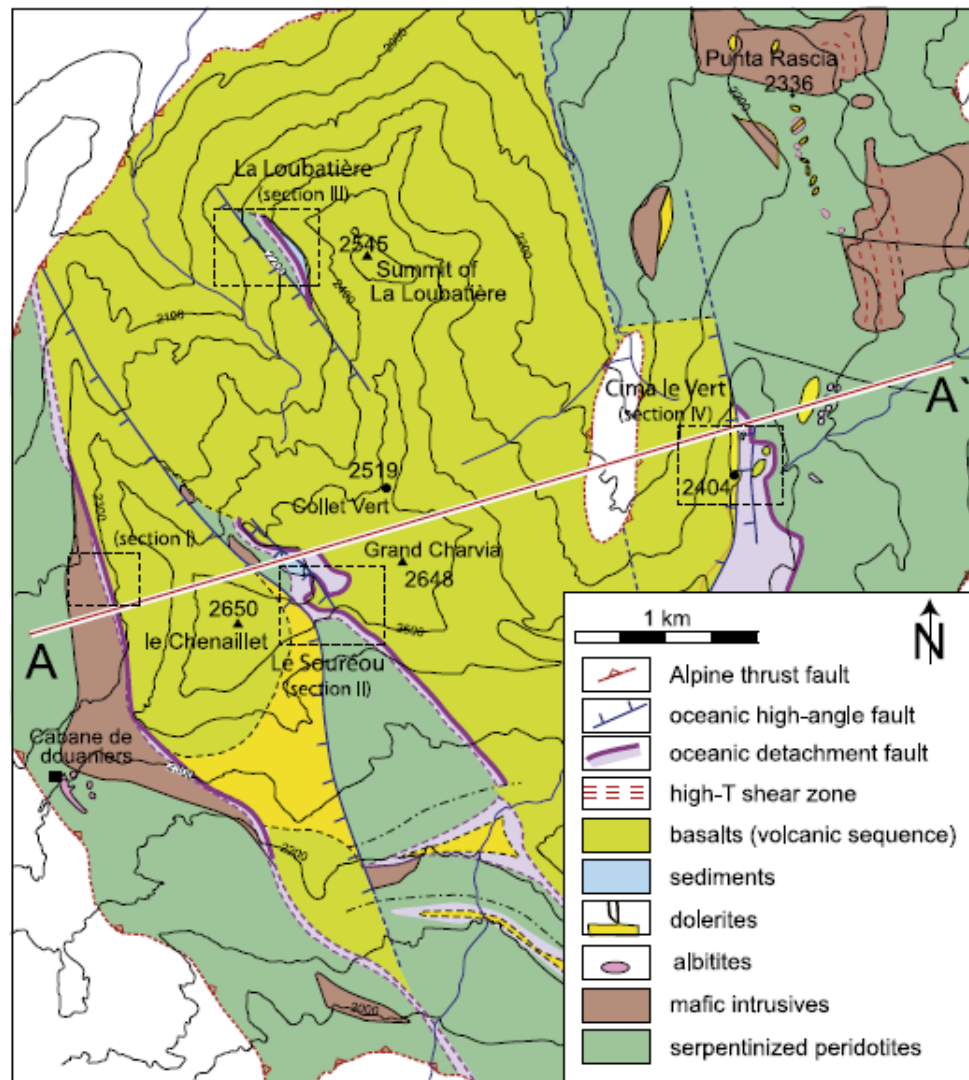
Orange

Carpenas

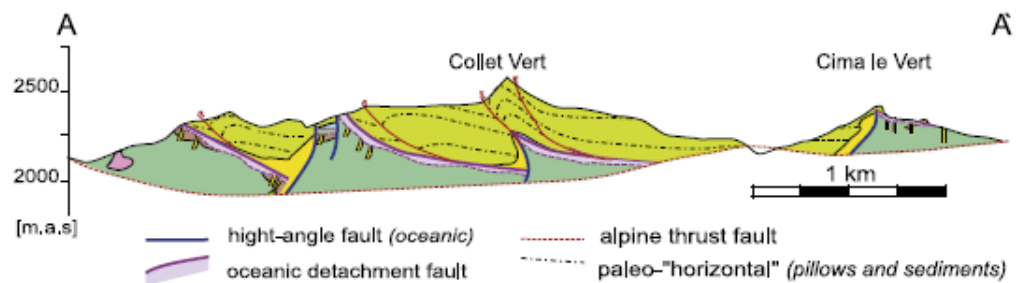
NÎMES

Pineroles





(Manatschal et al, 2011)

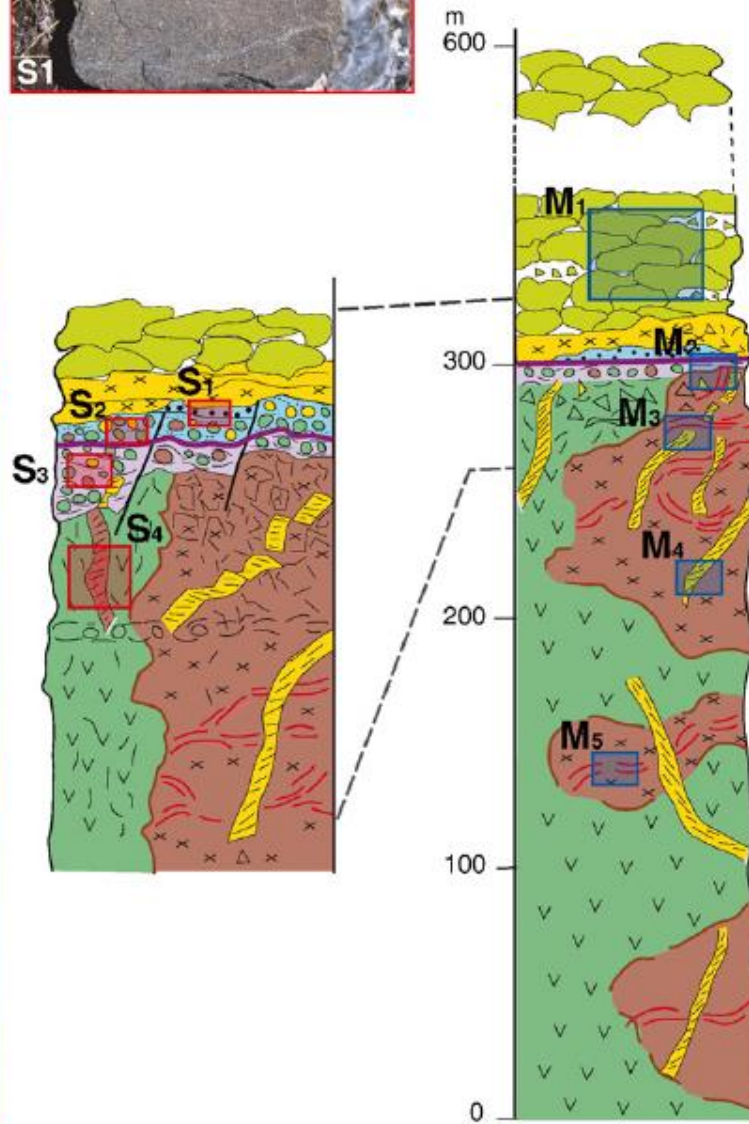




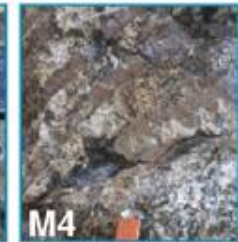


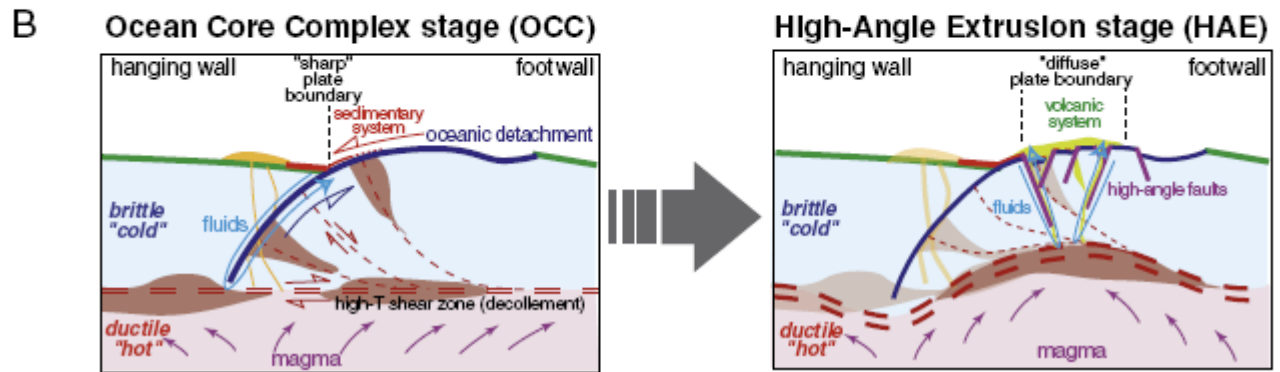
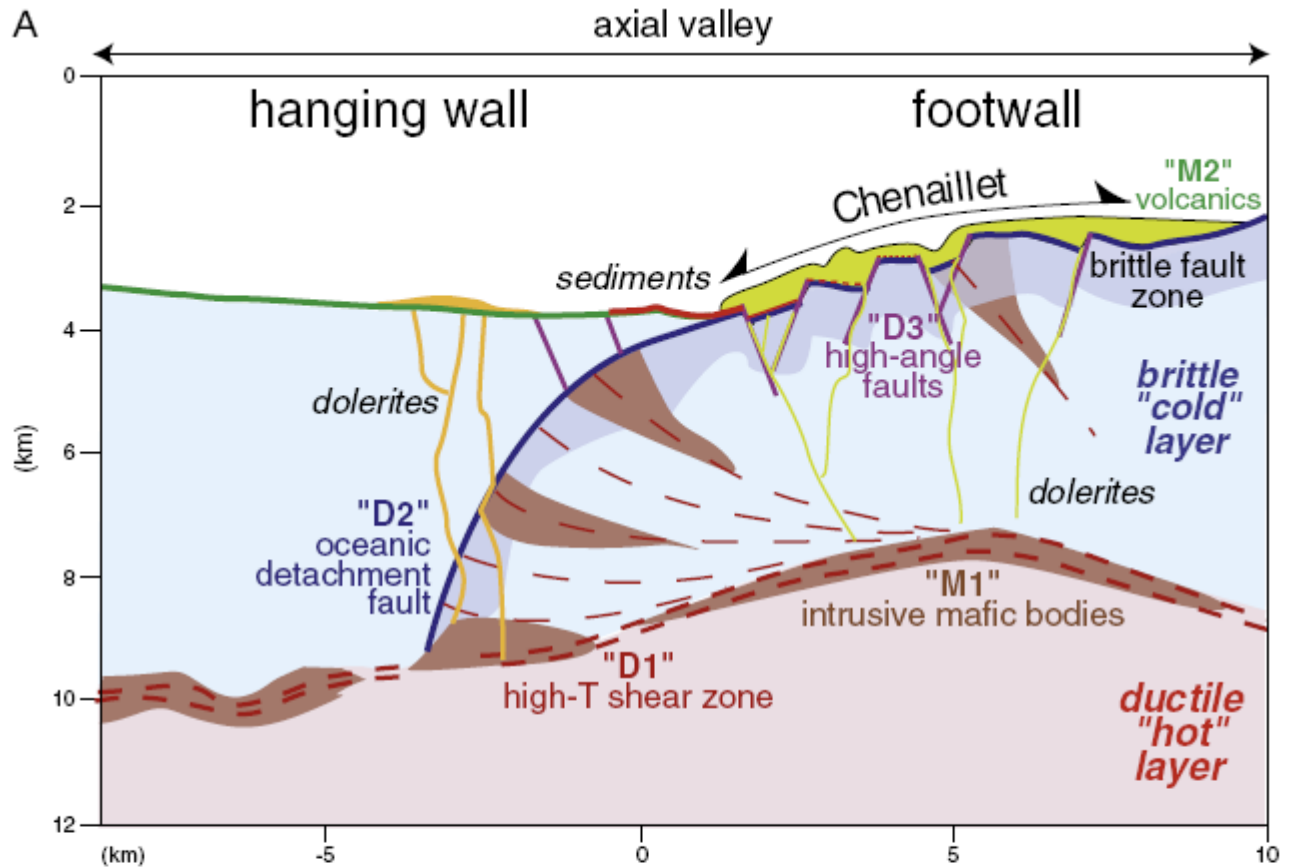


(Manatschal et al, 2011)



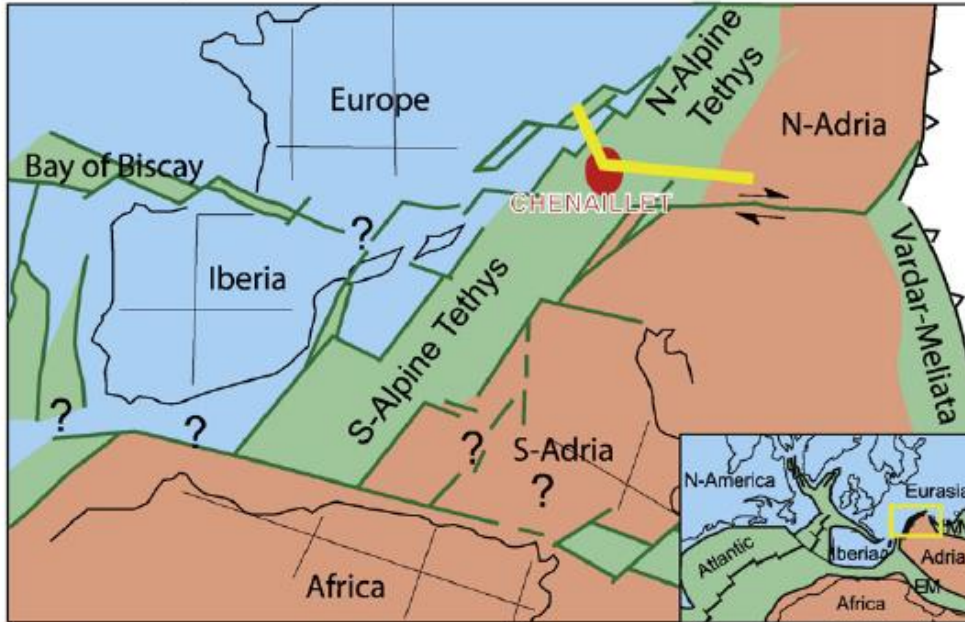
- basalts (*volcanic sequence*)
- dolerites (*massive volcanics*)
- sediments
- mafic intrusives
- serpentinized peridotite
- dolerites
- oceanic detachment fault
- high-T shear zone





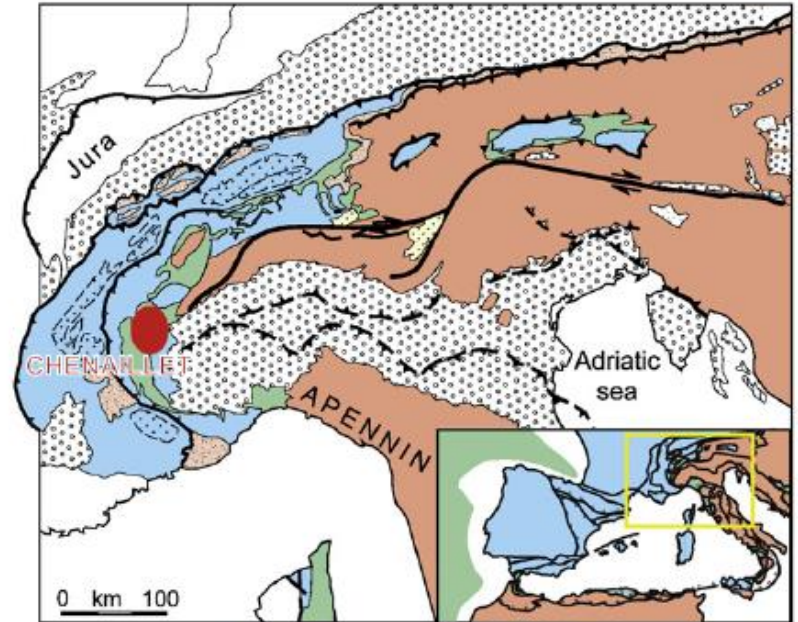
(Manatschal et al,
2011)

ALBIAN (100 Ma)

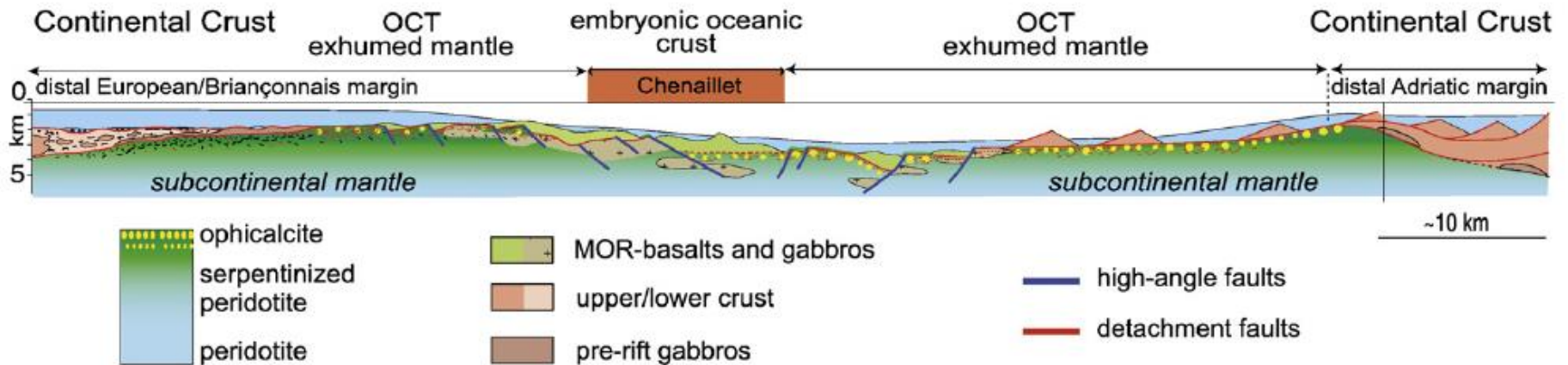


Adriatic/African units European/Iberia units Oceanic units

PRESENT DAY

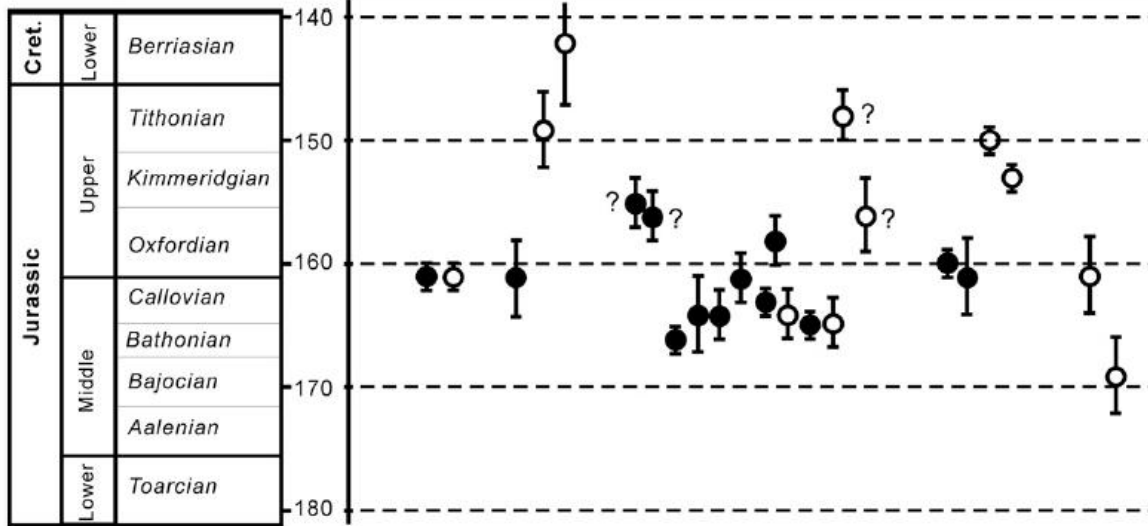
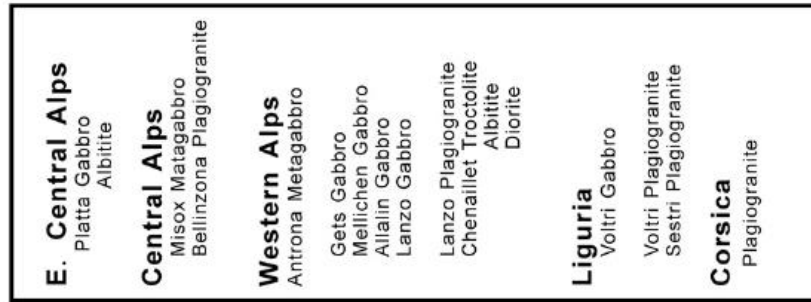


Flysch-units Granites (Cenozoic) Foreland deposits

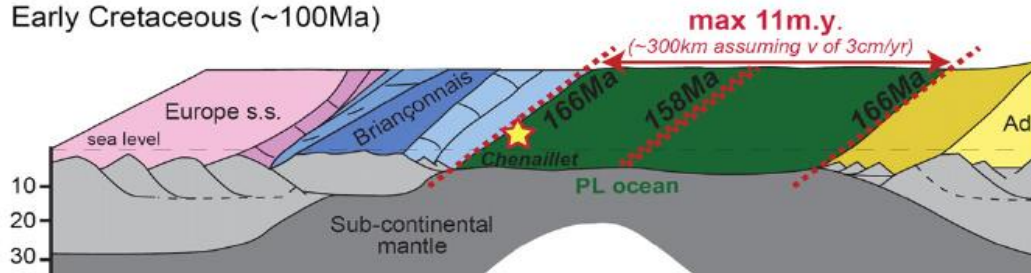


(Manatschal et al, 2011)

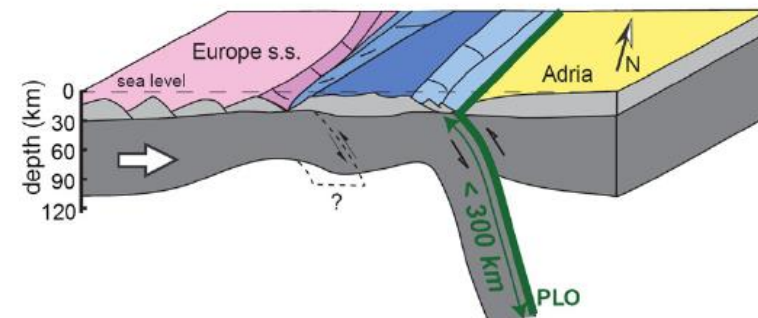
(Li et al, 2014)



Early Cretaceous (~100Ma)

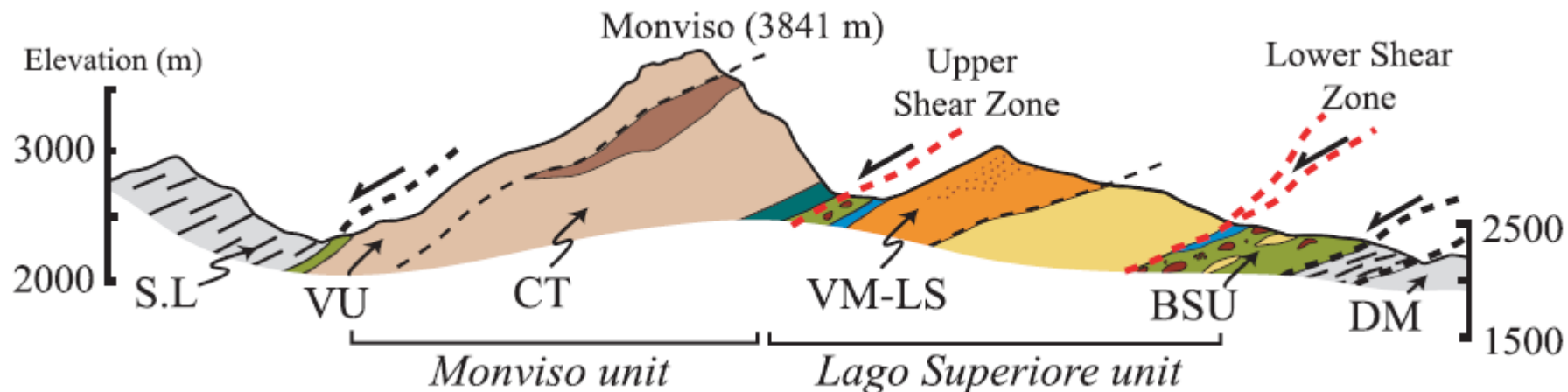


Middle Eocene (~45Ma)









VU (Vallanta Unit), CT (Costa Ticino unit), VM-LS (Viso Mozzo, Lago Superiore units), BSU (Basal Serpentinite Unit) and DM (Dora Maira)

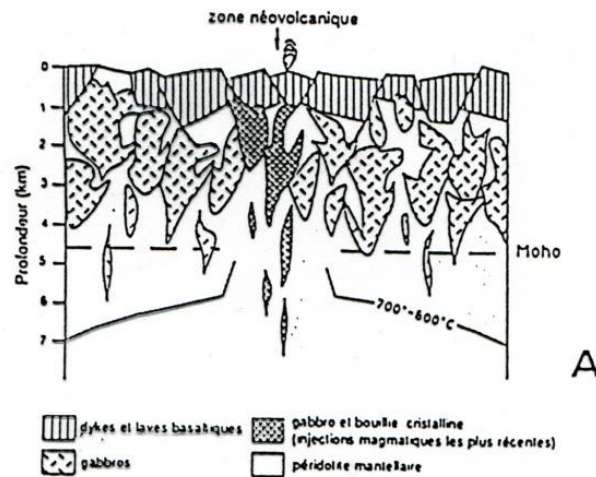
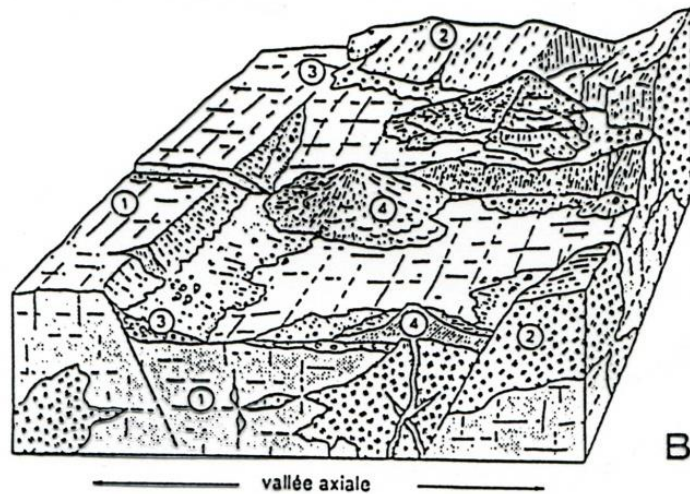
Monviso unit

- Foliated metabasalts
- Metasedimentary rocks
- Mg-Al metagabbro (+peridotite)

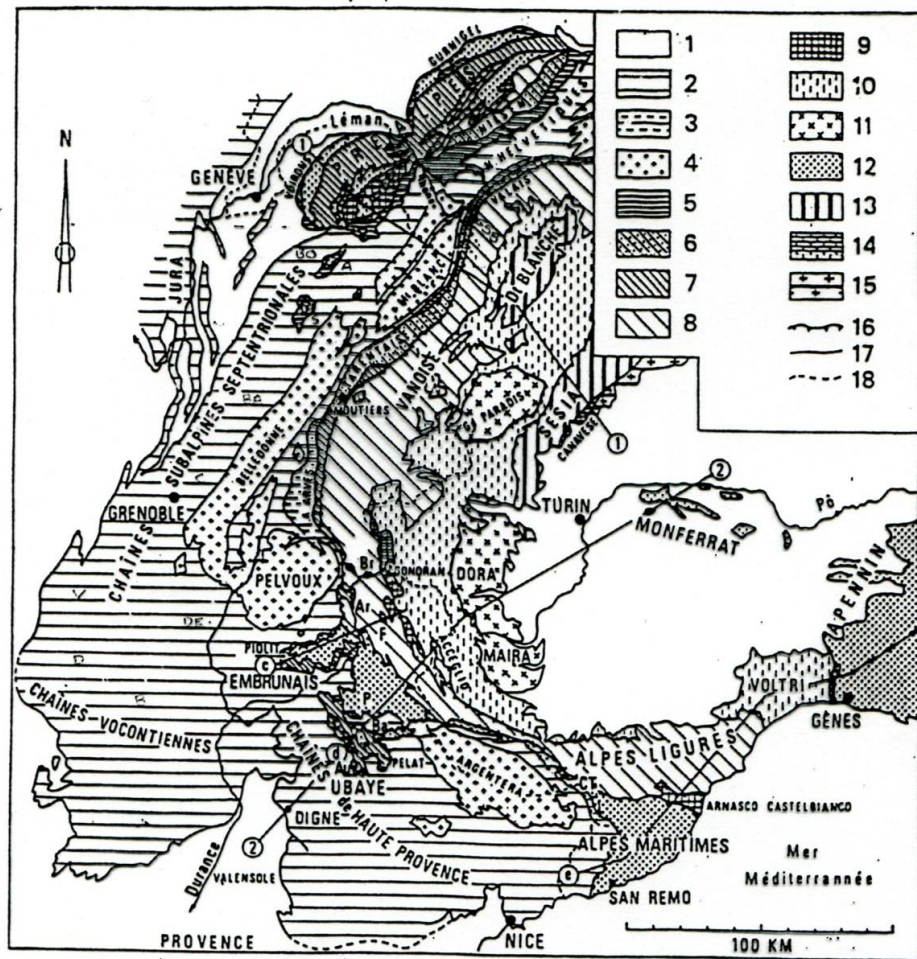
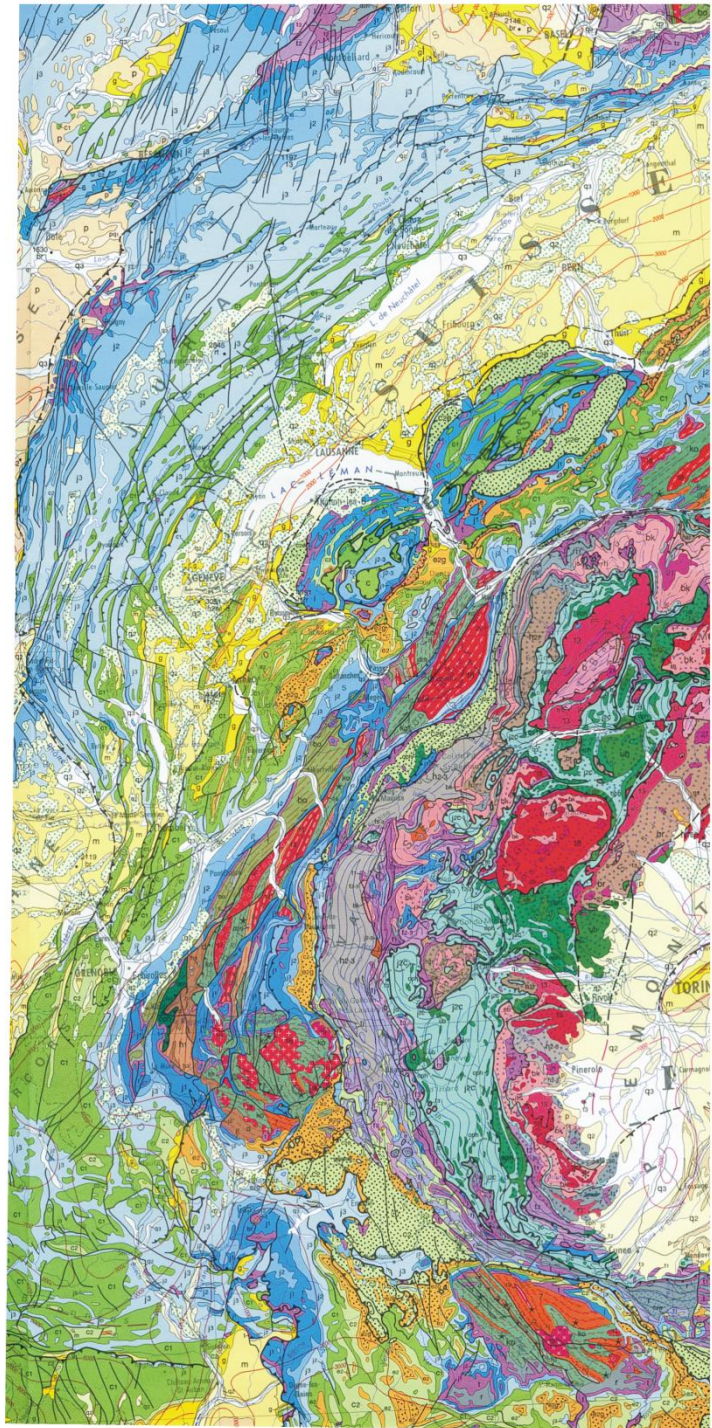
Lago Superiore Unit

- Foliated metabasalts & intrusive Fe-Ti metagabbros
- Metasedimentary rocks
- Mg-Al metagabbro
- Eclogitized Fe-Ti metagabbro
- Serpentinized peridotites

L'océan ligure : des fonds océaniques étroits
de type « atlantique »



A) Modèle de zone axiale de dorsale lente : l'accrétion tectonique est dominante, des poches magmatiques éphémères cristallisent sous la forme de corps de gabbros intrusifs dans le manteau sommital, sous une couche volcanique discontinue. Le manteau peut affleurer sur le plancher océanique. Dessin de M. Cannat (1990). B) Reconstitution schématique du socle océanique téthysien d'âge jurassique des Alpes franco-italiennes (Bassin liguro-piémontais), basée sur des observations de terrain dans les ophiolites de la zone des Schistes lustrés (Queyras). 1 : hornblende serpentinisée. 2 : gabbro. 3 : brèches ultramafiques/mafiques, essentiellement brèches de talus. 4 : volcans de pillow lavas isolés et débris volcaniques associés. Noter que les basaltes peuvent reposer directement sur les péridotites serpentinisées, ou sur leurs talus d'éboulis. Dessin de Y. Lagabrielle



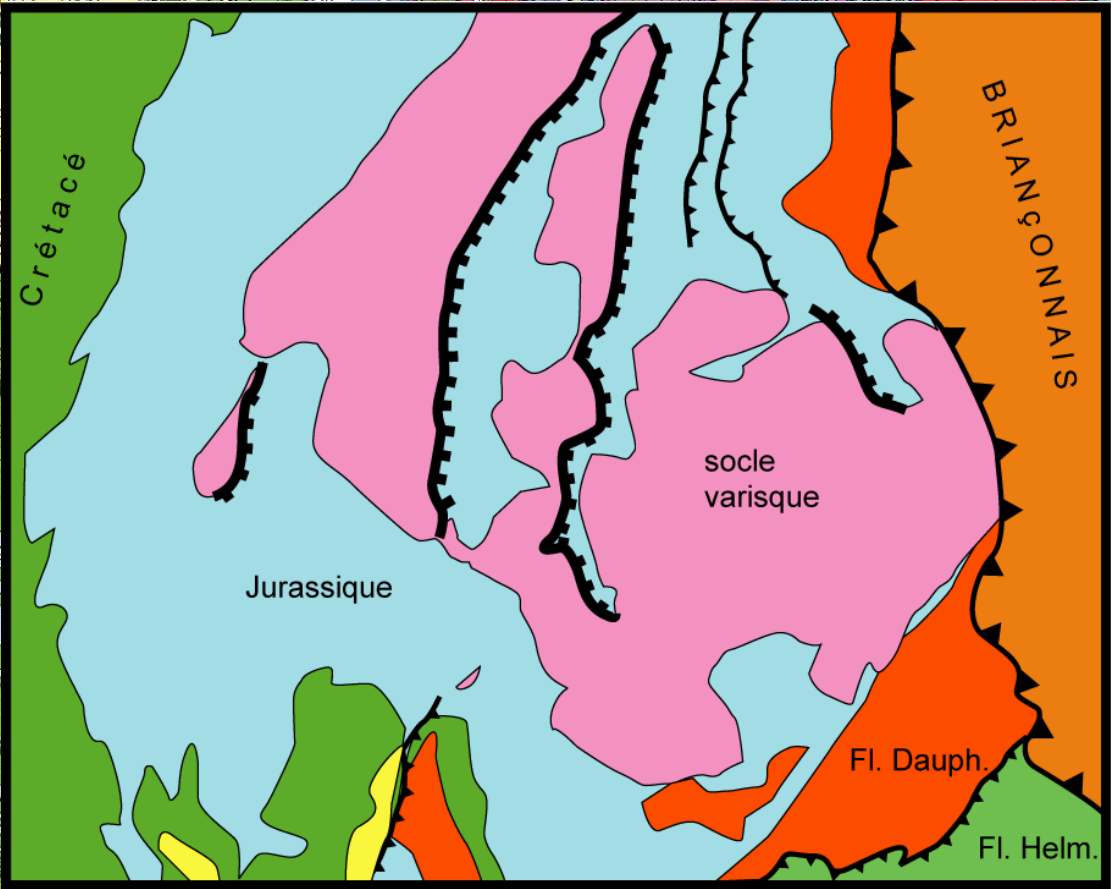
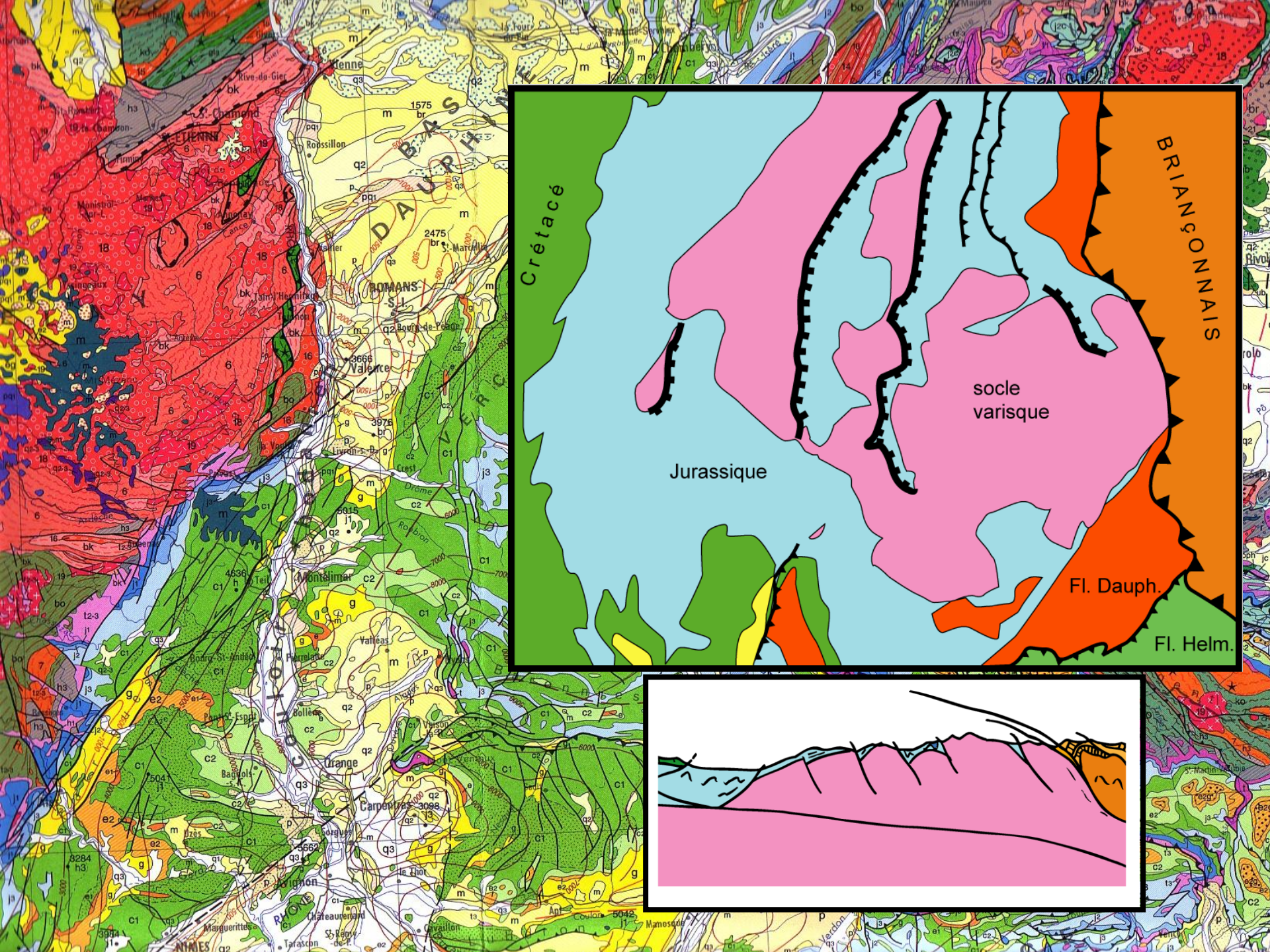
Esquisse structurale des Alpes occidentales, des Préalpes à l'Apennin septentrional.

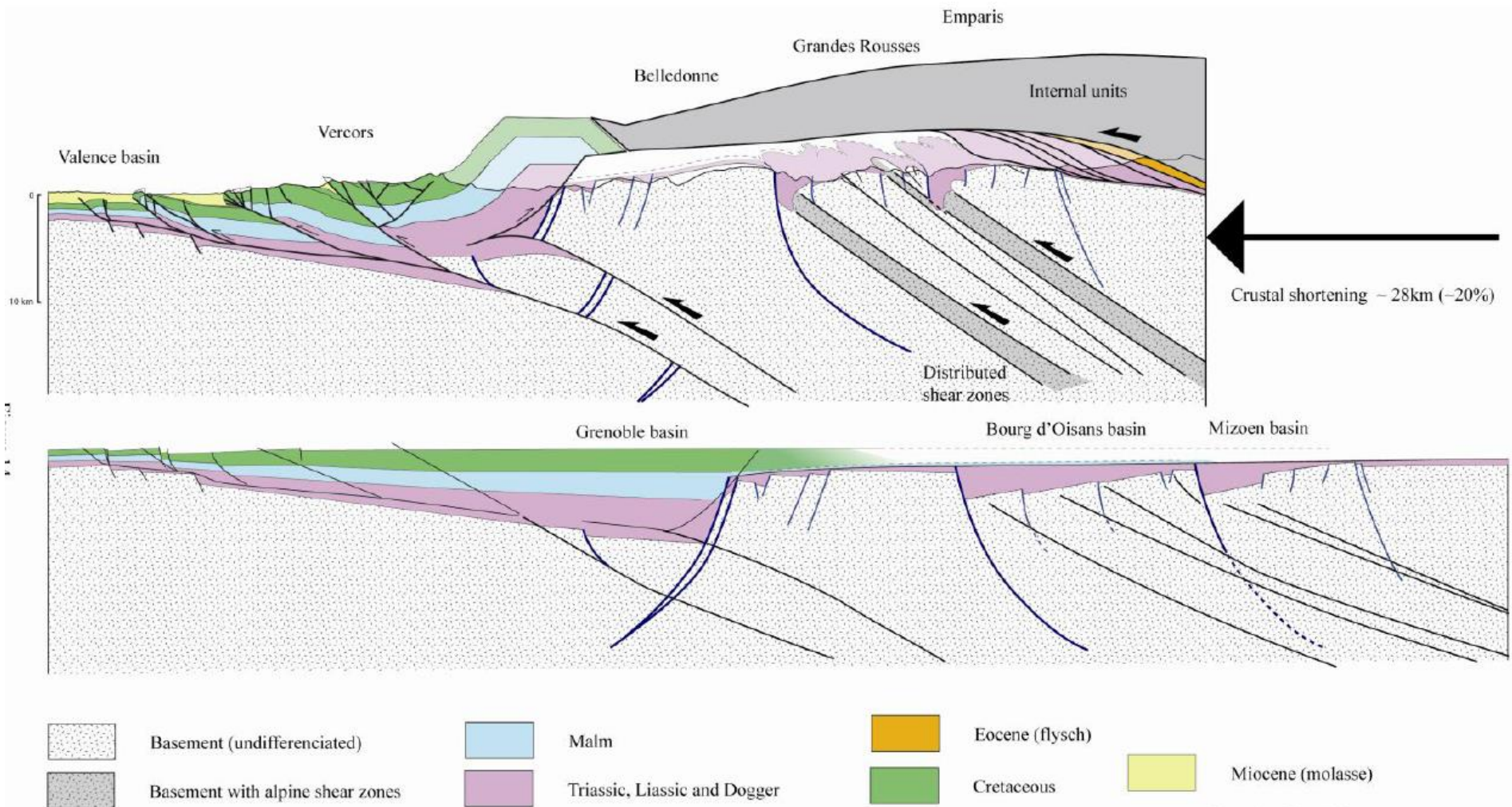
1. Bassins tertiaires et quaternaires péri-alpins ; 2. Couverture sédimentaire mésozoïque et cénozoïque de la zone externe ; 3. Unités parautochtones orientales majeures de la zone externe ; 4. Massifs cristallins externes et leur tégument permo-carbonifère ; 5. Nappes ultrahelvétiques (Préalpes inférieures) ; 6. Zone valaisanne (et nappe du Niesen des Préalpes) ; 7. Zone subbriançonnaise (et Préalpes médianes "plastiques") ; 8. Zone briangonnaise (et Préalpes médianes "rigides") ; 9. Unités prépiémontaises (et nappe de la Brèche des Préalpes) ; 10. Zone piémontaise ("Pays des Schistes lustrés") ; 11. Massifs cristallins internes sous la zone piémontaise ; 12. Flyschs allochtones et nappes ligures de l'Apennin ; 13. Unités ? austroalpines ? ; 14. Zone du Canavese ; 15. Cristallin insubrien (sud-alpin) ; 16. Chevauchement majeur ; 17. Limite d'unité tectonique ; 18. Frontière franco-italienne et franco-suisse ;

Ba. Barcelonnette (fenêtre de) ; Br. Briançon ; C.T. Col de Tende (unité parautochtone du) ; F. Furfande (klippe de Nisch de) ; P. Parpaillon (massif du) ;

II. Les Alpes franco-italiennes :
une structure impliquant la fermeture
d'un (ou plusieurs?) océan(s) lent(s)
et l'inversion d'une paléomarge passive

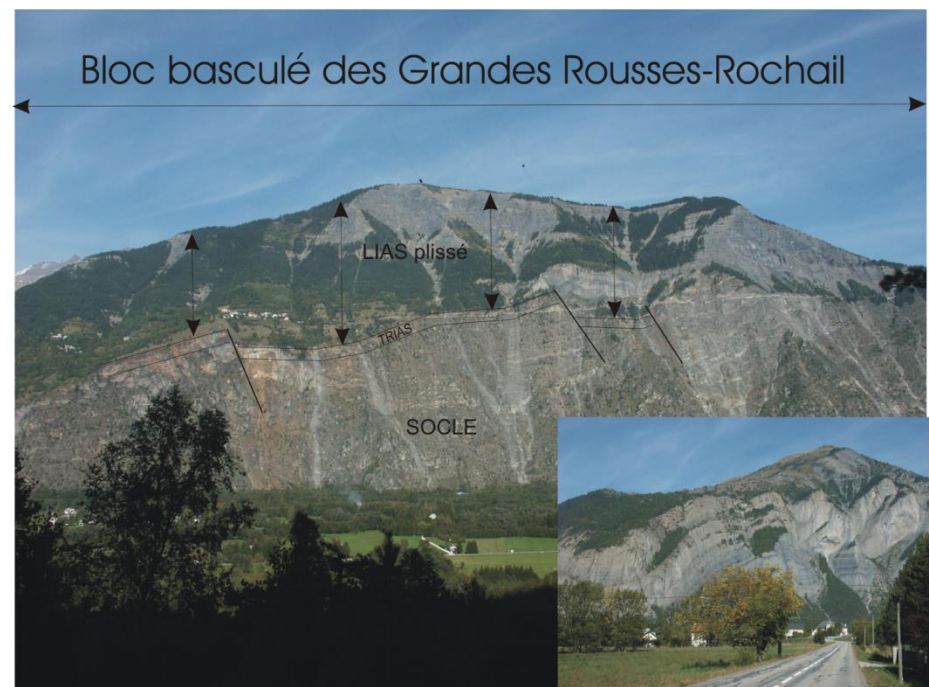
B. La marge européenne de l'océan ligure





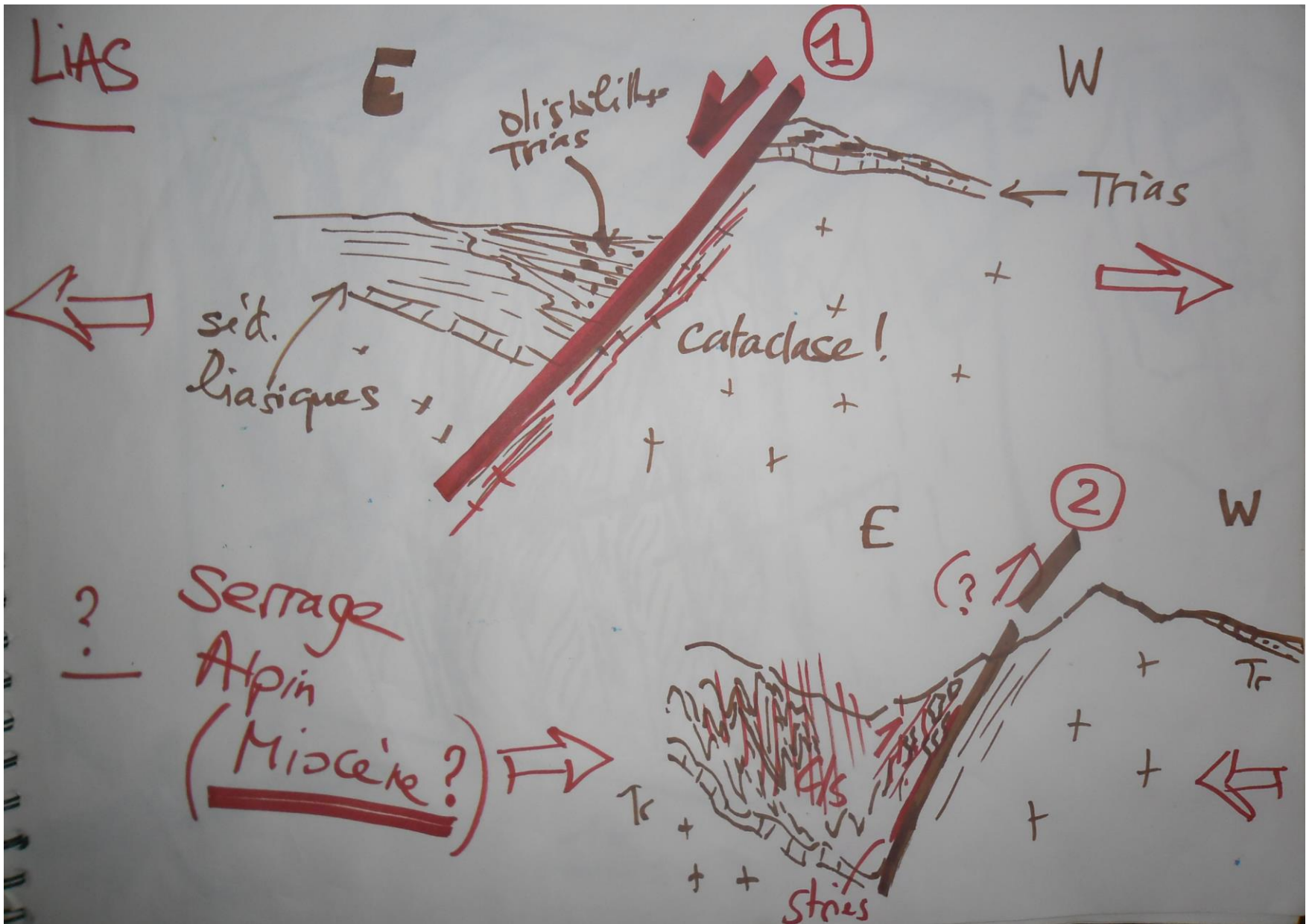
(Bellahsen et al., 2012)

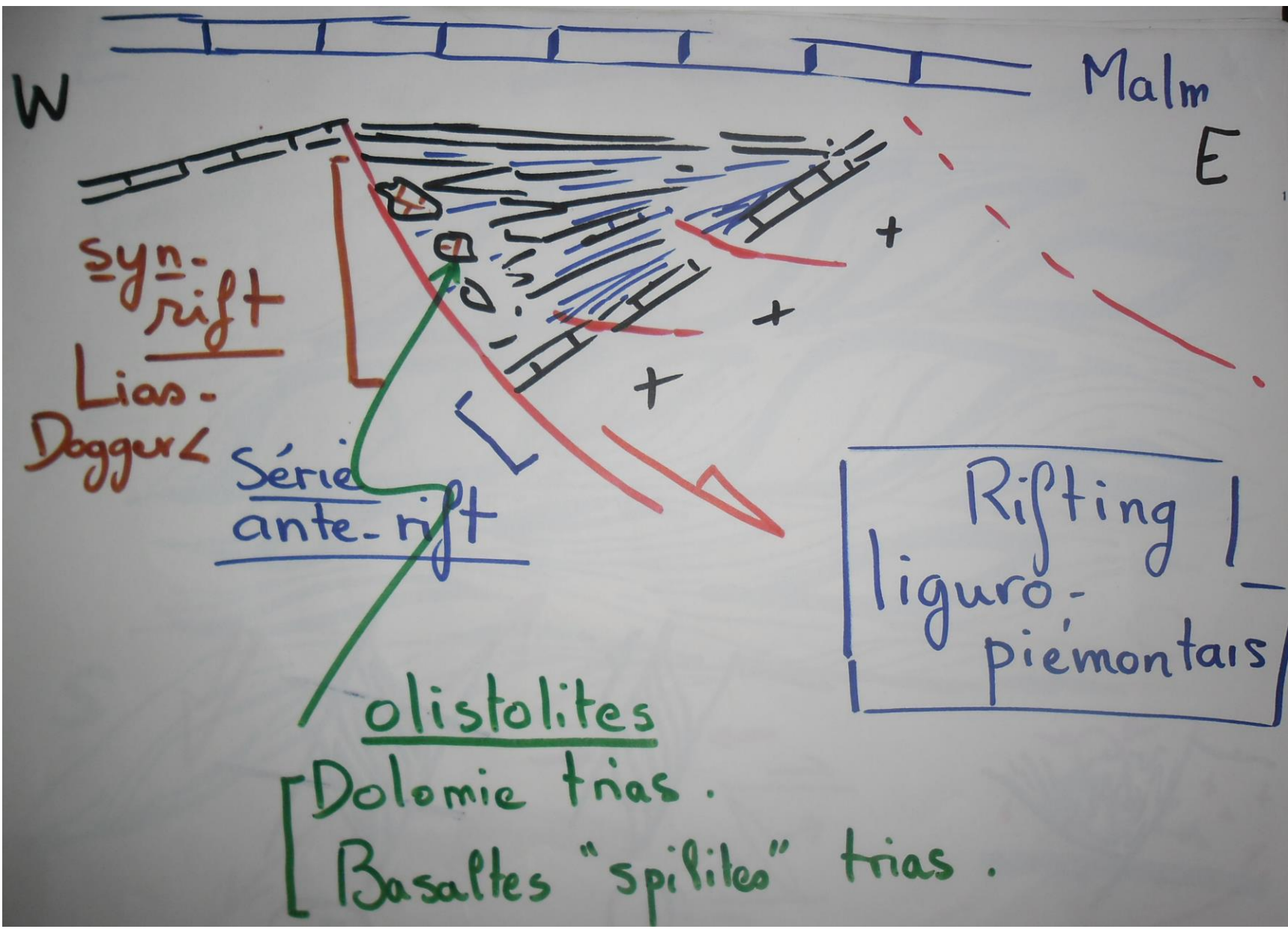












W

Malm
E

syn-rift

Lias-Dogger

Série ante-rift

olistolites

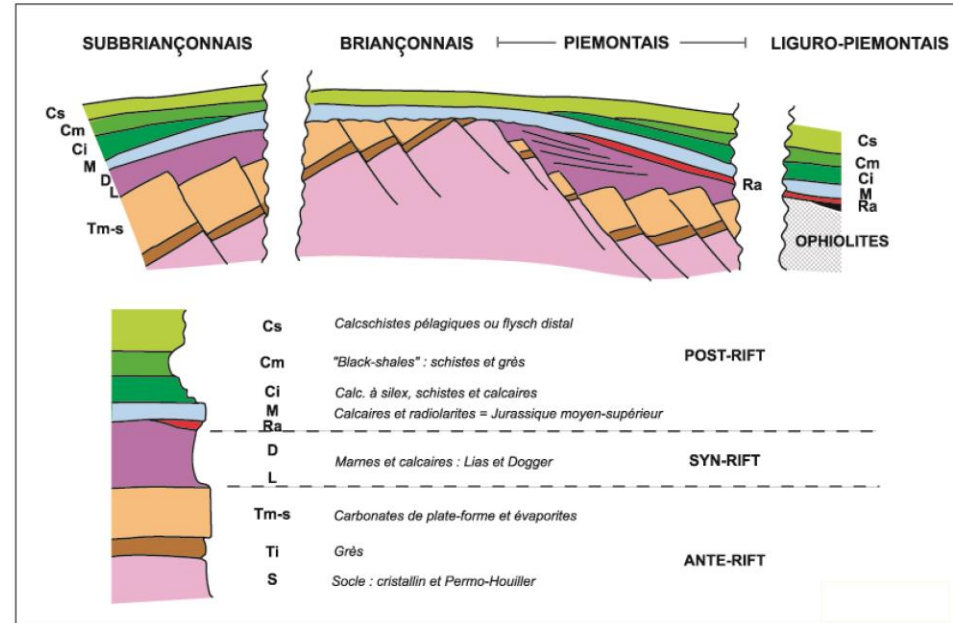
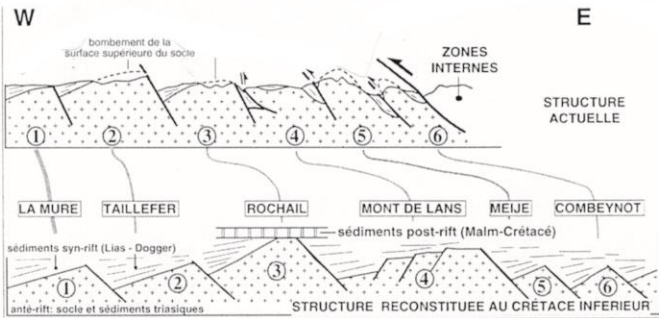
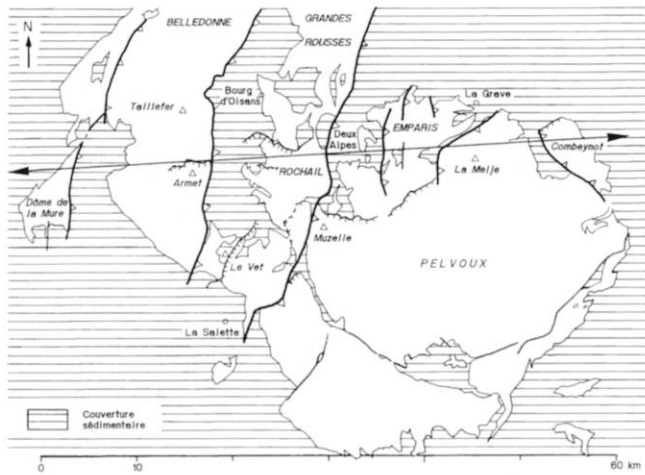
[Dolomie trias.

[Basaltes "spilites" trias.

Rifting
liguro-
piémontais

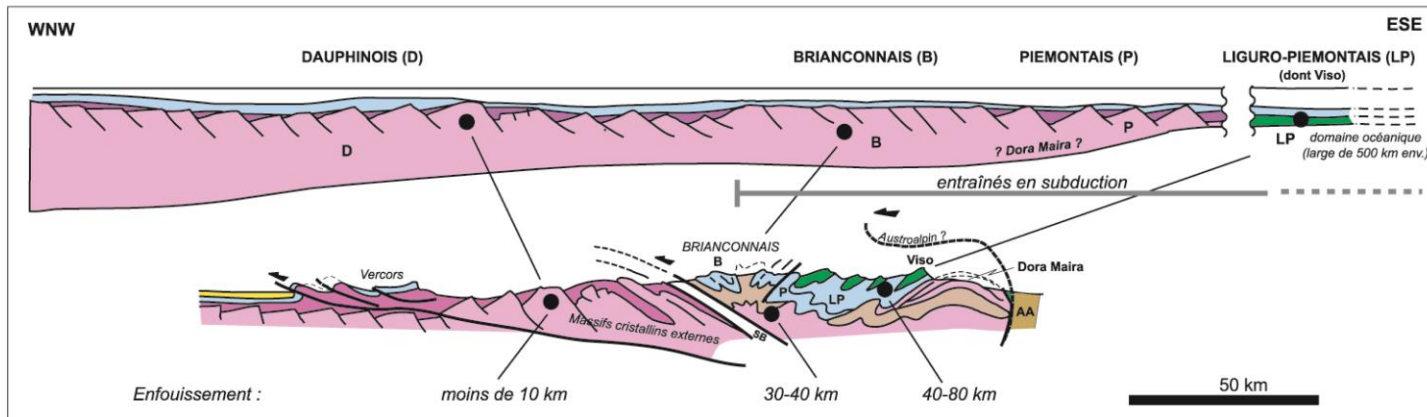
II. Les Alpes franco-italiennes :
une structure impliquant la fermeture
d'un (ou plusieurs?) océan(s) lent(s)
et l'inversion d'une paléomarge passive

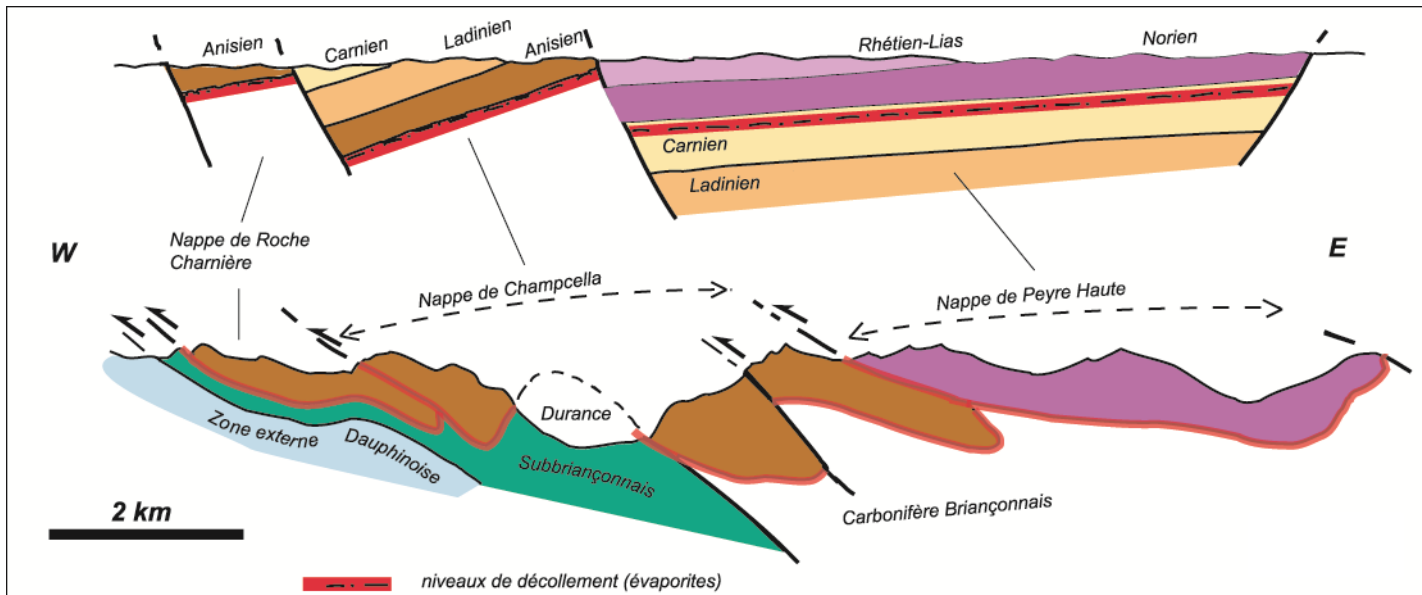
C. Essai de reconstitution paléogéographique



(Agard et Lemoine, 2003
Lemoine et al.)

Identification et reconstitution
d'une tectonique distensive
en blocs basculés dans le
domaine dauphinois

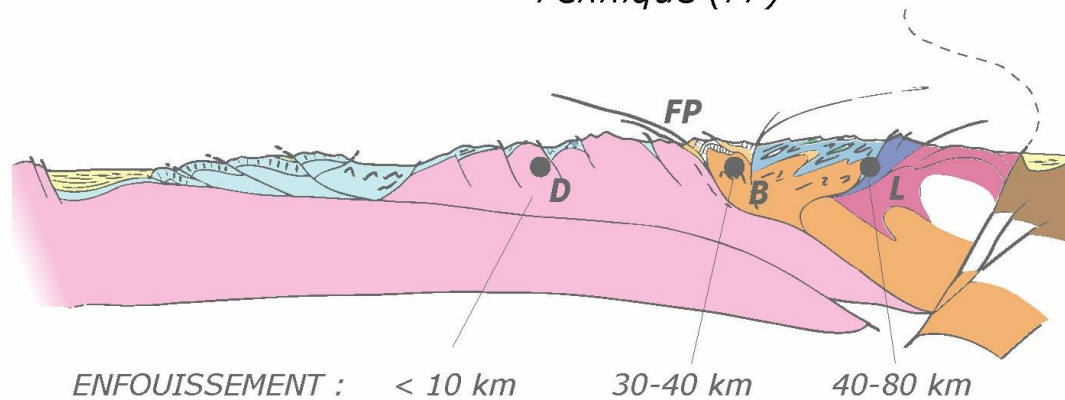
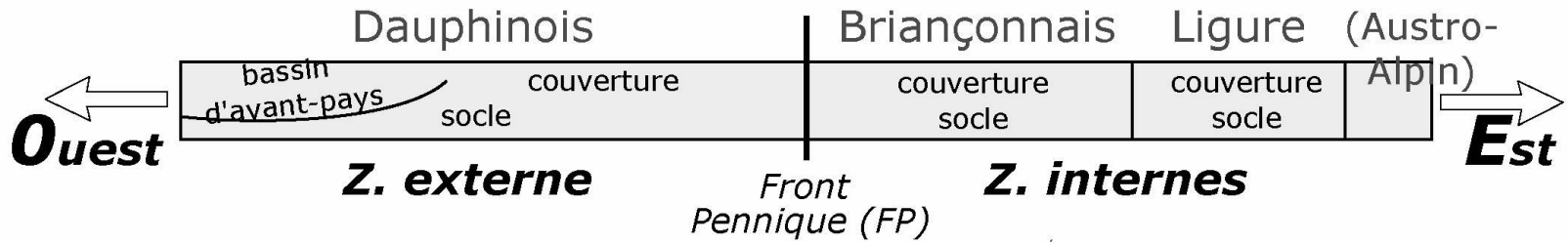
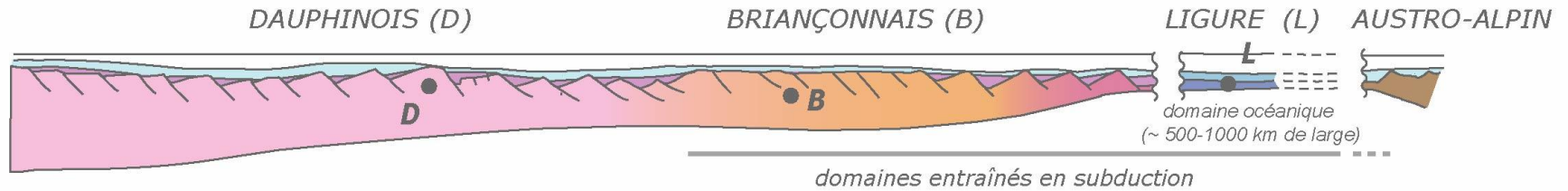




(Agard et Lemoine, 2003)

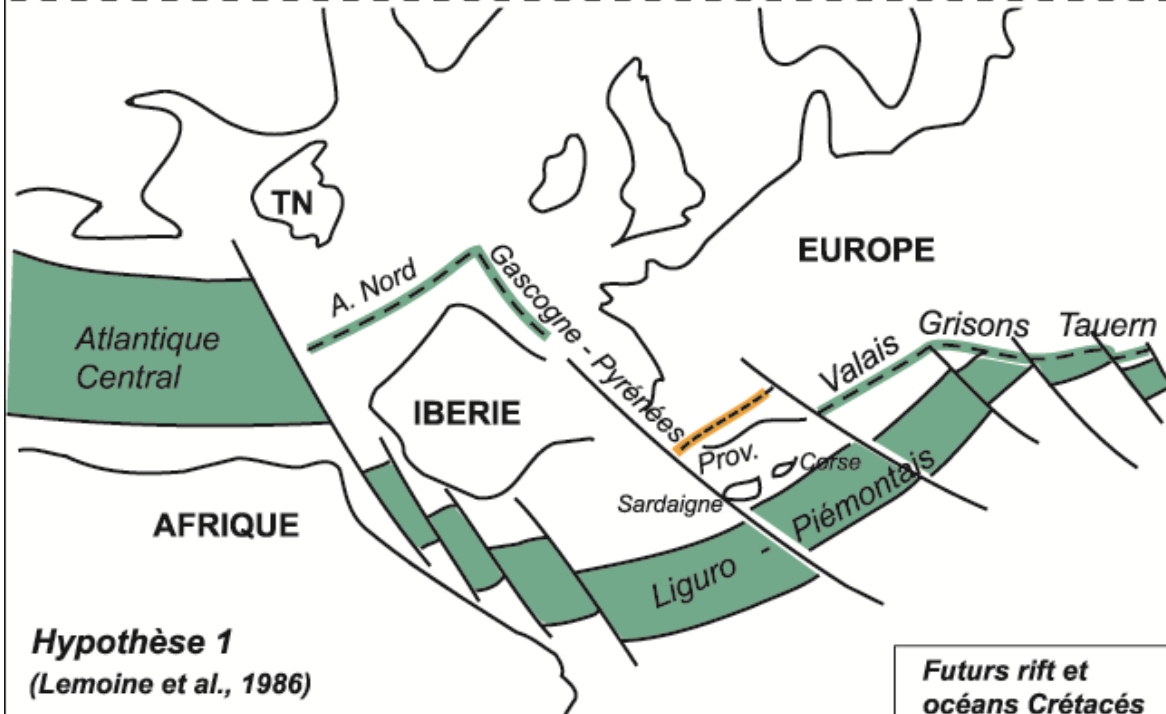
Un dispositif simple... dans les grandes lignes

AVANT (~ 120 Millions d'années)

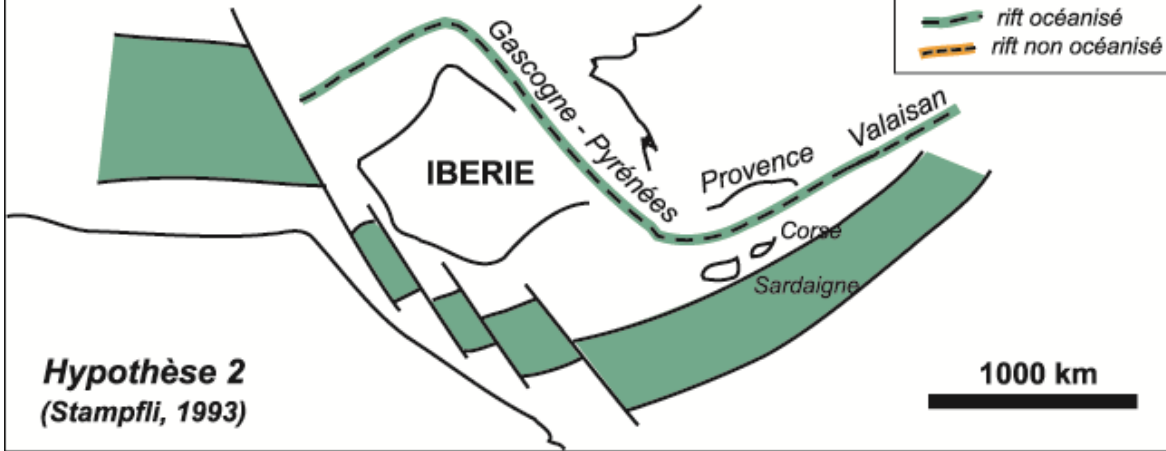


APRES (AUJOURD'HUI)

Situation au Jurassique supérieur



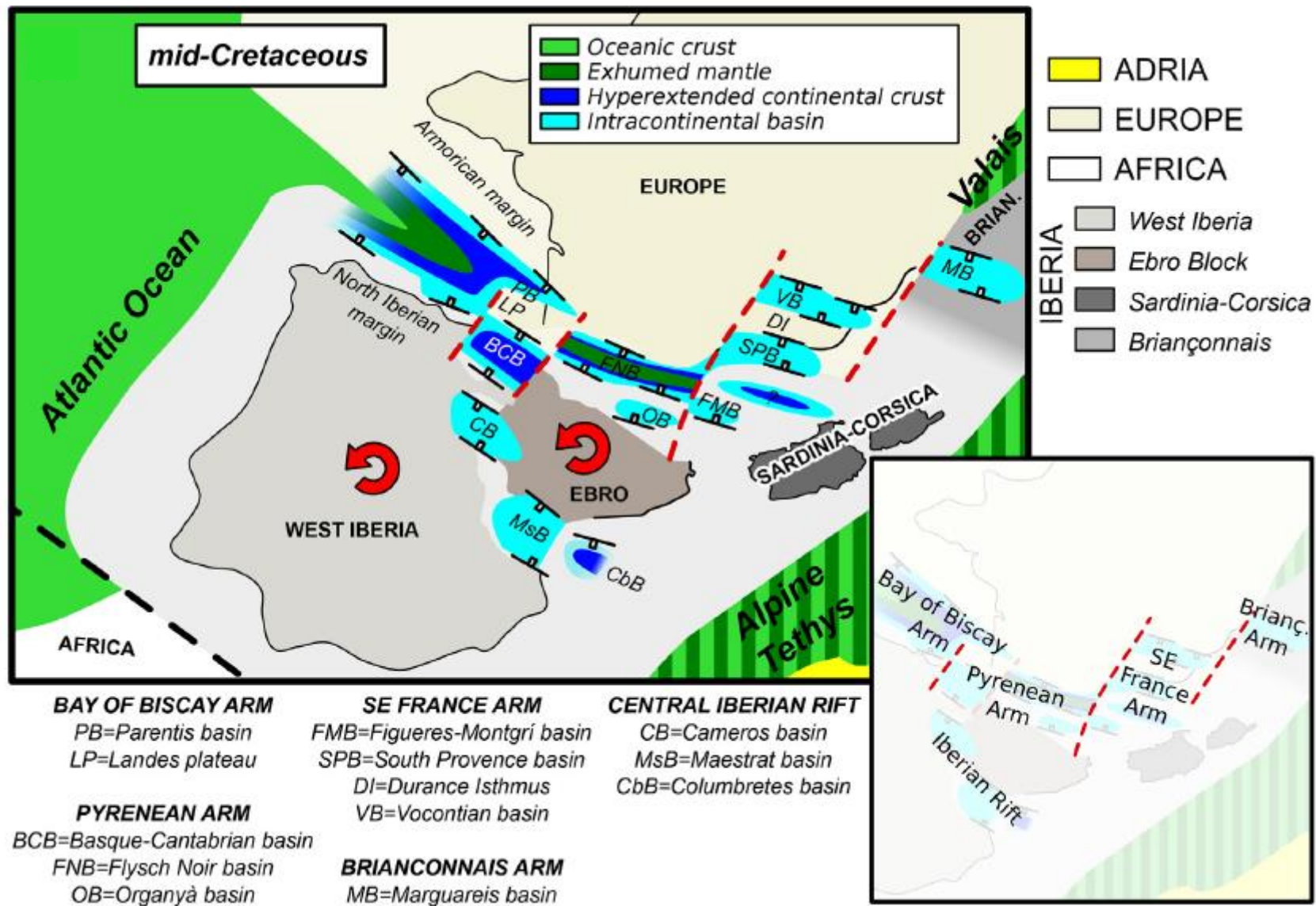
Hypothèse 1
(Lemoine et al., 1986)



Hypothèse 2
(Stampfli, 1993)

1000 km

(Agard et Lemoine, 2003)



Collision APULIE - EURASIE

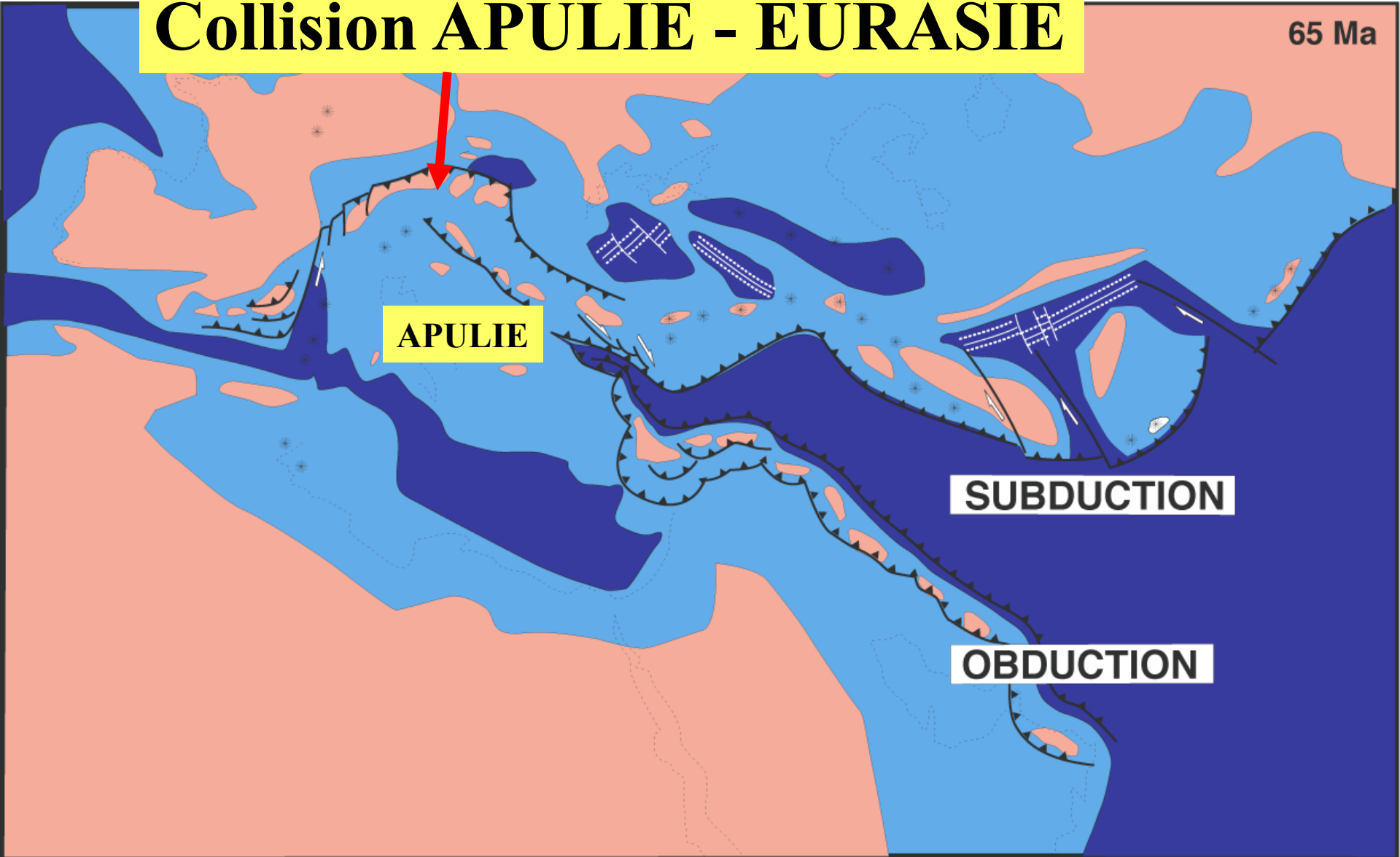
65 Ma

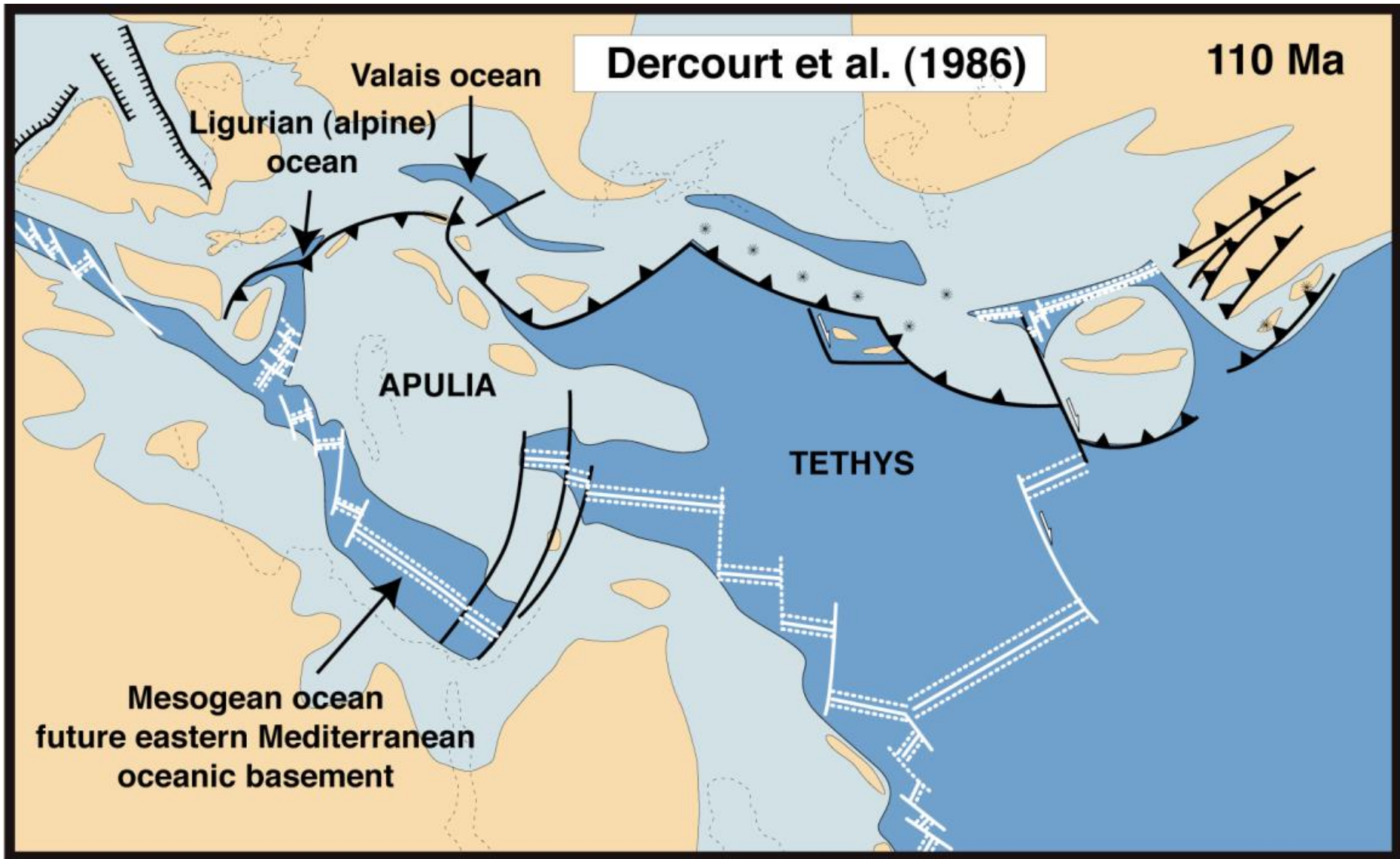
APULIE

SUBDUCTION

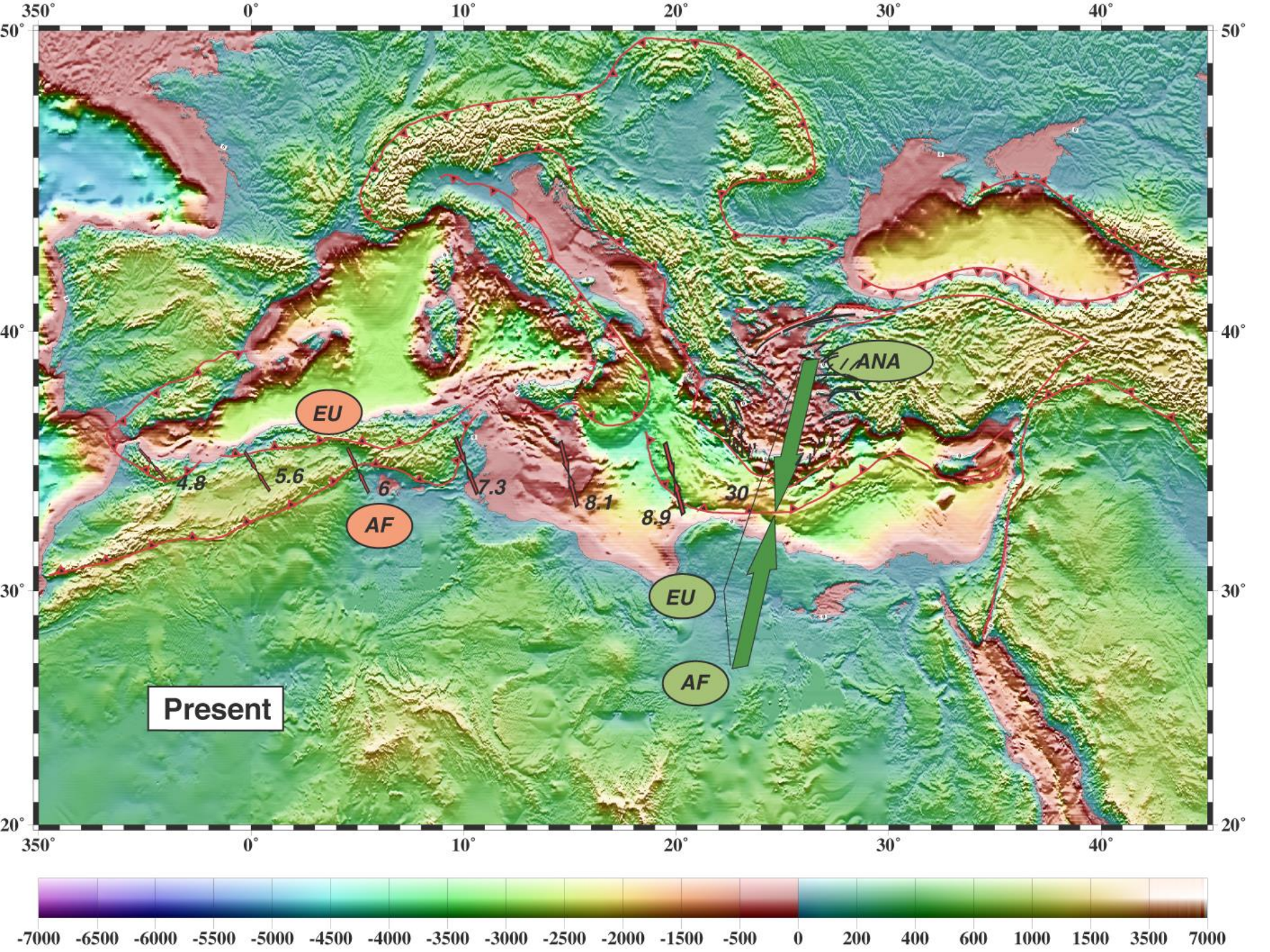
OBDUCTION

Dercourt et al., 1986

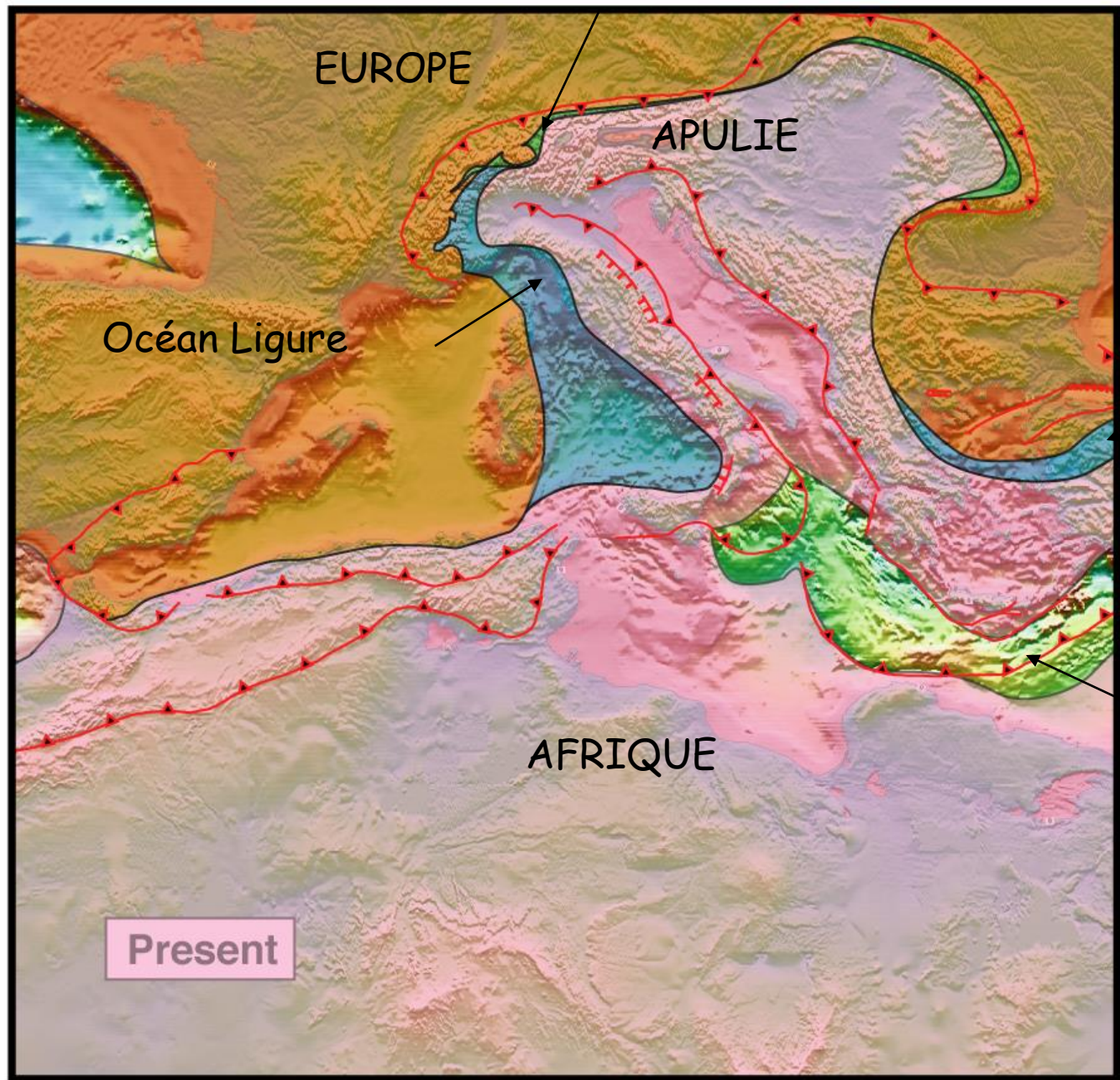




Mésogée : existence récemment remise en cause !!!



Océan Valaisan



EUROPE

APULIE

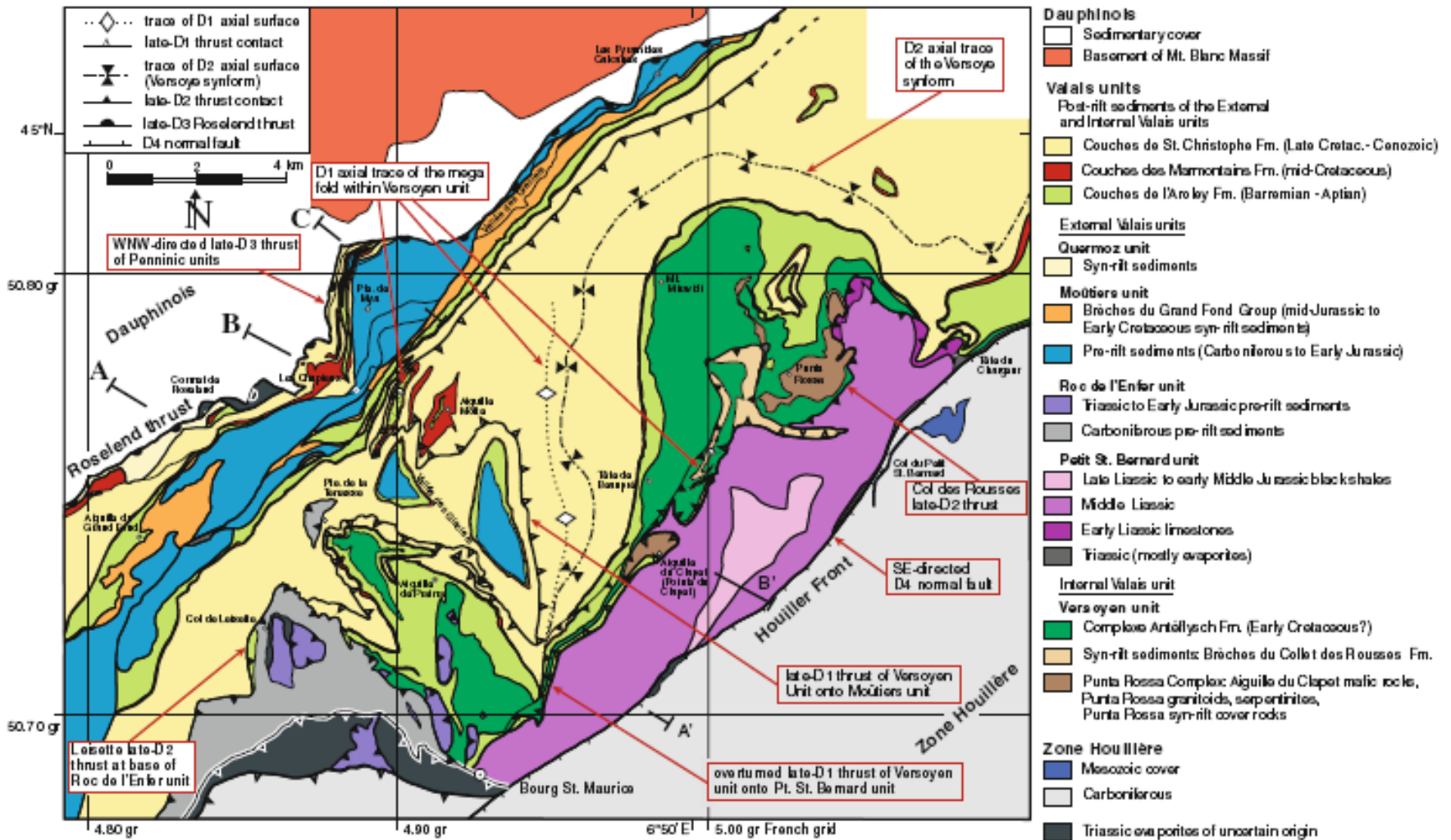
Océan Ligure

Téthys

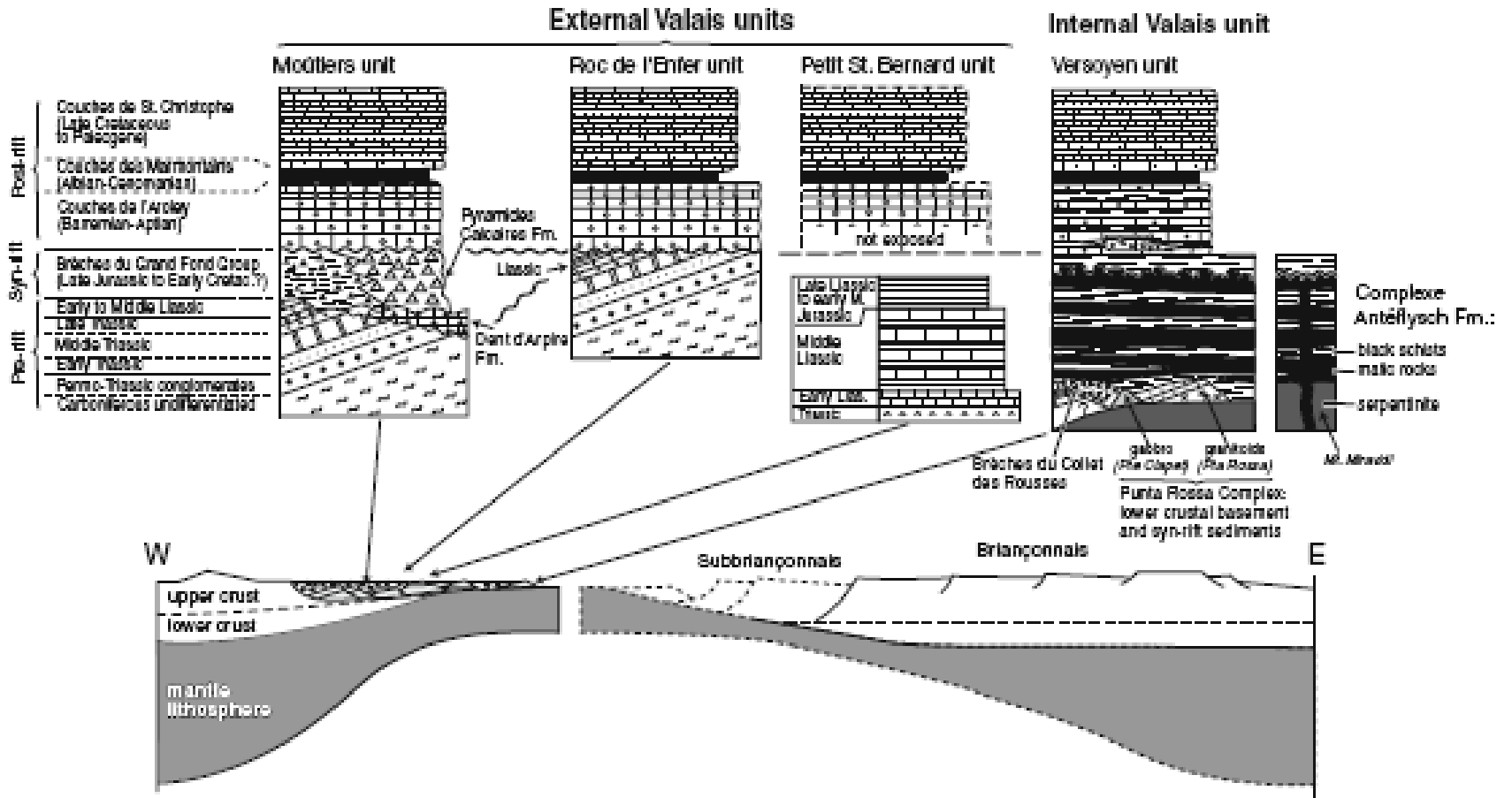
AFRIQUE

Mésogée (?)

Present



(Loprieno et al., 2011)

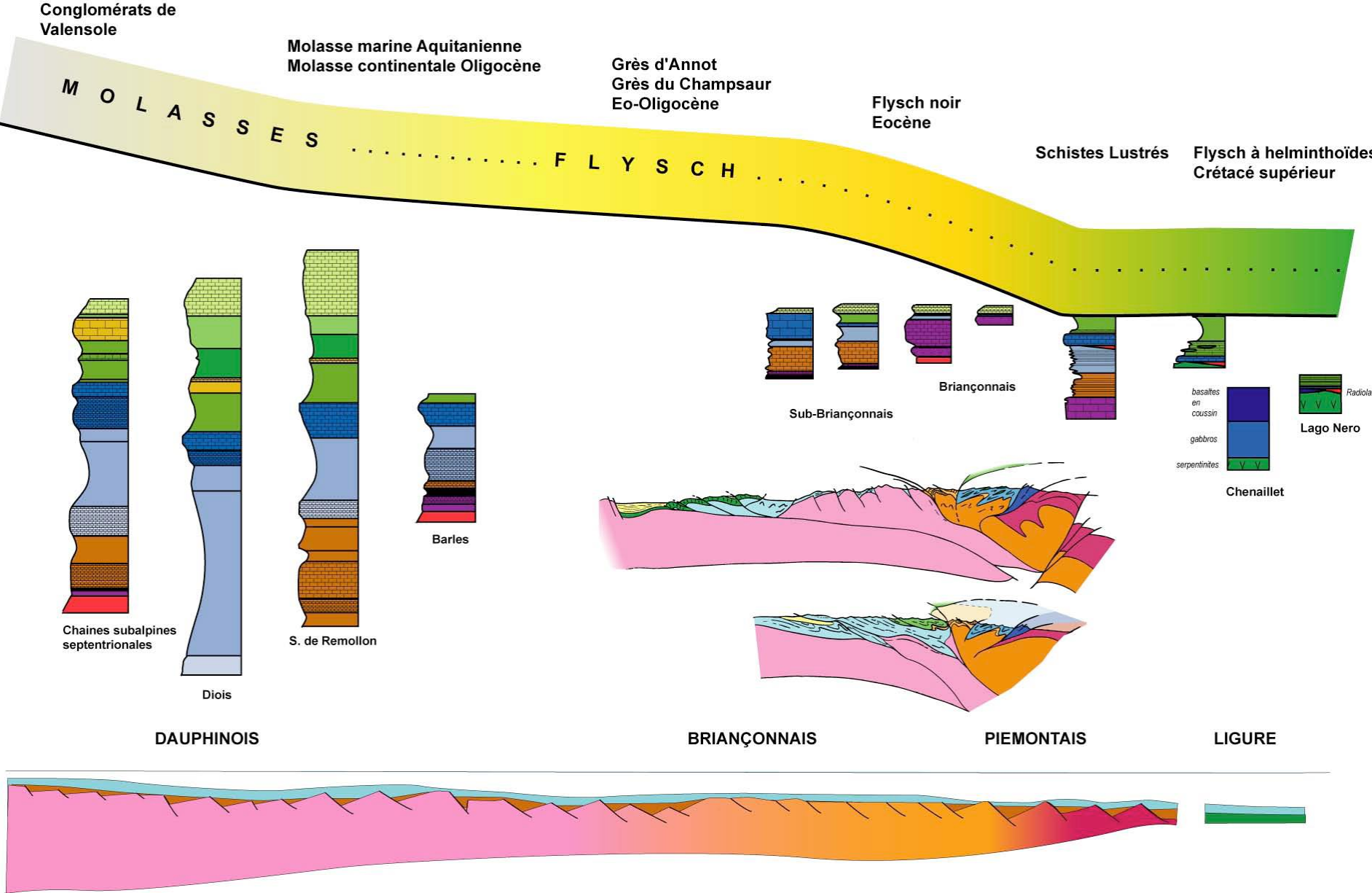


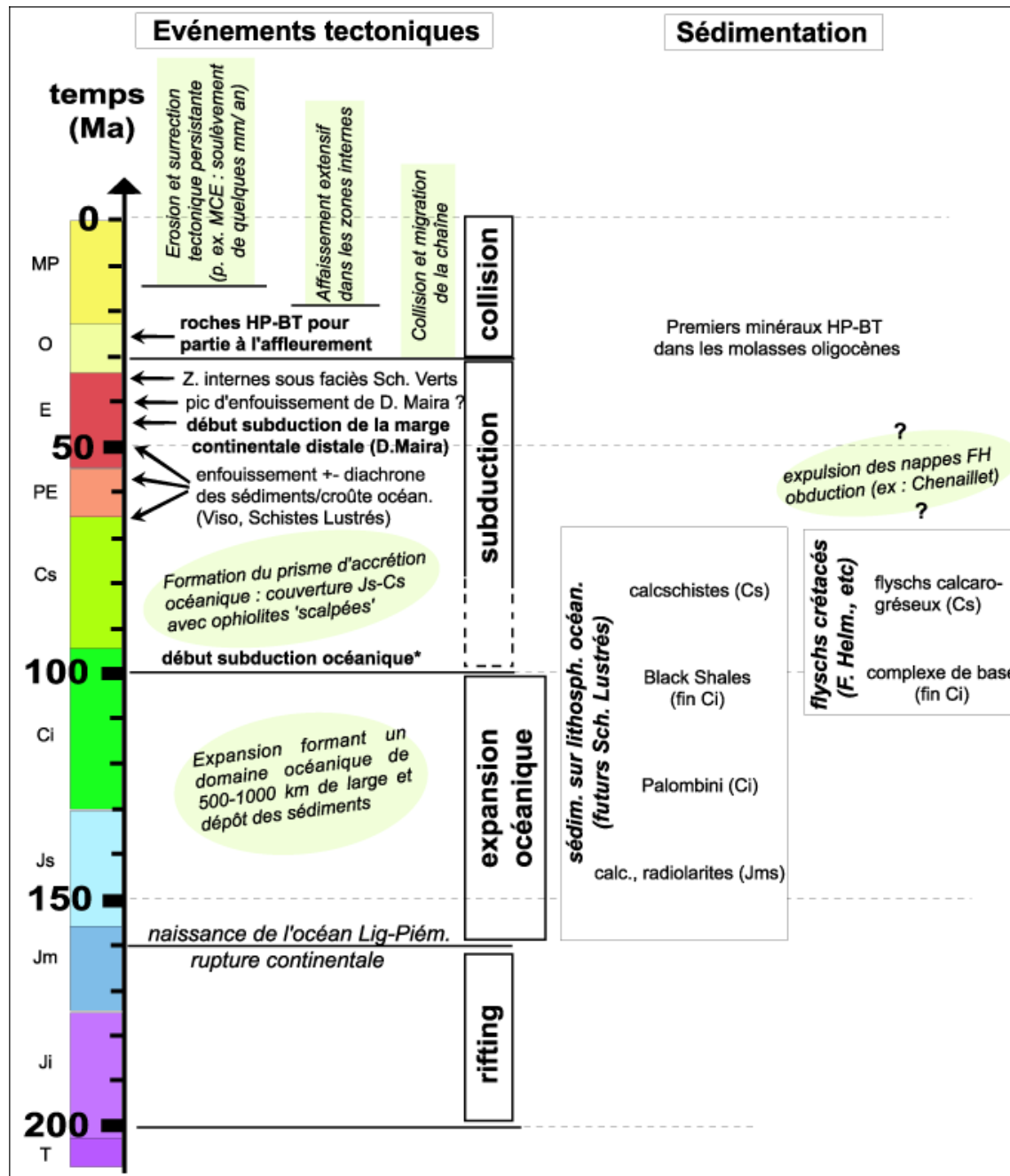
(Loprieno et al., 2011)

III. Calendrier et modèle d'évolution
des Alpes franco-italiennes; évolution récente;
réflexion sur la structure :

III. Calendrier et modèle d'évolution des Alpes franco-italiennes; évolution récente; réflexion sur la structure.

A. Calendrier

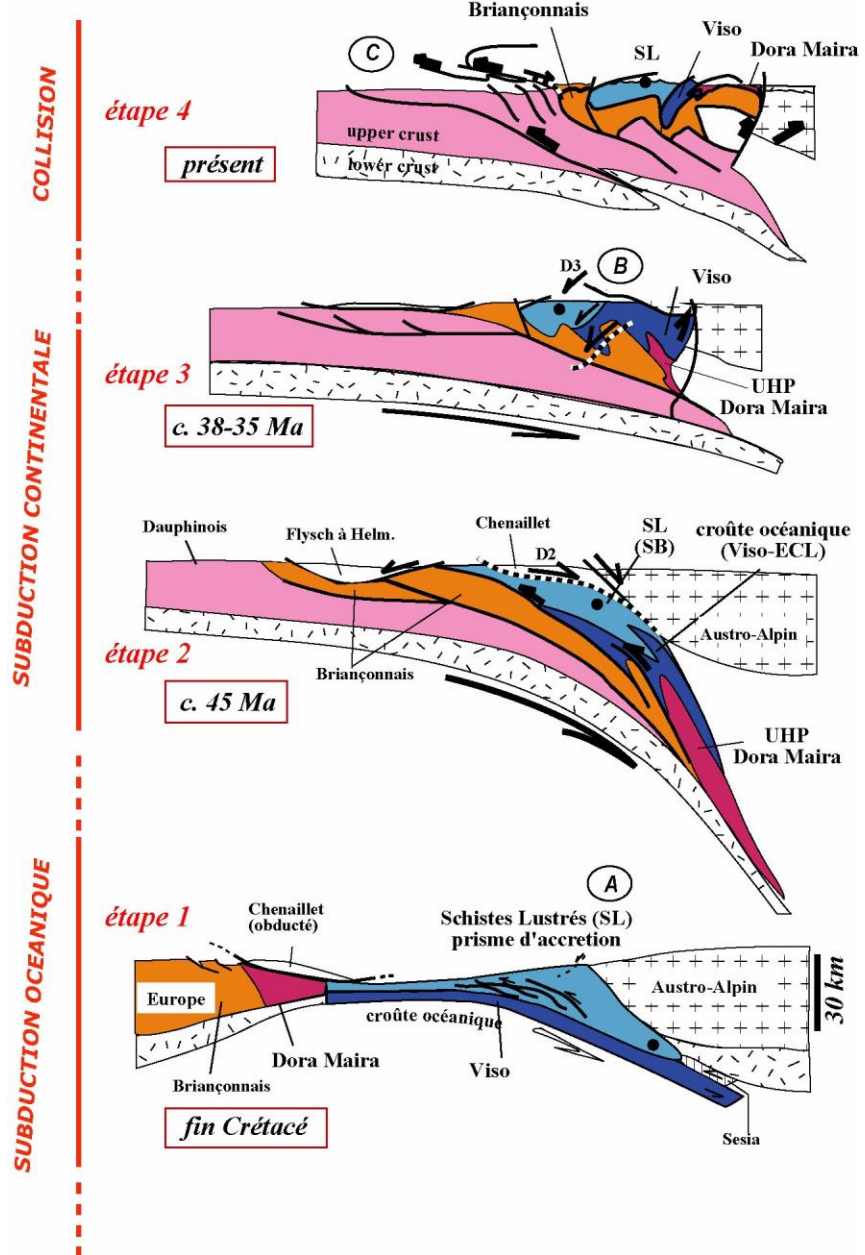




(Agard et Lemoine, 2003)

III. Calendrier et modèle d'évolution
des Alpes franco-italiennes; évolution récente;
réflexion sur la structure.

B. Modèle d'évolution



COLLISION

SUBDUCTION CONTINENTALE

SUBDUCTION OcéANIQUE

étape 4

présent

étape 3

c. 38-35 Ma

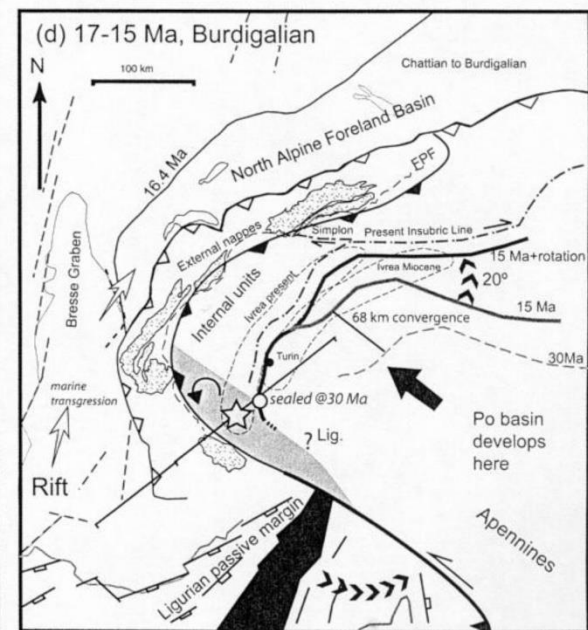
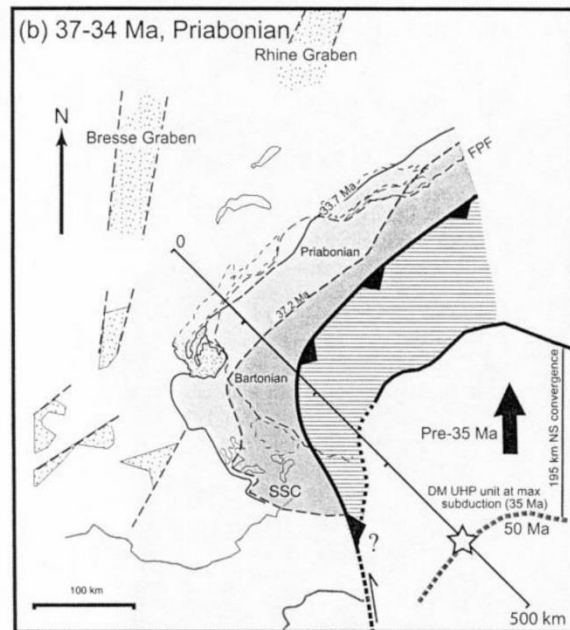
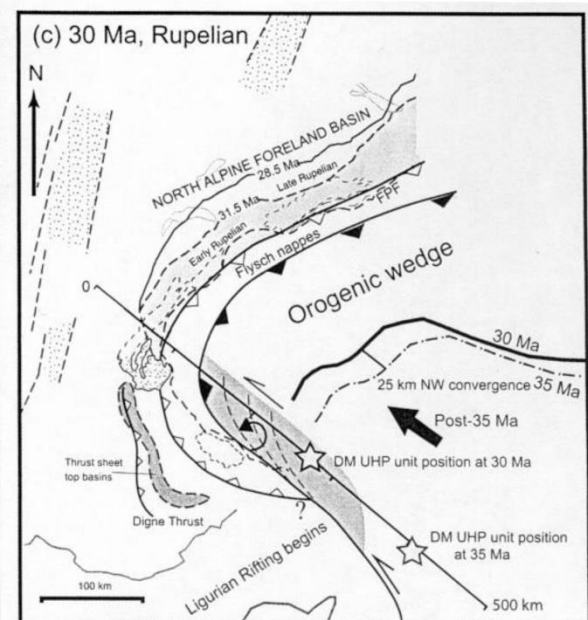
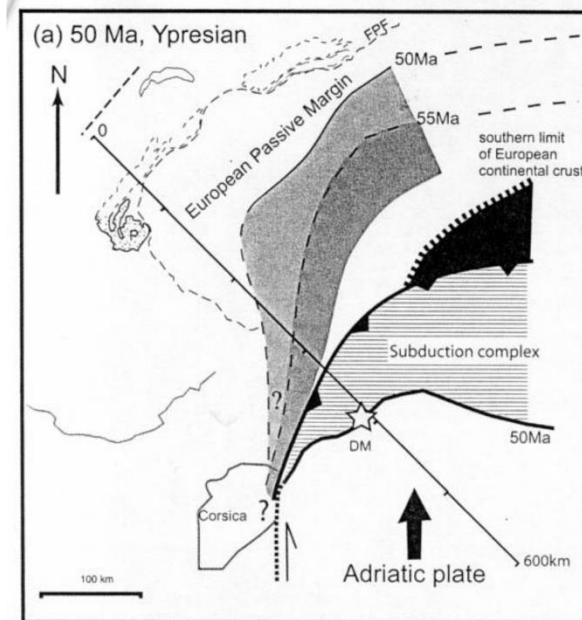
étape 2

c. 45 Ma

étape 1

fin Crétacé

30 km



(Ford et al., 2006)

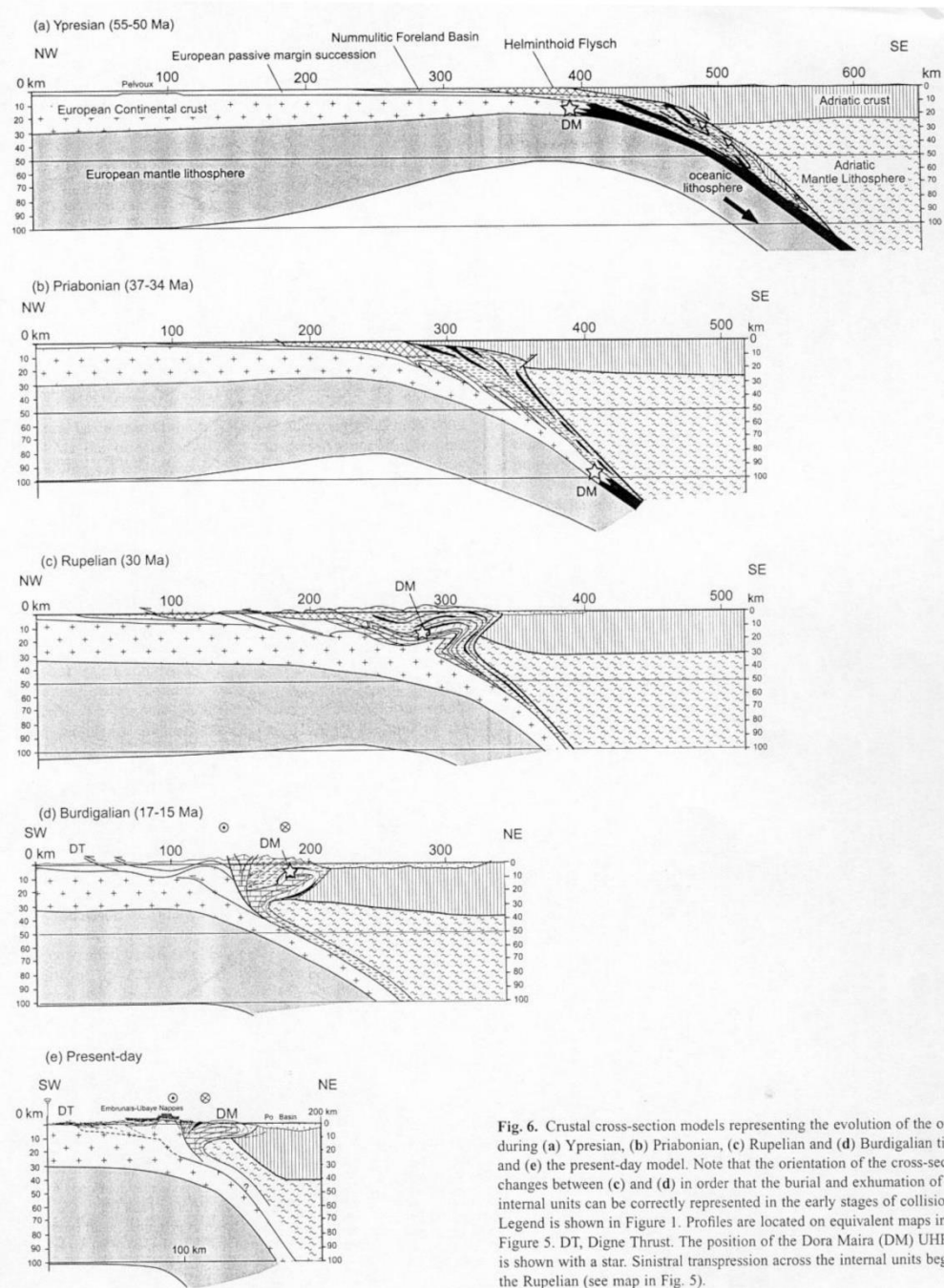
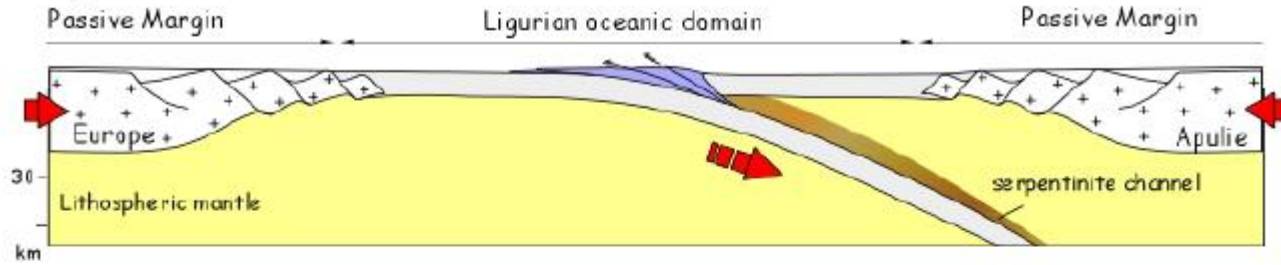
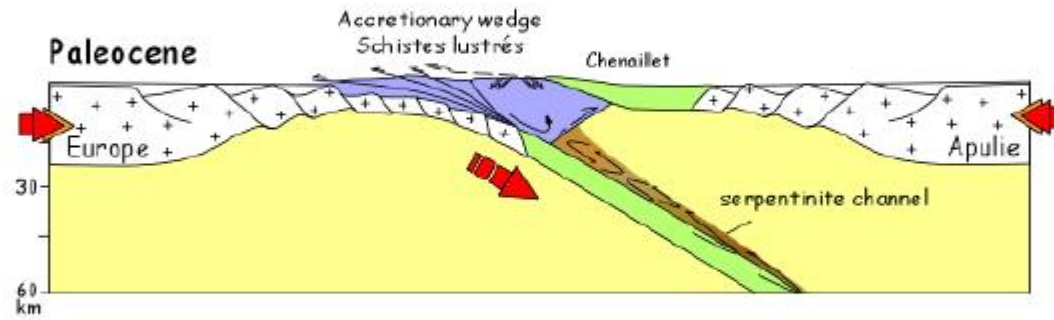


Fig. 6. Crustal cross-section models representing the evolution of the orogen during (a) Ypresian, (b) Priabonian, (c) Rupelian and (d) Burdigalian times and (e) the present-day model. Note that the orientation of the cross-section changes between (c) and (d) in order that the burial and exhumation of internal units can be correctly represented in the early stages of collision. Legend is shown in Figure 1. Profiles are located on equivalent maps in Figure 5. DT, Digne Thrust. The position of the Dora Maira (DM) UHP unit is shown with a star. Sinistral transpression across the internal units began the Rupelian (see map in Fig. 5).

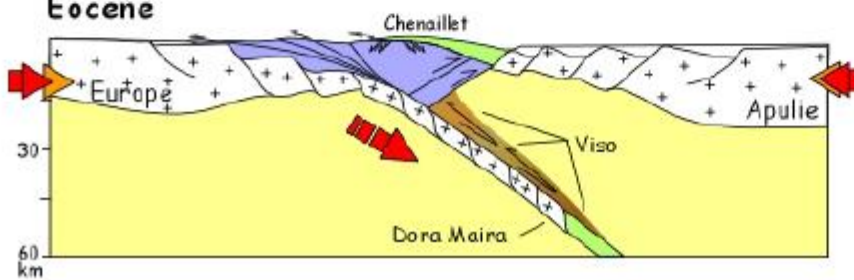
Upper Cretaceous

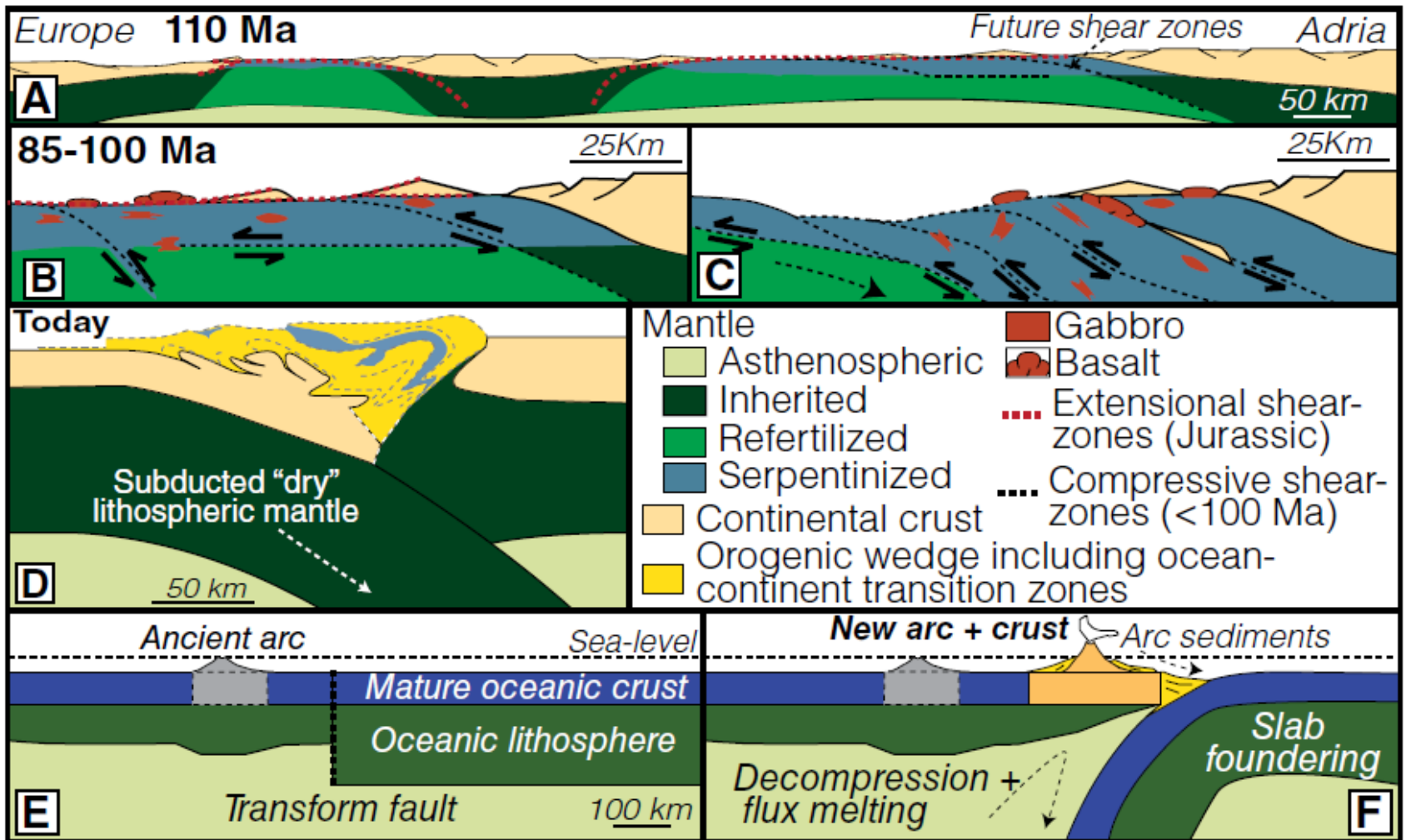


Paleocene



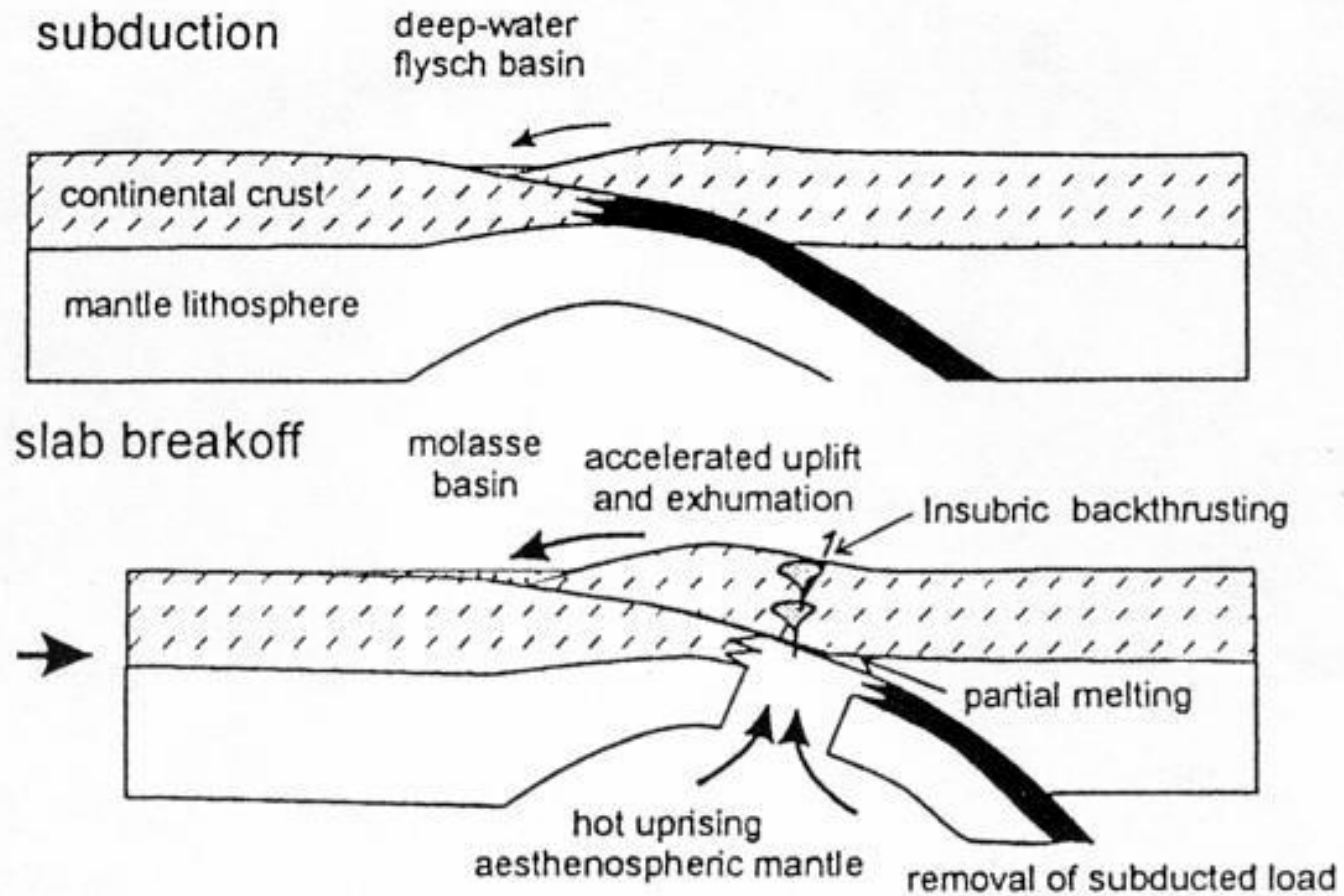
Eocene



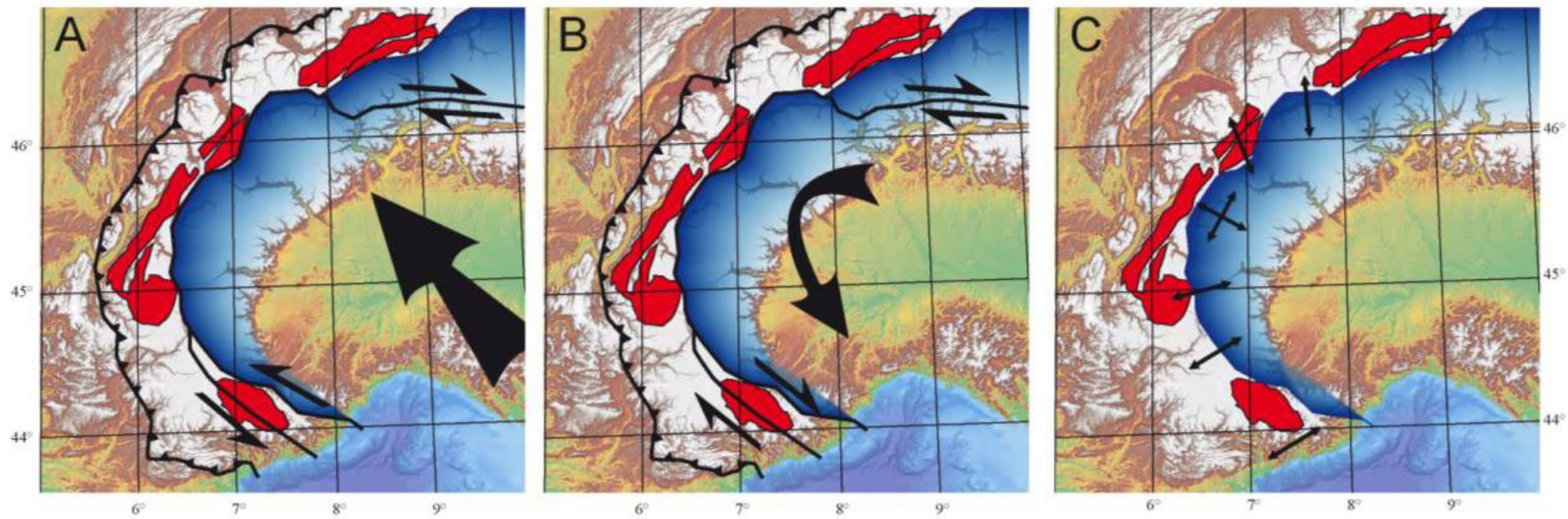


The closure of rift basins forming the **Piemont-Liguria ocean** did not follow a classical **Wadati-Benioff**-type subduction. Instead, subduction initiation at passive margins allowed for the accretion of the hydrated portion of the subducting plate within an orogenic wedge as subduction of dry subcontinental lithosphere inhibited magmatism during subduction initiation and ocean closure.

(McCarthy et al., 2018)



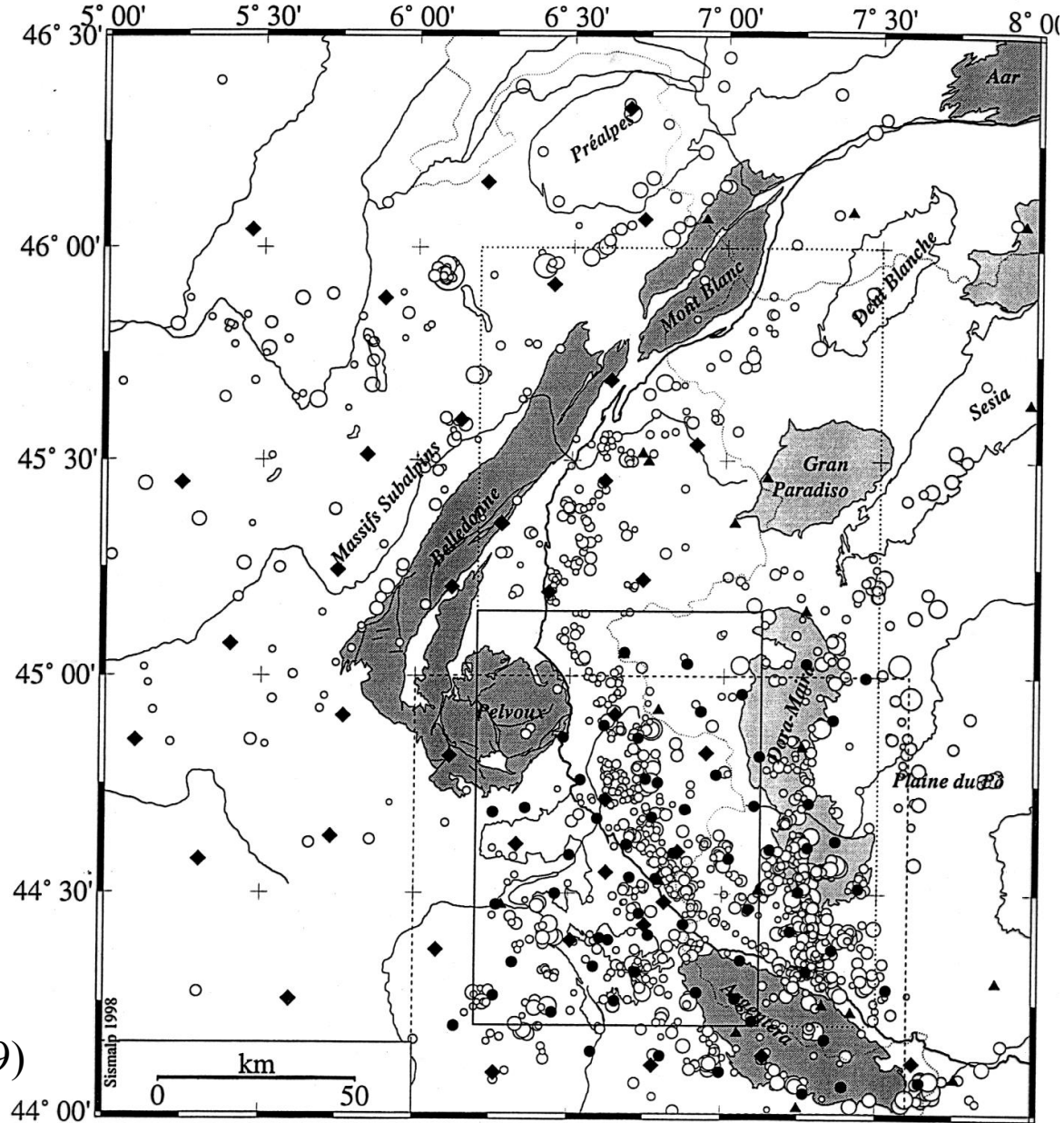
(D'après Sinclair)



(Bauve, thèse, 2013)

III. Calendrier et modèle d'évolution
des Alpes franco-italiennes; évolution récente;
réflexion sur la structure.

B. Evolution récente



(Sue et al., 1999)

Figure 3.7 - Localisation des réseaux Sismalp (losanges noirs), IGG (triangles noirs) et GéoFrance3D (disques noirs) dans l'arc alpin occidental, sur fond de sismicité instrumentale (Sismalp).
 Cadre plein : zone cible (chapitre III-2) ; cadre pointillé : zone élargie étudiée dans le chapitre III-3 ;
 cadre tireté : zone GéoFrance3D.

(Sue et al., 1999)

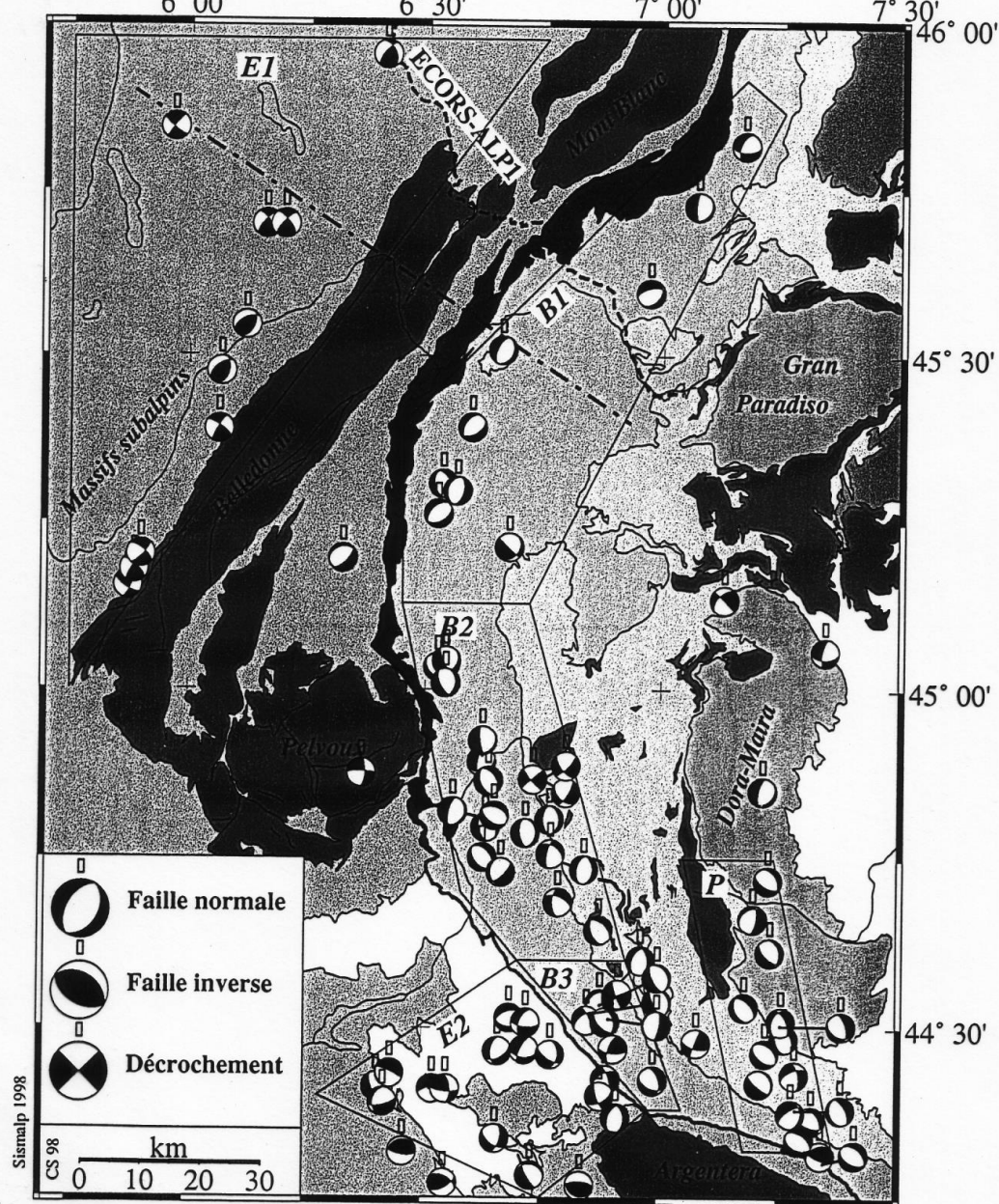
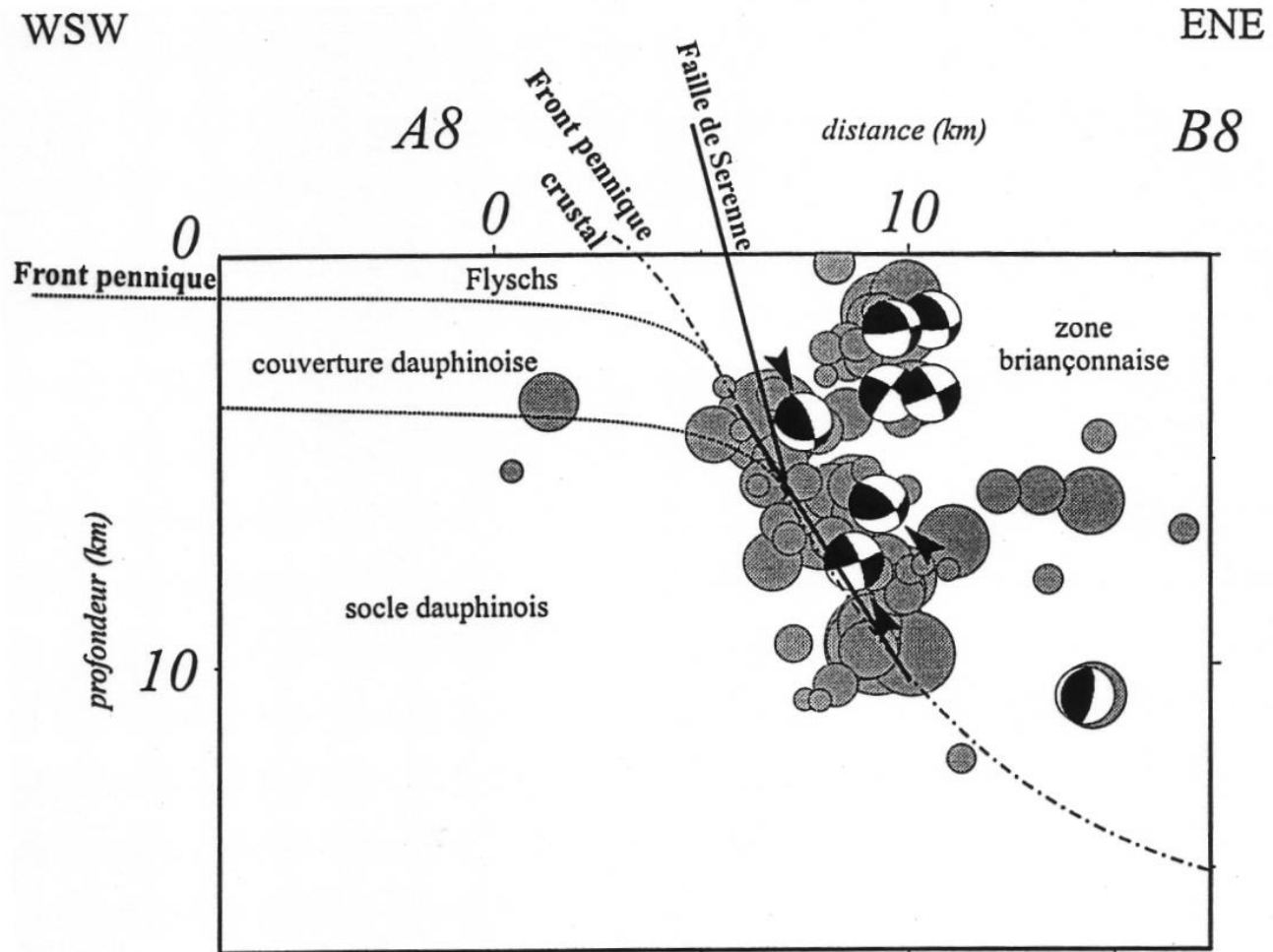
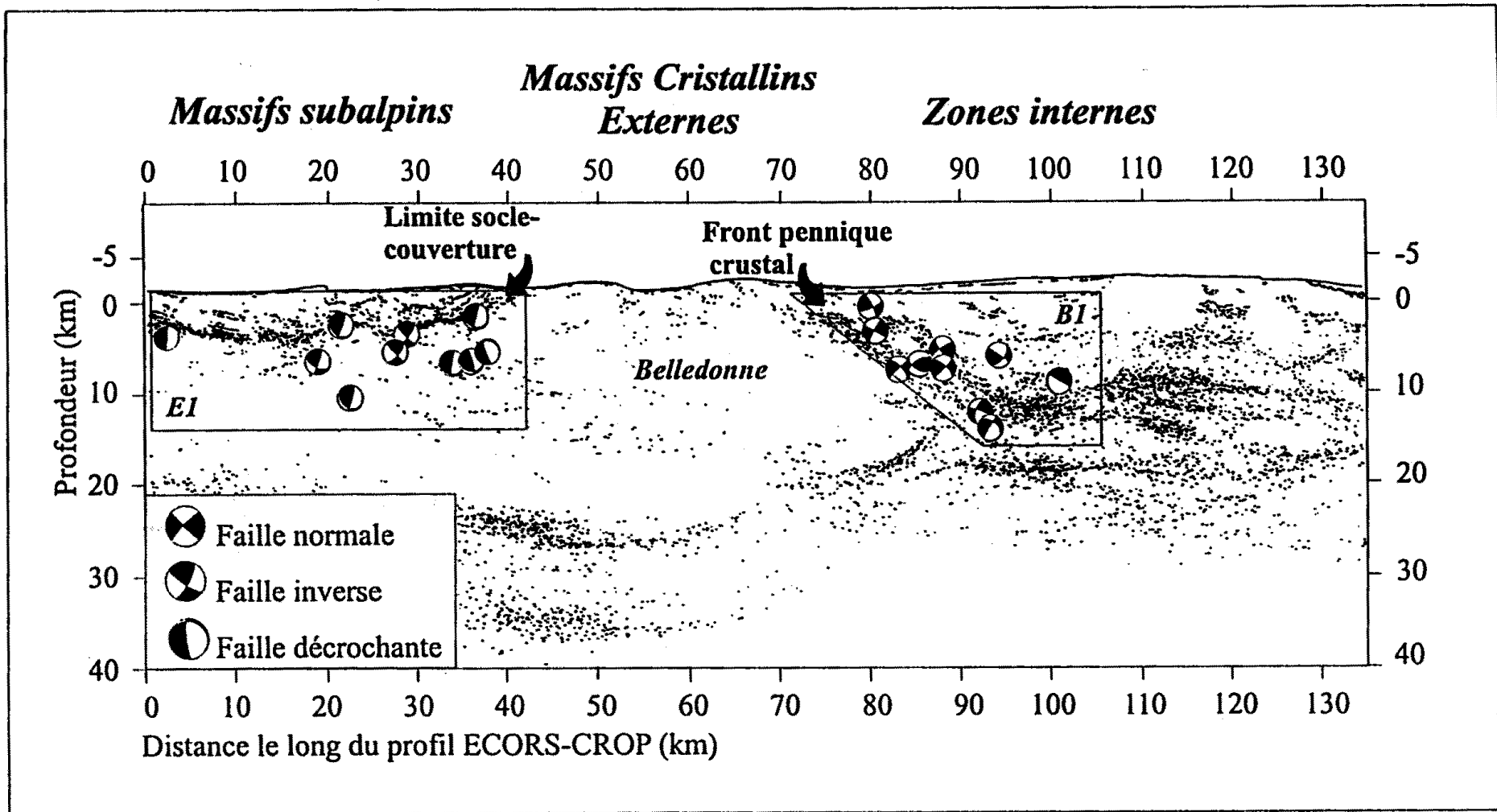


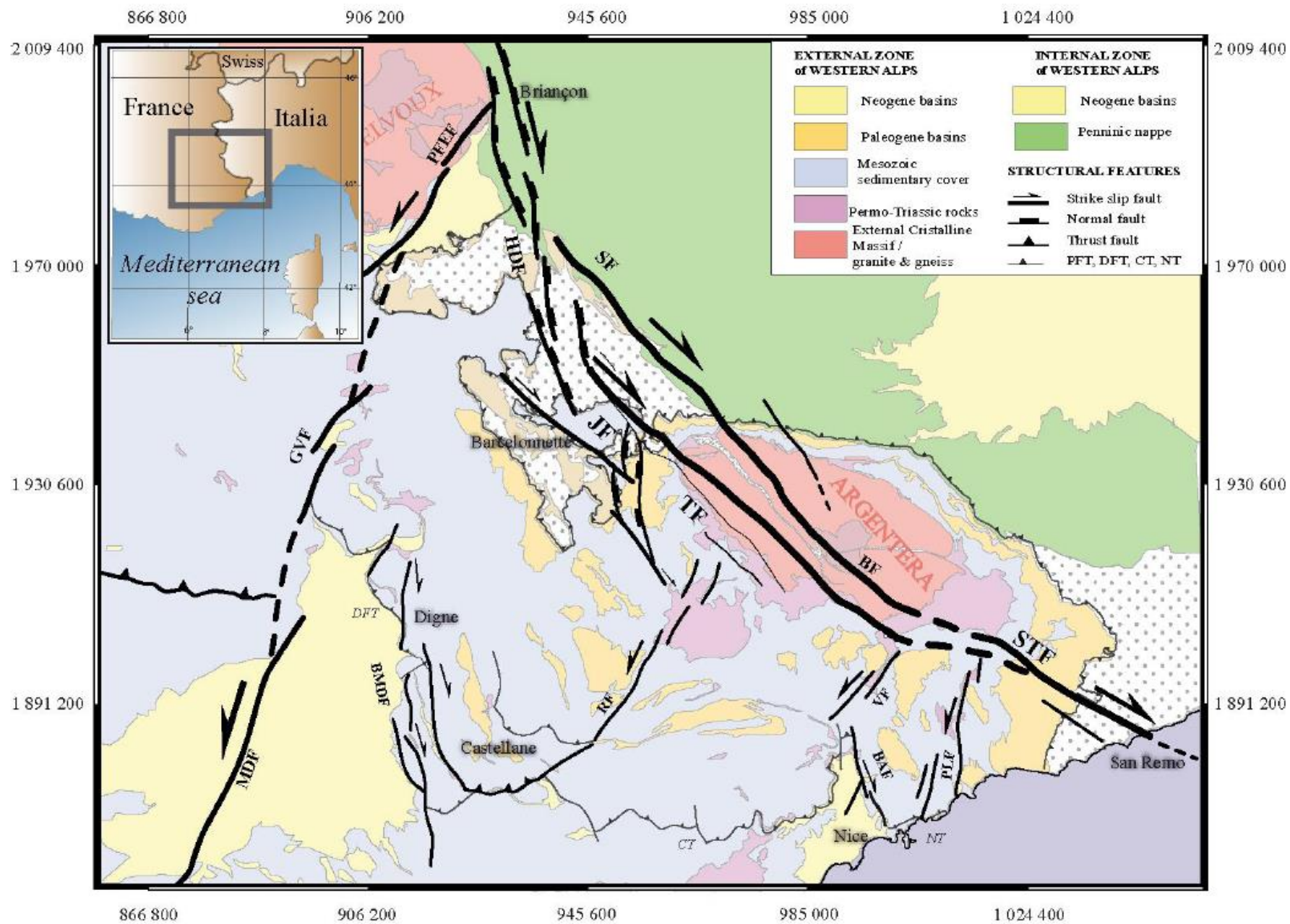
Figure 3.59 - Carte sismotectonique synthétique regroupant l'ensemble des solutions focales fiables accumulées dans cette partie avec les données Sismalp. Les zones E1, E2, B1, B2, B3 et P renvoient au chapitre III.4 sur l'inversion des solutions focales. Le trait pointillés situe la coupe de la figure 3.60.



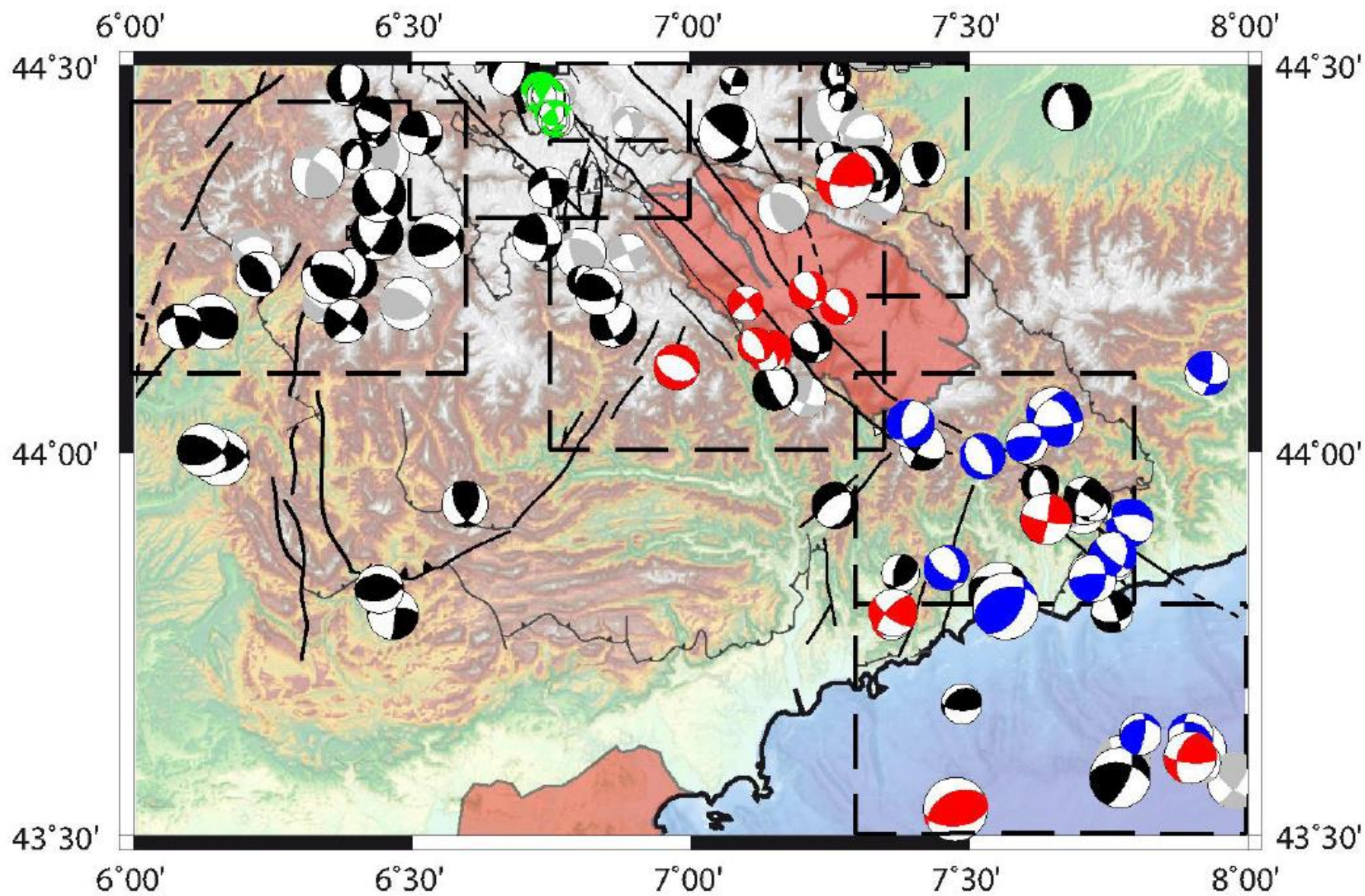
(Sue et al., 1999)



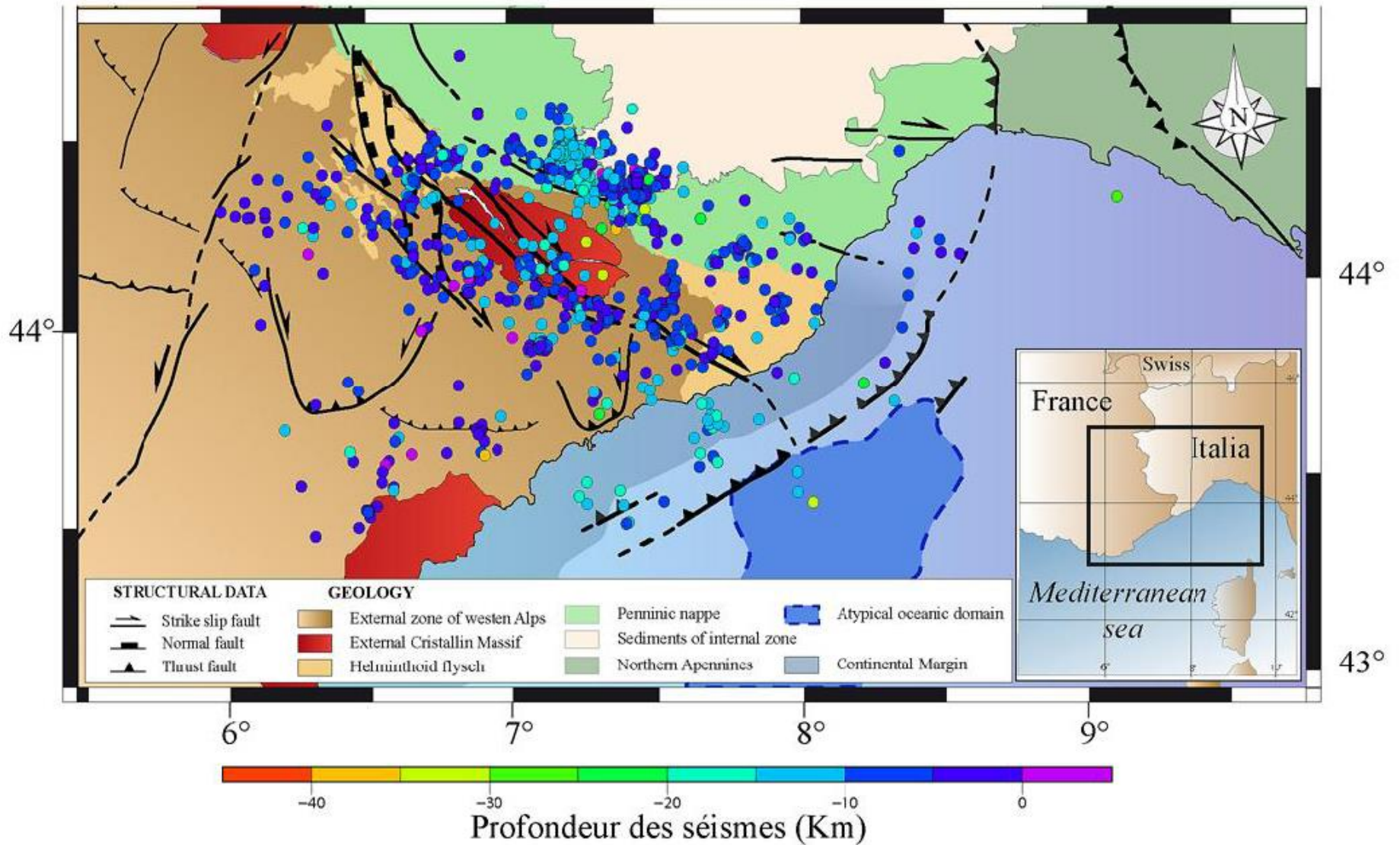
(Sue et al., 1999)



(Sanchez et al., 2010, 2011)



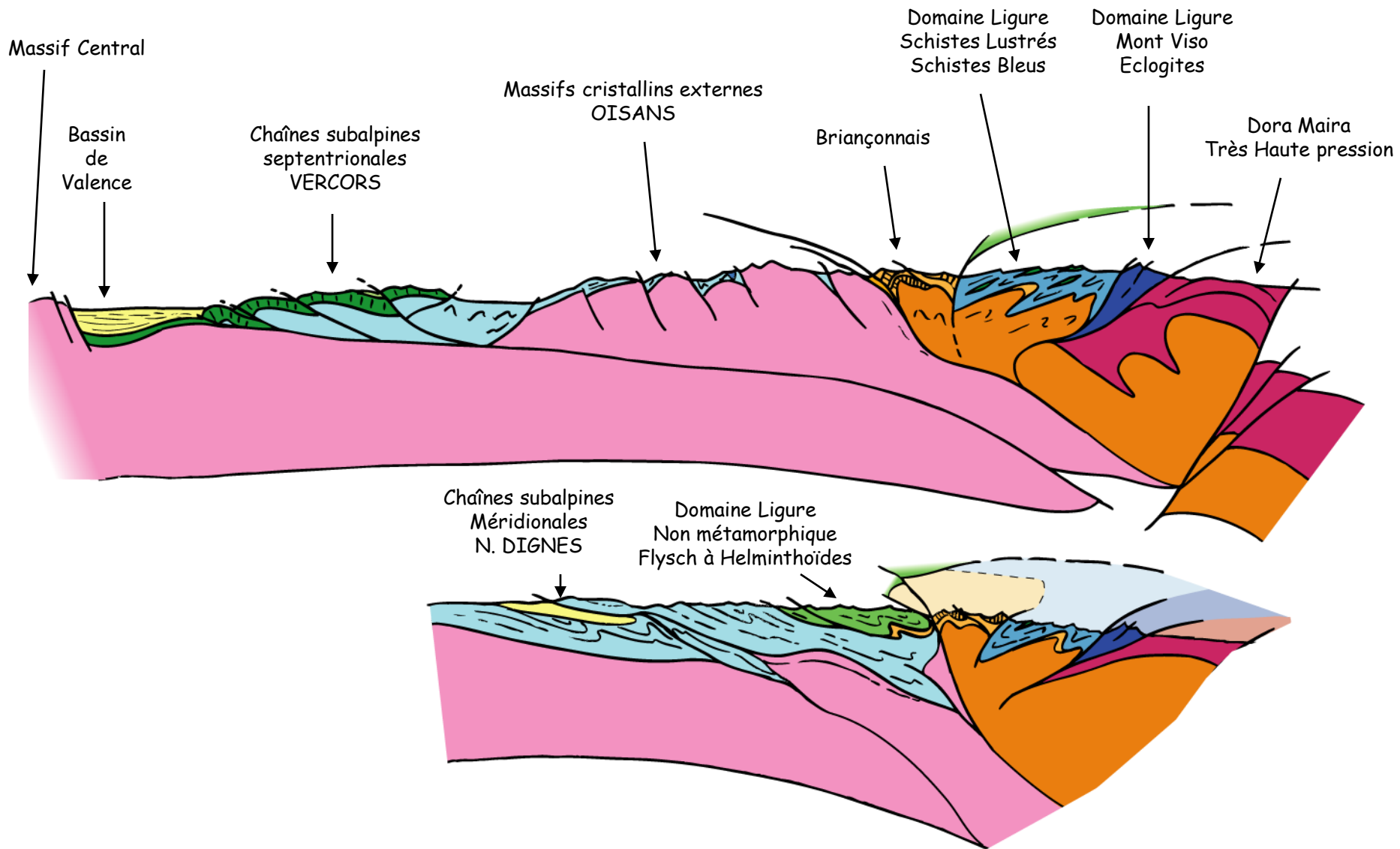
(Bauve, thèse, 2013)



(Bauve, thèse, 2013)

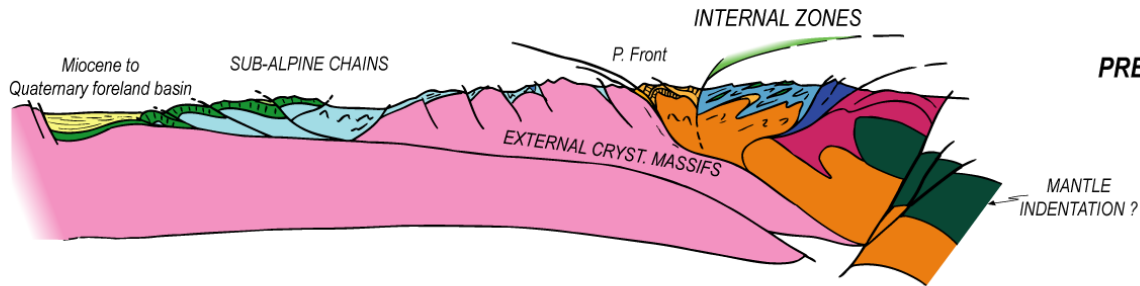
III. Calendrier et modèle d'évolution
des Alpes franco-italiennes; évolution récente;
réflexion sur la structure.

D. Une structure résultant
de l'emboîtement de 3 prismes
d'accrétion dans le temps et dans l'espace

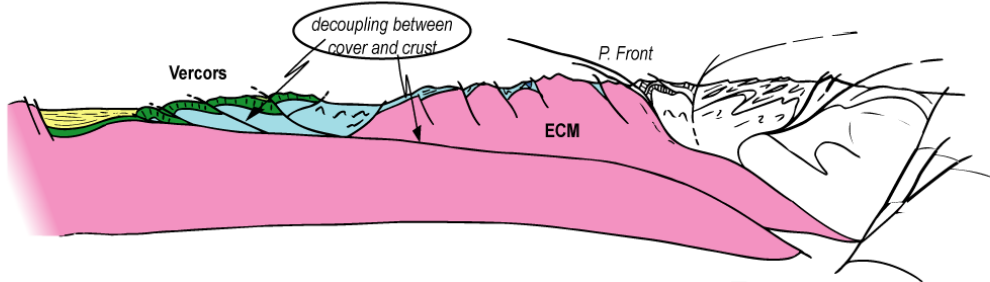


3 prismes emboîtés

(section across Vercors and the ECM)

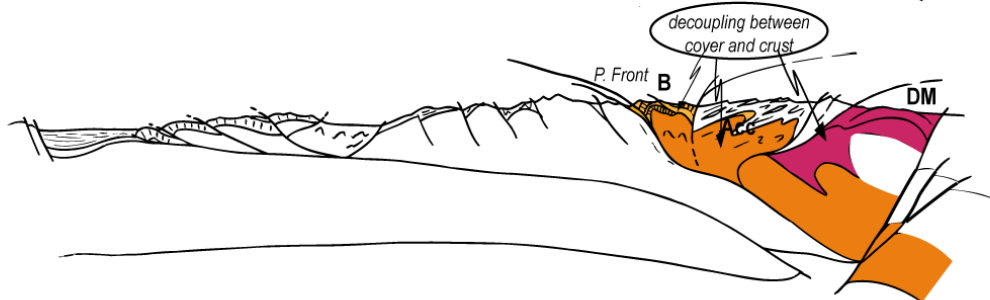


**PRESENT STATE: THE OROGENIC WEDGE
A LITHOSPHERIC-SCALE
ACCRETIONARY SYSTEM**



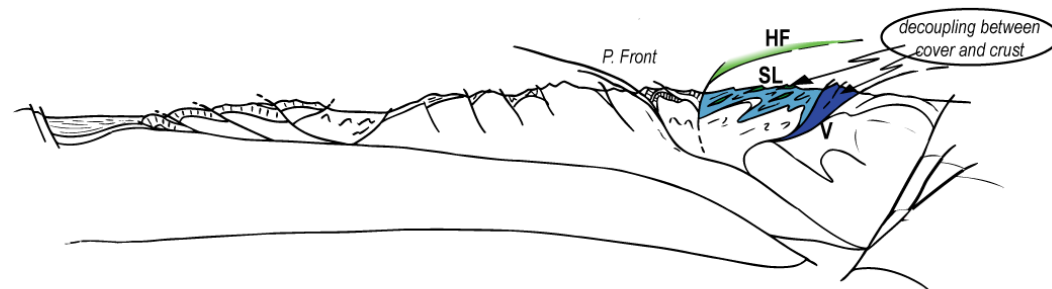
ACCRETION OF THE
EXTERNAL ZONES

3



REMNANTS OF AN EARLIER
ACCRETIONARY SYSTEM:
THE THINNED CONTINENTAL CRUST
= BRIANCONNAIS

2

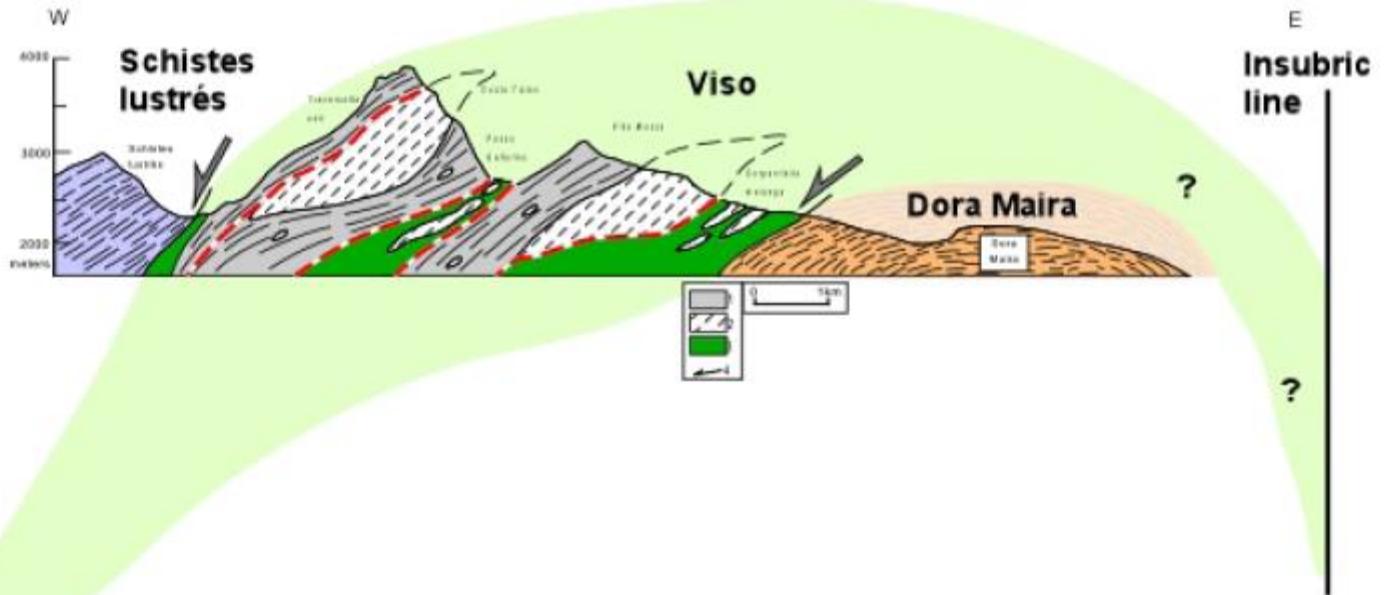


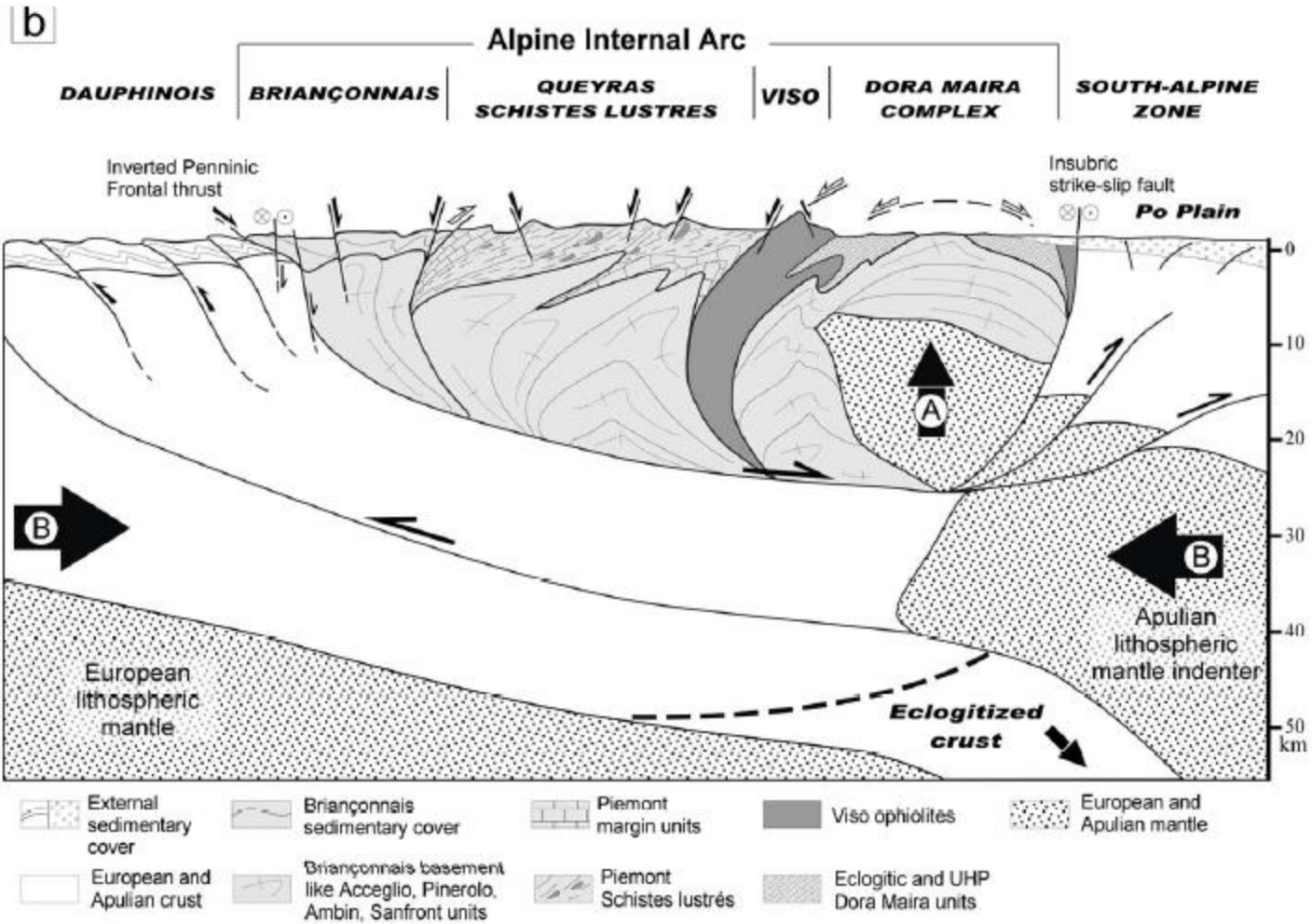
REMNANTS OF THE EARLIEST
ACCRETIONARY SYSTEM:
THE OCEANIC ACCRETIONARY WEDGE
= LIG.-PIEMONTESE

1

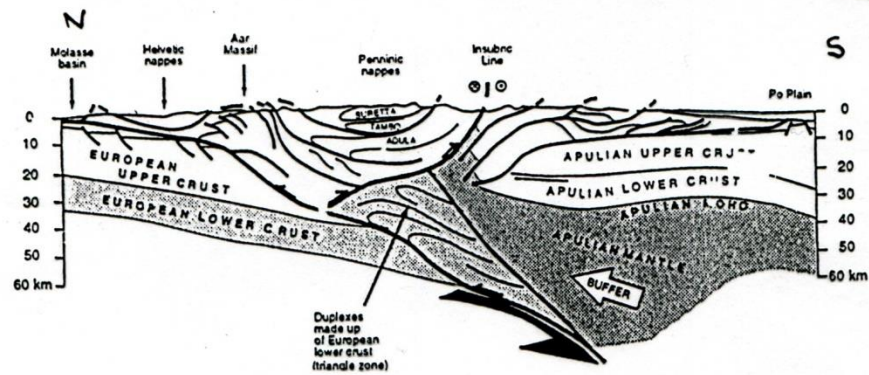
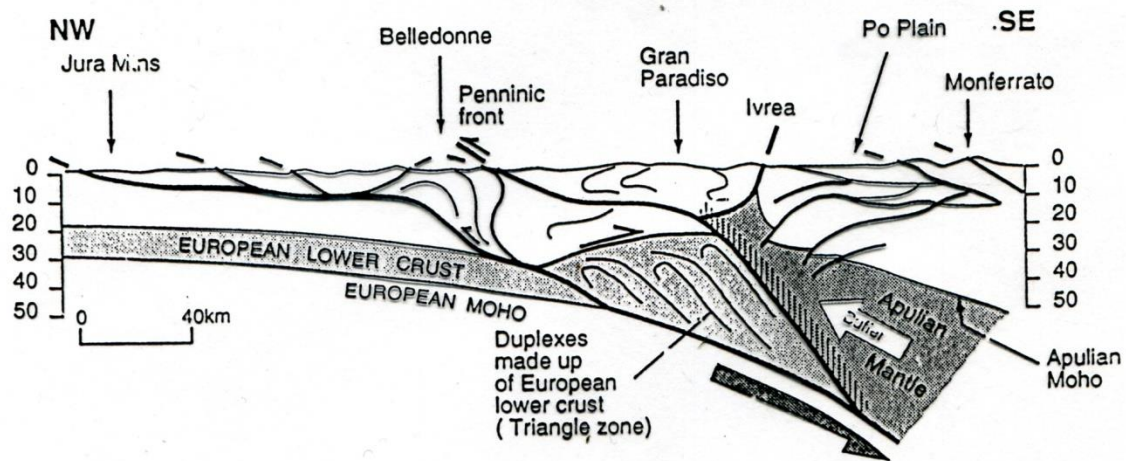
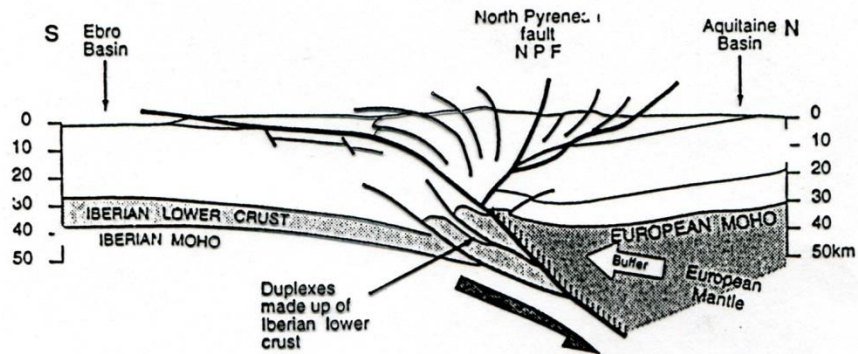
THREE IMBRICATED ACCRETIONARY SYSTEMS

- REMARKABLE FEATURES**
- 3 time intervals
 - 3 imbrication scales
 - decoupling between crust and cover





(Lardeaux et al., 2006)

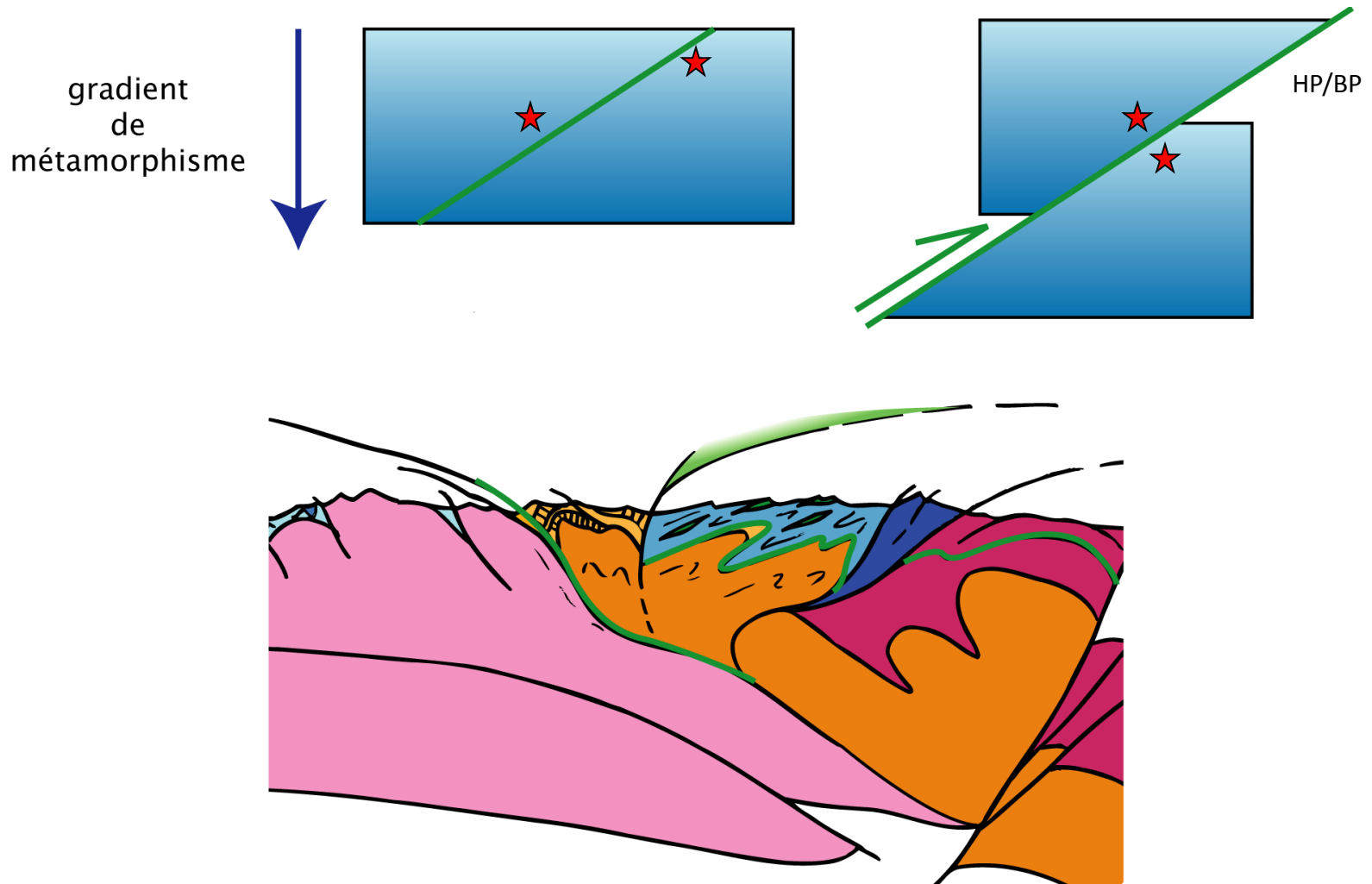


III. Calendrier et modèle d'évolution
des Alpes franco-italiennes; évolution récente;
réflexion sur la structure.

E. Éléments de brainstorming alpin

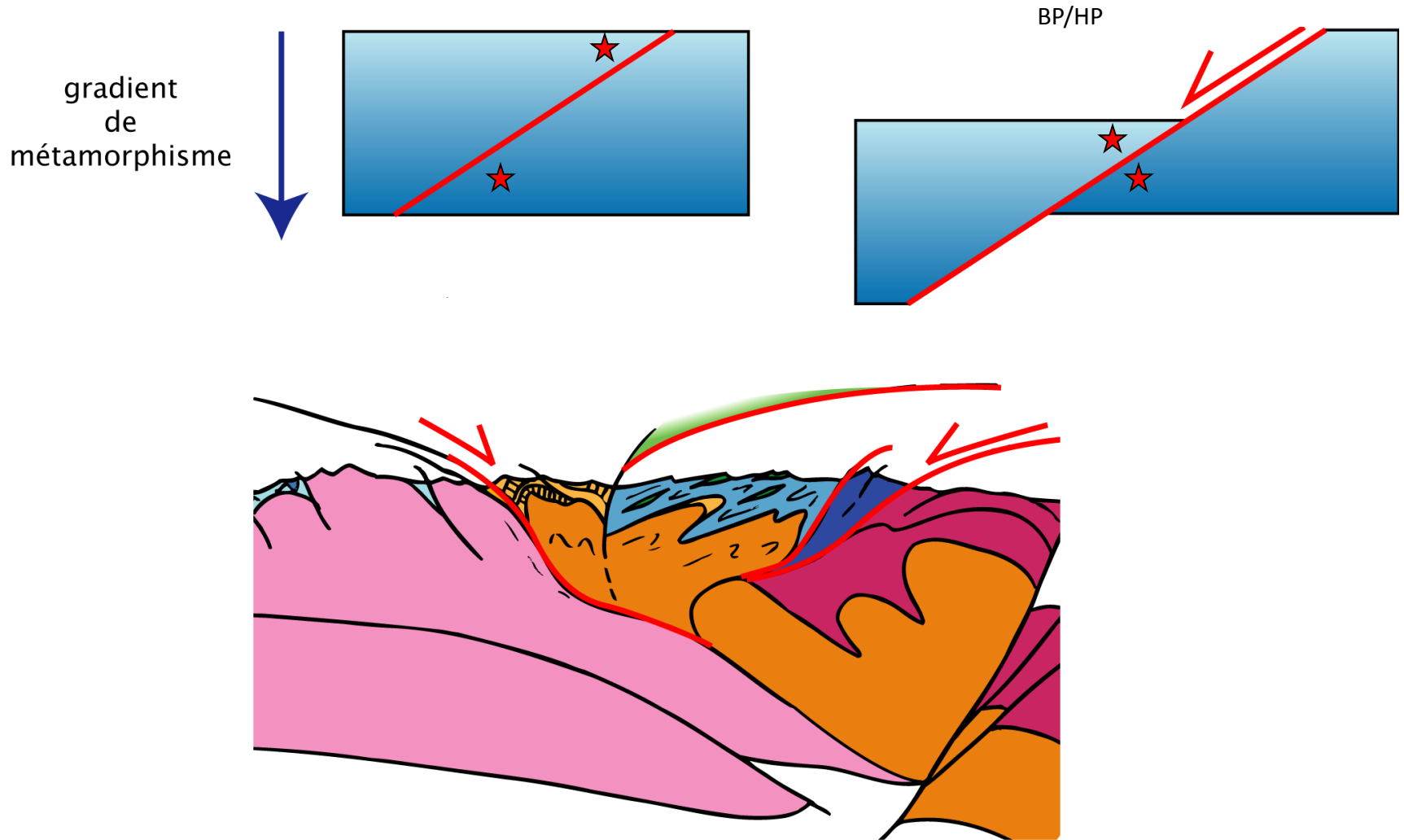
La signification
des principaux contacts tectoniques

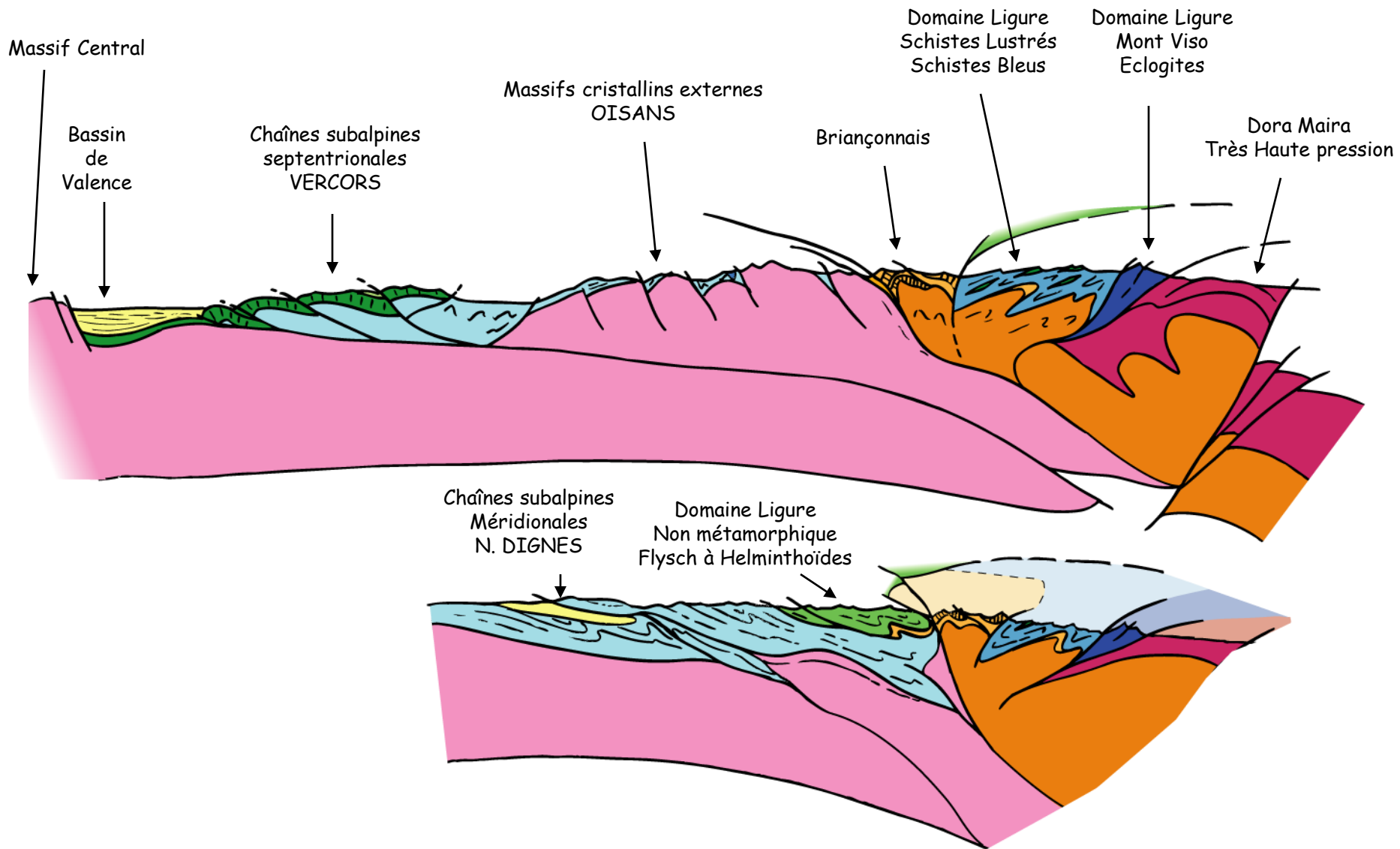
« chevauchement »



Les chevauchements épaississent la croûte

« détachement »

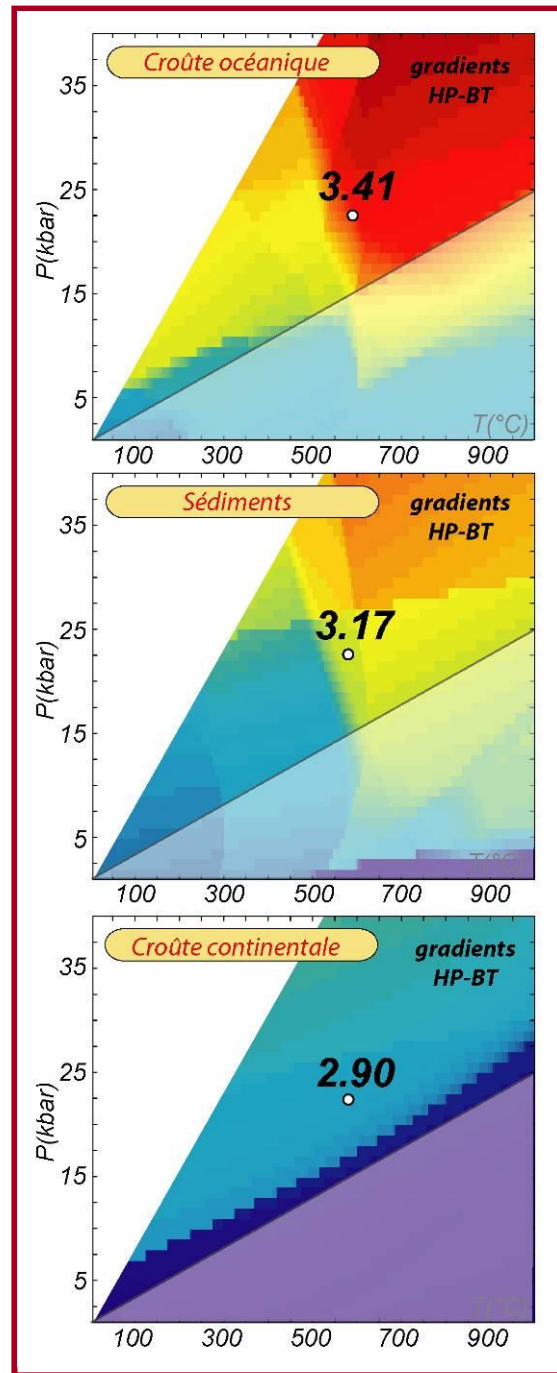
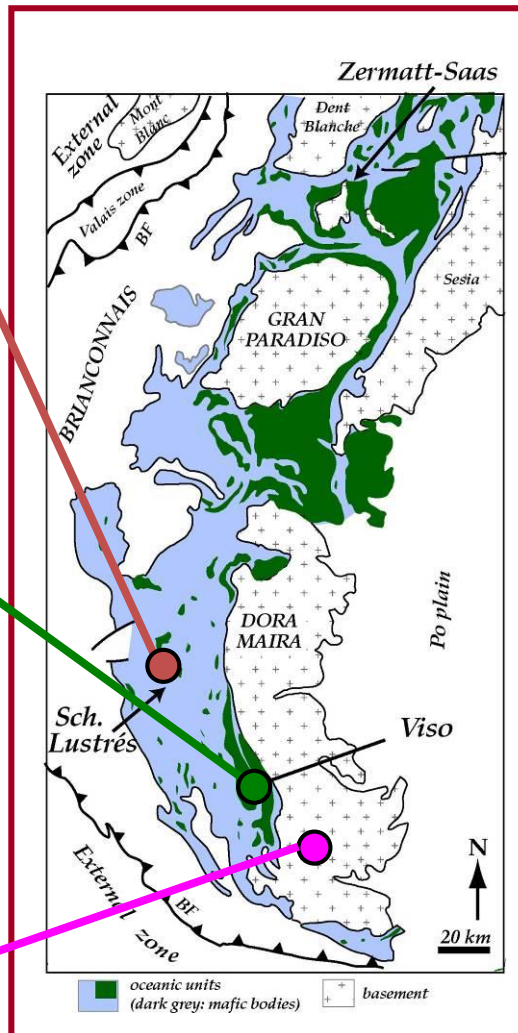
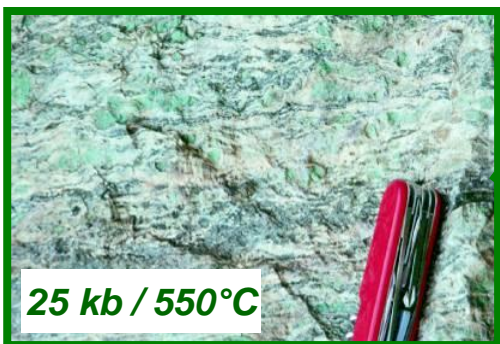
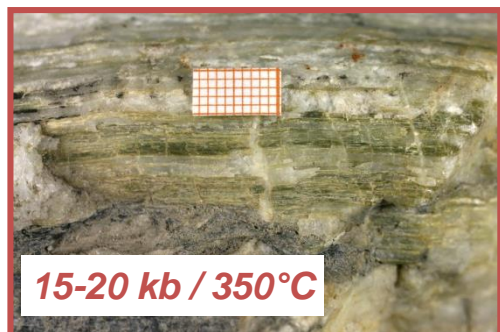




3 prismes emboîtés

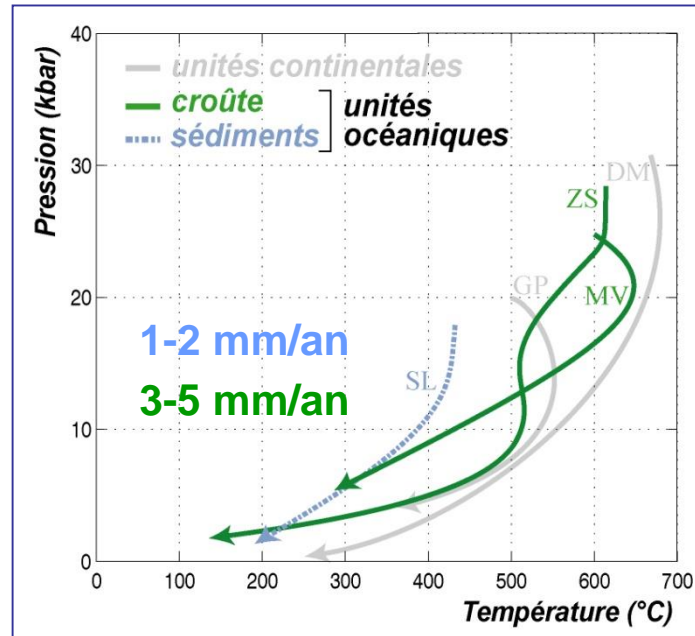
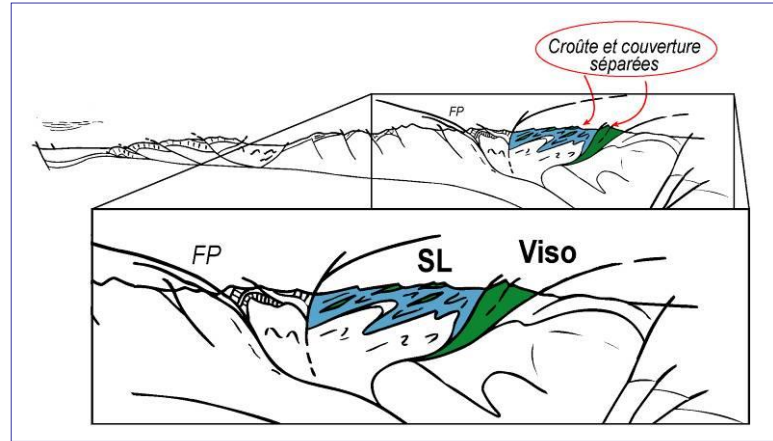
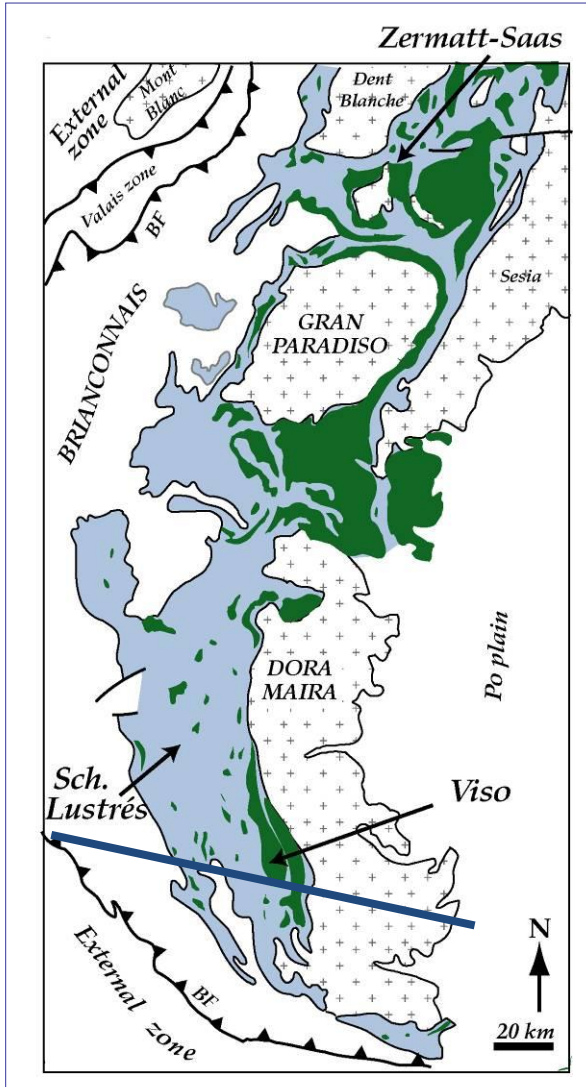
Subduction, exhumation...

Des matériaux mis en jeu différents

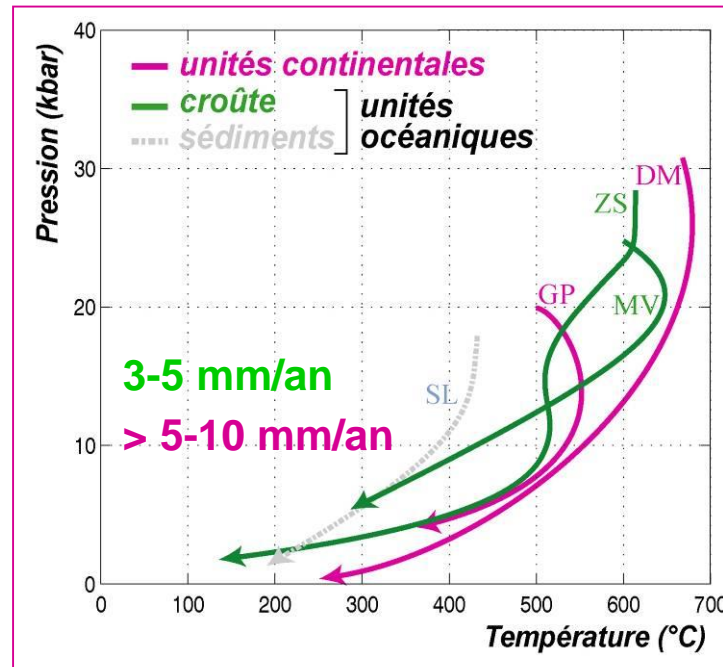
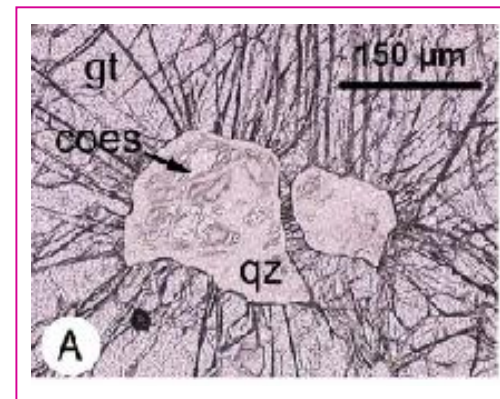
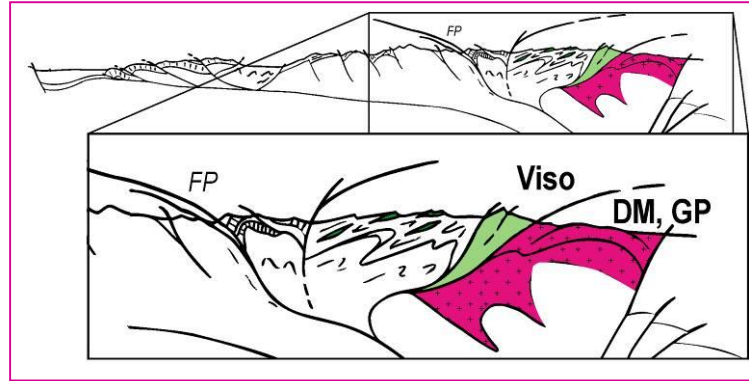
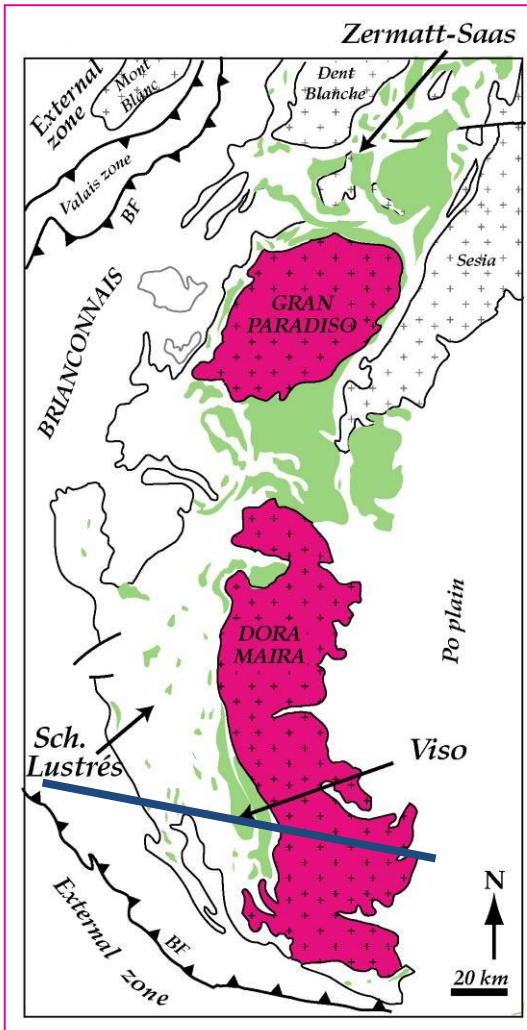


... avec des densités bien particulières

La subduction océanique



La subduction continentale



Observations importantes

- Exhumation de la marge subduite

- Conditions P-T-t et Vitesses d'exhumation

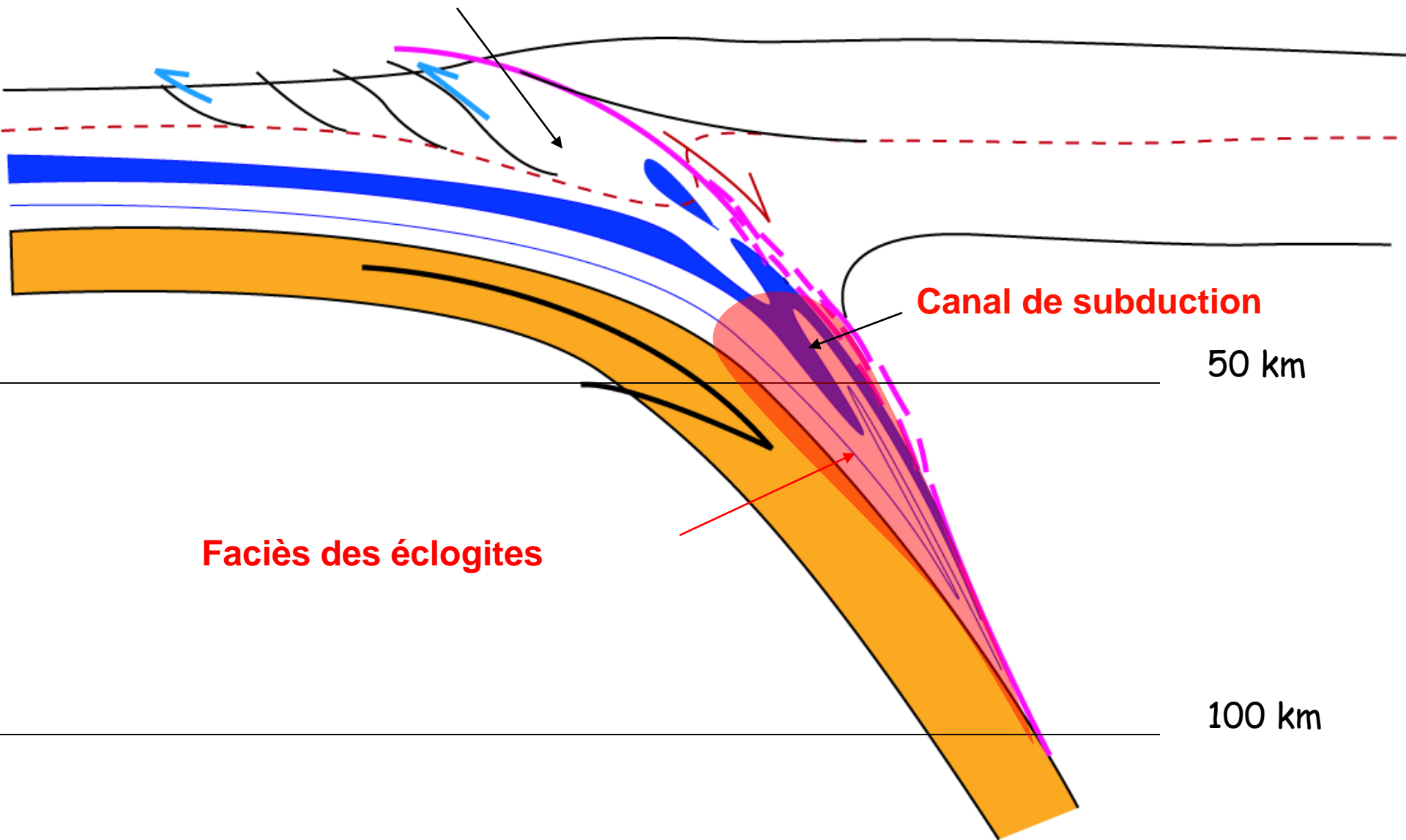
3-5 mm/an

> 5-10 mm/an

- Forte ressemblance avec l'exhumation de matériel océanique

Présence de roches métamorphisées à très grande profondeur,
plus profondément que le prisme d'accrétion

Prisme d'accrétion



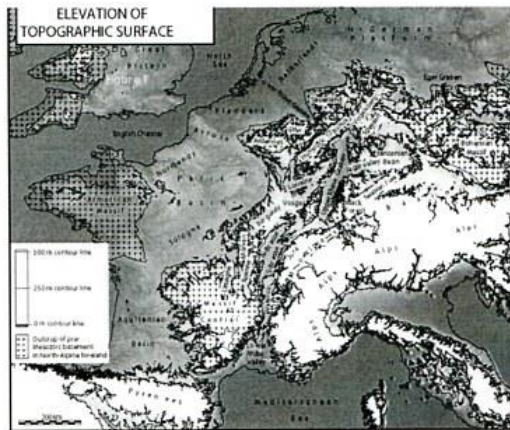
Canal de subduction

50 km

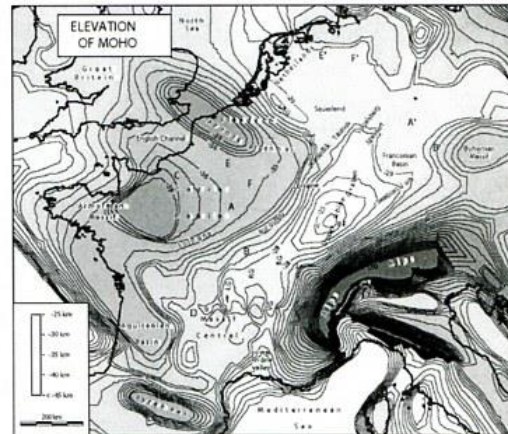
Faciès des éclogites

100 km

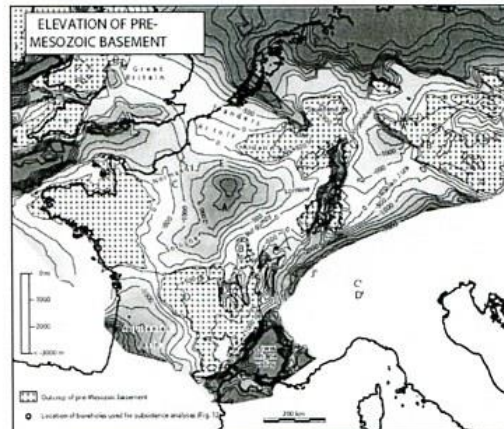
Un flambage lithosphérique alpin
dans l'avant-pays ?



Topographic map. The NW Alpine foreland is composed of topographic blocks (elevations above +250 m), where the pre-Mesozoic basement crops out, alternating with topographic basins (elevations below +250 m), where Mesozoic sediments have been deposited. The ECDS forms a system of linear topographic troughs.

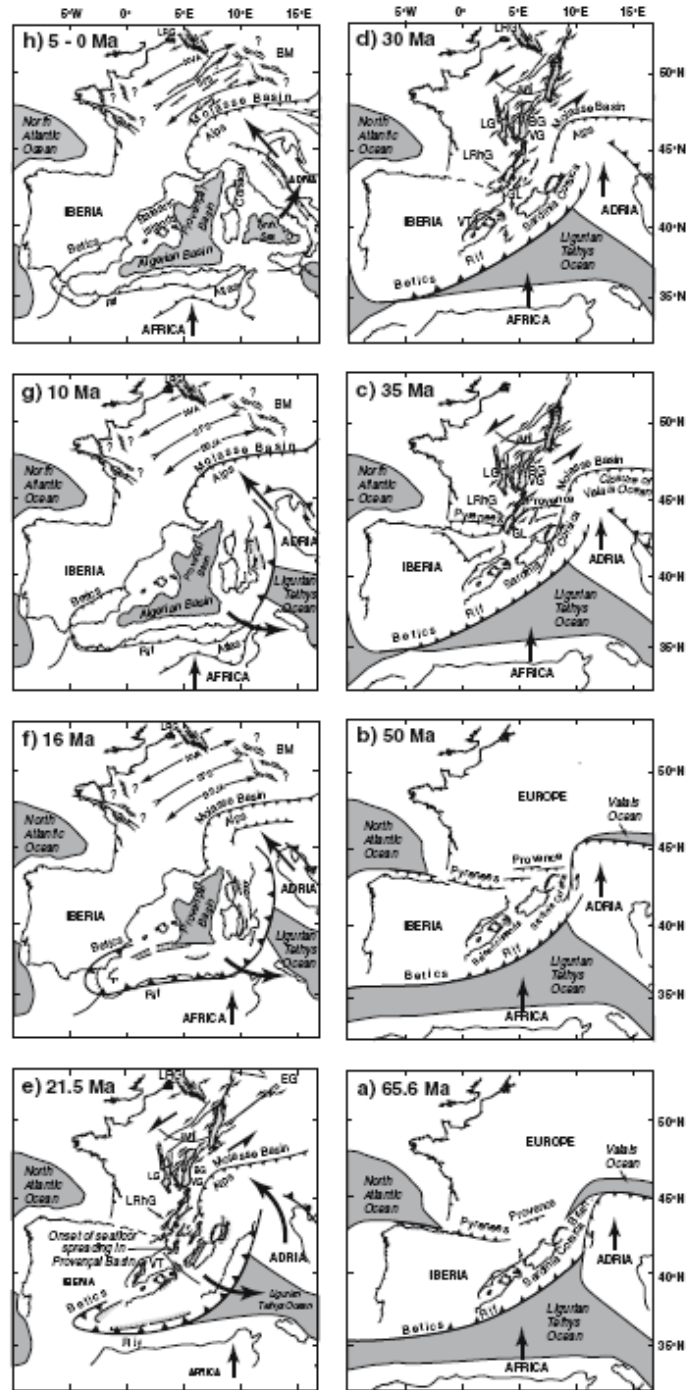


Contoured elevation map of the Moho in the NW Alpine foreland (adapted from Diets et al., 2006). Grabens: J. Jura Graben and thrust belt, LG. Lower Rhine Graben, LG. Lower Rhine Graben, V. Vosges, VG. Valence Graben, BF. Black Forest, BG. Bresse.



(Bourgeois et al., 2007)

Structural maps showing the evolution of the Alpine orogen and of its foreland during the Cenozoic. Geodynamic evolution of Mediterranean region after Lacombe and Jolivet (2005); location and geometry of faults in foreland after Dézes et al. (2004). Development of Jura thin-skinned fold-and-thrust belt (from 11 Ma onwards) not shown for clarity of drawing. *NVA* Normandy–Vogelsberg Anticline, *BSJA* Burgundy–Swabian Jura Anticline, *BG* Bresse Grabens, *BM* Bohemian Massif, *EG* Eger Graben, *GL* Gulf of Lion, *LG* Limagne Graben, *LRG* Lower Rhine Graben, *LRhG* Lower Rhône Grabens, *SFS* Sologne–Franconian Basin Syncline, *VT* Valencia Trough



(Bourgeois et al., 2007)

