Ocean crust in the mountains (ophiolitic series and orogenesis)

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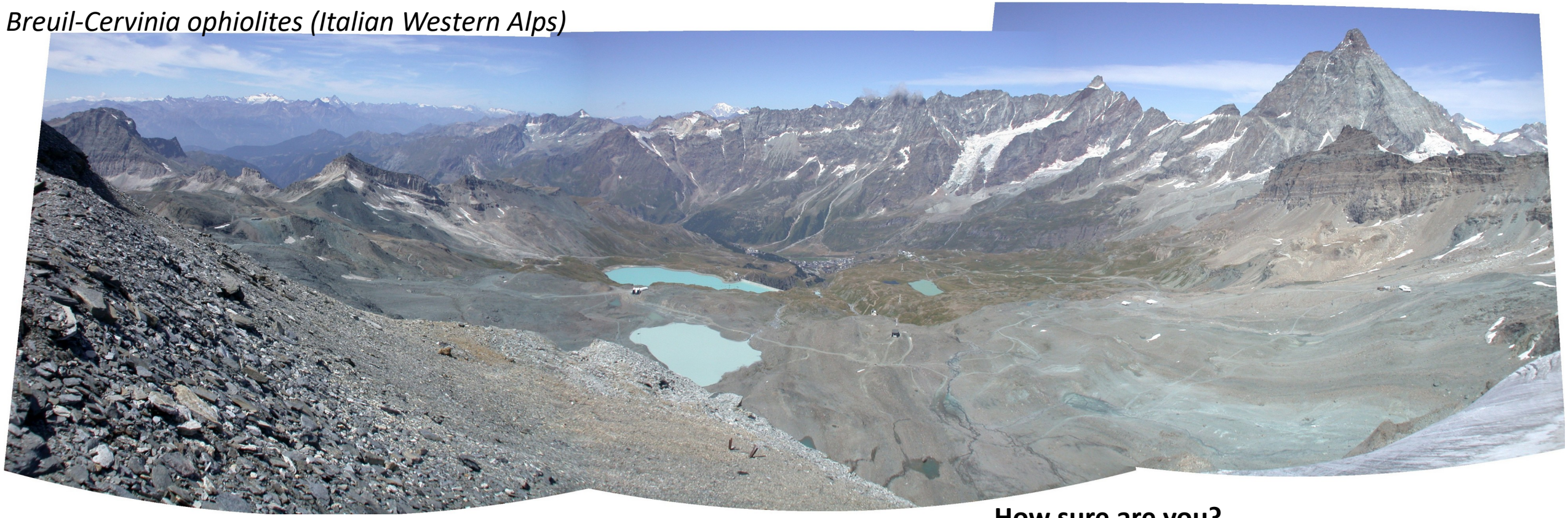
Czech Geological Survey (Praha, Czech Republic)

Breuil-Cervinia ophiolites (Italian Western Alps)



How sure are you?

Ophiolitic series =
Memory of lost oceans in mountain belts

Where are they emplaced in the orogens?
When are they emplaced during orogenic history?
How are they emplaced in the orogens?

Three major issues but first a bit of history….

A bit of history….

The etymology of the term « **ophiolite** » comes from the Greek « *ophios* »: snake and « *lithos* »: stone, in reference to the surface texture of some serpentinites that evoke the skin of these reptiles.

The term "**ophiolite**" was first used by Brongniart, A. (1813) to describe a sequence of green rocks (serpentinites, basalts) in the Alps.

Gastaldi, B. (1871); Lotti, B. (1885, 1886):
Brongniart's ophiolite association is « common » in Italian Alps and Appenines

Suess, F.E. (1875, 1909): **In the Alps, ophiolites are located along main thrusts.**

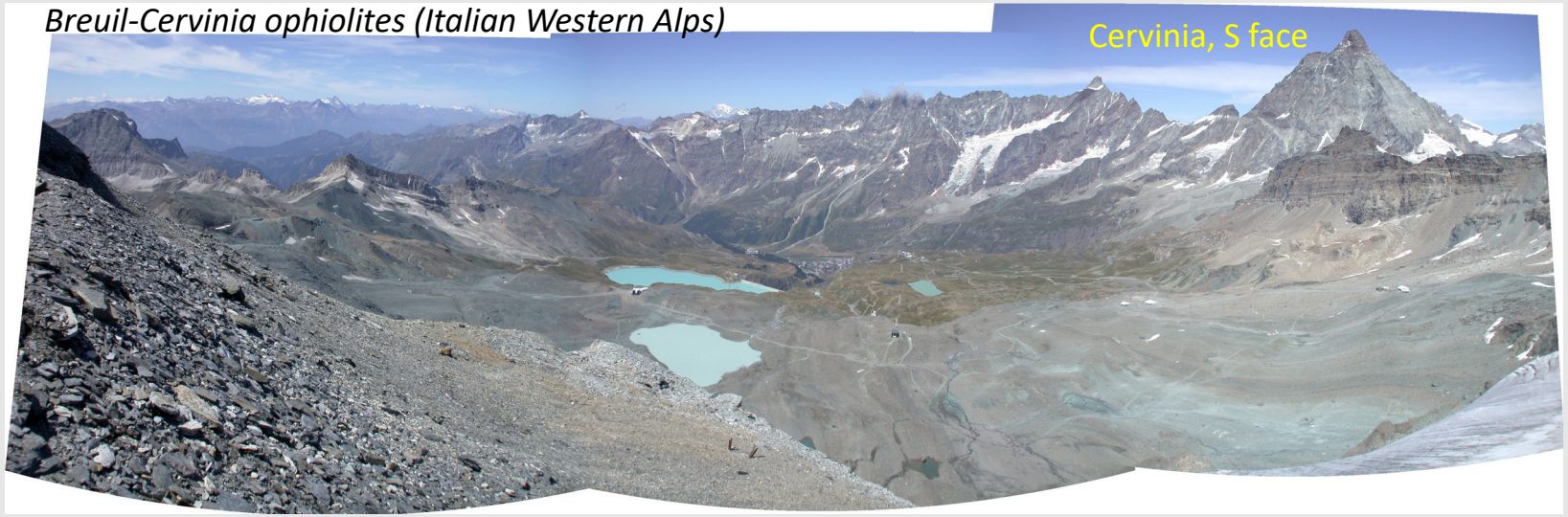
Lotti, B. (1886, 1910): **Ophiolites are submarine lava flows.**

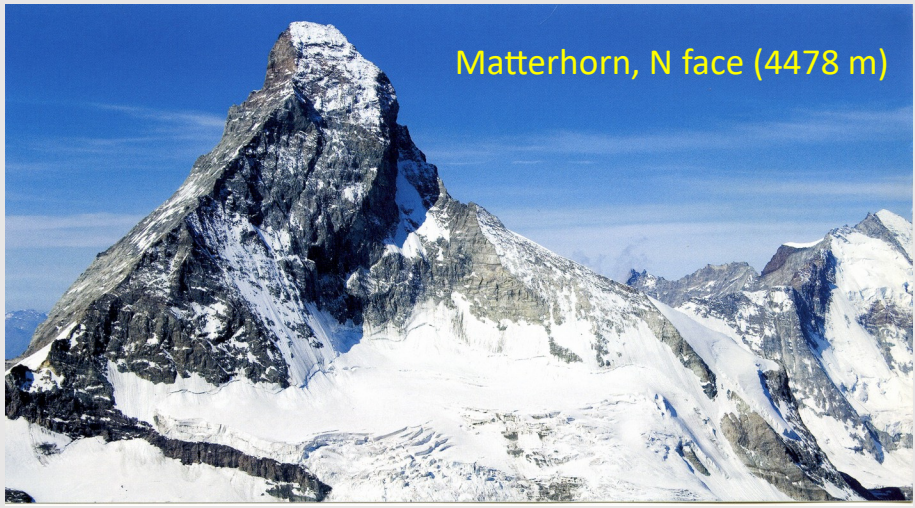
Teall, J.J.H. (1894): **Greenstones are associated with radiolarian cherts => deep-sea lavas (Palaeozoic British Isles).**

Pantanelli, D. (1880); Franchi S., Mattirolo E., Novarese V., Stella A. & Zaccagna D. (1908) :

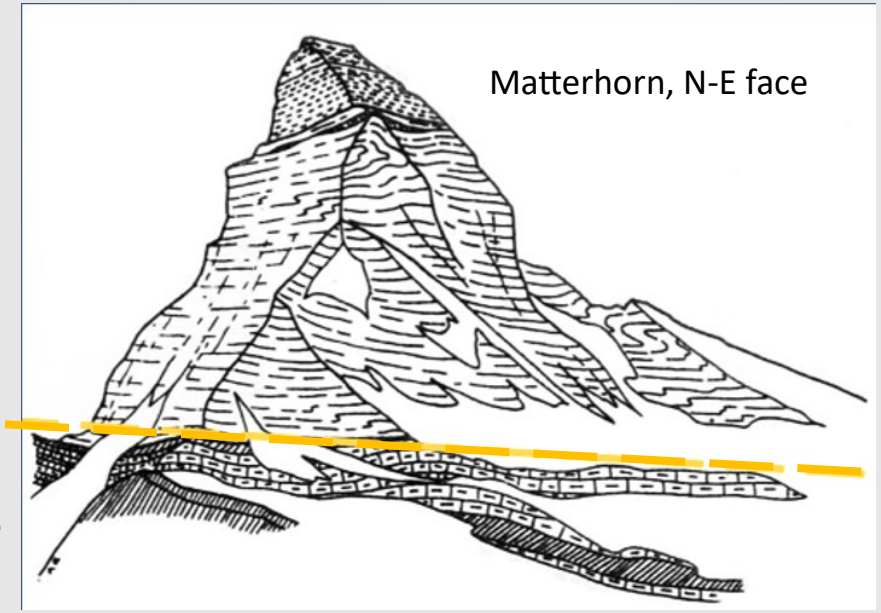
The "Pietre Verdi" from Piemontese Alps and Tuscany = Various greenstones (green basalts) closely associated with ancient marine sediments => marine area closed due to the formation of mountain belts !

Breuil-Cervinia ophiolites (Italian Western Alps)





Argand, E. (1911, 1916, 1924)



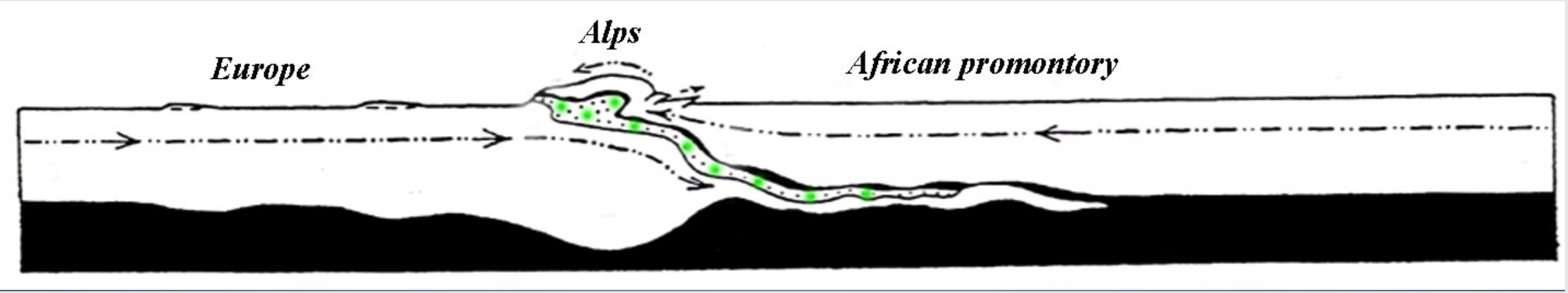
Various types of gneiss
= Continental crust

Pietre Verdi and calcschists
« ***Schistes Lustrés*** »

Marine basin

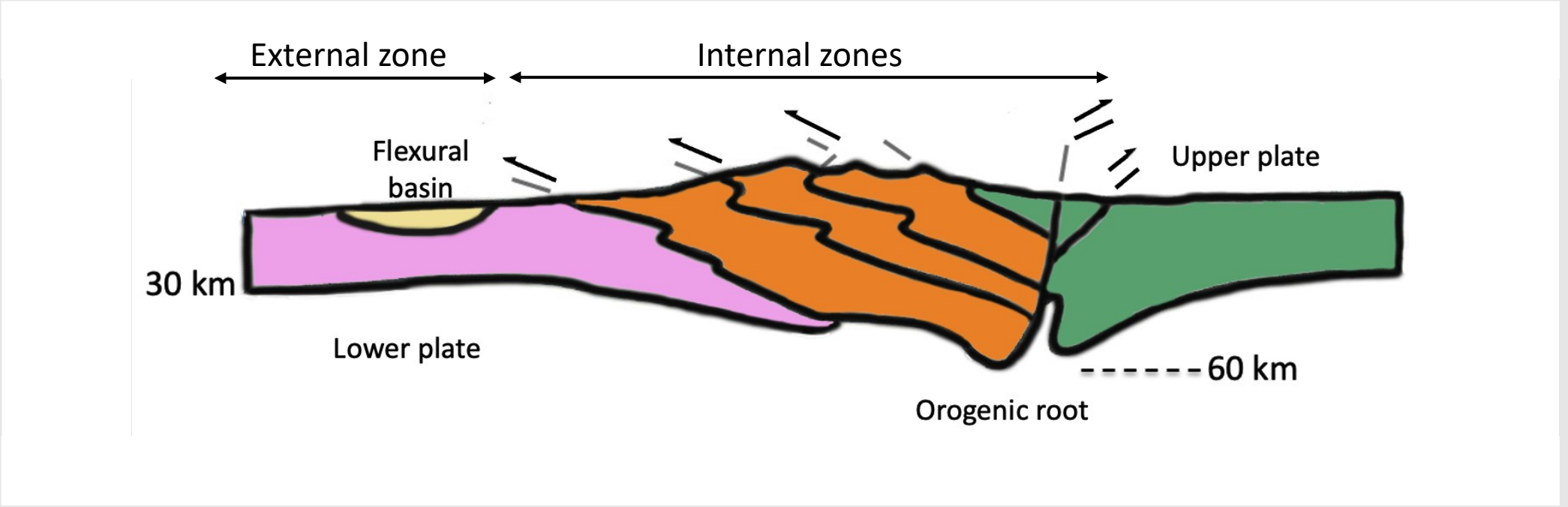
Argand, E. (1911, 1916, 1924) :

Orogenesis = Collision between continents that move horizontally and involves closures of “seas”.



Steinmann, G. (1905, 1927) : **Alpine ophiolites** = « ***Trilogy*** » **combining almost systematically ultramafic rocks (serpentinites), mafic rocks (basalts, gabbros) and pelagic marine sediments => « *Steinmann Trinity* ».**

Typical, crustal-scale, architecture of collision belts



External zone:
Deformed but weakly metamorphosed rocks from the lower plate.
Flexural basin=Molassic basin (foreland basin).

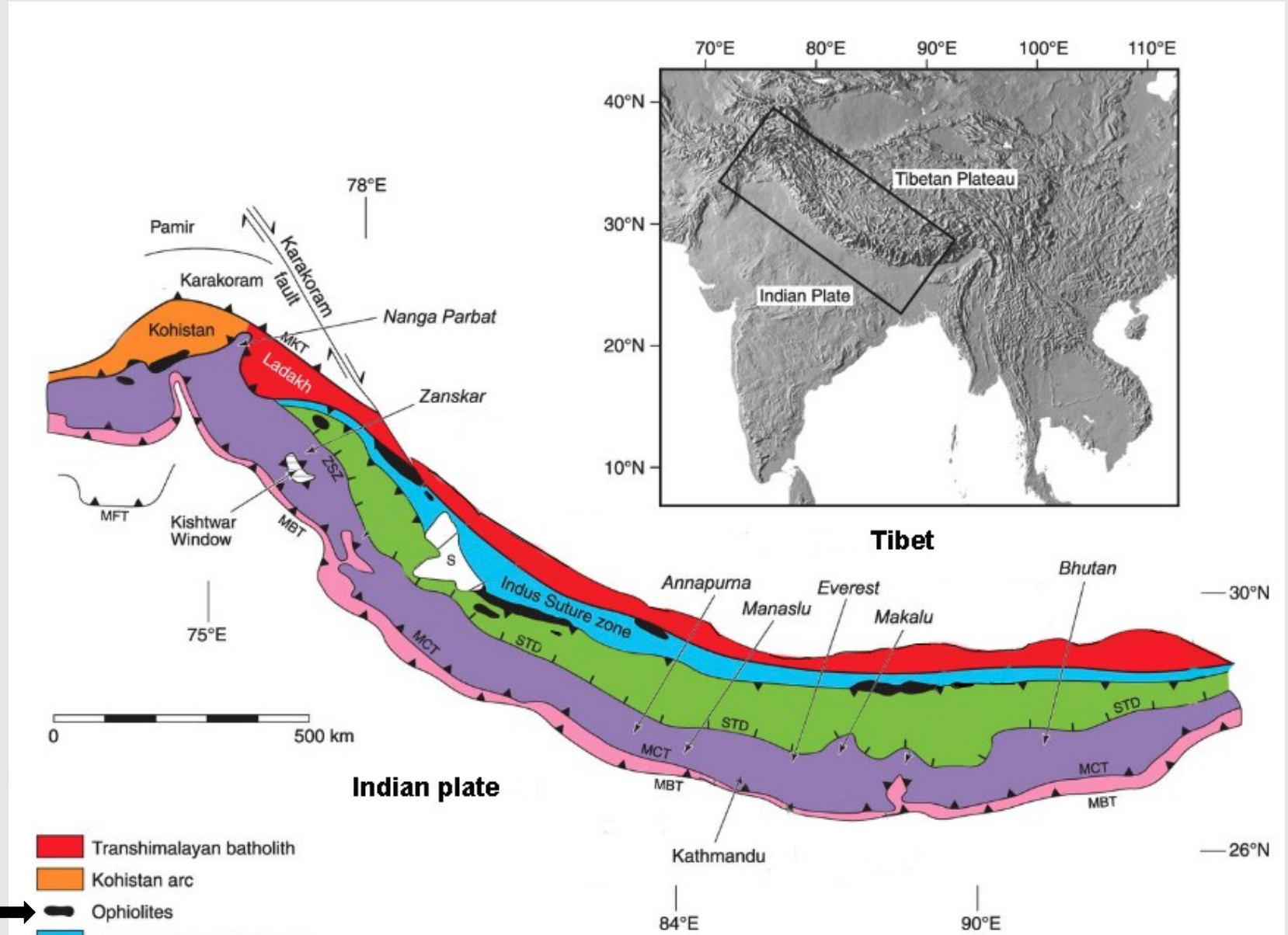
Internal zones:
Severely deformed and metamorphosed rocks from lower and/or upper plate.
« Orogenic wedge ».

WHERE?

The Himalayan example:
An emblematic continental collision belt

Indian plate: Lower plate
Tibet: Upper plate

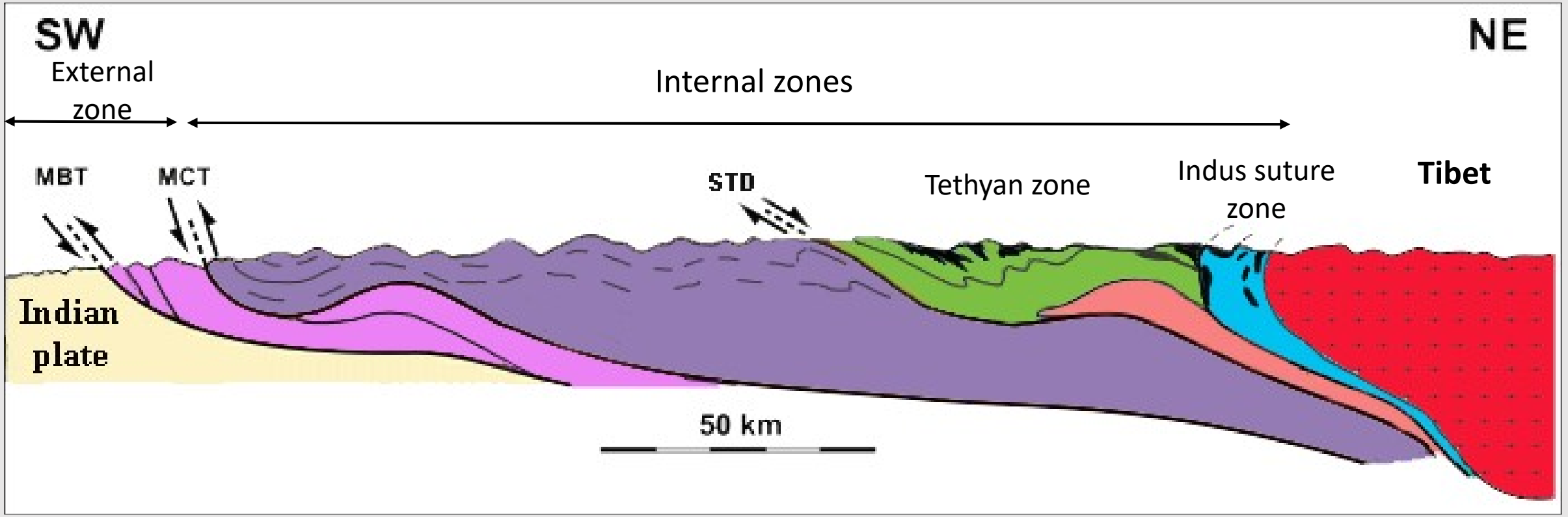
Main ophiolitic sequences →



Simplified tectonic map of the Himalaya

WHERE?

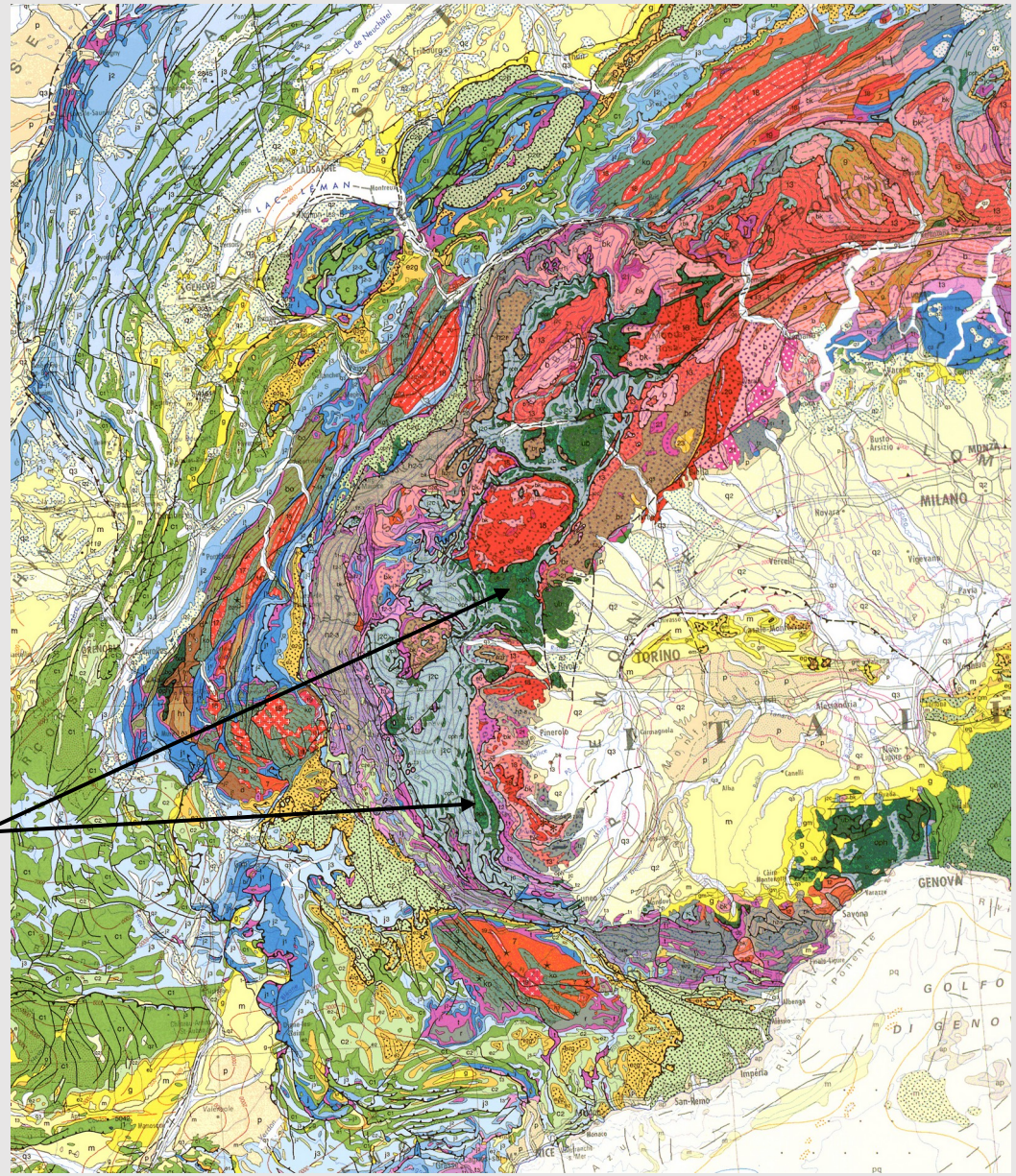
Ophiolites: In the innermost areas of the orogenic prism in association with metasediments.



WHERE?

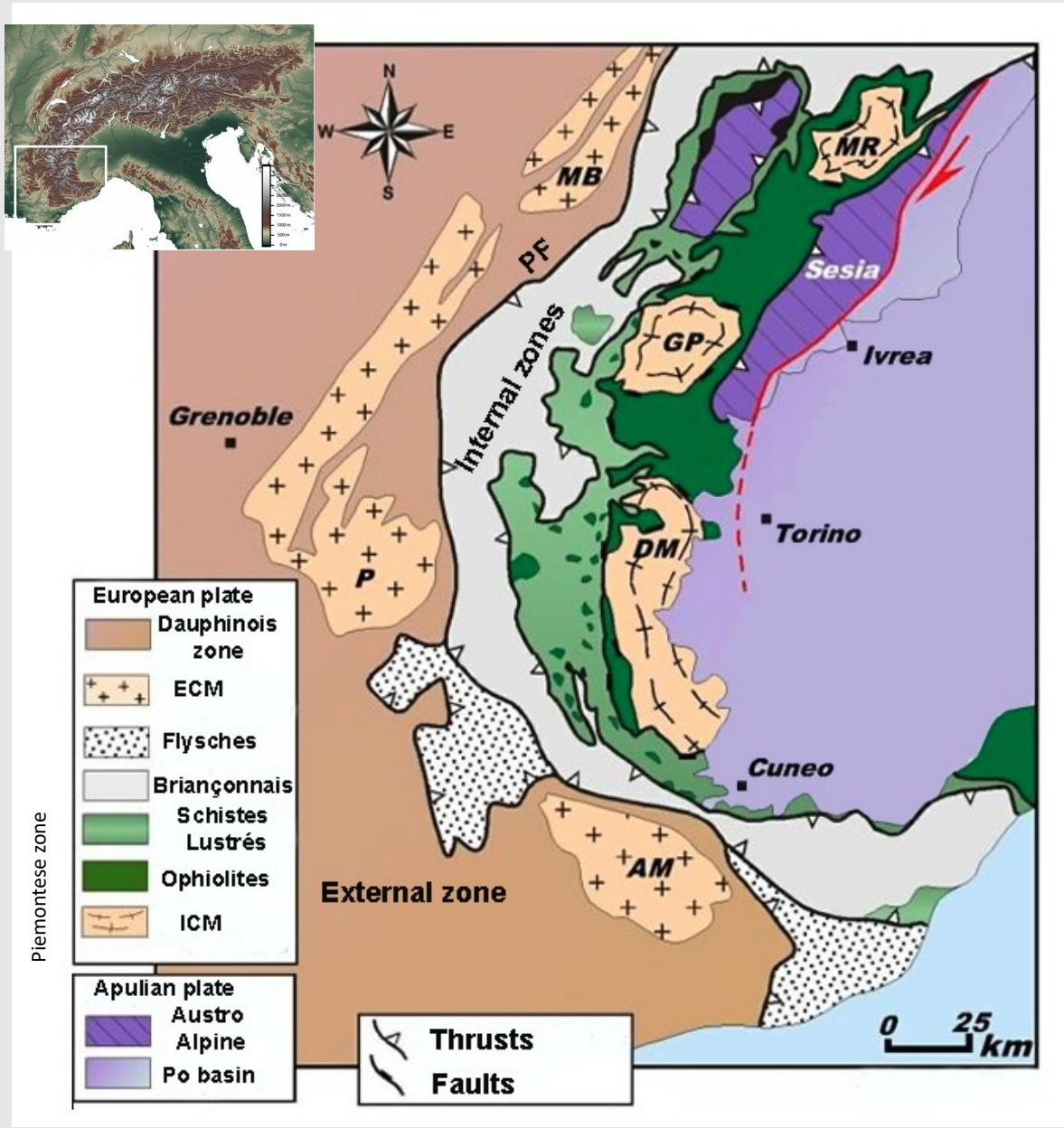
The Alpine example

1 Million geological of the western Alps



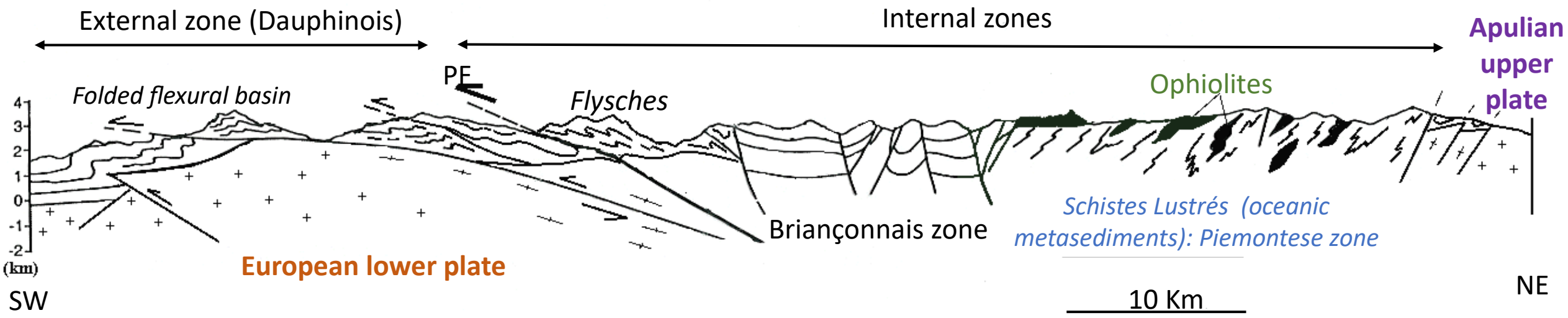
Ophiolites
In
dark green

Simplified tectonic map of the western Alps



WHERE?

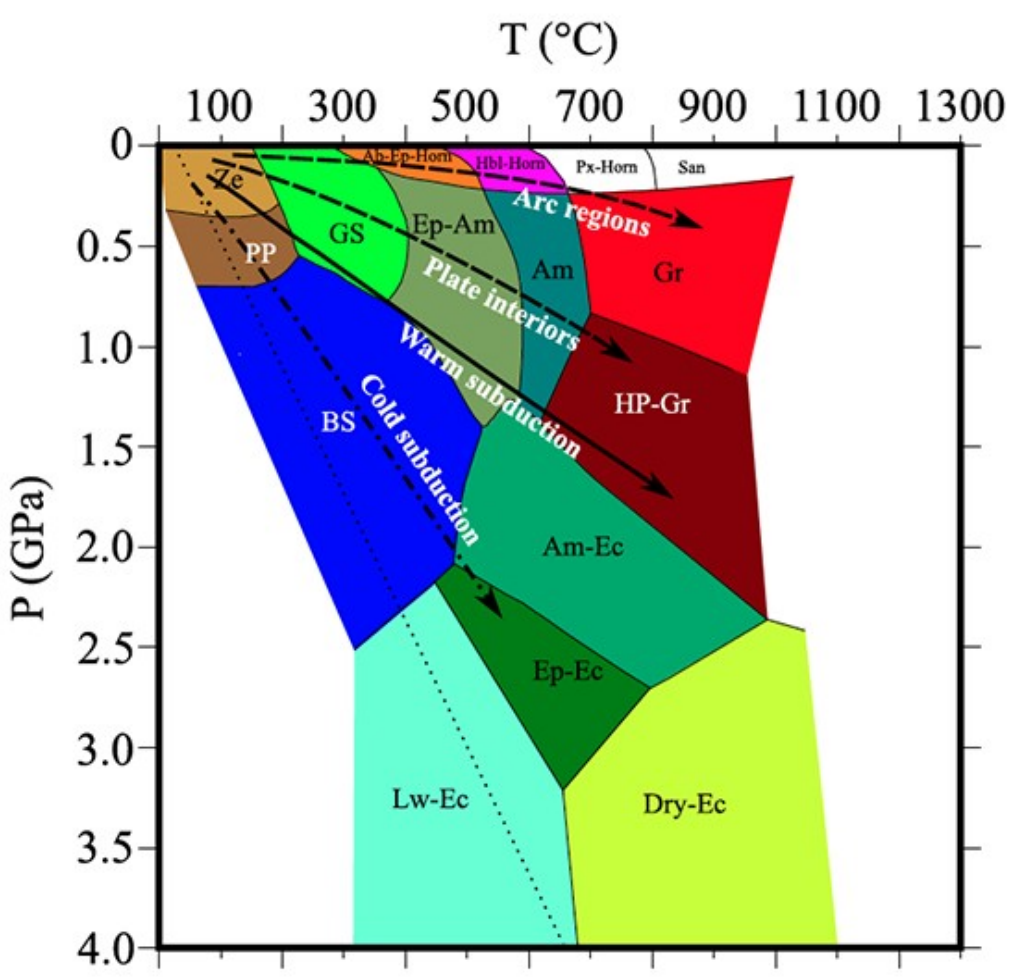
Ophiolites: In the innermost areas of the internal zones in association with oceanic metasediments.

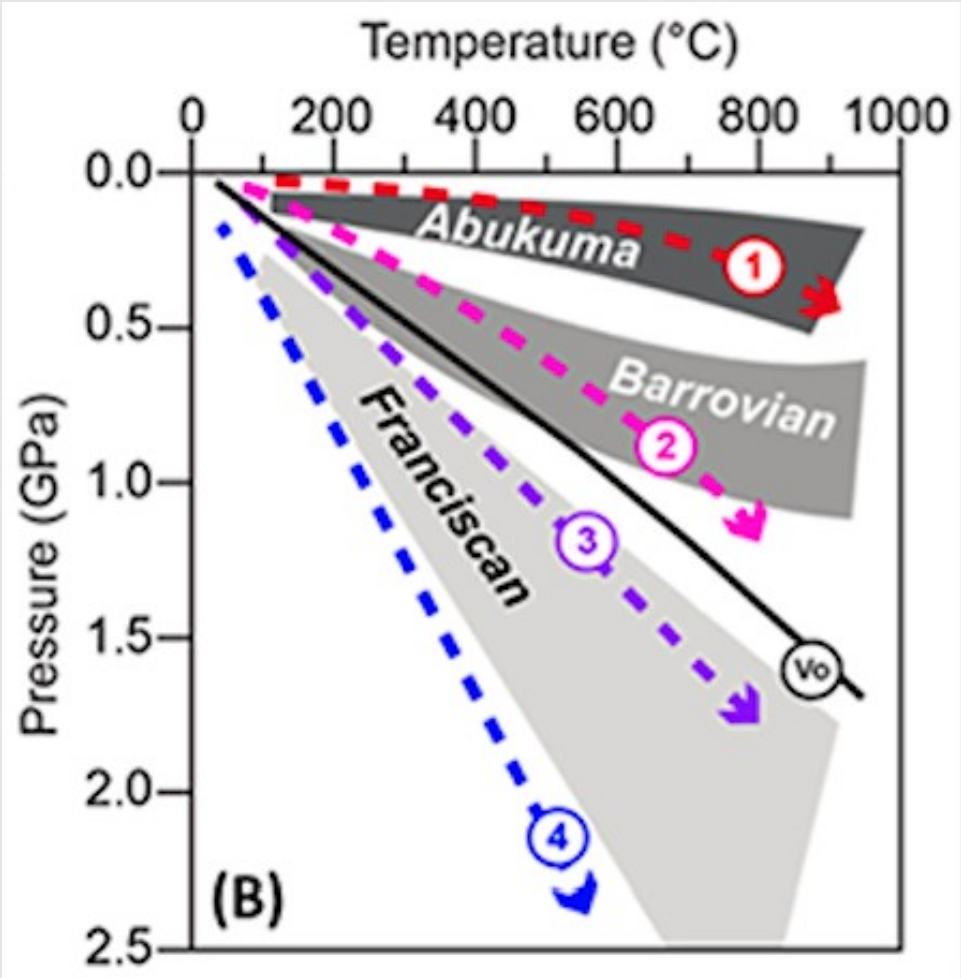


The ophiolites appear in the most internal, and therefore more metamorphic, areas of mountain ranges, where they highlight the so-called *suture zones* between two plates => understanding the ages and mechanisms of their emplacement therefore implies understanding the significance of metamorphic processes.

It is widely recognized, by metamorphic petrologists, that specific metamorphic facies series portray the thermo-mechanical evolutions of lithosphere active zones, as a function of tectonic environments

(i.e. geodynamic significance of metamorphic paleogradients)





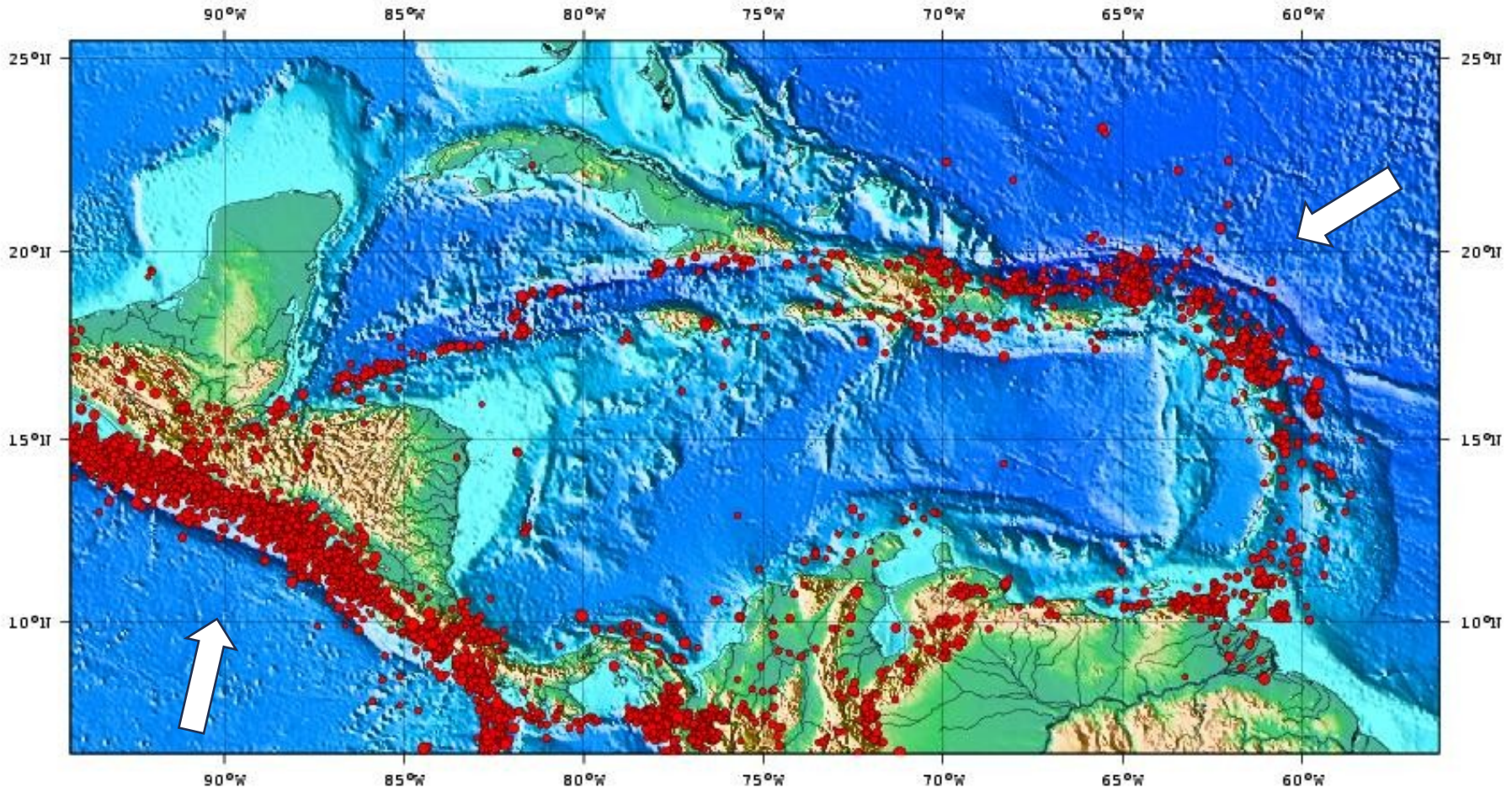
Blueschist facies and Eclogite facies rocks ⇔ Subduction zones setting (Franciscan type)

How sure are you?

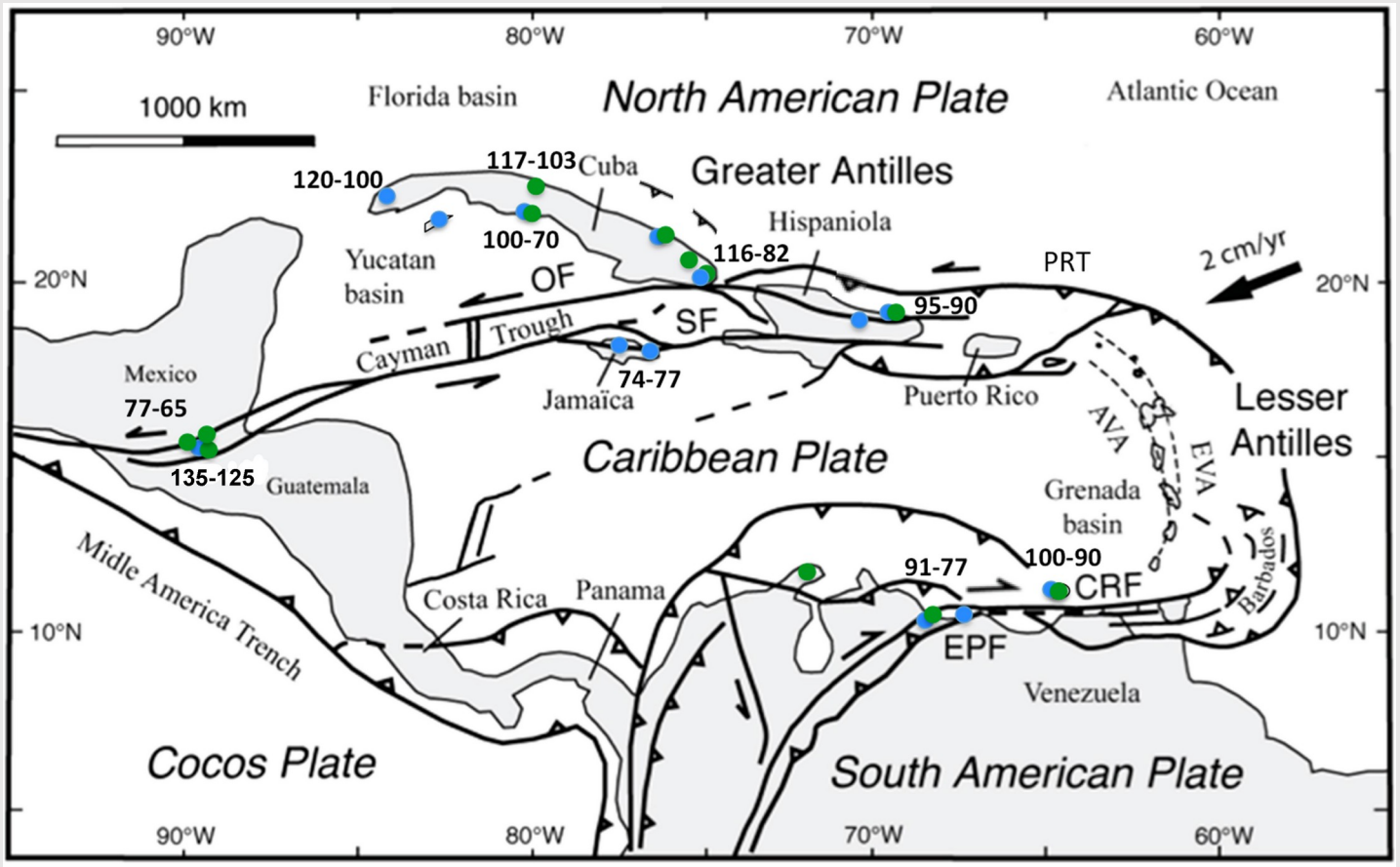
The principle of actualism is the cornerstone of paleo-geodynamics.

Metamorphism and linked geodynamic context in the Caribbean example .

Earthquakes (red points) and plate boundaries



The Caribbean example: Long lasting oceanic subduction (since lower Cretaceous), still active today and without continental collision

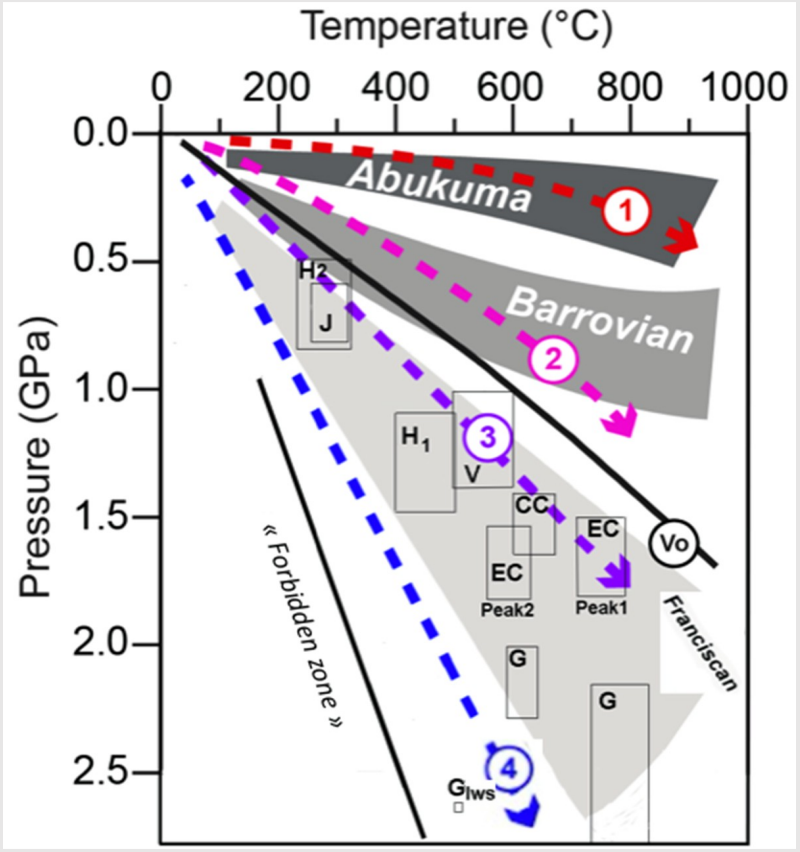


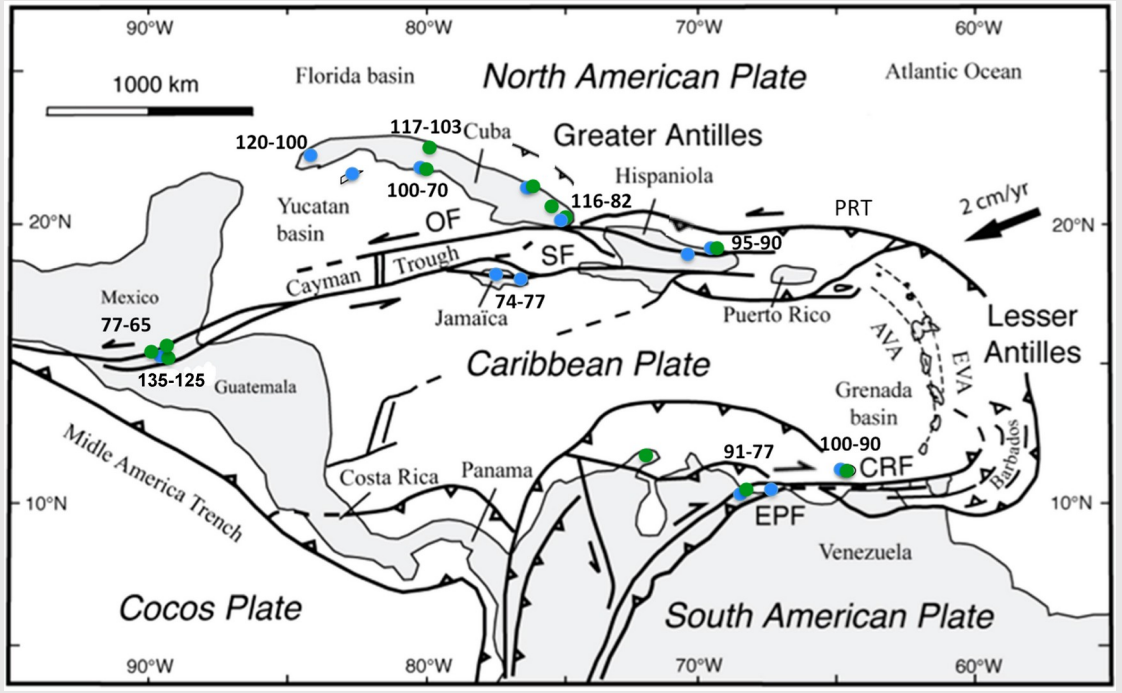
Eclogites

Blueschists

The Caribbean present-day configuration is the result of the east- ward progressive Pacific plate boundary moving between North and South America from Late Jurassic until its currrent position indicated by the active Lesser Antilles arc. This displacement was accompanied by a reversal of the subduction polarity, relative to the initial and abandoned trench (Kerr et al., 2003; Pindell and Kennan, 2009, ….)

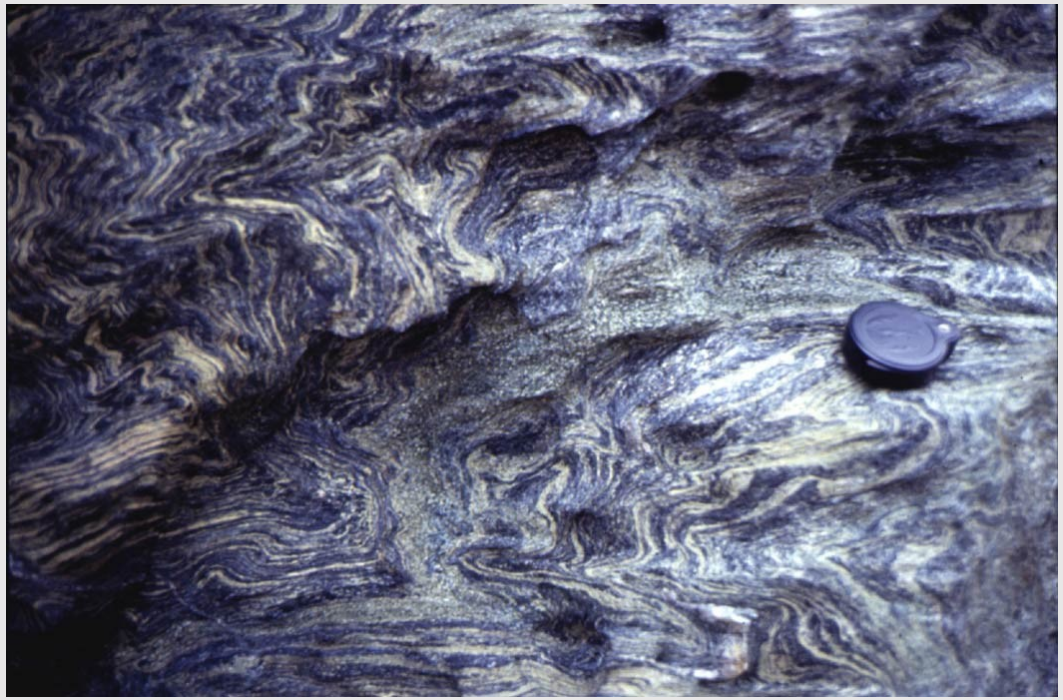
The Caribbean example: Long lasting oceanic subduction (since lower Cretaceous), still active today





● Eclogites ● Blueschist : Subducted oceanic Pacific crust

Simultaneously developed contrasted *P-T* conditions : At a global scale, probably reflects the versatility of subduction zones gradients with respect to a more dogmatic vision of 'steady-state' systems.



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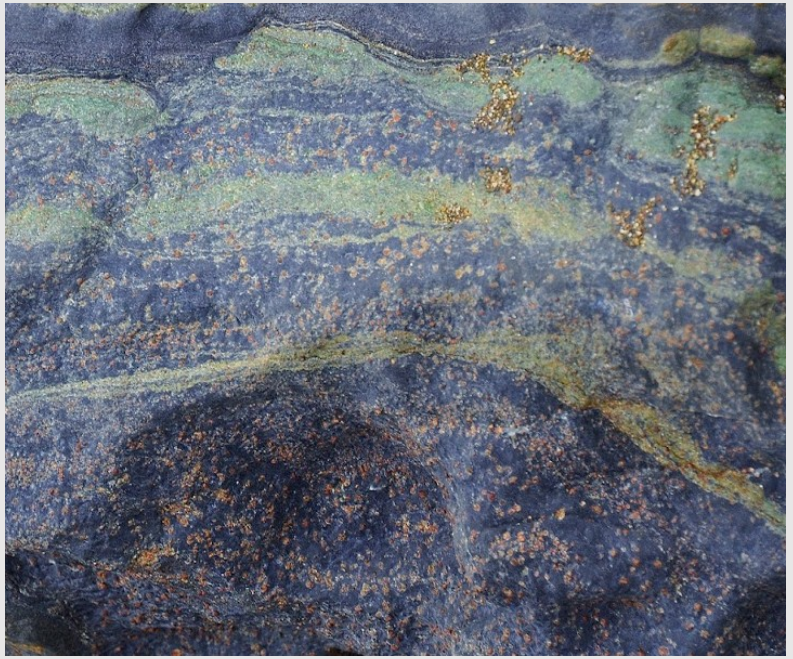
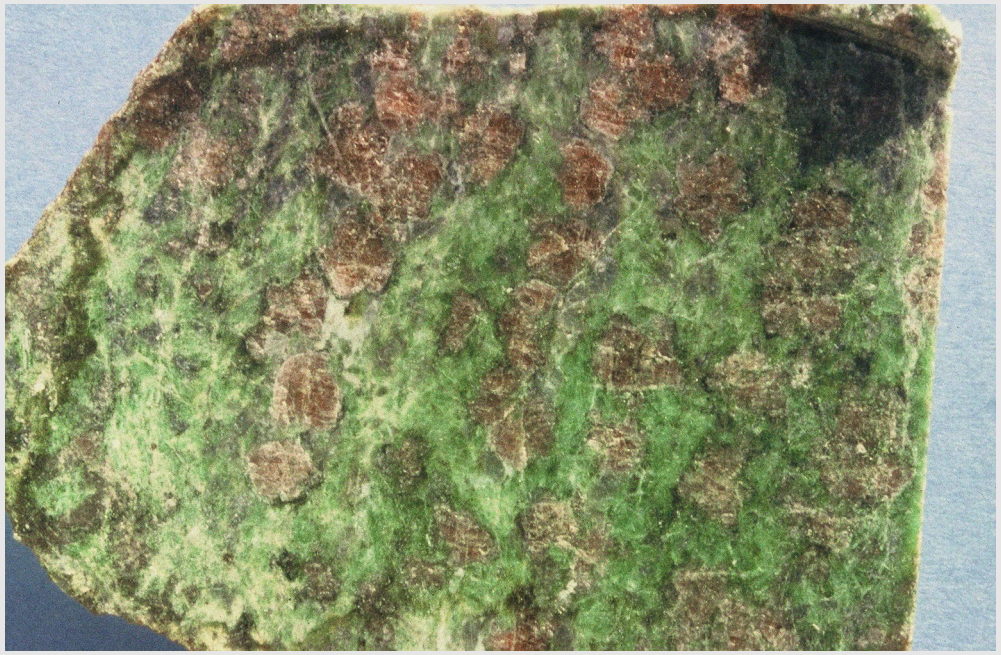
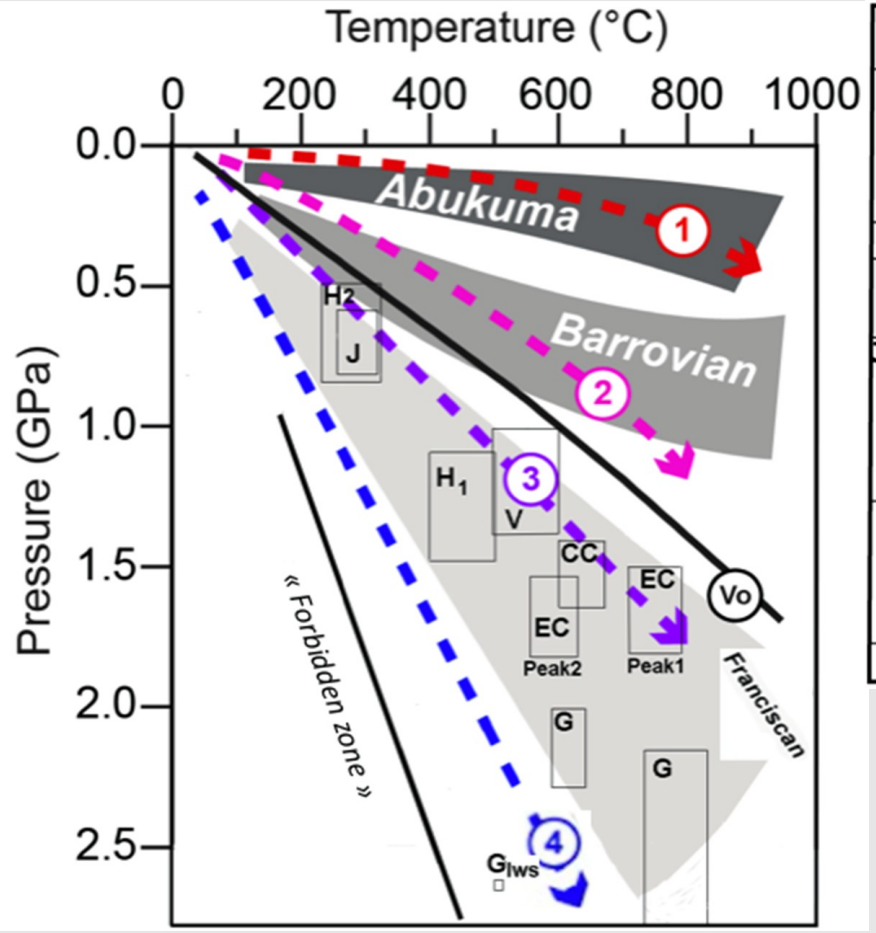
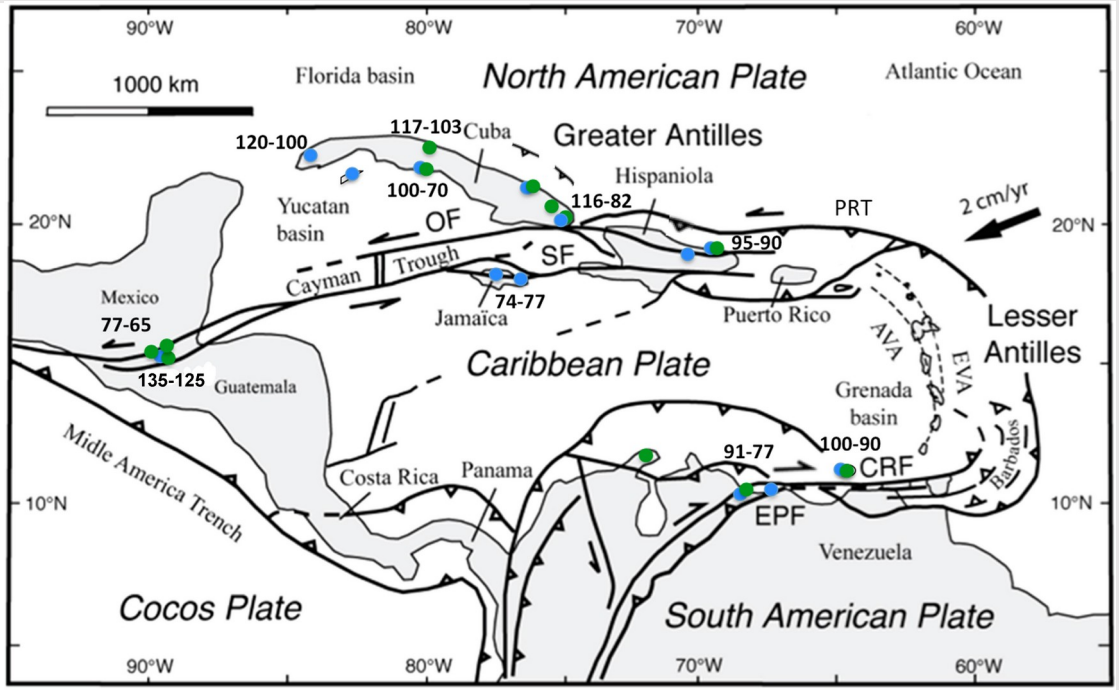


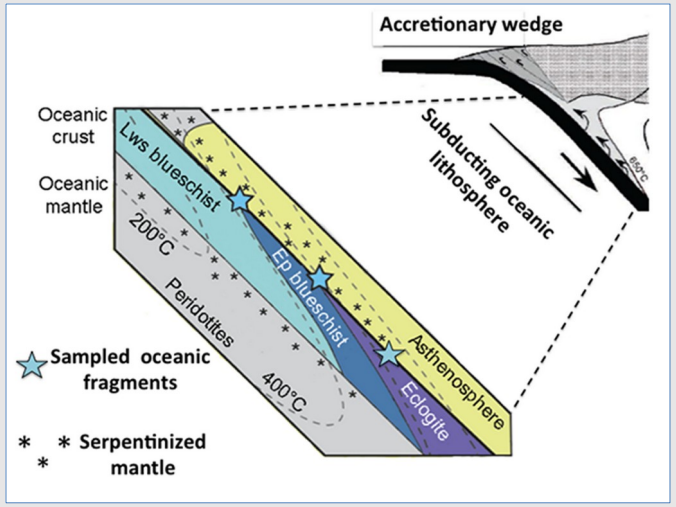


The principle of actualism is the cornerstone of paleo-geodynamics.

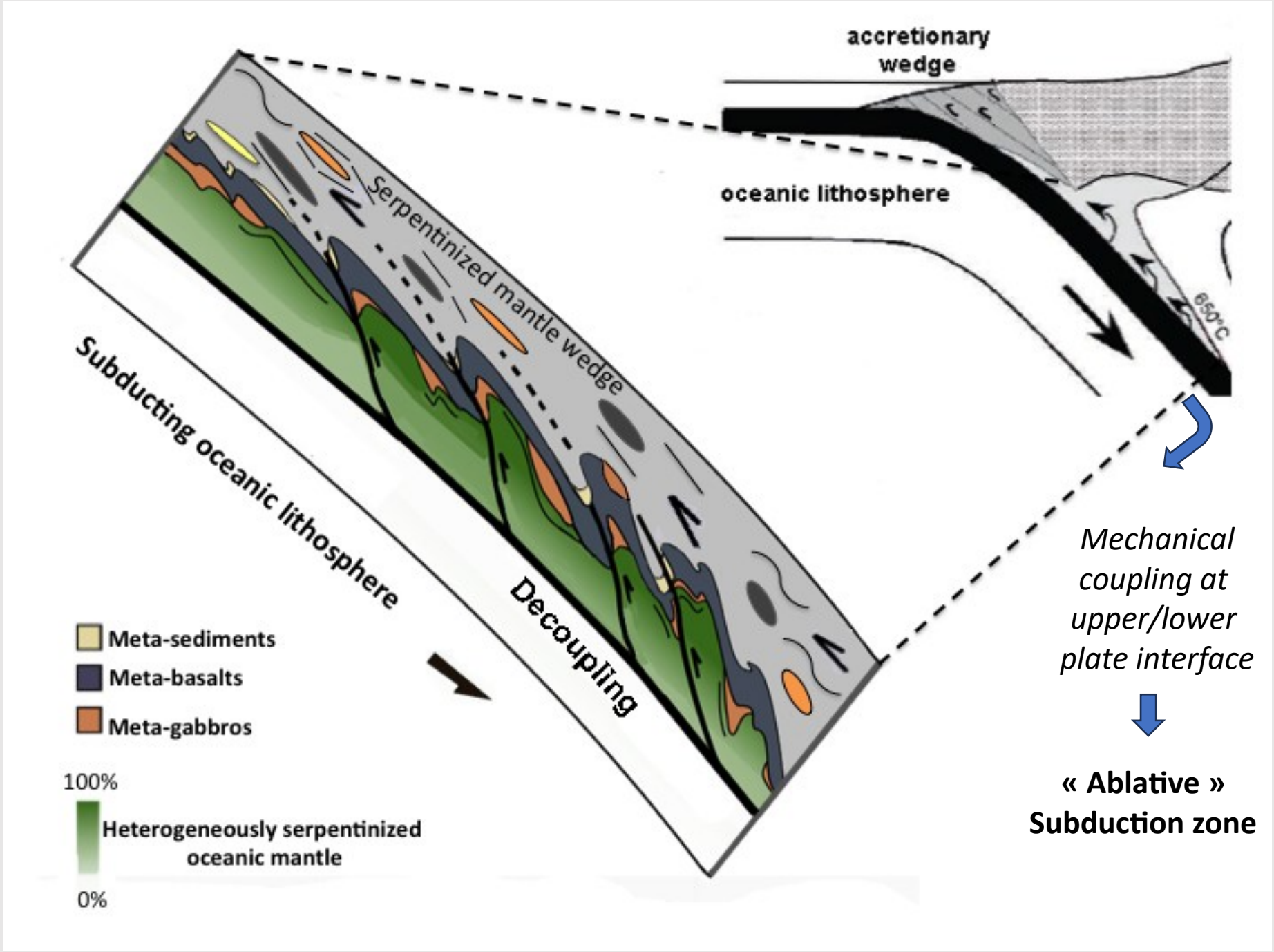




● Eclogites ● Blueschists



Both downgoing path and exhumation during active subduction



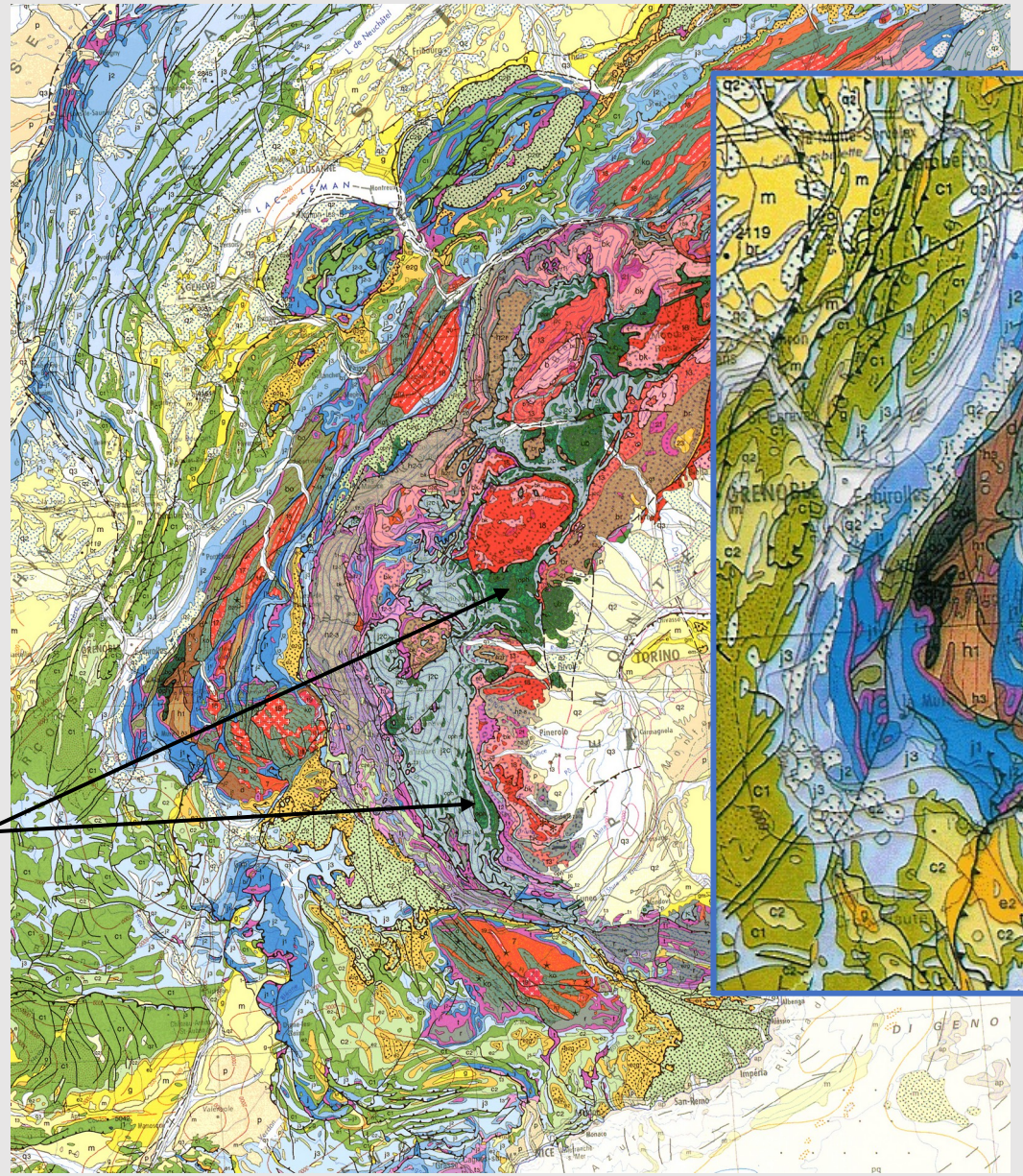
Mechanical coupling at upper/lower plate interface

« Ablative » Subduction zone

WHEN and HOW?

The example of Alpine ophiolites

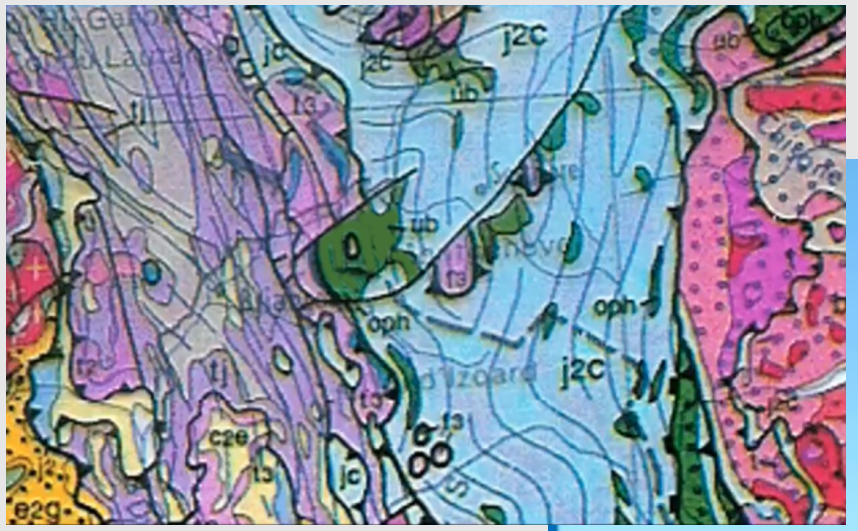
1 Million geological of the western Alps

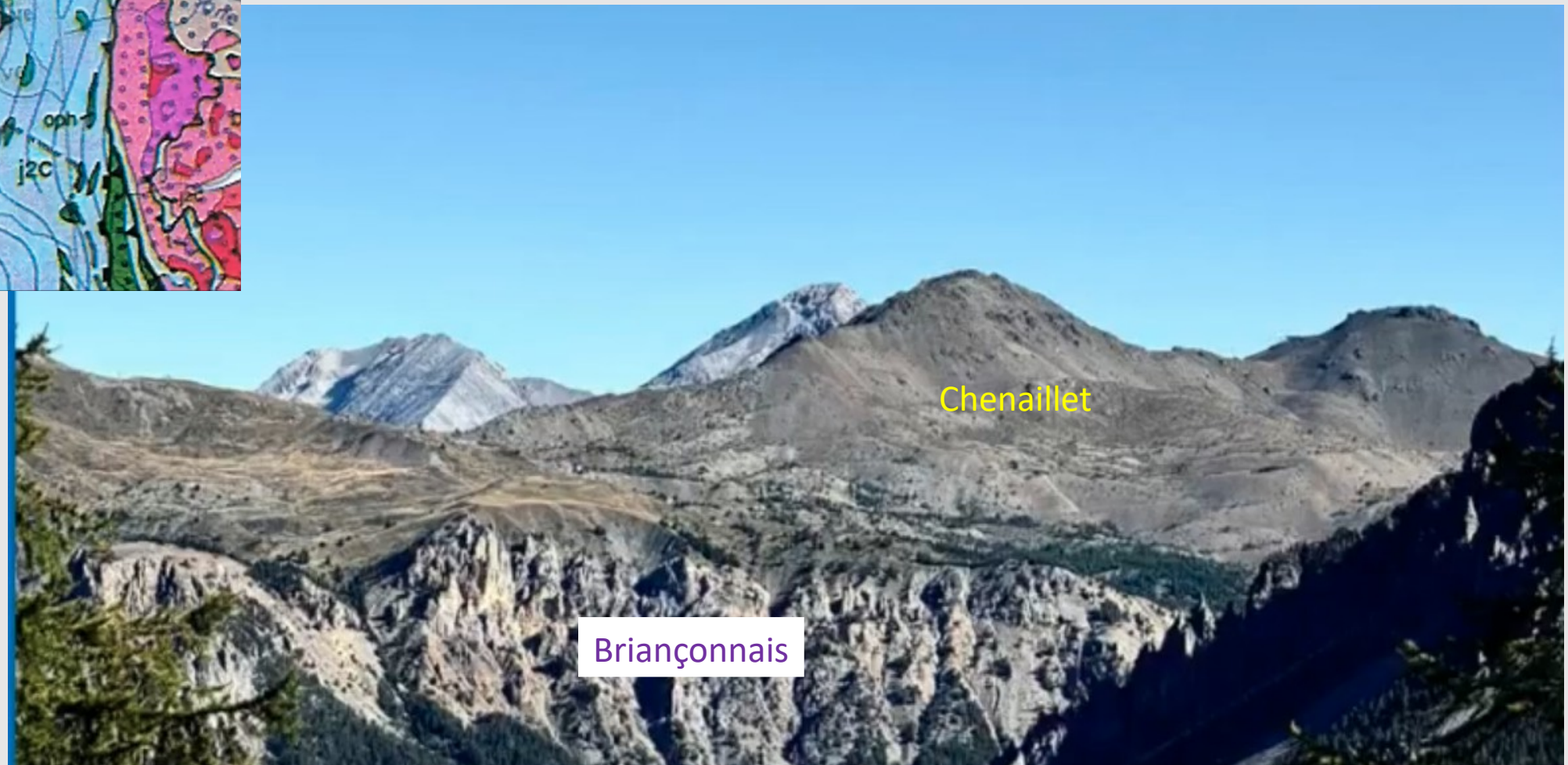


Ophiolites
In
dark green

WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif





WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif

Low crustal thickness < 2km : Low volumes of magmatic production

WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif

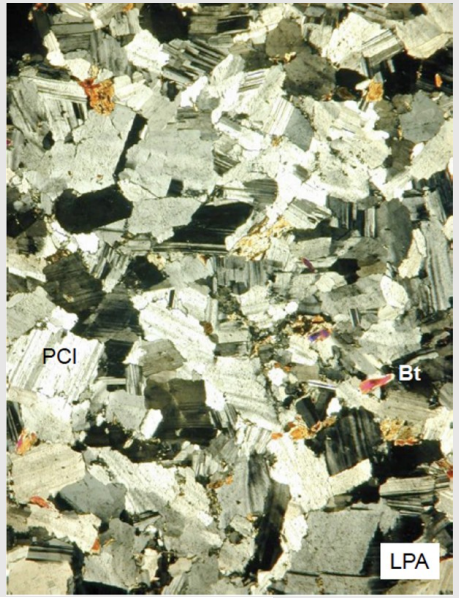
WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif

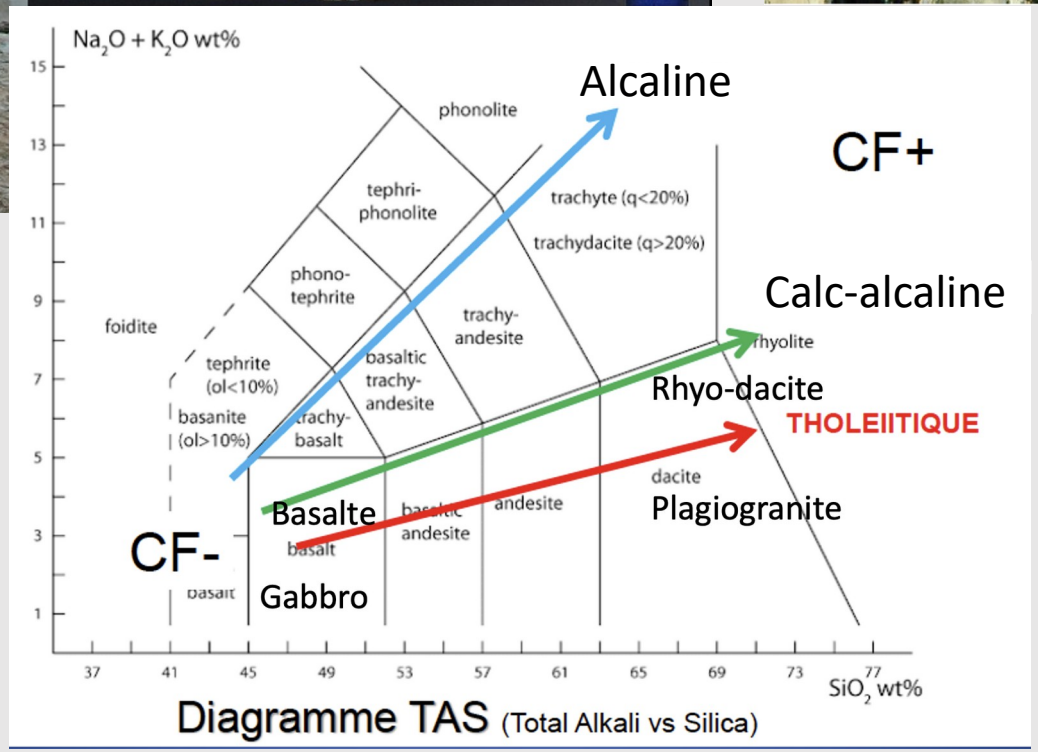
Rare basaltic dykes in the gabbros : lack of well defined « sheeted dyke complex »

WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif

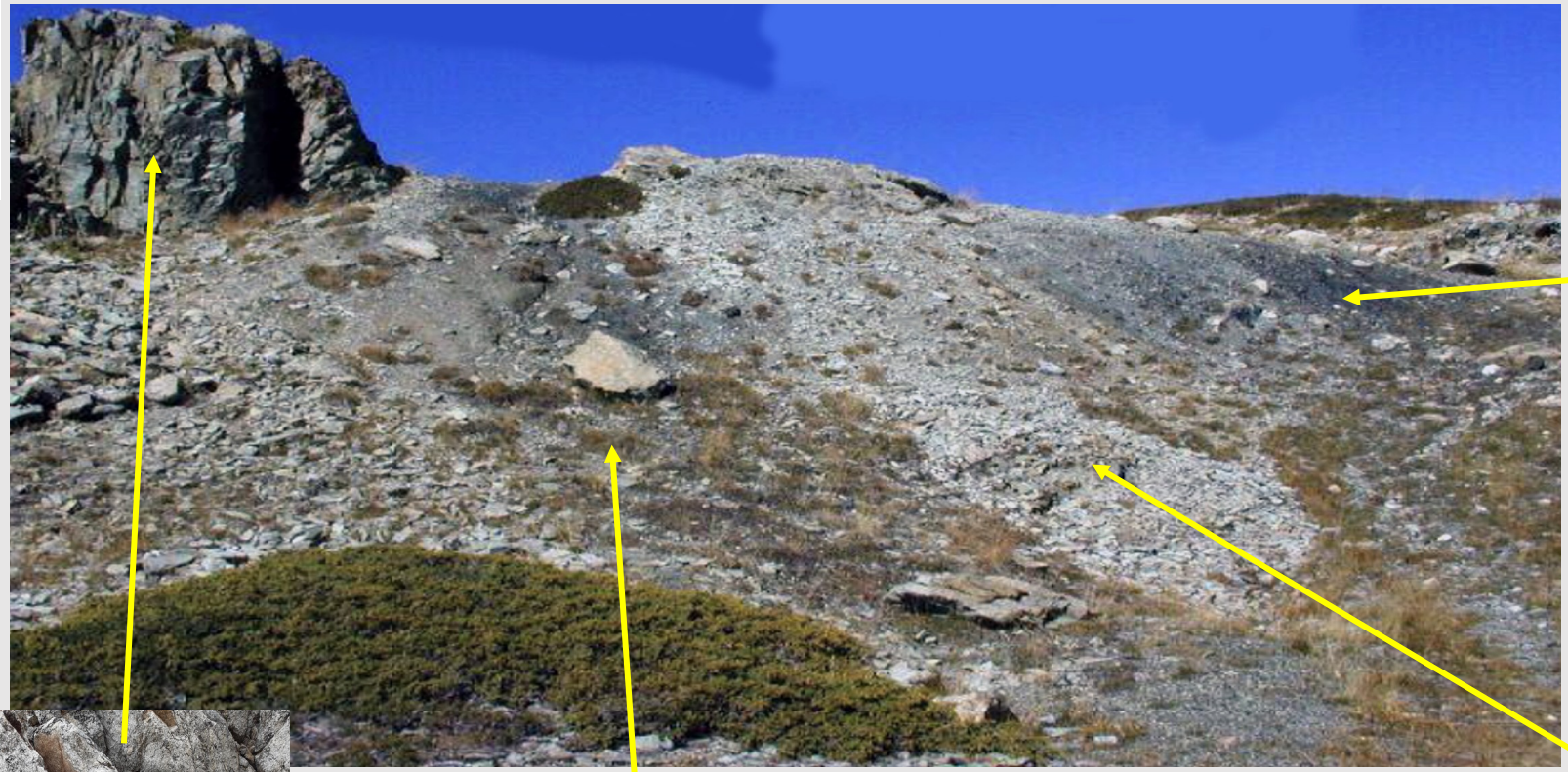


Tholeiitic series: Diagnostic for MORBs, i.e. oceanic crust



WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif



WHEN and HOW?

Serpentinized ocean floor

« ultramafic seafloor »

Diagnostic for slow-spreading ridges

WHEN and HOW?

Tectonic breccia: Fragments of serpentinites in radiolarites (oceanic sediments) => serpentinized mantle exhumed by fault systems.

Ocean-derived detritism.

Diagnostic for slow-spreading ridges

Paleontological dating of radiolarites: Middle Bathonian (Cordey et Bailly, 2007): 166-162 Ma.

WHEN and HOW?

Crystallization ages of magmatic minerals in differentiated liquids:

WR Sm/Nd dating on gabbros: Costa et Caby (2001): 180 Ma.

U/Pb magmatic zircons dating (crystallization ages) : Nicollet et al. (2022):161 +/- 0.8 Ma.

=> Jurassic oceanic crust

WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif

Plagiogranite

Magmatic zircons U/Pb dating (crystallization ages) :

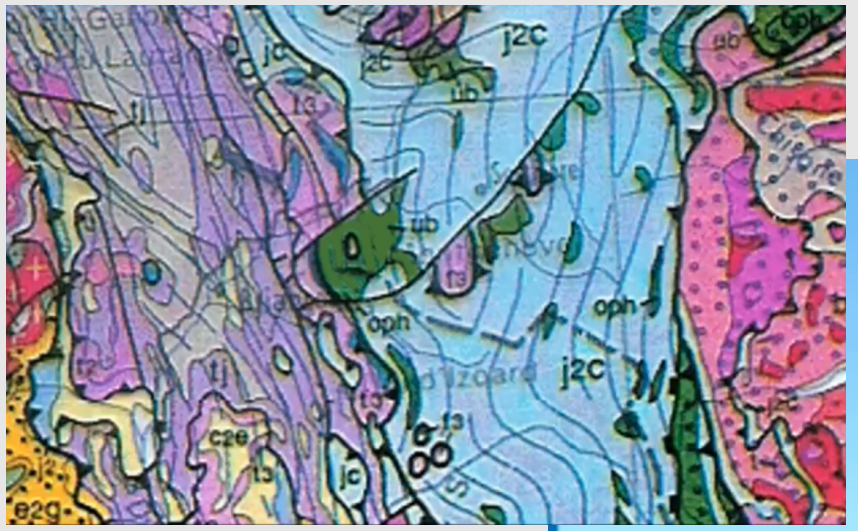
Costa et Caby (2001):160-150 Ma; Li et al. (2013): 165 Ma; Nicollet et al. (2022):161.8 +/- 1.7

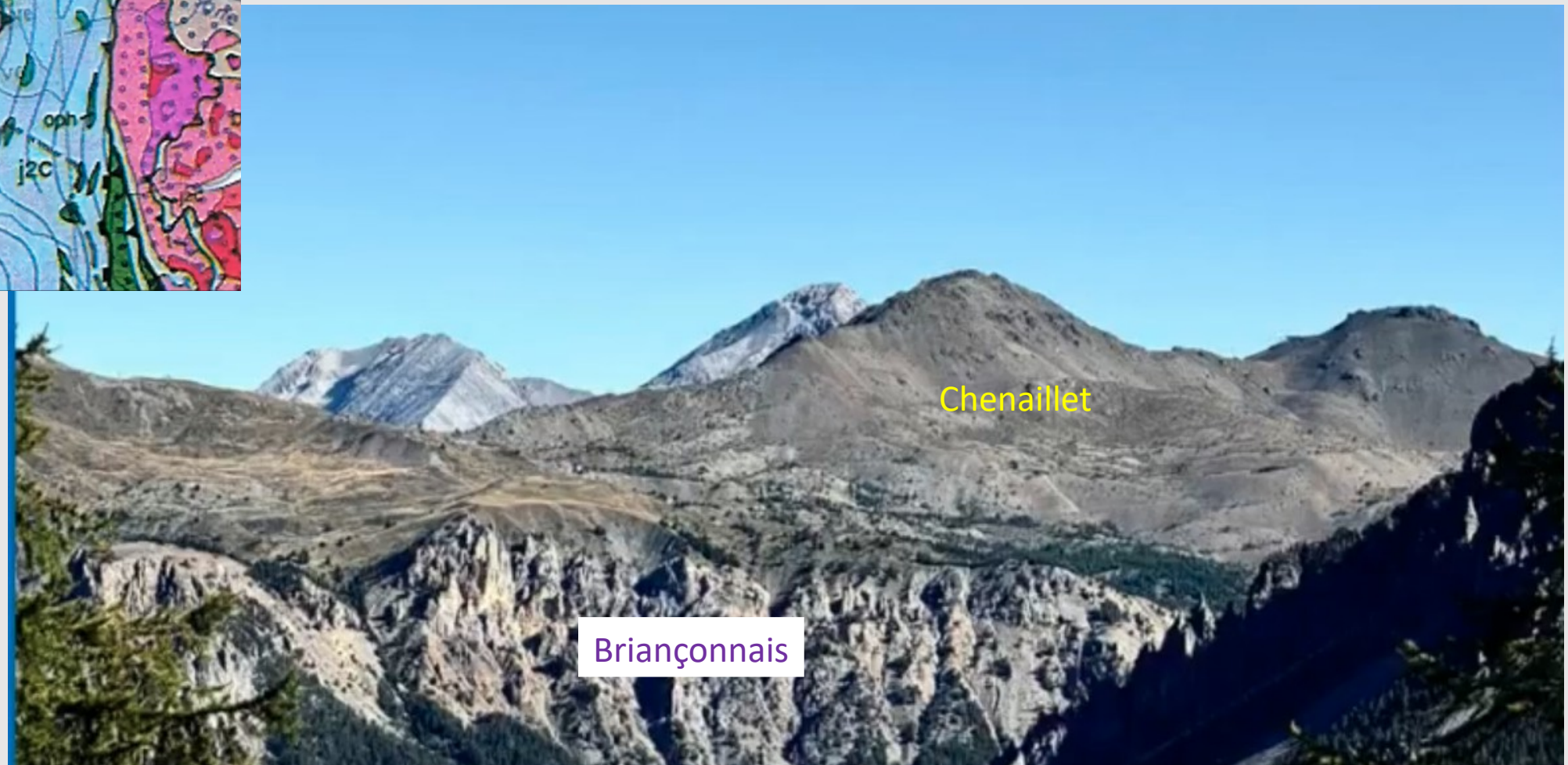
=> Jurassic oceanic crust

WHEN and HOW?

The example of Alpine ophiolites : The Chenaillet Massif

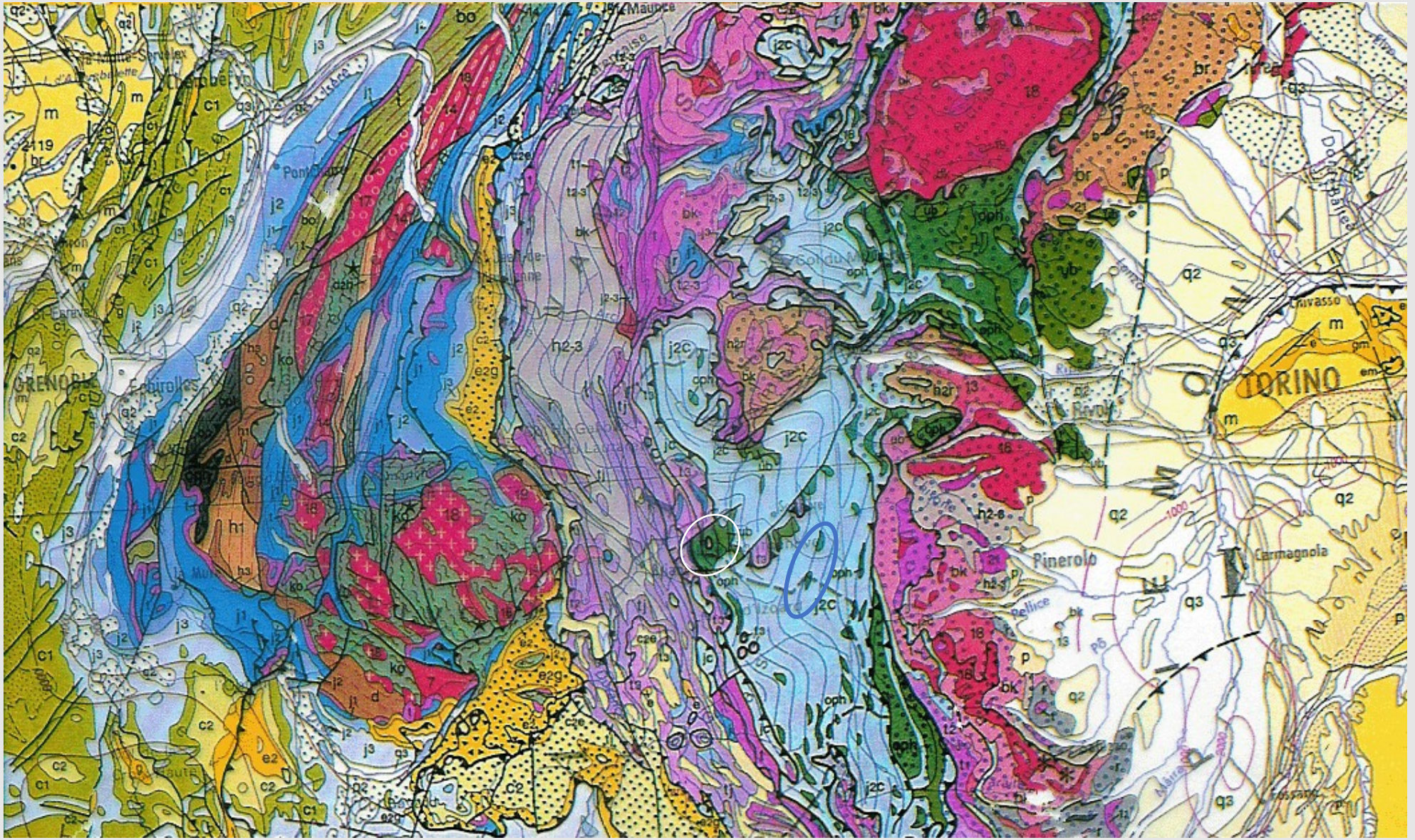
Well-preserved piece of Jurassic oceanic crust, produced at a slow-speading ridge and now resting upon different Alpine tectonic zones





WHEN and HOW?

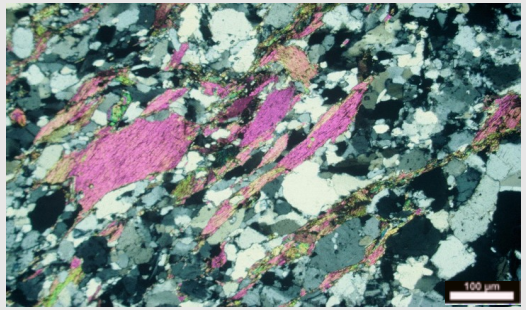
The example of Alpine ophiolites : Ophiolites embodied within oceanic meta-sediments (Schistes Lustrés)



WHEN and HOW?

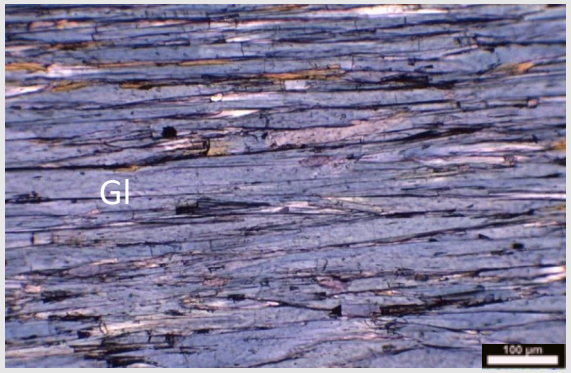
Ophiolites in the Piemontese Zone, Queyras, Bric Bouchet

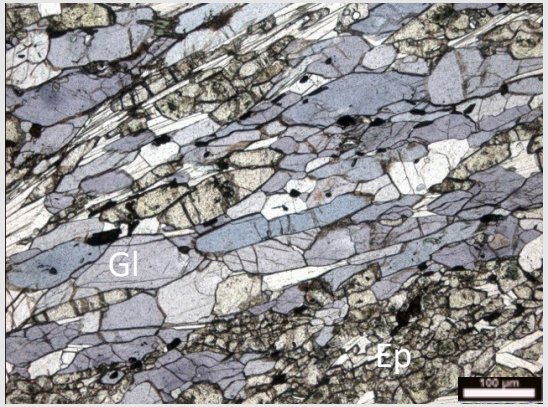
Calcschists: calcite bearing micaschists



Quartz + White mica (Phengite, HP/LT mica) + calcite

Blueschist facies metabasalt





Rb/Sr and Ar^{40}/Ar^{39} dating of phengites and glaucophanes:

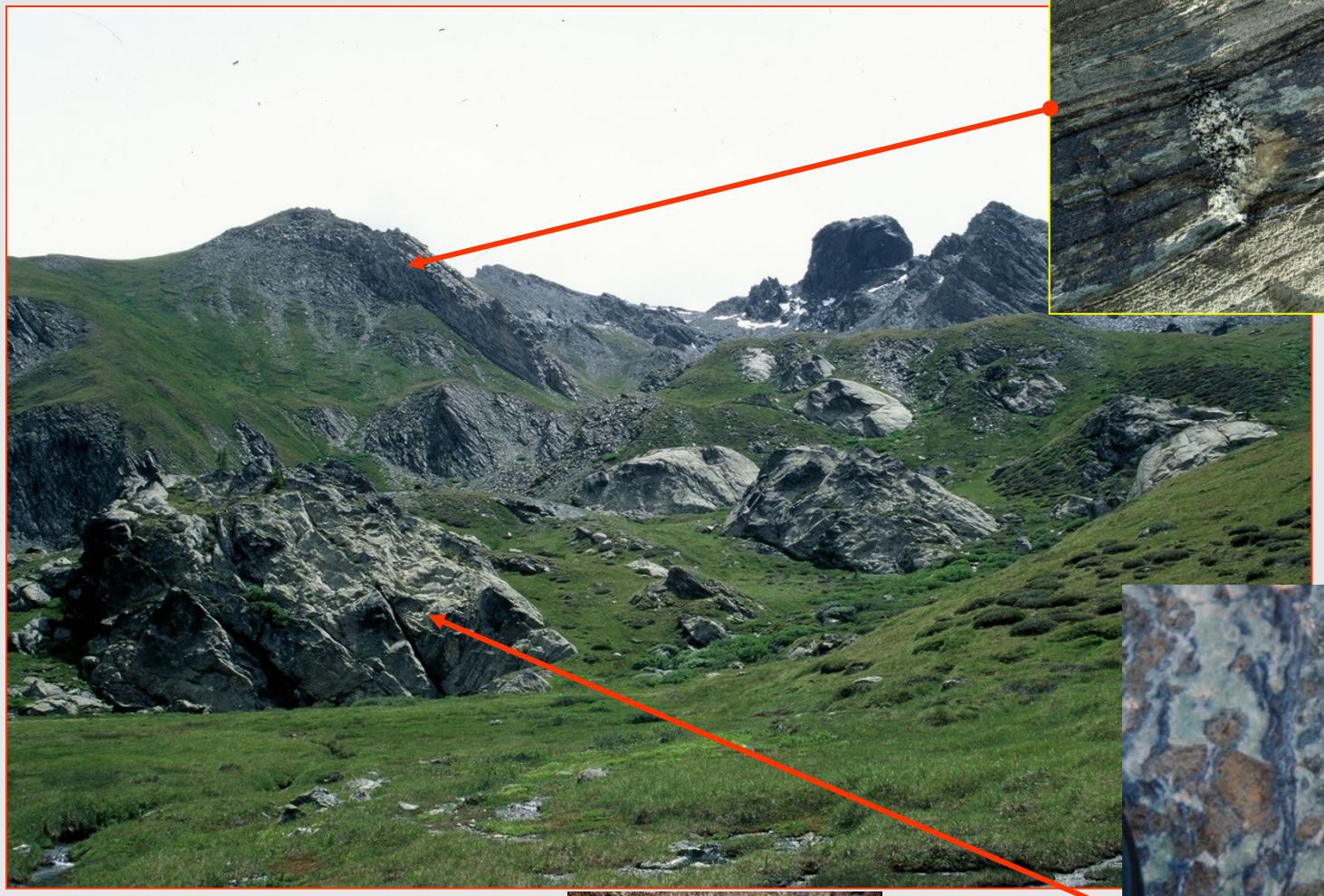
55-50 Ma (age of blueschist facies metamorphism):

Hunziker et al., 1992; Liewig et al., 1981; Frey et al., 1999; Agard et al., 2002, 2009;

Agard et Lemoine, 2003; Goffé et al., 2004; Oberhänsli et al., 2004; Schwartz et al.,

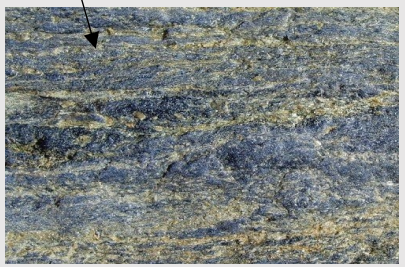
WHEN and HOW?

Ophiolites in the Piemontese Zone,
Queyras, Abriès.

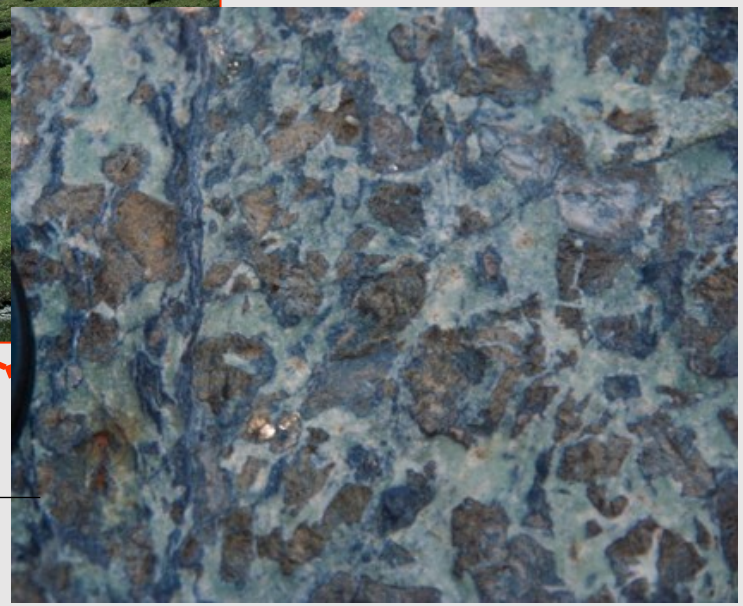


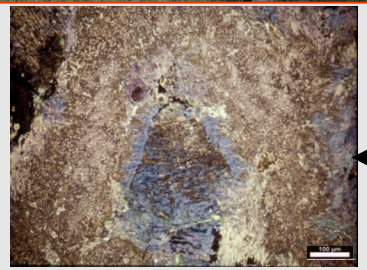
Boudins of metabasalts

Metasediments



Glaucophane and epidote bearing metabasalt

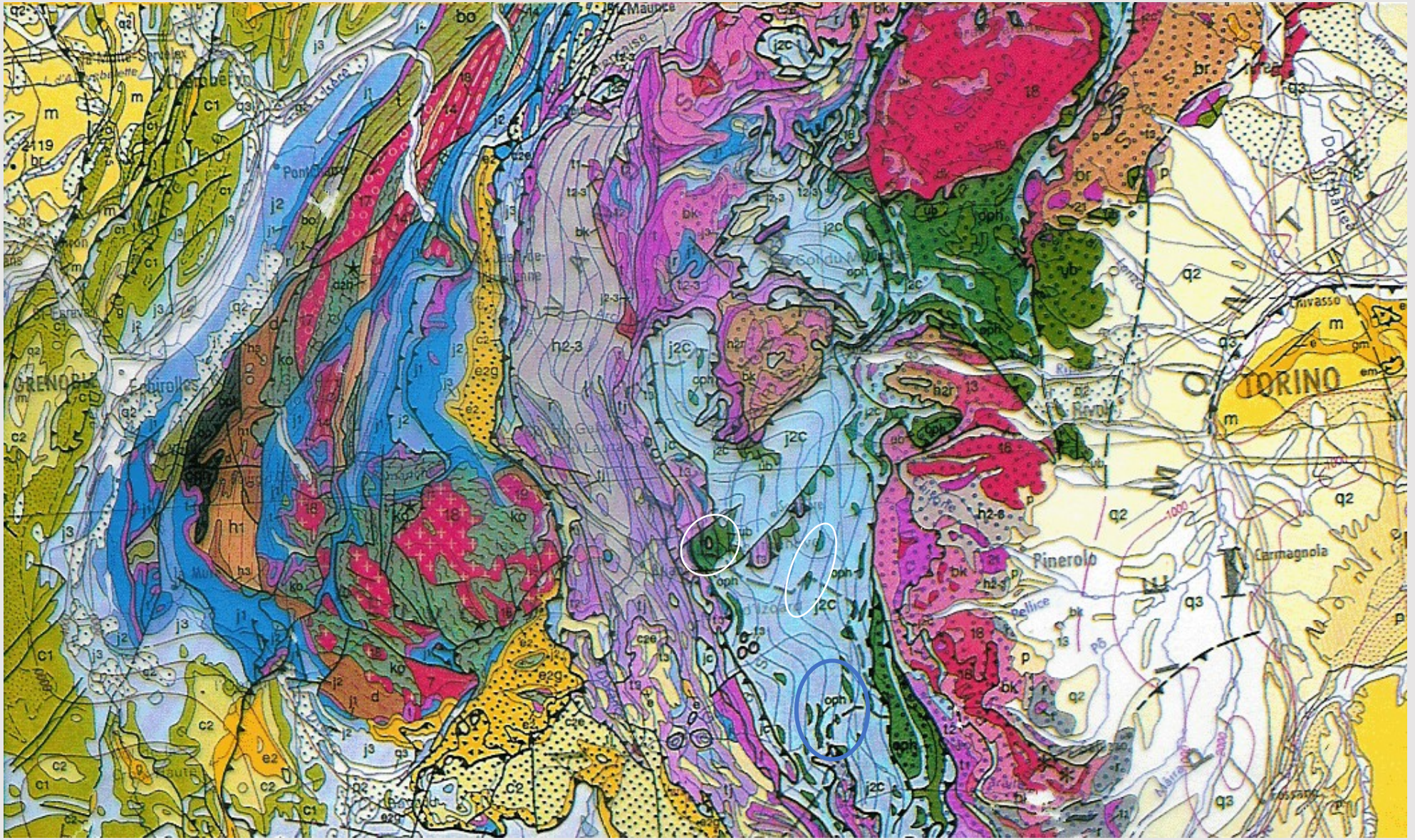




Glaucophane bearing metagabbros

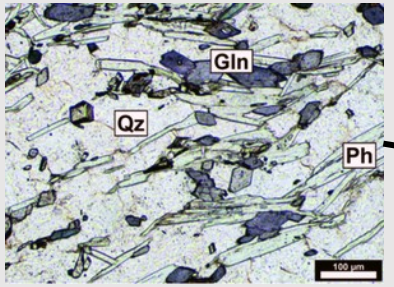
WHEN and HOW?

The example of Alpine ophiolites : Ophiolites embodied within oceanic meta-sediments (Schistes Lustrés)



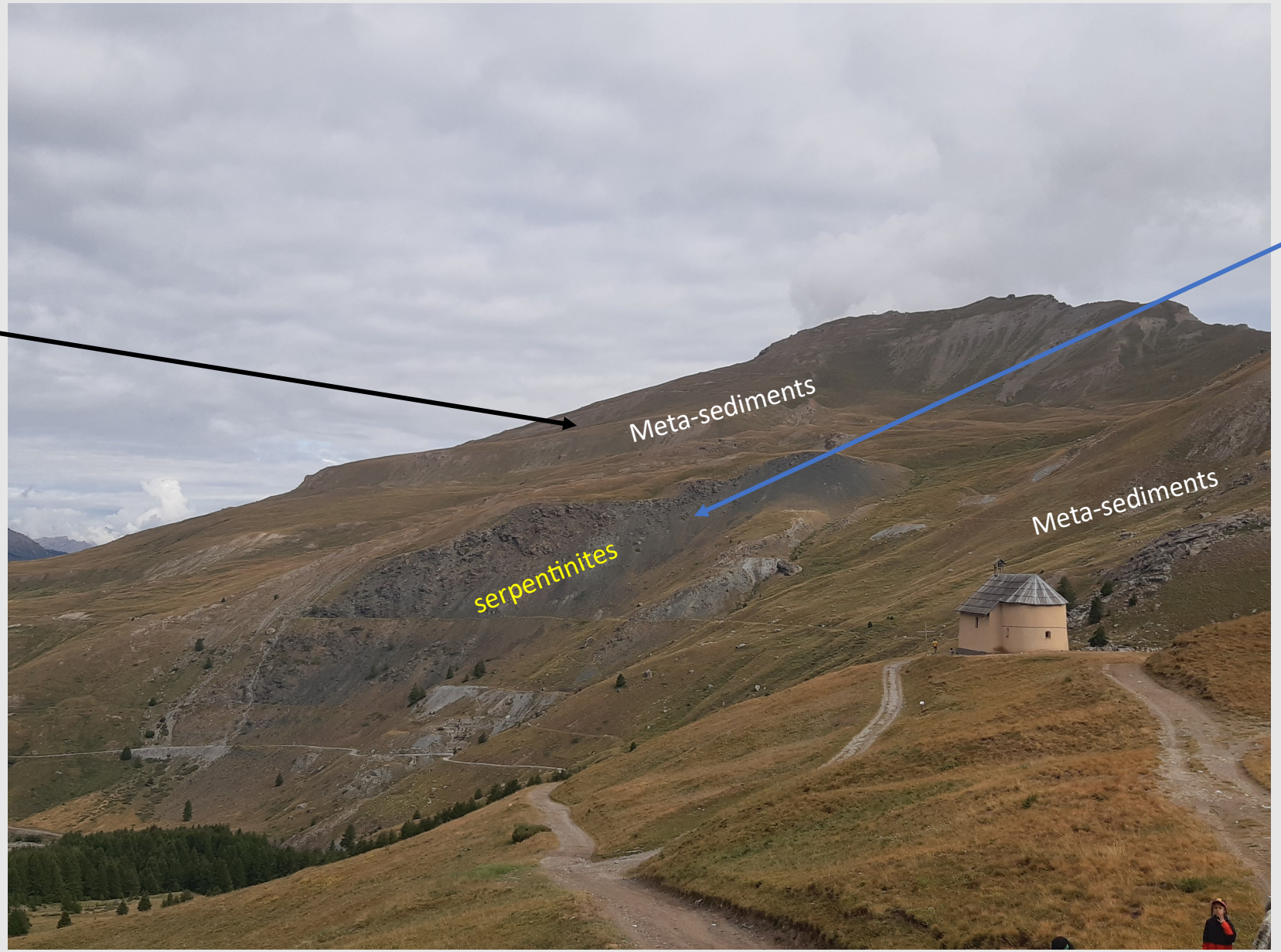
WHEN and HOW?

Ophiolites in the Piemontese Zone, Queyras, Saint-Véran



Ar^{40}/Ar^{39} dating of phengites:

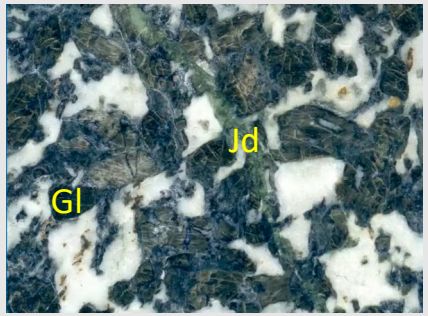
Blueschist facies metamorphism **at 55-50 Ma**



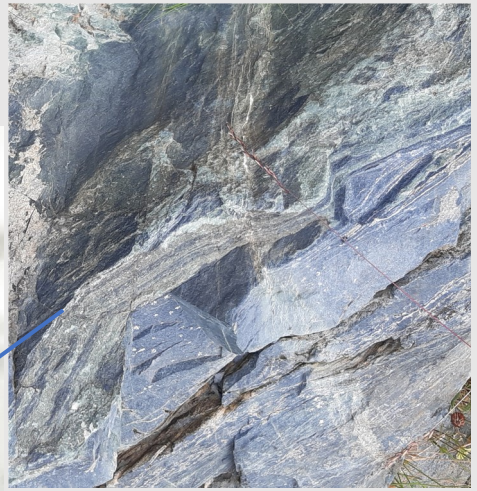
WHEN and HOW?

Ophiolites in the Piemontese Zone, Queyras, Saint-Véran

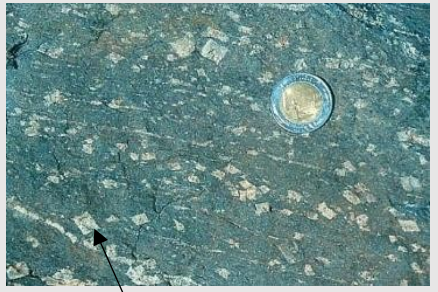
Blueschist facies metagabbros



Glaucophane + Jadeite



Blueschist facies metabasalts



Lawsonite (hydrated calcium silicate, typical for HP/LT conditions)

WHEN and HOW?

Ophiolites in the Piemontese Zone, Queyras, Saint-Véran

Glaucophane bearing metabasalts

Meta-sediments (marbles : meta-limestones)

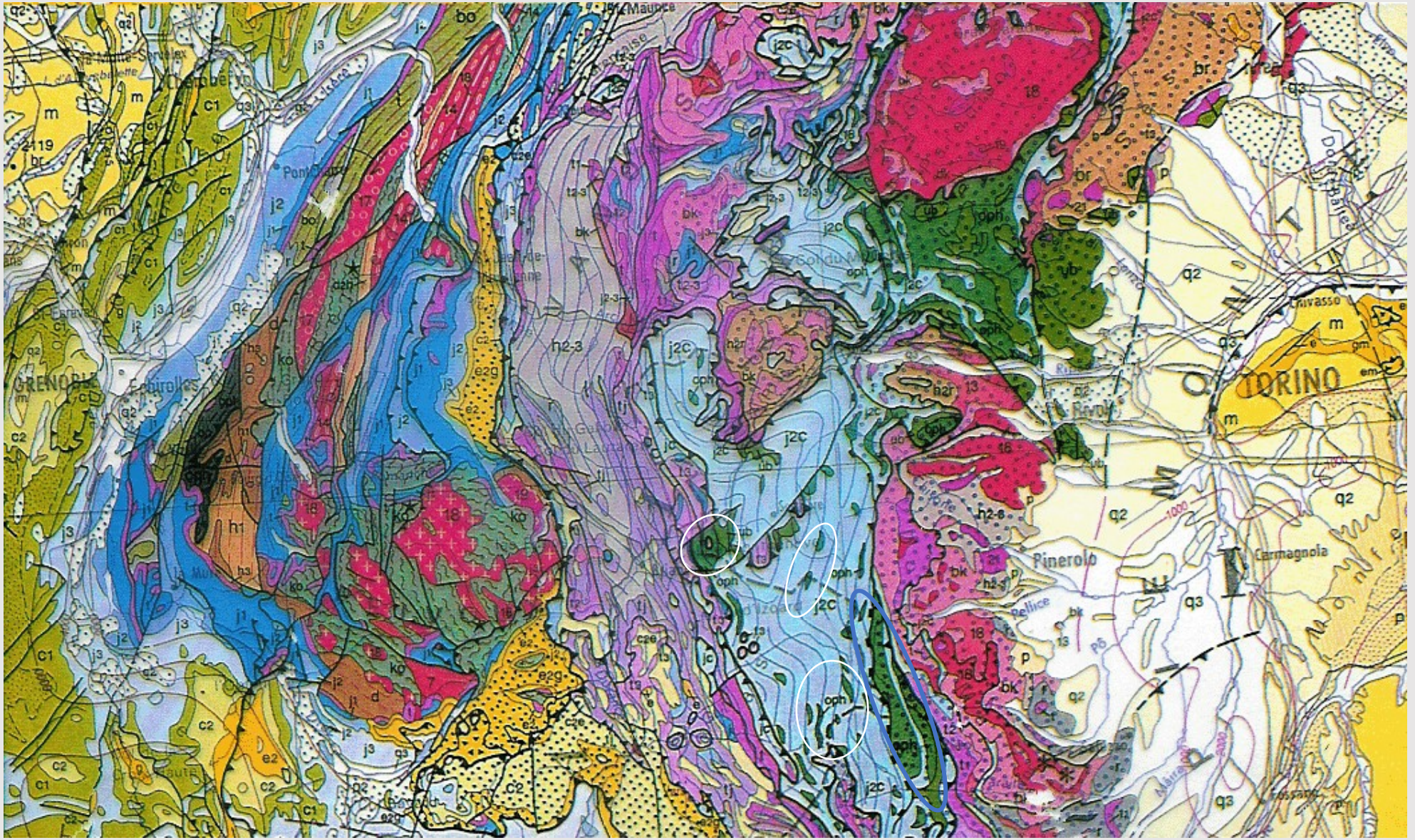
Blueschist facies Metabasalts retrogressed Under Greenschist facies conditions.

Blueschist facies: **55-50 Ma**

Greenschist facies: **40-38 Ma**

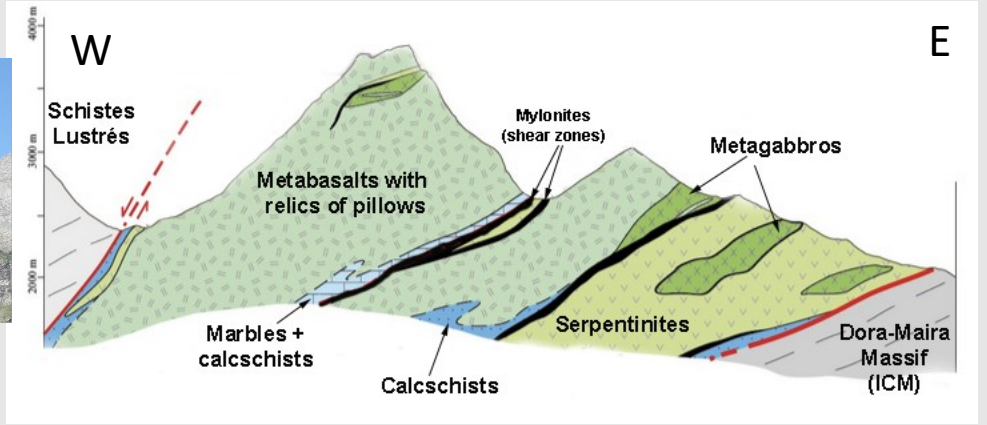
WHEN and HOW?

The example of Alpine ophiolites : Ophiolites embodied within oceanic meta-sediments (Schistes Lustrés)



WHEN and HOW?

The example of Alpine ophiolites : Monviso ophiolites



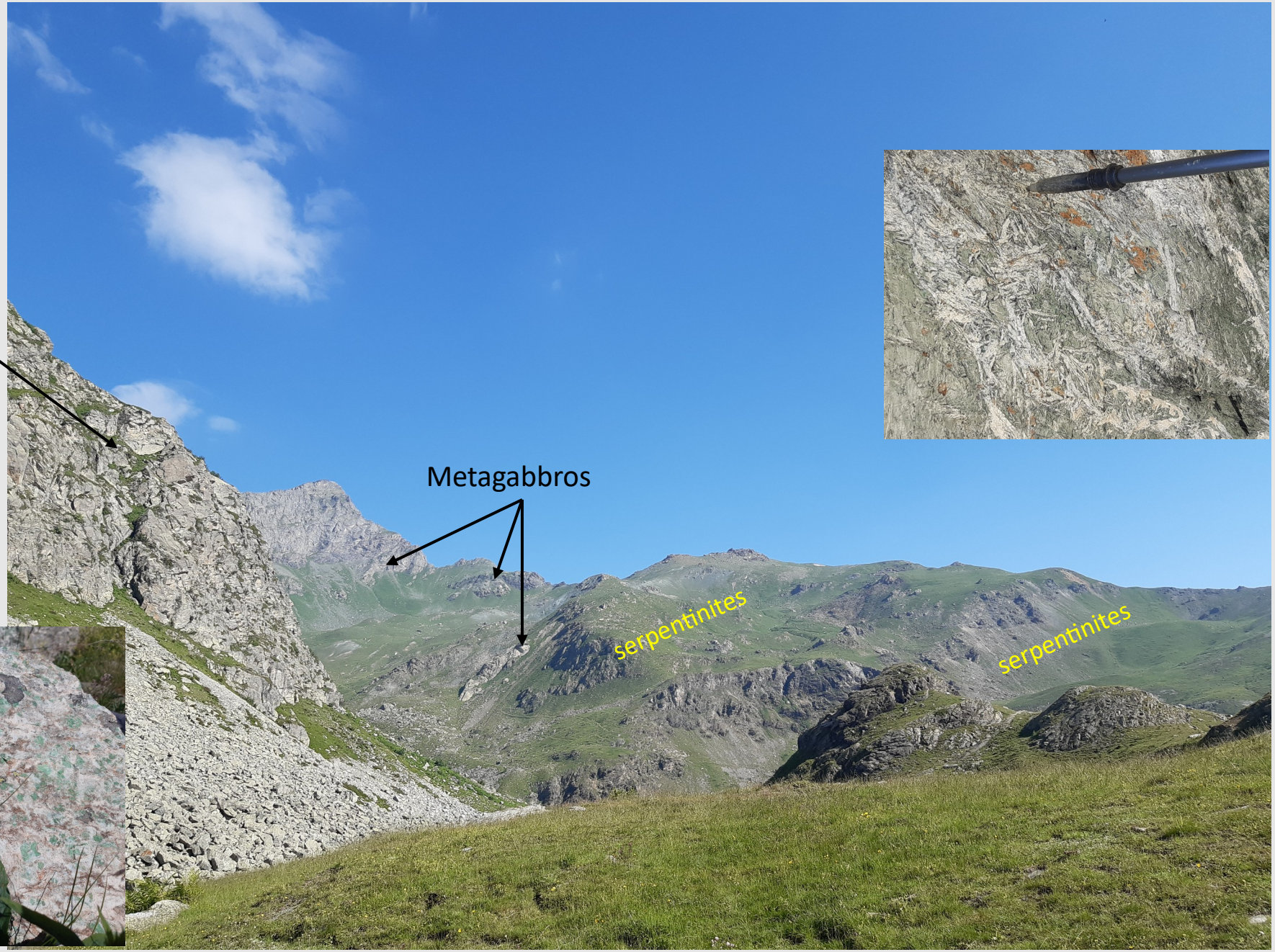
Lombardo et al., 1978; Schwartz et al., 2000, 2001; Angiboust et al., 2012.

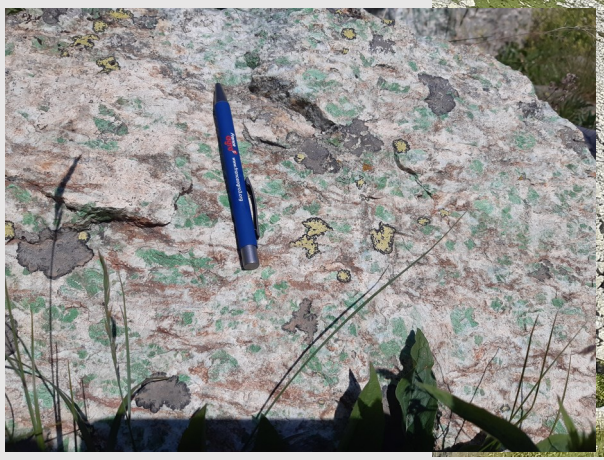
Lucky

Unlucky

WHEN and HOW?

The example of Alpine ophiolites : Monviso ophiolites

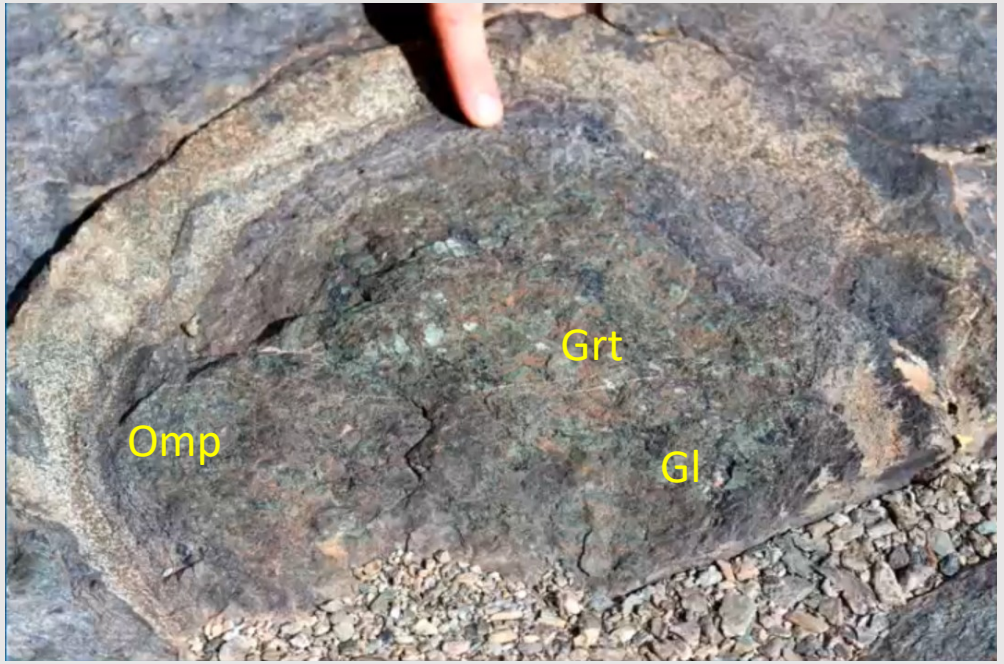




WHEN and HOW?

The example of Alpine ophiolites : Monviso ophiolites

Fully recrystallized metabasalt: **Eclogite sensu-stricto**
(garnet+omphacite+/-glaucophane +/-phengite)



Eclogite facies metabasalt with relic of pillow structure

Foliated eclogite

Ar^{40}/Ar^{39} dating of phengites; Lu/Hf dating of garnets; Sm/Nd dating of eclogites; in situ U/Pb zircon dating:
55-50 Ma (Monié and Philippot, 1989; Duchêne et al., 1997; Cliff et al., 1998; Rubatto et al., 2011; Angiboust et al., 2012)

WHEN and HOW?

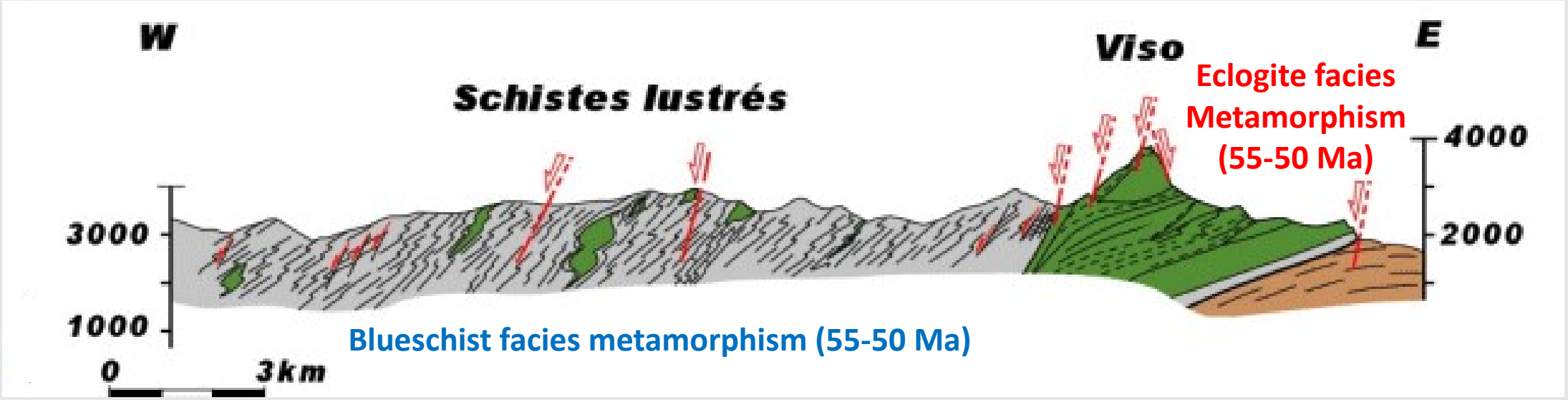
The example of Alpine ophiolites : Monviso ophiolites

Garnet + Phengite + Quartz + Jadeite bearing metasediments

Folded and retrogressed eclogite under blueschist and greenschist facies conditions
$\Rightarrow$ Exhumation dated in the time span of **45-38 Ma**

WHEN and HOW?

The example of Alpine ophiolites in the SW Alps: A summary



Ophiolites? Fragments of various sizes (metric to kilometers sized blocks) embodied within metasediments and/or serpentinites.

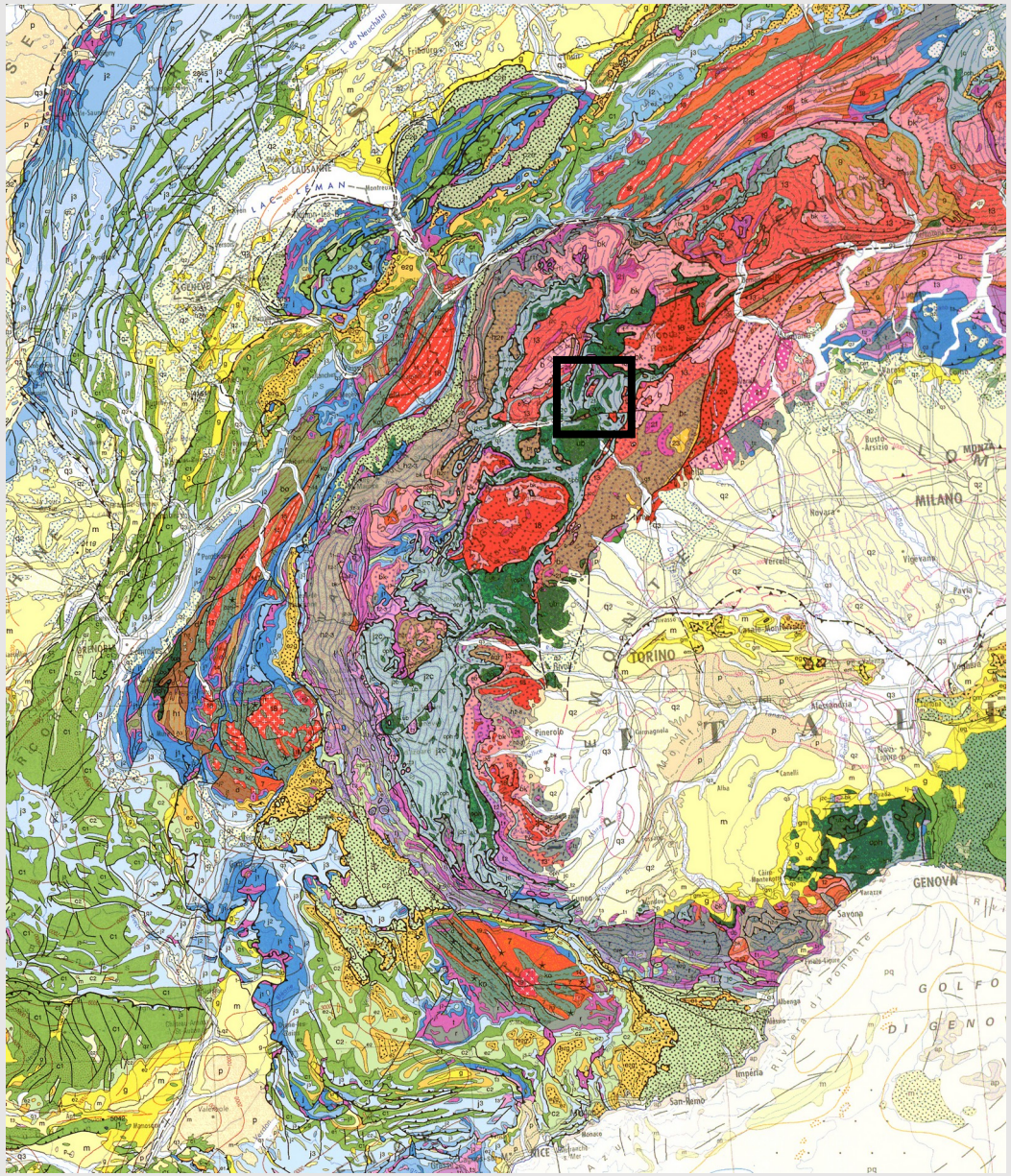
$\Rightarrow$ Disrupted fragments of oceanic lithosphere metamorphosed under HP/LT conditions (*Franciscan type metamorphism*).

In SW Alps: HP/LT metamorphism at 55-50 Ma, exhumation under LT conditions at 45-38 Ma

Is it the same in NW Alps ?

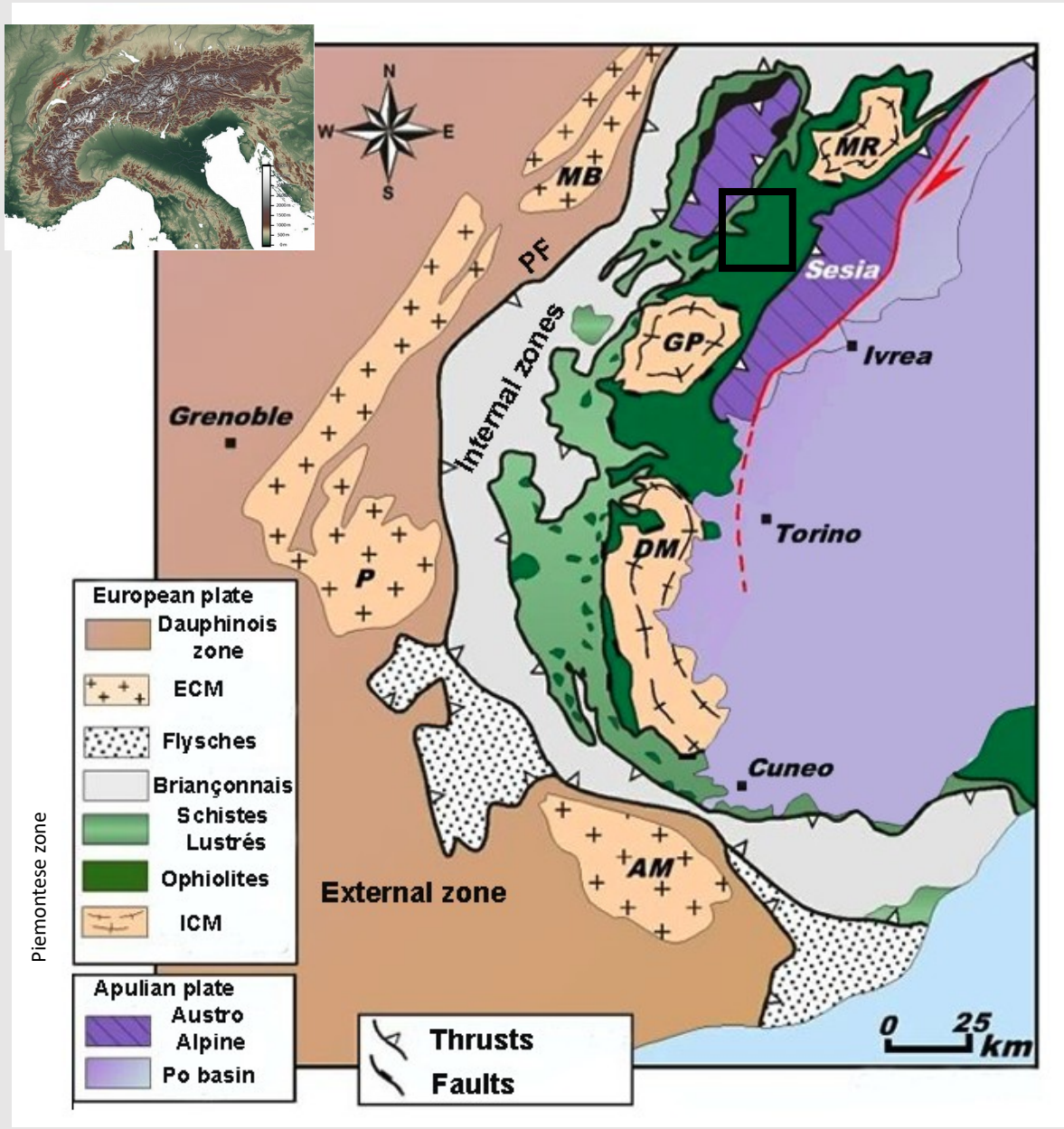
The Alpine example

1 Million geological of the western Alps



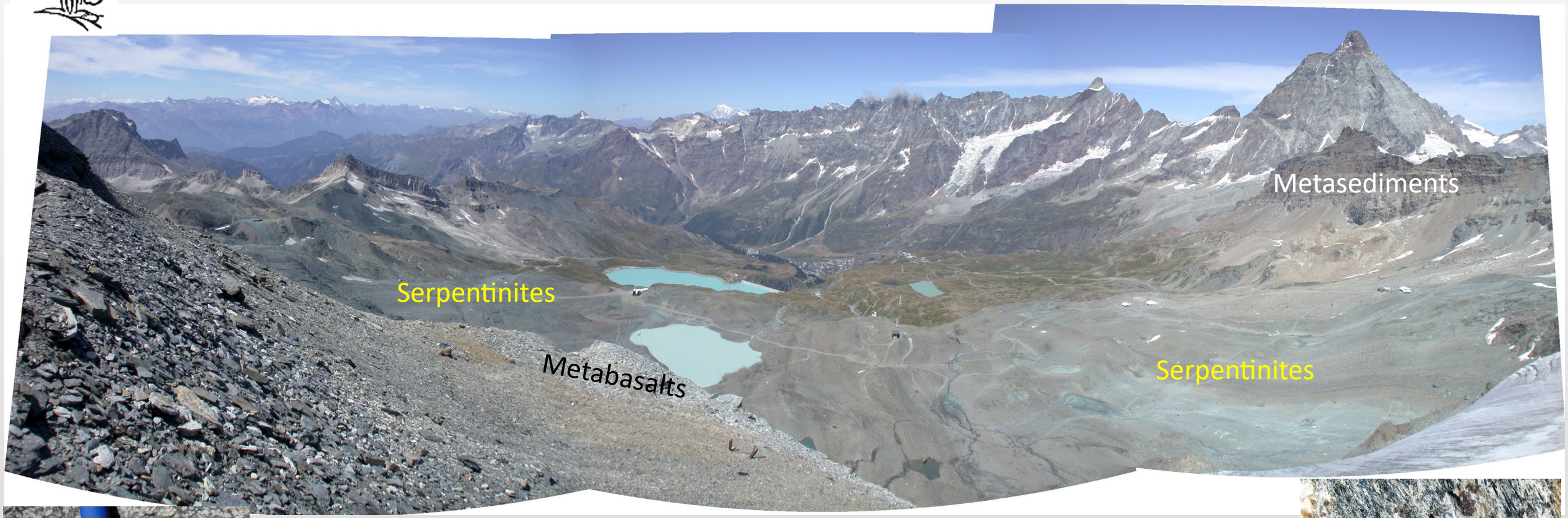
Ophiolites
In
dark green

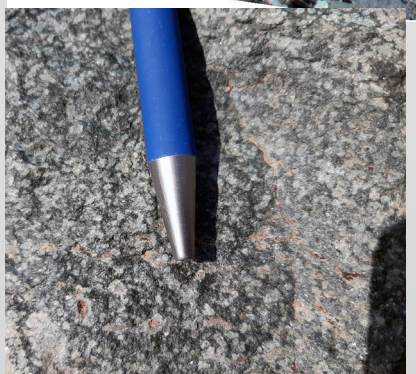
Simplified tectonic map of the western Alps



WHEN and HOW?

Breuil-Cervinia ophiolites (Italian Western Alps; Italian Swiss border)





Metabasalts:
Retrogressed eclogites

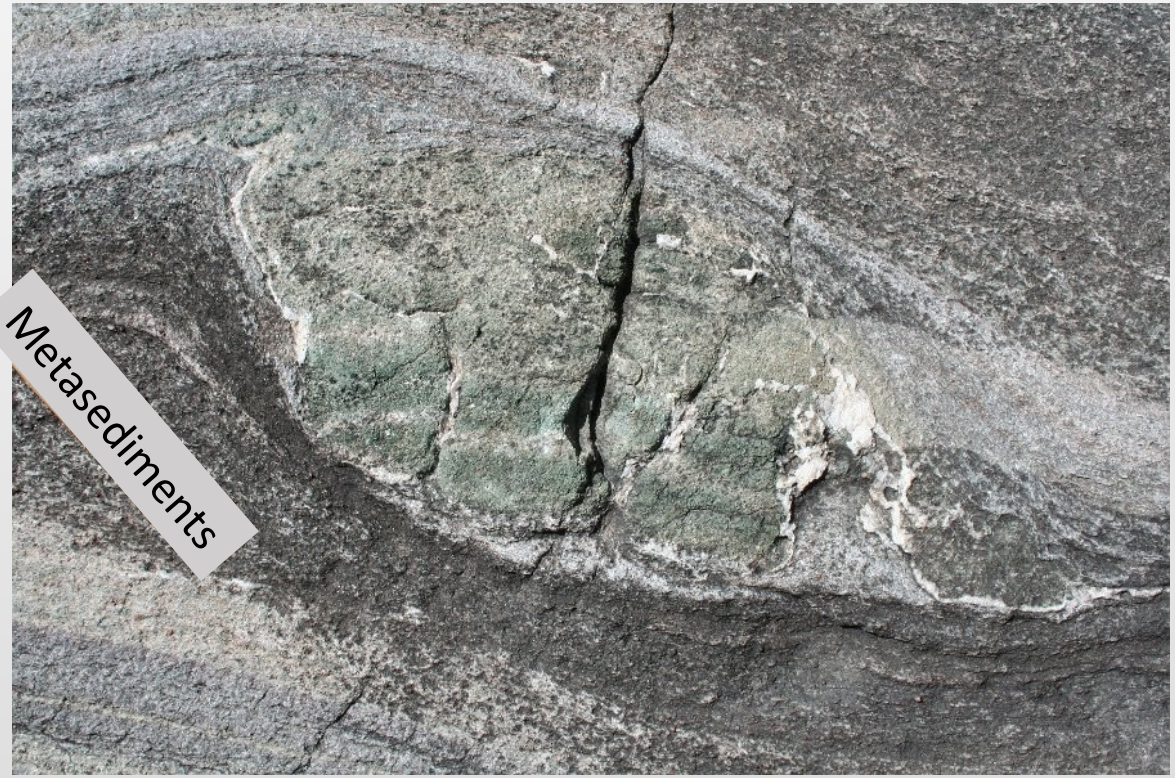
Eclogite facies: **65-50 Ma**
Botwell et al., 1994;
Rubatto et al., 1998;
Oberhänsli et al., 2004
Angiboust et al., 2009;
Rebay et al., 2018

Garnet+Quartz+
Phengite+Glaucophane
+/-Jadeite
metasediments

WHEN and HOW?

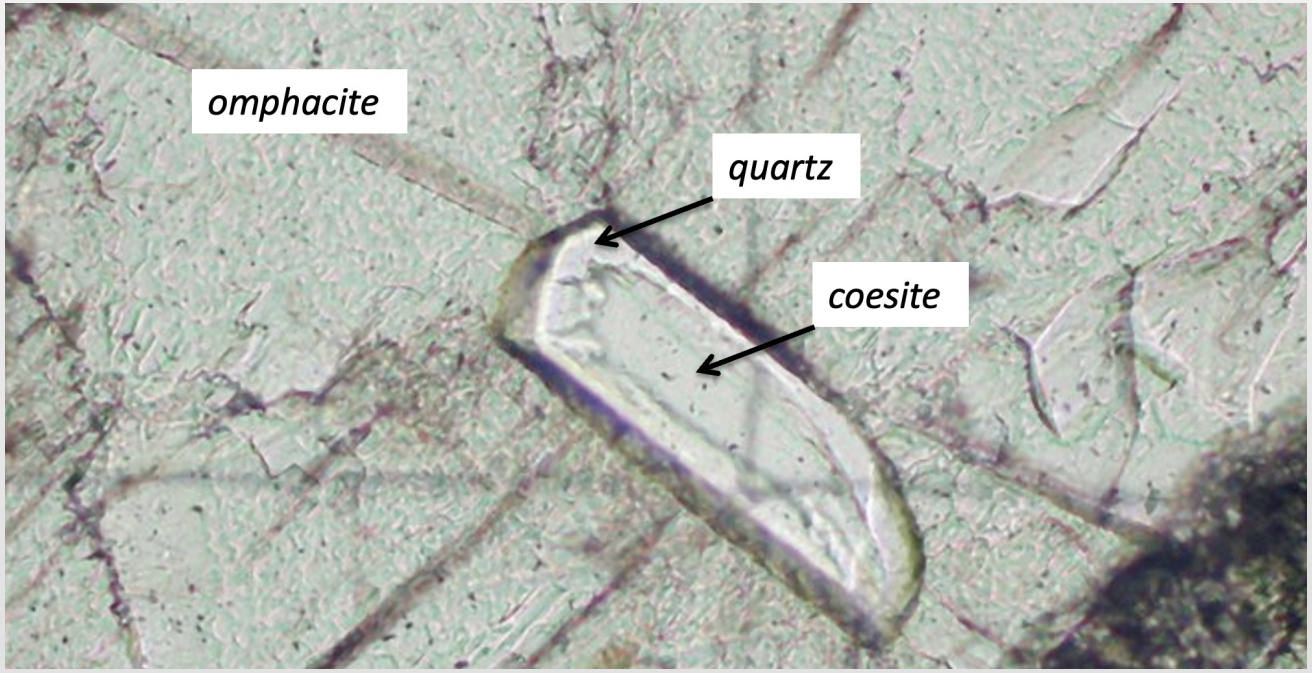
Breuil-Cervinia ophiolites (Italian Western Alps; Italian Swiss border)

Ultra High –Pressure conditions ! *(Barnicoat and Fry, 1986; Reinecke, 1991, 1998; Bucher, 2005; Angiboust, 2009; Groppo et al., 2009; Rebay et al.,2018 ; Lardeaux, 2024).*



Boudin of eclogite (i.e. metabasalt) in foliated marbles

Retrogression under Greenschist facies conditions 42-39 Ma (Skora et al., 2015; Rebay et al., 2018)



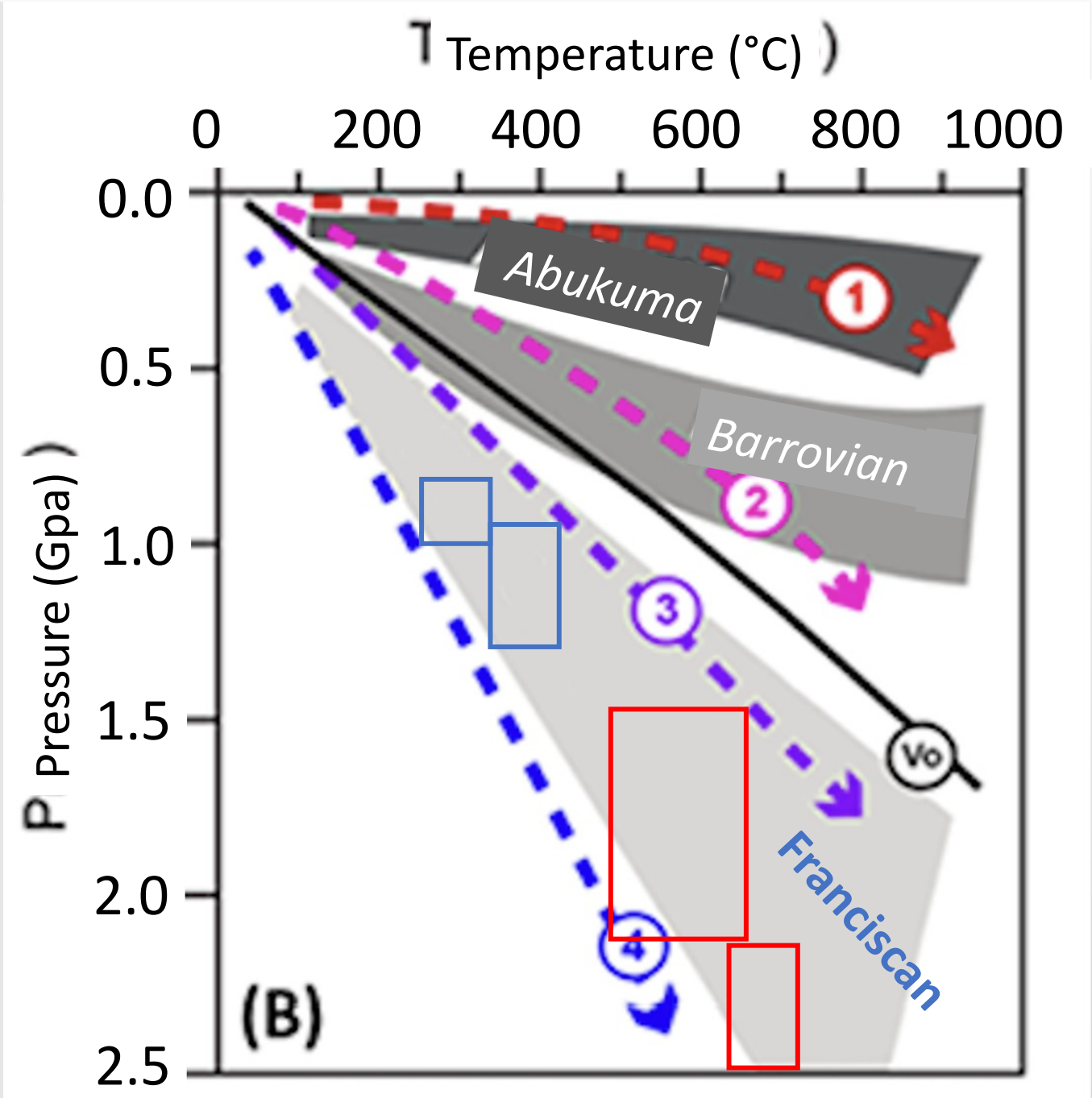
Relic of coesite included in an omphacite

Coesite : UHP SiO_2 polymorph.

Coesite=> Quartz during decompression.

WHEN and HOW? **The principle of actualism is the cornerstone of paleo-geodynamics.**

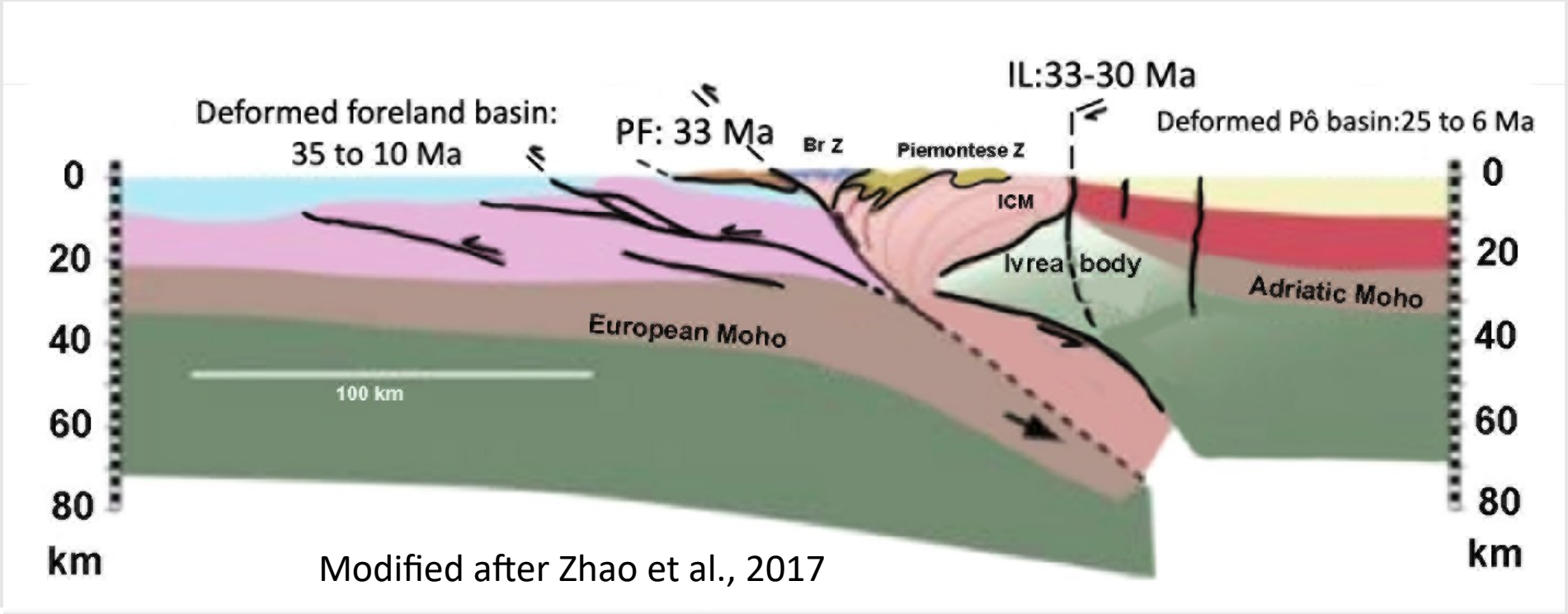
In the internal Piemontese Zone, ophiolites are fragments of subducted oceanic lithosphere.



And the exhumation? During subduction or continental collision?

WHEN and HOW?

Chronologic database: UHP and HP meta-ophiolites are retrogressed under Greenschist facies conditions (i.e. exhumed at depths < **10 km before 38 Ma**)



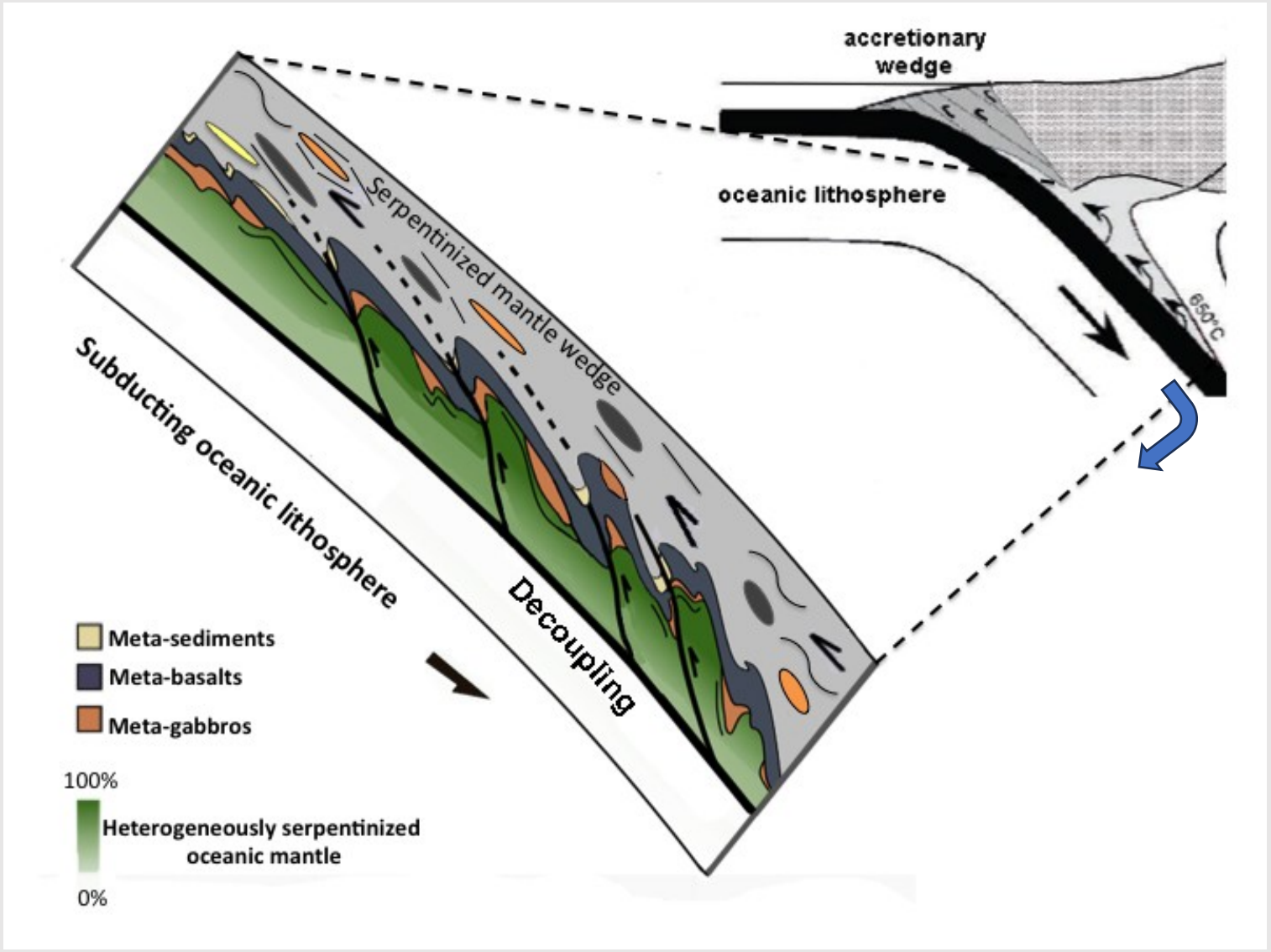
Modified after Zhao et al., 2017

Geophysical imagery of alpine collision
(Tardy et al. 1990; Schmid et al., 2004; Zhao et al.; 2017)

Main exhumation before continental collision

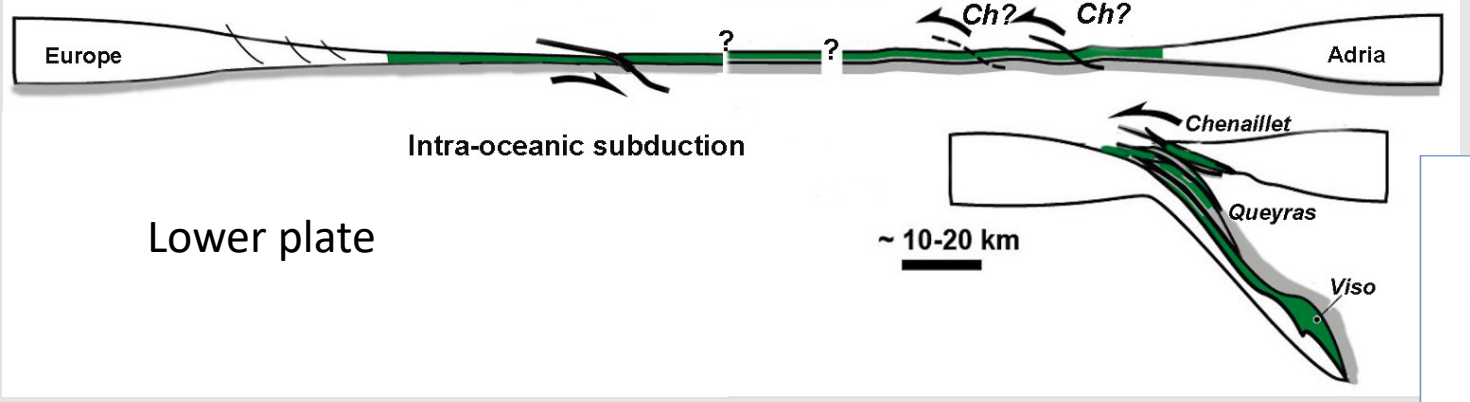
WHEN and HOW?

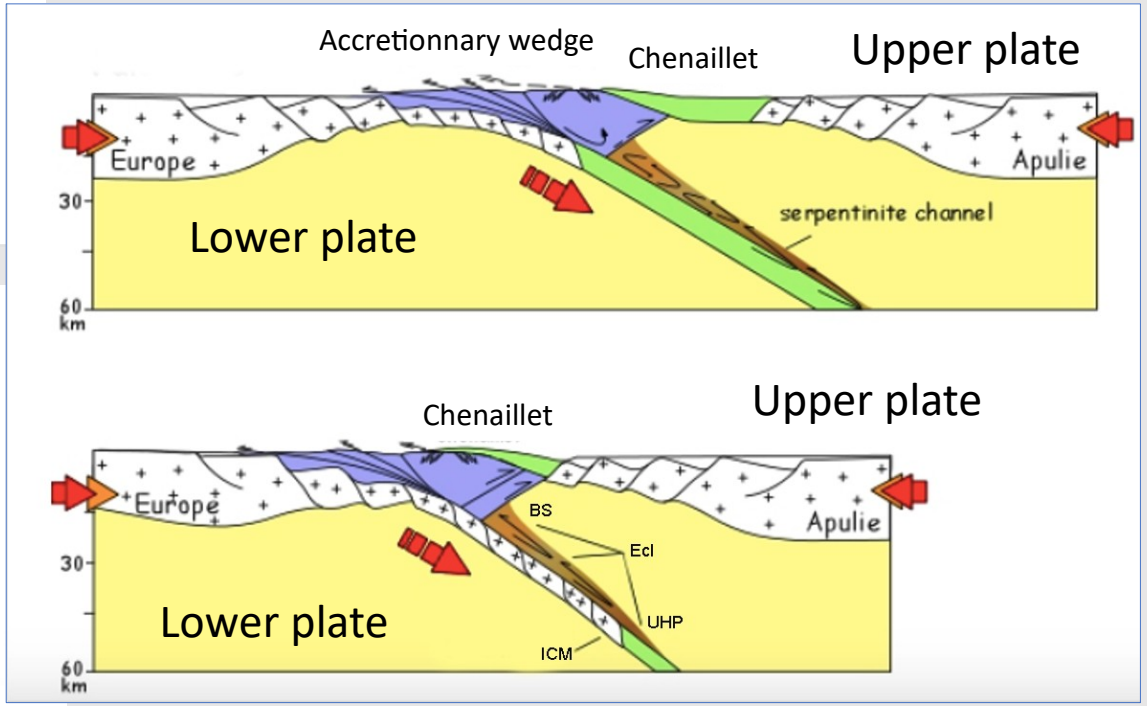
The principle of actualism is the cornerstone of paleo-geodynamics.

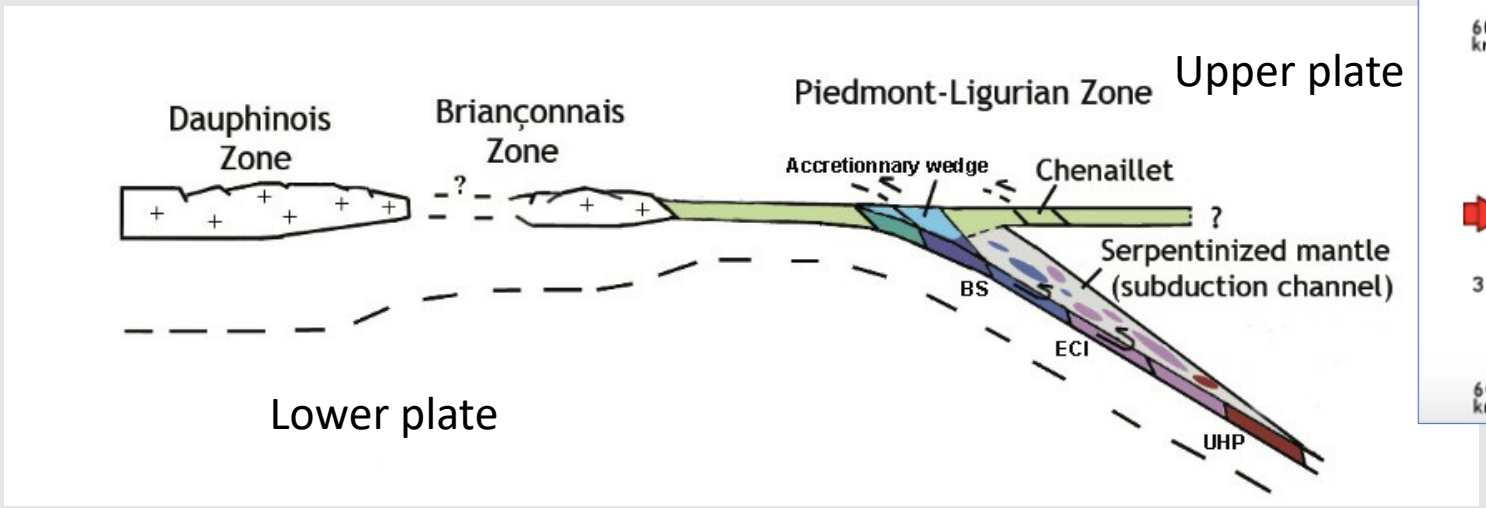


Ophiolites: Fragments of oceanic lithosphere Subducted and exhumed in a subduction channel

AND WHAT ABOUT THE CHENAILLET MASSIF?







Ophiolites in the mountains?

- Fragments of oceanic lithosphere, extracted from the lower plate, subducted and exhumed in a subduction channel.
- Fragments of oceanic lithosphere, located on the upper plate, obducted on the continental margin.