The western Alps

A geological-geophysical transect from the Rhône valley to the Torino Hills

27 Sept - 4 October 2011

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INVG Genova

Field Trip in the western Alps from the Rhône valley to the Torino Hills

27th of September 2011 to 4th of October 2011

List of Participants :

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Day 1 Tuesday 27th of September

Morning : arrival in Grenoble, short meeting in the laboratory

Lunch at the No Name restaurant

Stop 1.1 Afternoon: half day excursion to Saint-Eynard (Chartreuse), panoramic view over the Grenoble valley. General discussion.

Accommodation and dinner at Hotel "Les 3 Roses", Meylan

Day 2 Wednesday 28th of September

Morning 8 pm: travel by minibus to Valence

Stop 2.1 Presentation of the Alpine foreland and the Rhône Valley and further in the Tertiary foreland basin of Valréas (**Stop 2.2**).

Lunch in Nyons

Afternoon : travel along the D94 toward Gap,, crossing the Subalpine Mesozoic series (European passive margin sequence) overprinted by alpine folding (**Stops 2.3 & 2.4**) accommodation at Hotel Ibis in Gap.

Day 3 Thursday 29th of September

Morning : thin-skinned thrusting in the External Alps (Digne Thrust) and evidence of inversion of a Mesozoic basin, near La Saulce (S of Gap). Outcrop view of the Liassic series along D120, and panoramic view from the opposite side of the Durance valley (**Stops 3.1 to 3.3**).

Picnic above the Durance valley near Piégut

Afternoon : Cross section of the thick Jurassic series of the Digne nappe across the Remollon anticline, between Tallard and the Serre Ponçon dam (D900b) (**Stop 3.4**). Panoramic view from the East (Le Sauze) along D954, introducing a first set of nappes issued from the Tethyan oceanic domain (**Stop 3.5**).

accommodation at Hotel "Les flots bleus" at Savines le Lac

Day 4Friday 30th of September

Morning : panoramic view of this so-called Embrunais-Ubaye nappe system from nearby Savines (**Stop 4.1**). Travel to St Clément (N94), providing evidence that this first nappes stack has been overprinted by the Briançonnais Frontal Thrust (also improperly named Penninic Thrust).(**Stop 4.2**).

Picnic

Panoramic view of the Durance valley and the Briançonnais frontal Thrust (the boundary between the external and internal alps) (**Stop 4.3**). Introduction about its recent normal reactivation seen from the Mt Dauphin Quaternary terrace (**Stop 4.4**).
accommodation at Hotel "Les Barnières" in Guillestre.

Day 5 Saturday 1st of October

Morning : focus on the the Briançonnais frontal Thrust and its reactivation as a normal fault system in the Fournel Valley, landscape and outcrop evidence (west of Argentière la Bessée) (**Stop 5.1**)

Picnic

Afternoon : cross section throughout the Briançonnais anticline along the Guil valley from Guillestre to Château Queyras (D902), introductory discussion about metamorphism (**Stop 5.2**).
accommodation at Hotel "Les Barnières" in Guillestre

Day 6 Sunday 2nd of October

Whole day: visiting the Schistes Lustrés unit (blueschist nappe system) from Château Queyras to Col Agnel.
Morning Panorama at Château Queyras on the Roche Brune Briançonnais nappe system above the Schistes Lustrés (**Stop 6.1**), stop along the D205 showing the metasediments including basic lenses. (Vallon de Clausis) (**Stop 6.2**).

Picnic

Afternoon Blueschist gabbro at Col Agnel, and panorama on Monte Viso.(**Stop 6.3**)
accommodation at Hotel "Torinetto" at Sampeyre (Italy)

Day 7 Monday 3rd of October

Morning: Eclogites and serpentinites of the Monviso just north of the Val Varaita valley (**stop 7.1**). Then UHP Dora Maira continental massif (Parigi, south of Martiniana Po) : (**Stop 7.2**)

Picnic

crossing of the Pô plain, point of view of the Pô plain at Rooca di Cavour (usually cloudy ..) (**Stop 7.3**) accommodation at Moncalieri, "Hotel Rigolfo"

Day 8 Tuesday 4th of October

Morning : visting the Torino Hills (**Stop 8.1**) and Superga basilic
Afternoon : return to Grenoble.
Departure from Grenoble in the late afternoon or accommodation at Hotel "Les 3 Roses", Meylan

Overview of the geological context of the Western Alps

I.Introduction

The Alpine orogen resulted from the collision of the Adriatic microplate with the European continental margins of the Western Tethys ocean during Late Cretaceous to Early Tertiary times. The Africa-Europe convergence was trending N-S (Dewey et al., 1989;) but the Adriatic microplate may have moved independantly during the Tertiary (Handy et al., 2010). The Western Alpine orogen is well documented and the arcuate shape is related to change in relative motion of the Adriatic microplate, 35 Ma ago (Schmidt & Kissling, 2000; Ford et al., 2006, Handy et al., 2010; Dumont et al., in press). The subsequent Oligocene dynamics could be partly driven by the initiation of the Ligurian rollback subduction and associated eastward retreat (Vignaroli et al., 2009).

This geometry results from progressive deformation events from Eocene to Miocene, and involves rotations of ancient kinematic indicators during younger deformation stages, especially in the Internal Zones (Rosenbaum & Lister, 2005, Schwartz et al., 2007).

The present arc is outlined by a lithospheric thrust commonly called “Crustal Pennine Thrust” (CPT, Fig.1), that separates the External and Internal Zones and corresponds to at least 80 km offset of the moho (Gellec et al., 1990; Kissling et al., 2006; Lardeaux et al., 2006), but this feature occurred quite recently in Alpine history and does not follow the earlier Alpine kinematics and geometry particularly in the internal zones (Schmid & Kissling, 2000). However, in the footwall of the « Crustal Pennine thrust », that is, in the External Zone, the displacements and rotations are moderate (Aubourg et al., 1999). It is thus possible to observe the interference between differently oriented shortening stages during the development of continental collision more easily than in the Internal nappes stack whose building was polyphased.

Cross-folding in the External zone has been previously interpreted as interplay between Pyrenean and Alpine shortening events, that is between the Iberian and Apulian plates kinematic effects (i.e. Lemoine, 1972; Ford et al., 2006). Dumont et al. (in press) show that a significant part of N-S shortening is actually younger than the late Cretaceous « Pyrenean-Provence » event and just preceeded the westward Oligocene propagation of the Internal Nappes. It is proposed that these structures, which formed around the Eocene-Oligocene boundary, are linked to the NW propagating Adria-Europe collision during the early stage of the Alpine orogenesis.

II.Structural and stratigraphic setting of the external zone (from Dumont et al., Tectonics in press)

The External Zone of the Western Alps (fig.1) is composed of elevated crystalline basement massifs having recorded the Hercynian orogeny (e.g. Guillot et al., 2009), surrounded by Tethyan sedimentary cover of Mesozoic age and scattered remnants of Cenozoic Alpine foreland basins. The basement massifs trend NE-SW from Mont-Blanc to Belledonne, and NW-SE in the southernmost part of the Alpine arc (Argentera). The NE-SW trend corresponds to the Hercynian grain reactivated in large-scale tilted fault blocks during the Tethyan rifting (e.g. Lemoine et al., 1986 and references therein). This part of the European Tethyan palaeomargin experienced approximately E-W shortening in the footwall of the Pennine thrust during Alpine orogenesis (e.g. Dumont et al., 2008 and references therein).

This compressional interference structure was first affected by N-S shortening events commonly assigned to the « Pyrenean-Provence » stages, during late Cretaceous to Eocene times (Ford et al., 2006Michard et al., 2010). Subseqently, that is during late Eocene to earliest Oligocene, the first Alpine nappes (« Embrunais Nappes »), composed of late Cretaceous deep-water sediments likely of oceanic origin and of Mesozoic cover detached from the distal part of the European palaeomargin, were gravitationally transported with an approximately NW direction towards more proximal portions of the European foreland (Ford et al., 2006). It is observed that the later stages of thrust system propagation (from middle Oligocene onwards) were more radially directed (i.e. Platt et al., 1989). The main associated structure is a crustal-scale thrust that we call « Crustal Pennine Thrust » CPT (fig. 1), which is the present limit between the non-metamorphic foreland (including the early Embrunais Nappes) and the metamorphic, Internal Nappes stack (Sue and Tricart, 2006).

The Mesozoic series overlains a sharp late Hercynian unconformity, developed as a peneplanation surface which became flat and horizontal over the whole study area between late Carboniferous and early Triassic times. The so-called Dauphiné type Mesozoic sequence is characterised by the following formations :

- Late middle to Late Triassic: thin peritidal dolomites showing only minor thickness variation, which implies that the whole area remained flat and horizontal until near end-Triassic times. The Triassic sequence, which is only made of carbonates in Dauphiné, remains attached to the basement, but it thickens further S and SE in the SE-France basin, and also in the Internal Nappes, including evaporites which provide widespread detachment layers.
- The startpoint of intracontinental rifting is marked by thin but widespread ash layers with scattered alkaline to transitional basaltic flows.
- Lowermost Liassic (early to middle Hettangian) transgressive platform carbonates grade upwards into thick early Liassic to Middle Jurassic hemipelagic marls and limestones. These latter formations are coeval with reapeted stages of extensional faulting (Chevalier et al., 2003), which mark the Tethyan rifting and show important thickness and facies changes due to differential subsidence (Lemoine et al., 1986).
- Late Jurassic to early Cretaceous pelagic, post-rift carbonates are rarely preserved in the Dauphiné massifs, but there the post-rift unconformity is locally observed thanks to Tithonian limestones directly overlying the Hercynian basement. The post-rift cover is widespread further to the west and south, providing the thick carbonate series of the Subalpine massifs.
- The Upper Cretaceous formations recorded the earliest, north-directed compressional deformation (pre-Senonian folding) in the Devoluy Subalpine massif, due to the motion of the Iberian block (Michard et al., 2010).
- The Tertiary series from Paleocene to Quternary first developed in the proximal footwall of the Internal Nappes and progressively migrated outwards with the building of the Orogenic wedge. The detrital sediments, first marine then continental, record the erosion of the nascent reliefs.

III. Structural and stratigraphic setting of the internal zone (from Lardeaux et al., 2006)

The Briançonnais zone consists mainly of late Paleozoic, Tethyan sediments and pre-Alpine basement rocks (Ambin and Acceglio massifs). The Briançonnais sedimentary zone corresponds to a tectonic pile of thrust sheets involving ante-, syn- and post-rift sediments originated upon a thinned passive margin (Lemoine et al., 1986; Claudel and Dumont, 1999). This nappe pile was folded during Oligocene times and, acting as a mechanically contrasted multilayer, gave rise to regional west and east-verging folds and associated thrusts. The latter are known as the Briançonnais backfolds and backthrusts and correspond to the present-day alpine fan-shaped structure (Tricart, 1984). These poly-deformed rocks are also metamorphosed under lawsonite-greenschist facies conditions (Goffé et al., 2004). In this part of the Briançonnais zone, a dense, regional-scale fault network attests to a Neogene to present-day extension (see details in Sue and Tricart, 2003). The Briançonnais basement consists of pre-Alpine magmatic and metamorphic rocks, whose Permo-Carboniferous sedimentary covers are preserved in some places but strongly re-worked and metamorphosed during Alpine orogeny. The metamorphic evolution of these basement slices contrasts sharply with respect to the evolution of the cover nappe pile. In the Briançonnais basement units, upper blueschist and/or eclogite facies conditions have been deciphered (Goffé et al., 2004). These significant metamorphic gaps are consistent with the existence of severe tectonic decoupling between the Briançonnais units. For example, the Acceglio massif is regarded as a low-angle extruded unit, bounded to the west by a normal fault and to the east by an inverse fault, within the overlying Piedmont Schistes lustrés of Queyras (Schwartz et al., 2000).

The composite Piedmont zone comprises the Queyras Schistes lustrés complex, the Monviso and Rocciavré ophiolitic complexes and the Dora Maira internal crystalline massif. The Queyras Schistes Lustrés were derived from Liassic to late Cretaceous sediments deposited in the oceanic domain (Lemoine et al., 1986). These sediments were strongly deformed and metamorphosed during alpine subduction and they outcrop today as foliated and polydeformed calcschists enclosing boudinaged decametric to kilometric-sized ophiolitic bodies. At the regional scale, the main structure is a pile of imbricated thrust sheets related to the building of an accretionary wedge during the Paleogene. The Queyras Schistes Lustrés show an apparent monoclinal structure dipping towards the WSW. This pile, which underwent repeated and severe refolding under blueschist facies metamorphic conditions is associated with this tectonic evolution and grades up eastwards from low-temperature blueschist to high-temperature blueschist facies conditions (Agard et al., 2001; Schwartz, 2002). A ductile normal fault separates the Queyras Schistes lustrés complex from the Monviso ophiolitic massif (Ballèvre et al., 1990; Blake and Jakyo, 1990). The latter is dominated by remnants of the Tethyan oceanic lithosphere that was strongly deformed and metamorphosed under eclogite facies conditions (Lombardo et al., 1978; Lardeaux et al., 1987) during the Eocene (Monié and Philippot, 1989; Duchêne et al., 1997). Contrasted eclogitic conditions have been deciphered in the Monviso massif (Messiga et al., 1999; Schwartz et al., 2000) indicating that this massif is composed of imbricated eclogitic units. The Monviso eclogites are separated from the internal crystalline massif of Dora Maira by a ductile normal fault (Blake and Jakyo, 1990; Schwartz et al., 2001). Situated in the lowermost structural position in the studied cross sections, the Dora Maira massif corresponds to a stack of deeply exhumed continental basement slices involved in a “dome like” structure (Henry et al., 1993; Michard et al., 1993). Here again, significantly contrasted metamorphic conditions have been inferred (Chopin et al., 1991; Henry et al., 1993). Quartz-bearing eclogite facies rocks outcrop at the top of the Dora Maira dome and overlie the coesite-bearing eclogitic unit. The tectonic contact between coesite and quartz-bearing eclogitic units is also a normal fault. This pile of thin (< 1km) high to ultra-high pressure metamorphic units rests upon a lowermost blueschist facies tectono-metamorphic unit (Pinerolo-Sanfront unit) along a thrust contact. The latter unit is similar, with respect to the lithologies, structural position and metamorphic evolution, to Briançonnais basement slices (Michard et al., 1993; Henry et al., 1993).

References (cited in the text and in the figures)

Agard, P., Monié, P., Jolivet, L. & Goffé, B., 2002. Exhumation of the Schistes Lustrés complex: in situ laser probe Ar/Ar constraints and implications for the Western Alps. *Journal of Metamorphic Geology,* **20**, 599-618.

Agard, P., Yamamoto, P., Jolivet, L. & Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms. *Earth Sciences Reviews*, **92**, 53-79.

Angiboust, S., Langdon, R., Agard, P., Waters, D. J. & Chopin, C., 2011. Eclogitization of the Monviso ophiolite (W. Alps) and implications on subduction dynamics. *Journal of Metamorphic Geology*, **doi:10.1111/j.1525-1314.2011.00951.x**.

Aubourg, C. & Chabert-Pelline, C., 1999. Neogene remagnetization of normal polarity in the Late Jurassic Block shales from the southern Subalpine chains (French Alpes). Evidence for late anticlockwise rotations. *Tectonophysics*, **308**, 473-486.

Ballèvre, M., Lagabrielle, Y. & Merle, 1990. Tertiary ductile normal faulting as a consequence of lithospheric stacking in the Western Alps. *Société Géologique de France, mémoires*, **156**, 227-236.

Besson, D., 2005. Architecture du bassin rhodano-provencal miocène (Alpes, SE France). Relations entre déformation, physiographie et sédimentation dans un bassin molassique d'avant-pays. *Ph. D. Thesis,* Ecole des Mines, Paris, 449p.

Blake, C. & Jayko, A. S., 1990. Uplift of high pressure rocks in the Western Alps: evidence of structural attenuation along low angle normal faults. *Mémoire de la Socièté Géologique de france,* **156**, 228-237.

Chopin, C., 1984. Coesite and pure pyrope in high-grade blueschists of the Western Alps. *Contributions to Mineralogy and Petrology*, **86**, 107-118.

Chopin, C., 2003. Ultrahigh-pressure metamorphism : tracing continental crust into the mantle. *Earth and Planet Science Letters,* **212**, 1-14.

Chopin, C., Henry, C. & Michard, A., 1991. Geology and Petrology of the coesite bearing terrain, Dora Maira massif, Western Alps. *European Journal of Mineralogy,* **3**, 263-291.

Chopin, C. & Schertl, H. B., 1999. The UHP unit in the Dora Maira massif, western Alps. *International Geology Reviews*, **41**, 765-780.

Deville, E. & Sassi, W., 2006. Contrasting thermal evolution of thrust systems: An analytical and modeling approach in the front of the Western Alps. *AAPG Bulletin,* **90**, 887-907.

Duchêne, S., Blichert-Toft, J., Luais, B., Télouk, P., Lardeaux, J. M. & Albarède, F., 1997a. The Lu-Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. *Nature*, **387**, 586-589.

Duchene, S., Lardeaux, J. M. & Albarede, F., 1997. Exhumation of eclogites: Insights from retrograde depth-time path analysis. *Tectonophysics*, **280**.

Dumont, T., 1998. Sea-Level changes and early rifting of a European Tethyan margin in the western Alps and Southeastern France. In: de Graciansky P.C., Hardenbol J., Jacquin T. & Vail P.R. (Eds): Mesozoïc and Cenozoic sequence stratigraphy of European Basins. *Society of Economic Petrologists and Mineralogists, Special Publicatio*, **60**, 623-642.

Dumont, T., Champagnac, J. D., Crouzet, C. & Rochat, P., 2008. Multistage shortening in the Dauphiné zone (French Alps): the record of Alpine collision and implications for pre-Alpine restoration. *Swiss Jour. Geosc*, **101**, 89-110.

Dumont, T., Simon-Labric, T., Authemayou, C. & Heymes, T., in press. Lateral termination of the north-directed Alpine orogeny and onset of westward escape in the Western Alpine arc: structural and sedimentary evidence from the external zone. Tectonics, **DOI10.1029/2010TC002836**.

Dumont, T., Schwartz, S., Guillot, S., Tricart, P. & Jourdan, S., in press. Structural and Sedimentary records of the Oligocene revolution in the Western Alpine arc. *Journal of Geodynamics.*

Ford, M., Duchêne, S., Gasquet, D. & Vanderhaeghe, O., 2006. Two-phase orogenic convergence in the external and internal SW Alps. *Journal of Geological Society of London*, **163**, 1-12.

Gidon, M. *Website*: Geological Atlas of the French Alps. **http://www.geol-alp.com**.

Goffé, B. & Schwartz, S., Lardeaux, J.M., and Bousquet, R., 2004. Explanatory notes to the map: Metamorphic structure of the Alps, western and Ligurian Alps. *Mitteilungen der Osterreichischen Mineralogischen Gessellschaft*, **149**, 125-144.

Graciansky de, P. C., Roberts, D. G. & Tricart, P., 2010. *The Western Alps, from rift to passive margin to orogenic belt: an integrated overview*. Elsevier, Amsterdam.

Guellec, S., Mugnier, J. L., Tardy, M. & Roure, F., 1990. Neogene evolution of the western Alpine foreland in the light of Ecors data and balanced cross-section. *in : Mem. Soc. Géol. France,* **156**, 165-184.

Guillot, S., Di Paola, S., Ménot, R. P., Ledru, P., Spalla, M. I., Gosso, G. & Schwartz, S., 2009. Evidence for a main Paleozoic suture zone in the Belledonne, Grandes Rousses and Oisans massifs (External Crystalline Massifs, Western Alps). *Bulletin de la Société Géologique de France*, **180**, 487-500.

Guillot, S., Hattori, K., Agard, P., Schwartz, S. & Vidal, O., 2009. Exhumation processes in oceanic and continental subduction contexts: a review. *In S. Lallemand and F. Funiciello (eds.) "Subduction Zone Dynamics", Springer-Verlag Berlin Heidelberg.*, **doi 10.1007/978-3-540-87974-9**, 175-204,.

Guillot, S., Schwartz, S., Hattori, K., Auzende, A. & Lardeaux, J. M., 2004. The Monviso ophiolitic Massif (Western Alps), a section through a serpentinite subduction channel. *In: (eds.) Beltrando, M., Lister, G., Ganne, J. and Boullier, A., Evolution of the western Alps: insights from metamorphism, structural geology, tectonics and geochronology, Journal of the Virtual Explorer*, **16**, Paper 6.

Henry, C., Michard, A. & Chopin, C., 1993. Geometry and structural evolution of ultra-high-pressure and high-pressure rocks from the Dora-Maira massif, Western Alps, Italy. *Journal of Structural Geology*, **15**, 965-981

Kissling, E., Schmid, S., Lippitsch, R., Ansorge, J. & Fügenschuh, B., 2006. Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography. *In: Gee D.G. & Stephenson R.A. (eds.): European Lithosphere Dynamics. Geol. Soc. London Memoirs*, **32**, 129-145.

Lardeaux, J. M., Schwartz, S., Paul, A., Tricart, P., Guillot, S., Béthoux, N. & Masson, F., 2006. A crustal-scale cross section of the southwestern Alps combining geophysical and geological imagery. *Terra Nova*, **doi:10.1111/j.1365-3121.2006.00706x**.

Lemoine, M., Bas, T., Arnaud-Vanneau, A., Arnaud, H., Dumont, T., Gidon, M., Bourbon, M., Graciansky de, P. C., Rudkiewcz, J. L., Mégard-Galli, J. & Tricart, P., 1986. The continental margin of the Mesozoic Tethys in the Western Alps. *Marine and Petroleum Geology*, **3**, 179-199.

Lombardo, B., Nervo, R., Compagnoni, R., Messiga, B., Kienast, J. R., Mevel, C., Fiora, L., Piccardo, G. & Lanza, R., 1978. Osservazioni preliminari sulle ofioliti metamorfiche del monviso (Alpi occidentali). *Rendiconti Societa Italiana di Mineralogia e Petrologia*, **34**, 253-305.

Lombardo, B., Rubatto, D. & Castelli, D., 2002. Ion microprobe U-Pb dating of zircon from a Monviso metaplagiogranite: implications for the evolution of the Piedmont-Liguri Tethys in the western Alps. *Ofioliti*, **27**, 109-117.

Malusa, M., Faccenna, C., Garzanti, E. & Polino, R., 2011. Divergence in subduction zones and exhumation of high pressure rocks (Eocene Western Alps). *Earth and Planet Science Letters*, **310**, 21-32.

Manatschal, G., Munterer, O., Lavier, L., Minshull, T.A. & Peron-Pinvidic, G, 2007. Observations from the Alpine Tethys and Iberia Newfoundland margins pertinent to the interpretation of continental breakup. *Geol. Soc. London, Spec. Publ.*, **282**, 291-324.

Marchant, R. H. & Stampfli, G. M., 1997. Subduction of continental crust in the Western Alps. *Tectonophysics*, **269**, 217-235

Masson, F., Verdun, J., Bayer, R. & Debeglia, N., 1999. Une nouvelle carte gravimétrique des Alpes occidentales et ses conséquences structurales et tectoniques. *Compte Rendus Geoscience*, **329**, 865-871.

Merle, O. & Michon, L., 2001. The formation of the West European Rift; a new model as exemplified by the Massif Central area. *Bull. Soc. Géol. France*, **172**, 213-221.

Messiga, B., Kienast, J.-R., Rebay, G., Riccardi, M. P. & Tribuzio, R., 1999. Cr-rich magnesio-chloritoid eclogites from the Monviso ophiolites (Western Alps, Italy). *Journal of Metamorphic Geology*, **17**, 287-299.

Michard, A., Chopin, C. & Henry, C., 1993. Compression versus extension in the exhumation of the Dora-Maira coesite-bearing unit, Western Alps, Italy. *Tectonophysics*, **221**, 173-193.

Michard, A., Dumont, T., Andreani, L. & Loget, N., 2010. Cretaceous folding in the Dévoluy Mountains (Subalpine Chains, France): Gravity-driven detachment at the European paleomargin versus compressional event. *Bulletin de la Société Géologique de France*, **180**.

Michon, L., 2000. Dynamique de l'extension continentale, application au rift ouest-européen. *Ph.D. Thesis*, University of Clermont Ferrand, 263p.

Monié, P. & Chopin, C., 1991. 40Ar/39Ar dating in coesite-bearing and associated units of the Dora Maira massif, Western Alps. *European Journal of Mineralogy*, **3**, 239-262.

Monié, P. & Philippot, P., 1989. Mise en évidence de l'âge Eocène moyen du métamorphisme de haute pression dans la nappe ophiolitique du Monviso (Alpes Occidentales) par la méthode Ar-Ar. *Compte-rendus de l'Académie des Sciences*, **309**, 245-251.

Morag, N., Avigad, D., Harlavan, Y., McWilliams, M. & Michard, A., 2008. Rapid exhumation and mountain building in the Western Alps: Petrology and 40Ar/ 39Ar geochronology of detritus from Tertiary basins of southeastern France. *Tectonics*, **27**, 1-18.

Mosca, P., 2007. Contesto strutturale e deposizionale della Collina di Torino alla terminazione occidentale dei thrusts Sudalpini. *Rendiconti Società Geologica Italiana*, **4**, 277-278.

Paul, A., Cattaneo, M., Thouvenot, F., Spallarossa, D., Béthoux, N. & Fréchet, J., 2001. A three-dimensional crustal velocity model of the southwesternAlps from the local earthquake tomography. *Journal Geophysical Research*, **106**, 19367-19389.

Philippe, Y., Deville, E. & Mascle, A., 1998. Thin-skinned inversion tectonics at oblique basin margins: example of the western Vercors and Chartreuse Subalpine massifs (SE France). *Geol. Soc. London, Spec. Publ.*, **134**, 239-262.

Philippot, P. & Kienast, J. R., 1989. Chemical-microstructural changes in eclogite-facies shear zones (Monviso, Western Alps, north Italy) as indicators of strain history and the mechanism and scale of mass transfer. *Lithos*, **23**, 179-200.

Piana, F. & Polino, R., 1995. Tertiary structural relationships between Alps and Apennines: the critical Torino Hill and Monferrato area. Northwestern Italy. *Terra Nova*, **7**, 138-143.

Platt, J. P., Behrmann, J. H., Cunningham, P. C., Dewey, J. F., Helman, M., Parrish, M., Shepley, M. G., Wallis, S. & Weston, P. J., 1989. Kinematics of the Alpine arc and the motion history of Adria. *Nature Geosciences*, **337**, 158-161.

Polino, R., Ruffini, R. & Ricci, B., 1991. Le molasse terziarie della collina di Torino: relazioni con la cinematica alpina. *Atti Ticinensi Scienze della Terra*, **34**, 85-95.

Rosenbaum, G. & Lister, G. S., 2005. The Western Alps from the Jurassic to Oligocene: spatio-temporal constraints and evolutionary reconstructions. *Earth Science Reviews*, **69**, 281-306.

Rubatto, D. & Hermann, J., 2003. Zircon formation during fluid circulation in eclogites (Monviso Western Alps): implications for Zr and Hf budget in subduction zones. *Geochimica and Cosmochimica Acta*, **66**, 2173-2187.

Schertl, H.-P. & Schreyer, W., 2008. Geochemistry of coesite-bearing „pyrope quartzites“ and related rocks from the Dora-Maira Massif, Western Alps. *European Journal of Mineralogy*, **20**, 791-809.

Schmid, S., Fügenschuh, B., Kissling, E. & Schuster, R., 2004. Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geol. Helv.*, **97**, 93-117.

Schmid, S. M. & Kissling, E., 2000. The arc of the western Alps in the light of geophysical data on deep crustal structure. *Tectonics*, **19**, 62-85.

Schreiber, D., Lardeaux, J.-M., Martelet, G., Courrioux, G. & Guillen, A., 2010. 3-D modelling of Alpine Mohos in Southwestern Alps. *Geophysical Journal Interior*, **DOI : 10.1111/j.1365-246X.2009.04486.x.**

Schwartz, S., 2000. La zone piémontaise des Alpes occidentales: un paléo-complexe de subduction. *Ph-D thesis, University of Lyon, 278p.*

Schwartz, S., Allemand, P. & Guillot, S., 2001. Numerical model of the effect of serpentinites on the exhumation of eclogitic rocks : insights from the Monviso ophiolitic massif (Western Alps). *Tectonophysics*, **42**, 193-206.

Schwartz, S., Guillot, S., Tricart, P., Bernet, M., Jourdan, S., Dumont, T. & Montagnac, G., in press. Source tracing of detrital serpentinite in the Oligocene molasse deposits from Western Alps (Barrême basin): implications for relief formation in the Internal Zone. *Geological Magazine*.

Schwartz, S., Lardeaux, J. M., Guillot, S. & Tricart, P., 2000. Diversité du métamorphisme éclogitique dans le massif ophiolitique du Monviso 'Alpes Occidentales, Italie). *Geodinamica Acta*, **13**, 169-188.

Schwartz, S., Lardeaux, J. M. & Tricart, P., 2000. La zone d'Acceglio (Alpes cottiennes): un nouvel example de la croûte continentale éclogitisée dans les Alpes occidentales. *Compte-rendus de l'Académie des Sciences*, **330**, 859-866.

Schwartz, S., Lardeaux, J. M., Tricart, P., Guillot, S. & Labrin, E., 2007. Diachronous exhumation of subducted HP metamorphic rocks from southwestern Alps: evidences from fission-track analysis. *Terra Nova*, **19**, 133-140.

Schwartz, S., Tricart, P., Lardeaux, J. M., Guillot, S. & Vidal, O., 2009. Final exhumation of an accretionary wedge (Queyras Schistes Lustrés, Western Alps): deformation sequence and associated P-T-t path. *Geological Society of American Bulletin*, **doi:10.1130/b26223.1**.

Sénéchal, G. & Thouvenot, F., 1991. Geometrical migration of line-drawings: a simplified technique applied to ECORS data, in: /Continental Lithosphere: Deep Seismic Reflection/s, R. Meissner, L. Brown, H.J. Dürbaum, W. Franke, K. Fuchs, F. Seifert (eds). *AGU Geodynamics Series*, **22**, 401-407.

Séranne, M., 1999. The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. *Geol. Soc. London, Spec. Publ.*, **156**, 15-36.

Sissingh, W., 2001. Tectonostratigraphy of the West Alpine foreland: correlation of Tertiary sedimentary sequences, change in eustatic sea-level and stress regimes. *Tectonophysics*, **333**, 361-400.

Stehly, L., Fry, B., Campillo, M., N. M. Shapiro, N. M., Guilbert, J., Boschi, L. & Giardini, D., 2009. Tomography of the Alpine region from observations of seismic
ambient noise. *Geophys. J. Int.*, **178, 338–350 doi: 10.1111/j.1365-246X.2009.04132.x**.

Sue, C., Delacou, B., Champagnac, J., Allanic, C., Tricart, P. & Burkhard, M., 2007. Extensional neotectonics around the bend of the Western/Central Alps: an overview. *International Journal of Earth Sciences*, **96**, 1101-1129.

Sue, C. & Tricart, P., 1999. Late Alpine brittle extension above the Frontal Pennine Thrust near Briançon, Western Alps. *Eclogae Geologicae Helvetiae.*, **92**, 171-181.

Sue, C. & Tricart, P., 2002. Widespread normal faulting in the Internal Western Alps: a new constraint on arc dynamics. *Journal of the Geological Society, London*, **159**, 61-70.

Thouvenot, F., Paul, A., Frechet, J., Bethoux, N., Jenatton, L. & Guiguet, R., 2007. Are there really superposed Mohos in the southwestern Alps? New seismic data from fan profiling reflections. *Geophysical Journal Interior*, **170**, 1180-1194.

Tricart, P., 1984. From passive margin to continental collision : a tectonic scenario for the Western Alps. *American Journal of Science*, **284**, 97-120.

Tricart, P., Amaudric du Chaffaut, S., Ayoub, C., Ballèvre, M., Caby, R., Gout, C., Lagabrielle, Y., Leblanc, D., Le Mer, O., P., P. & Saby, P., 2003. Carte géol. France (1/50 000), feuille Aiguilles-Col Saint Martin (848). Orléans: BRGM.

Tricart, P., Lardeaux, J.-M., Schwartz, S. & Sue, C., 2006. The late extension in the inner western Alps: a synthesis along the south-Pelvoux transect. *Bulletin de la Société Géologique de France*, **177**, 299-310.

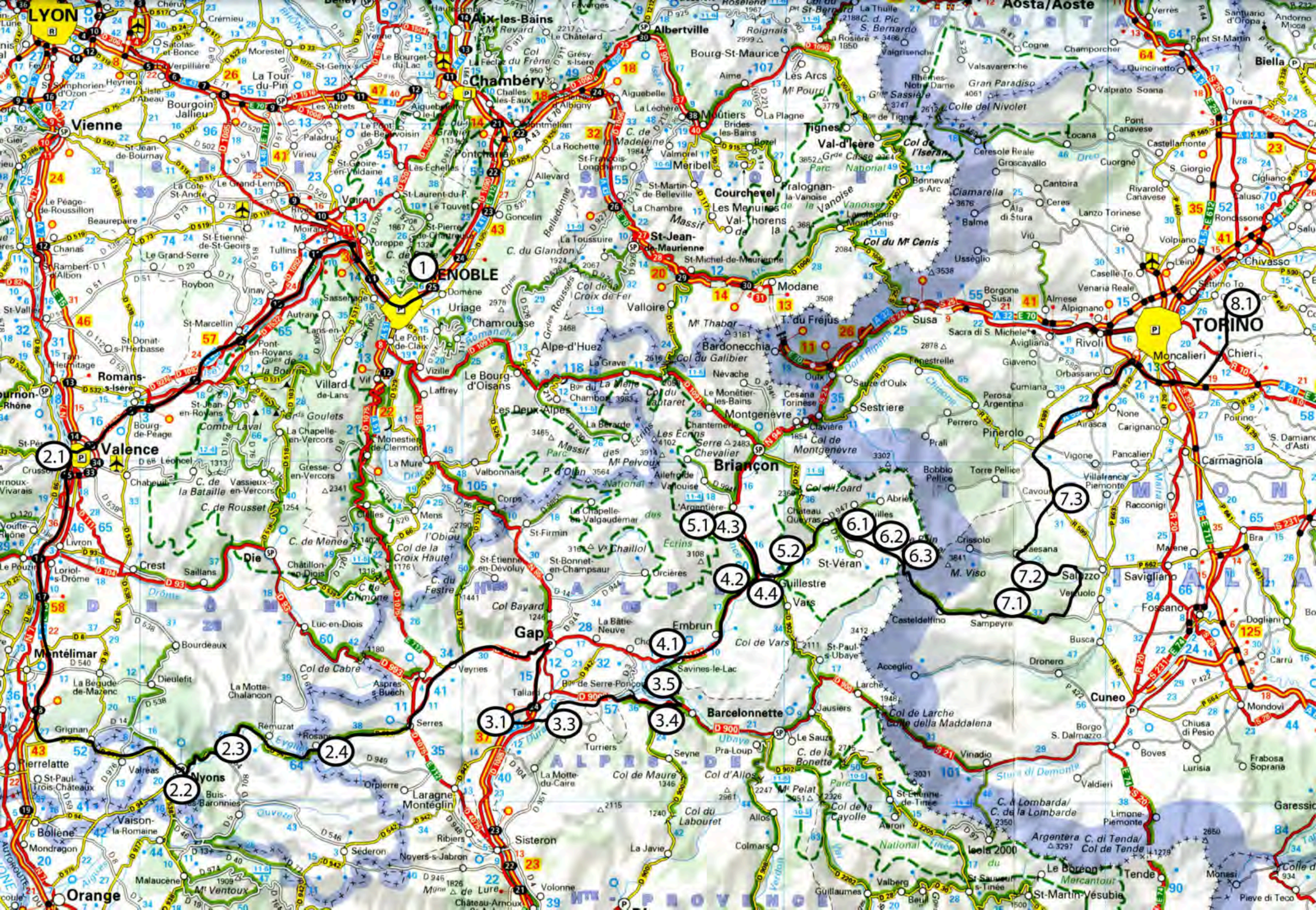
Tricart, P. & Schwartz, S., 2006. A north-south section across the Queyras Schistes Lustrés (Piedmont zone, Western Alps): Syn-collision refolding of a subduction wedge. *Eclogae geol. Helv.*, **99 Doi 10.1007/s00015-006-1197-6**.

Tricart, P., Schwartz, S., Sue, C. & Lardeaux, J. M., 2004. Evidence of synextension tilting and doming during final exhumation from analysis of multistage faults (Queyras Schistes lustrés, Western Alps). *J. Struct. Geol.*, **26**, 1633-1645.

Tricart, P., Van Der Beek, P., Schwartz, S. & Labrin, E., 2007. Diachronous late-stage exhumation across the western Alpine arc: constraints from apatite fission-track thermochronology between the Pelvoux and Dora-Maira Massifs. *Journal of the Geological Society, London*, **164**, 163-174.

Vignaroli, G., Faccenna, C., Rossetti, F. & Jolivet, L., 2009. Insights from the Apennines metamorphic complexes and their bearing on the kinematics evolution of the orogen. *Geological Society Special Publications*, **311**, 235-256.

Waldhauser, F., Kissling, E., Ansorge, J. & Mueller, S., 1998. Three-dimensional interface modelling with two-dimensional seismic data: the Alpine crust-mantle boundary. *Geophysical Journal Interior*, **135**, 264-278.



LYON
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Valence
Romans-s-Isère
Montélimar
Orange
Nyons
Grenoble
Chambéry
Aix-les-Bains
Albertville
Bourg-St-Maurice
Moûtiers
St-Jean-de-Maurienne
Modane
Briançon
Gap
Embrun
Guillestre
Barcelonnette
Sisteron
Die
Crest
Serres
Veynes
Sestriere
Susa
Pinerolo
Saluzzo
Cuneo
TORINO
Moncalieri
Chieri
Aosta/Aoste
Biella
Savigliano
Fossano
Col de Vars
Col de Larche
Col de Montgenèvre
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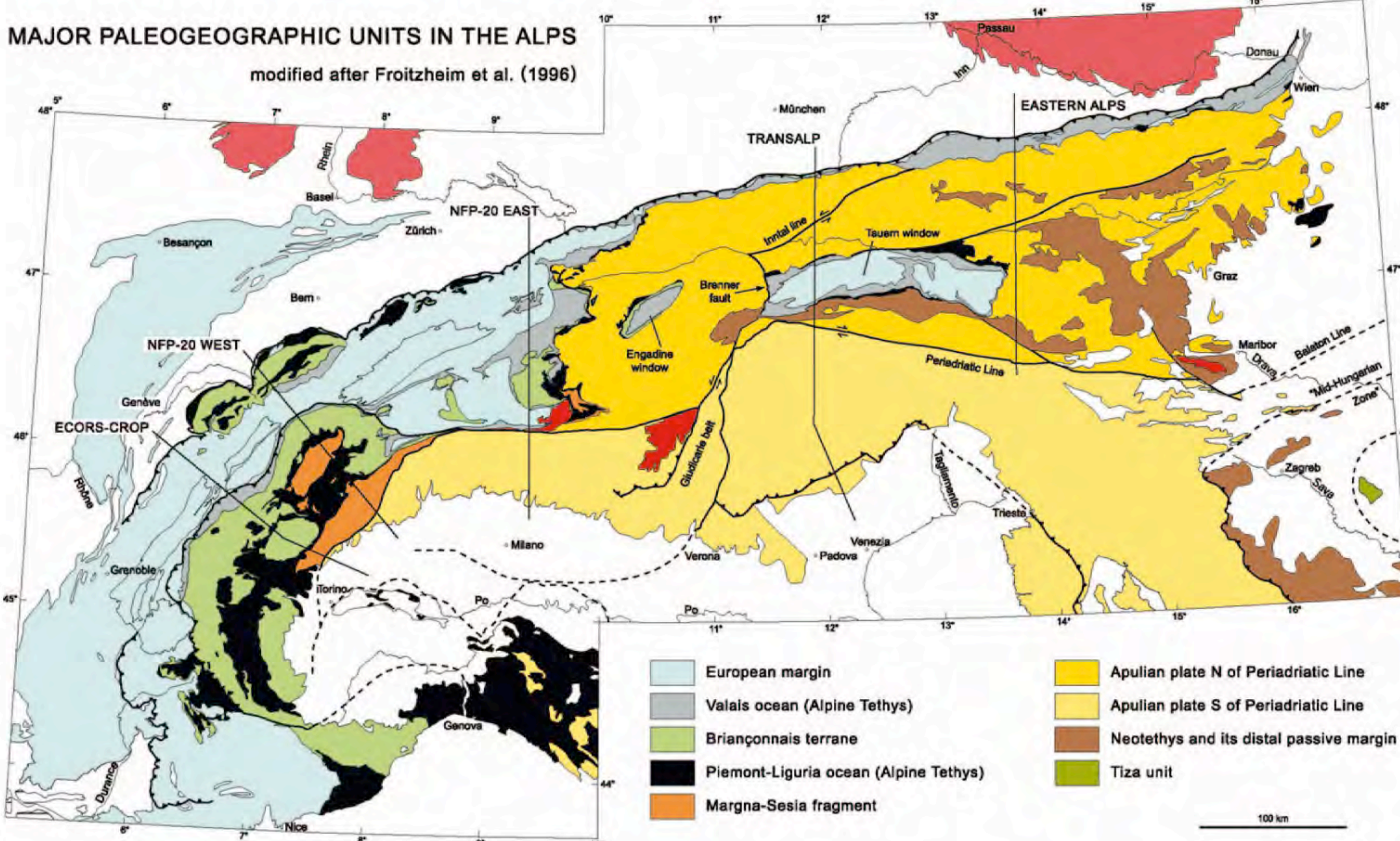
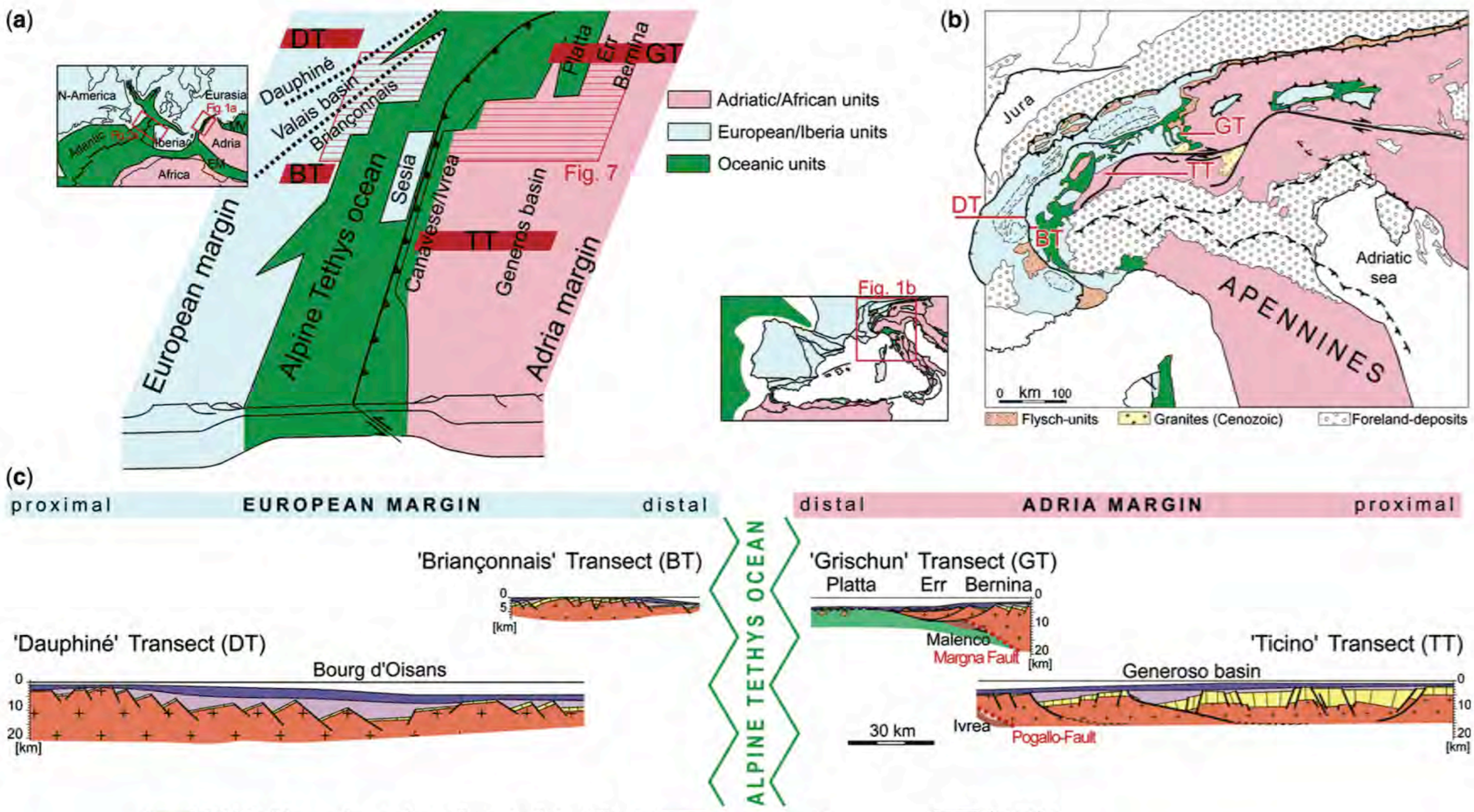
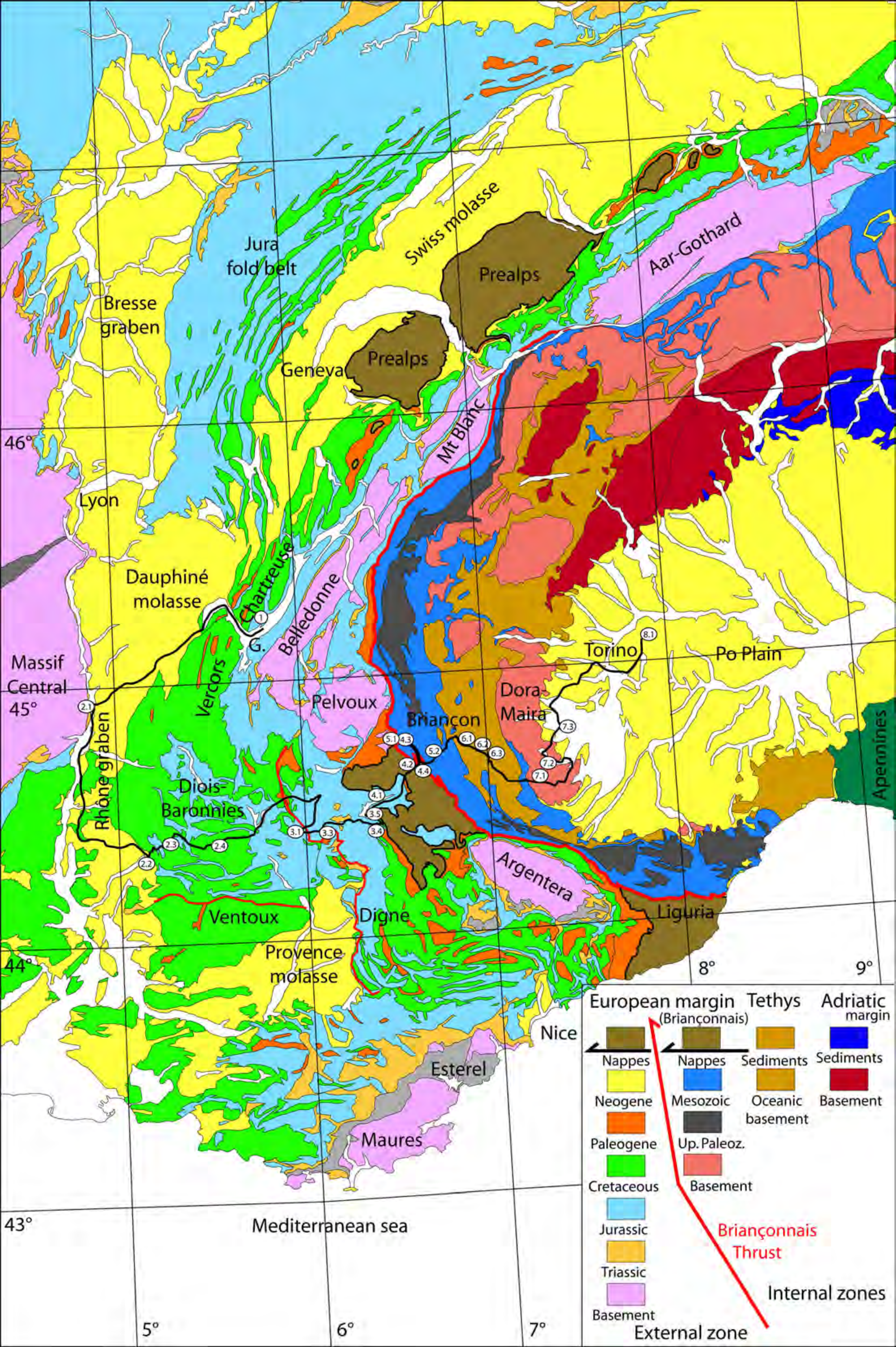


in Schmid et al., 2004



Palaeogeographic situation of the Alpine Tethys ocean and adjacent margins during Late Cretaceous,
(Manatschal et al., 2007, modified after Dal Piaz, 1995).



Jura
fold belt
Swiss molasse
Bresse
graben
Prealps
Prealps
Geneva
Aar-Gothard
Mt Blanc
46°
Lyon
Chartreuse
Belledonne
Dauphiné
molasse
G.
Torino
Po Plain
Massif
Central
45°
Vercors
Pelvoux
Briançon
Dora
Maira
Apennines
Rhône graben
Diois-
Baronnies
Argentera
Ventoux
Digne
Liguria
Provence
molasse
44°
8°
9°
Nice
Esterel
Maures
43°
Mediterranean sea
5°
6°
7°
European margin
(Briançonnais)
Tethys
Adriatic
margin
Nappes
Nappes
Sediments
Sediments
Neogene
Mesozoic
Oceanic
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Paleogene
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Cretaceous
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Jurassic
Triassic
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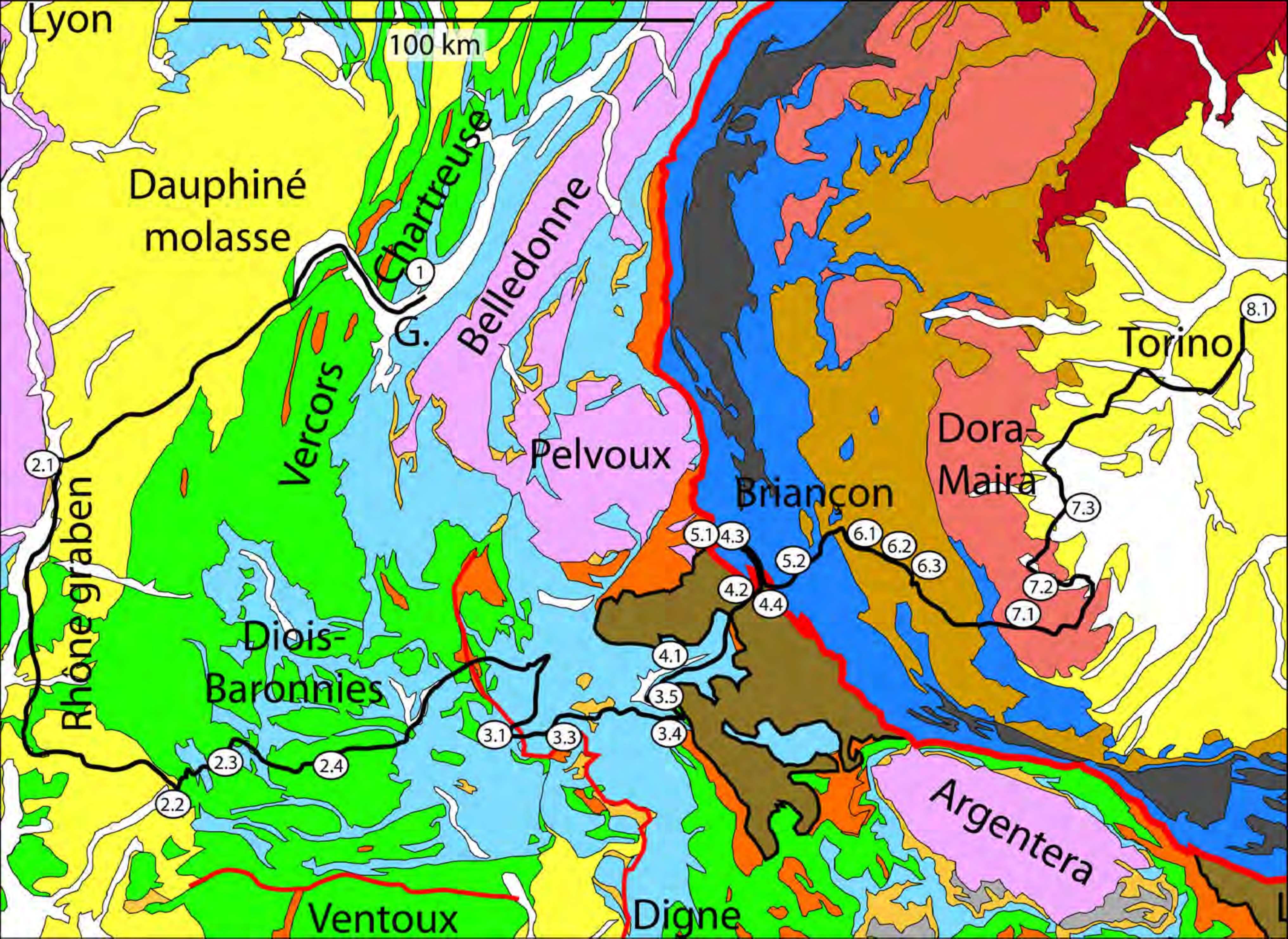
Briançonnais
Thrust
Internal zones
External zone


Lyon
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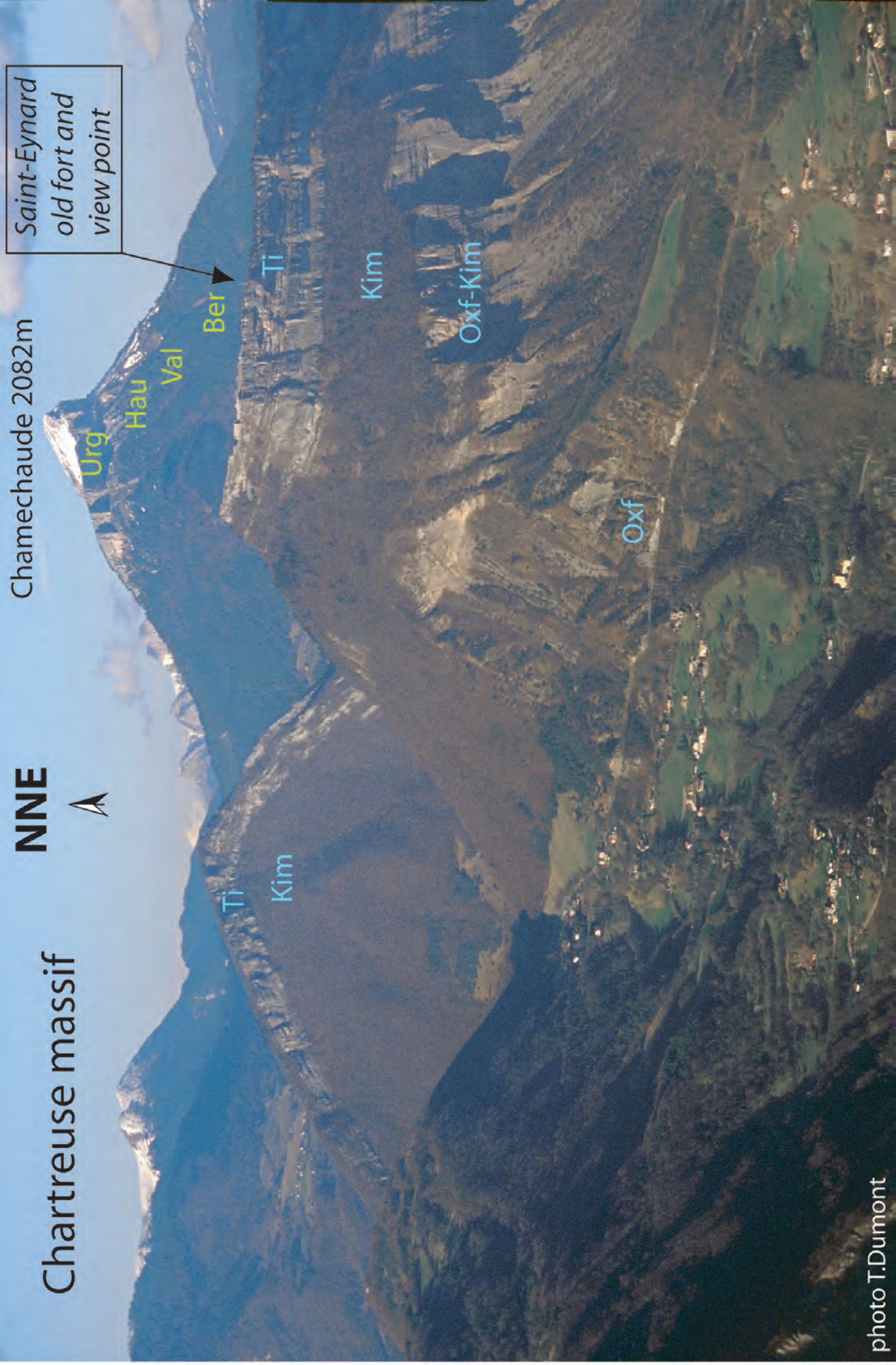
Diois-
Baronnies
Argentera
Ventoux
Digne

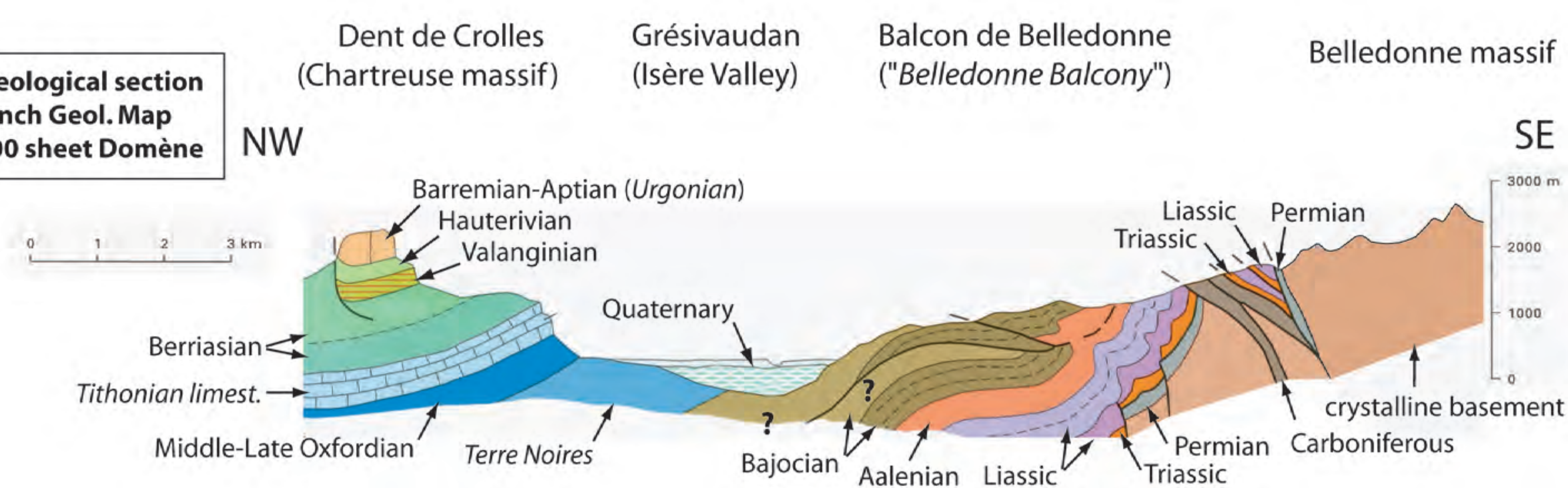
1/1000000 geological map, BRGM

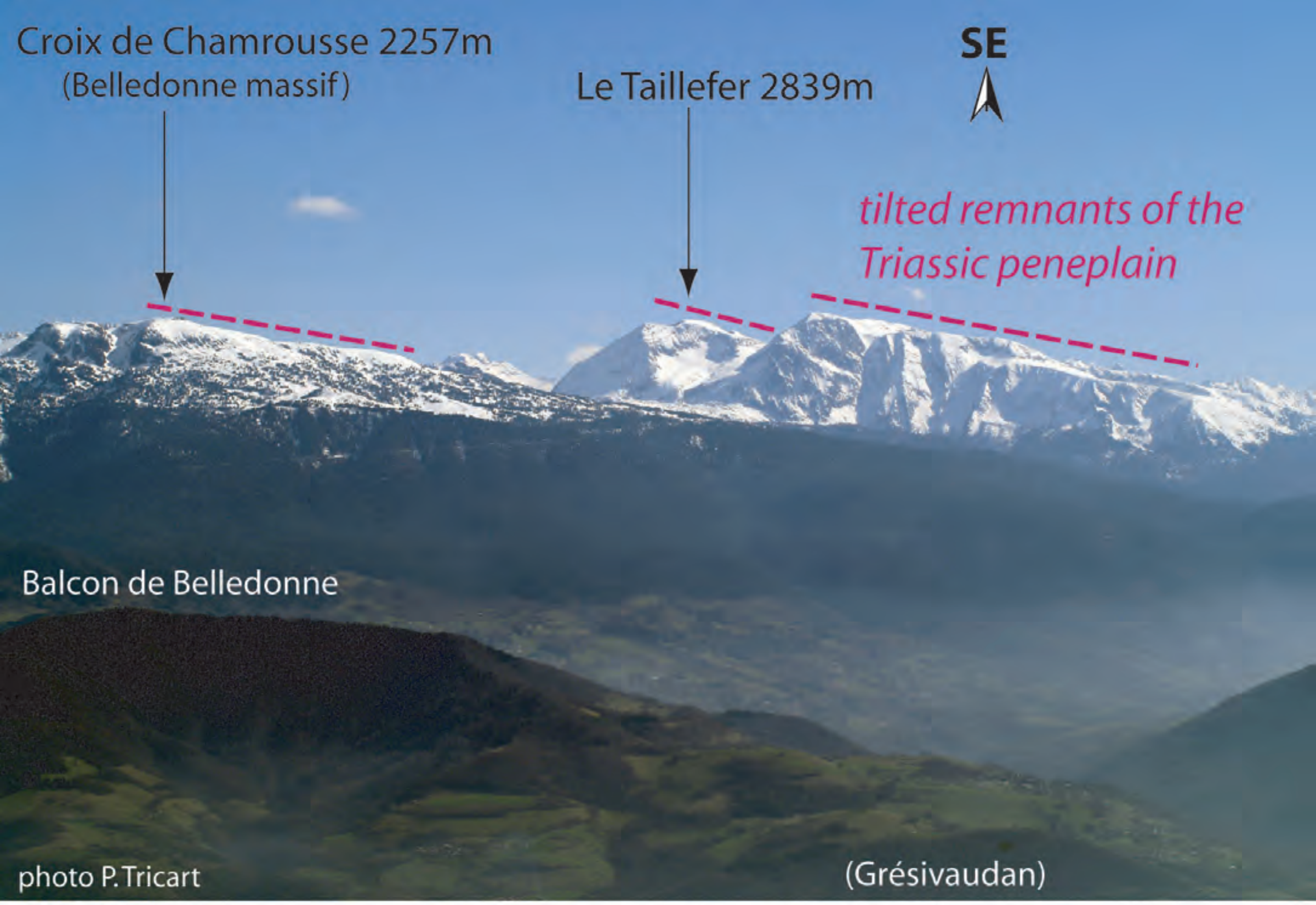


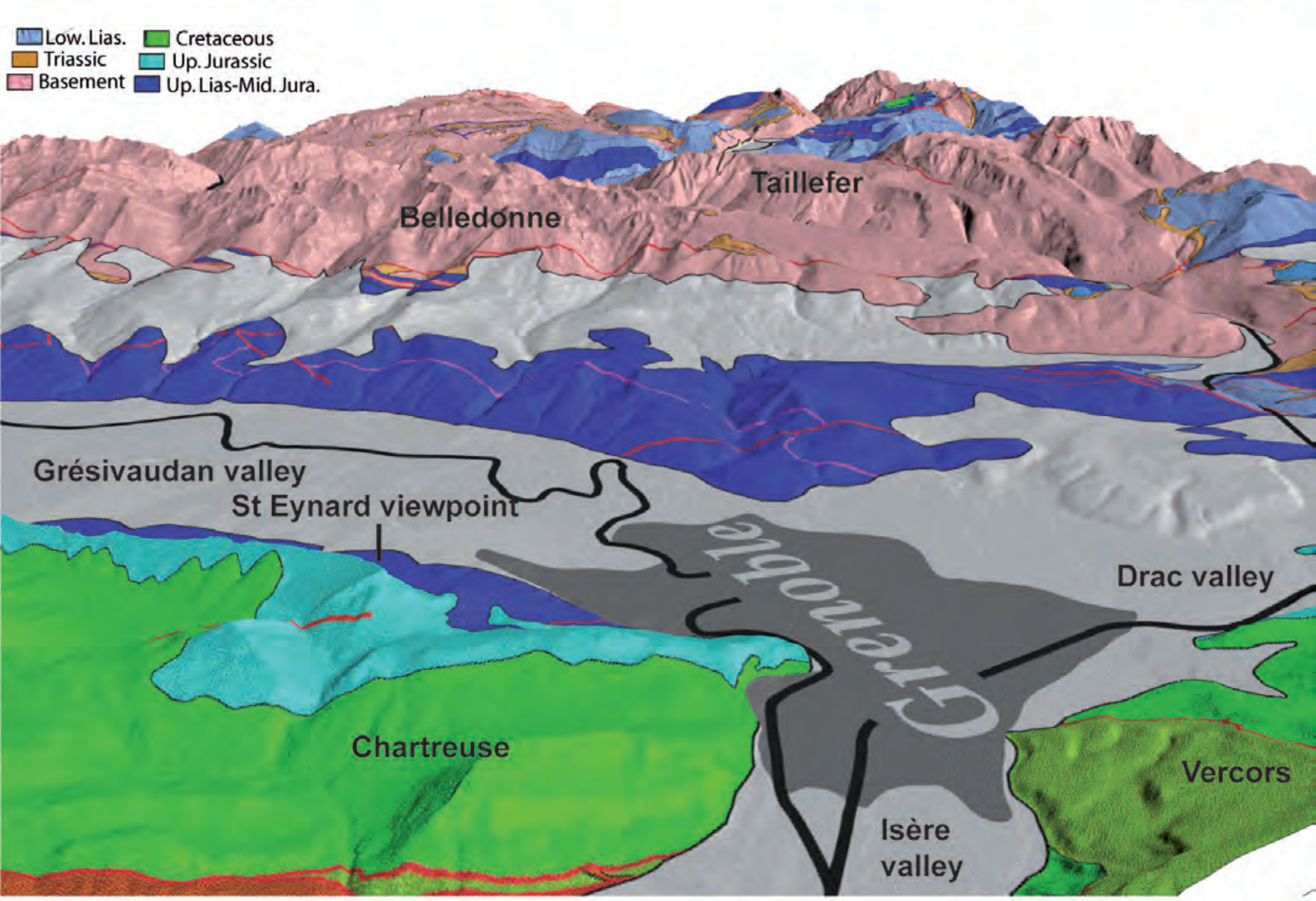
Day 1: Aerial view of the southern Chartreuse massif near Grenoble

Ti: Tithonian
Kim: Kimmeridgian
Oxf: Oxfordian
Val: Valanginian
Ber: Berriasian
Urg: Urgonian
Hau: Hauterivian

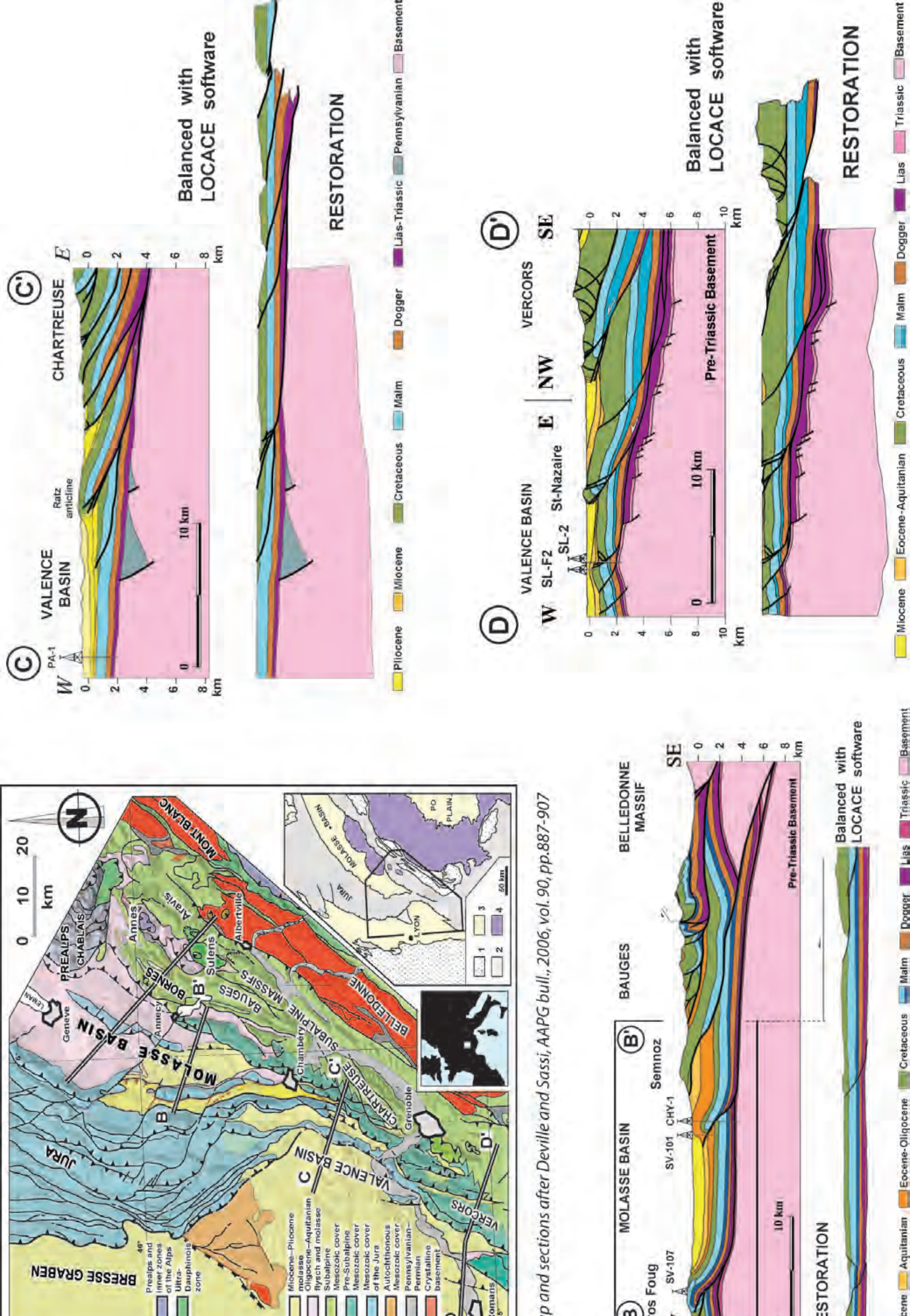
Simplified geological section after the French Geol. Map scale 1:50 000 sheet Domène



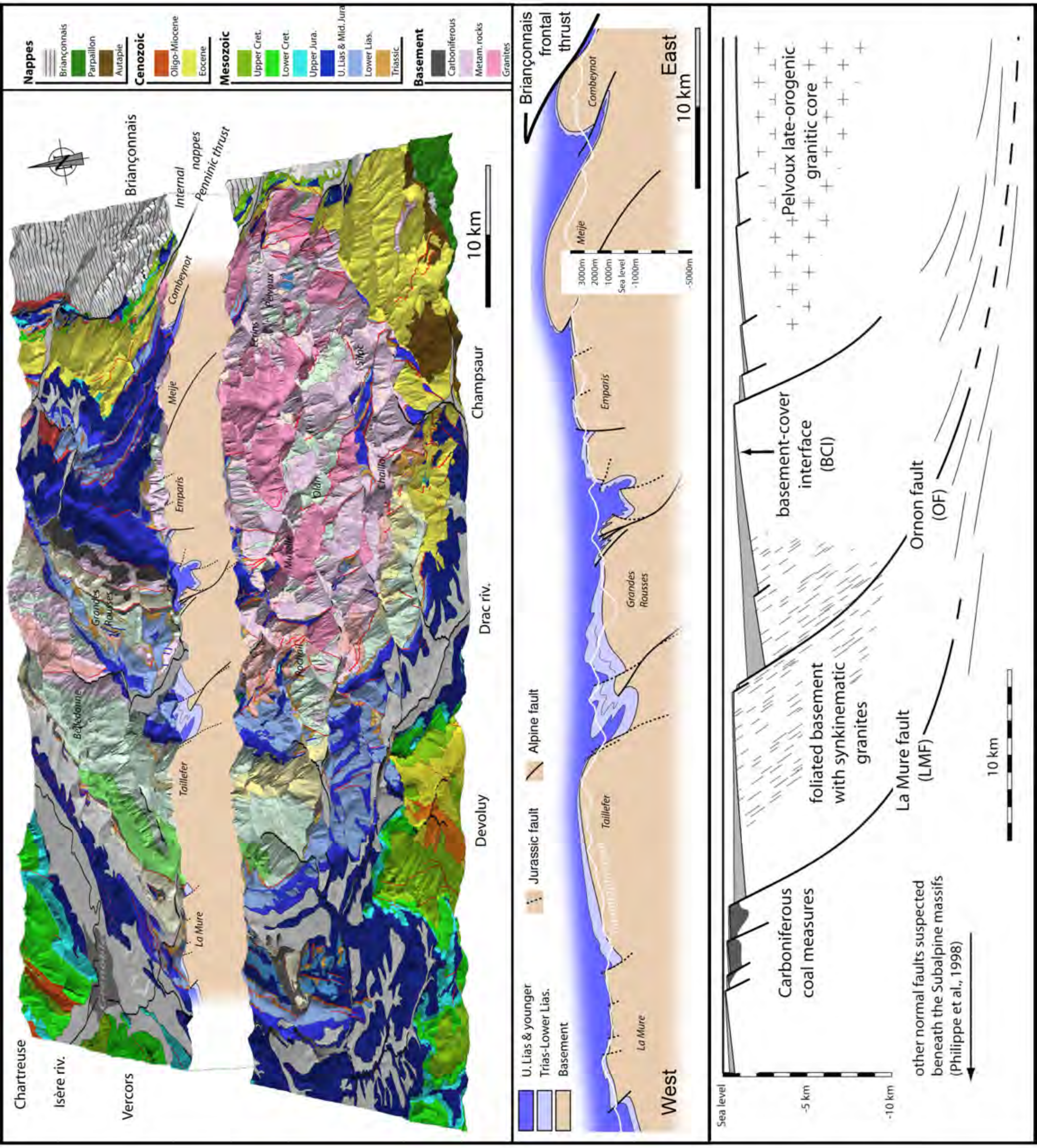




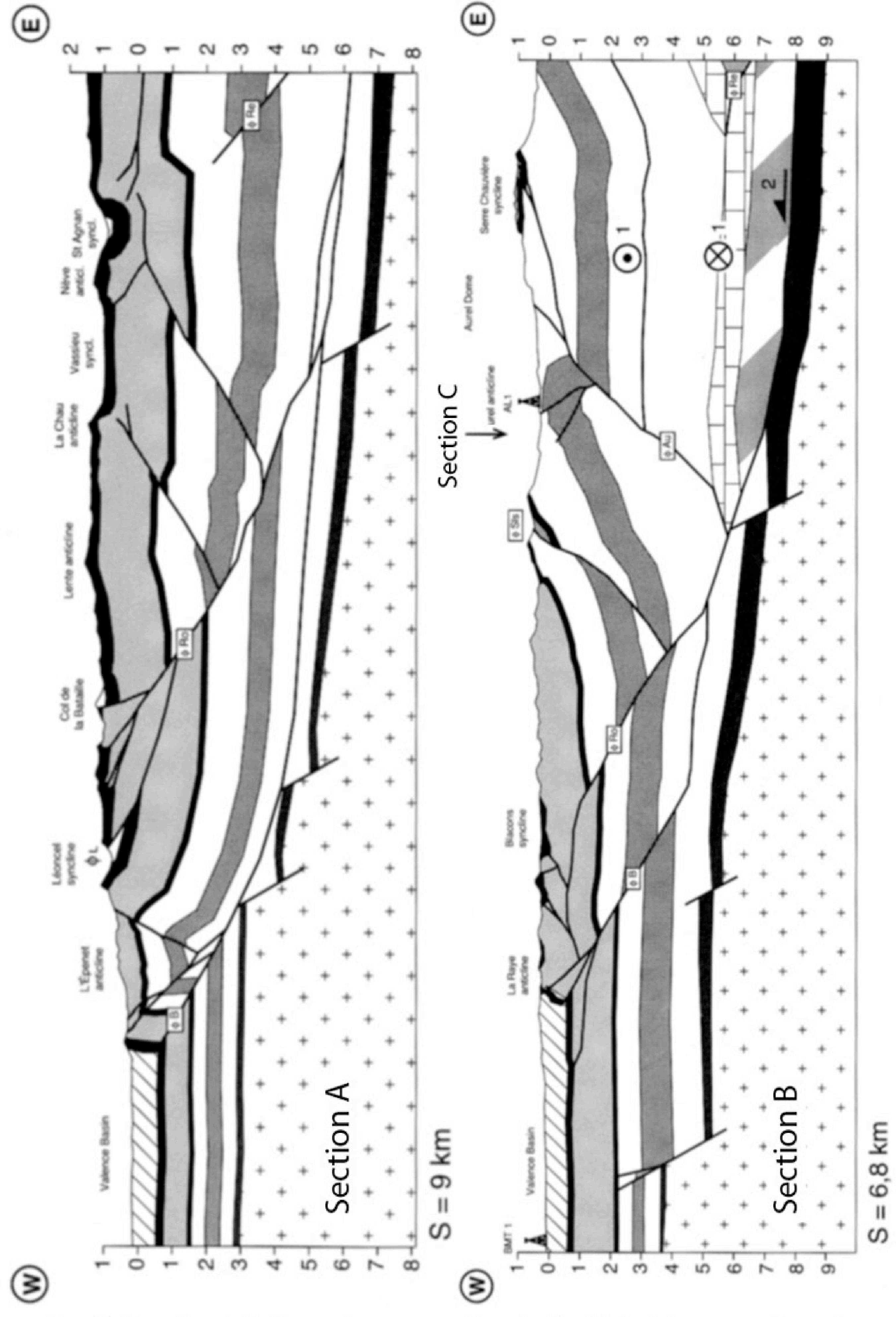
Day 1: The cristalline basement massifs of the External Zone.
The so-called peneplain, a flat erosion surface which truncated the Hercynian chain and which was covered by shallow marine sediments during Triassic, is now tilted and uplifted to ~3000m.



Day 1: balanced cross-sections in the Subalpine massifs and foreland basin, after Deville & Sassi (2006).



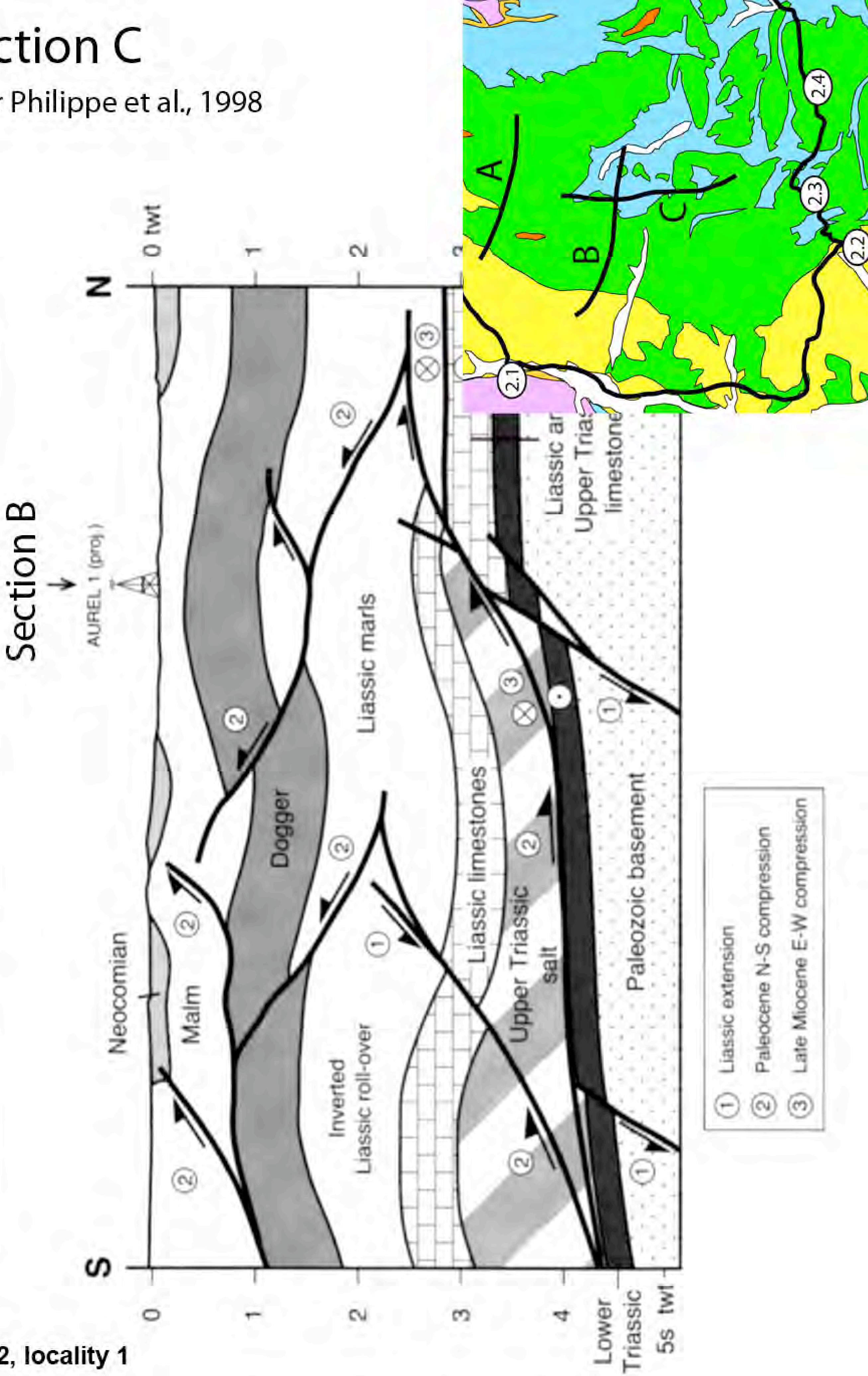
The cristalline basement massifs near Grenoble are issued from Jurassic tilted blocks formed during the Tethyan rifting. They were uplifted and moderately shortened during the Alpine orogenesis (after Dumont et al., 2008, modified).



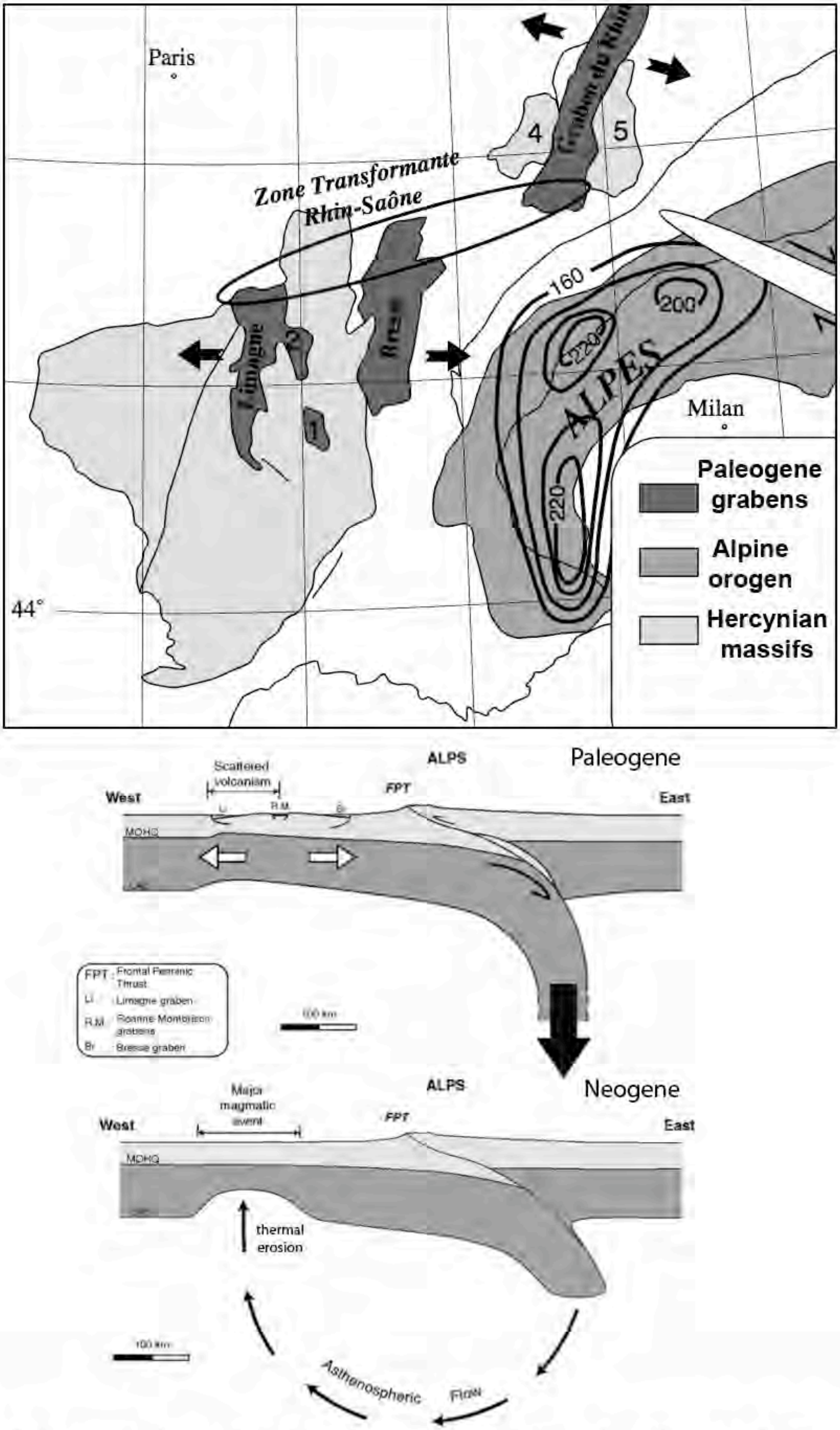
Day 2, locality 1: balanced cross-sections in the Subalpine massifs and foreland basin, after Philippe et al. (1998). See location on the next fig.

Section C

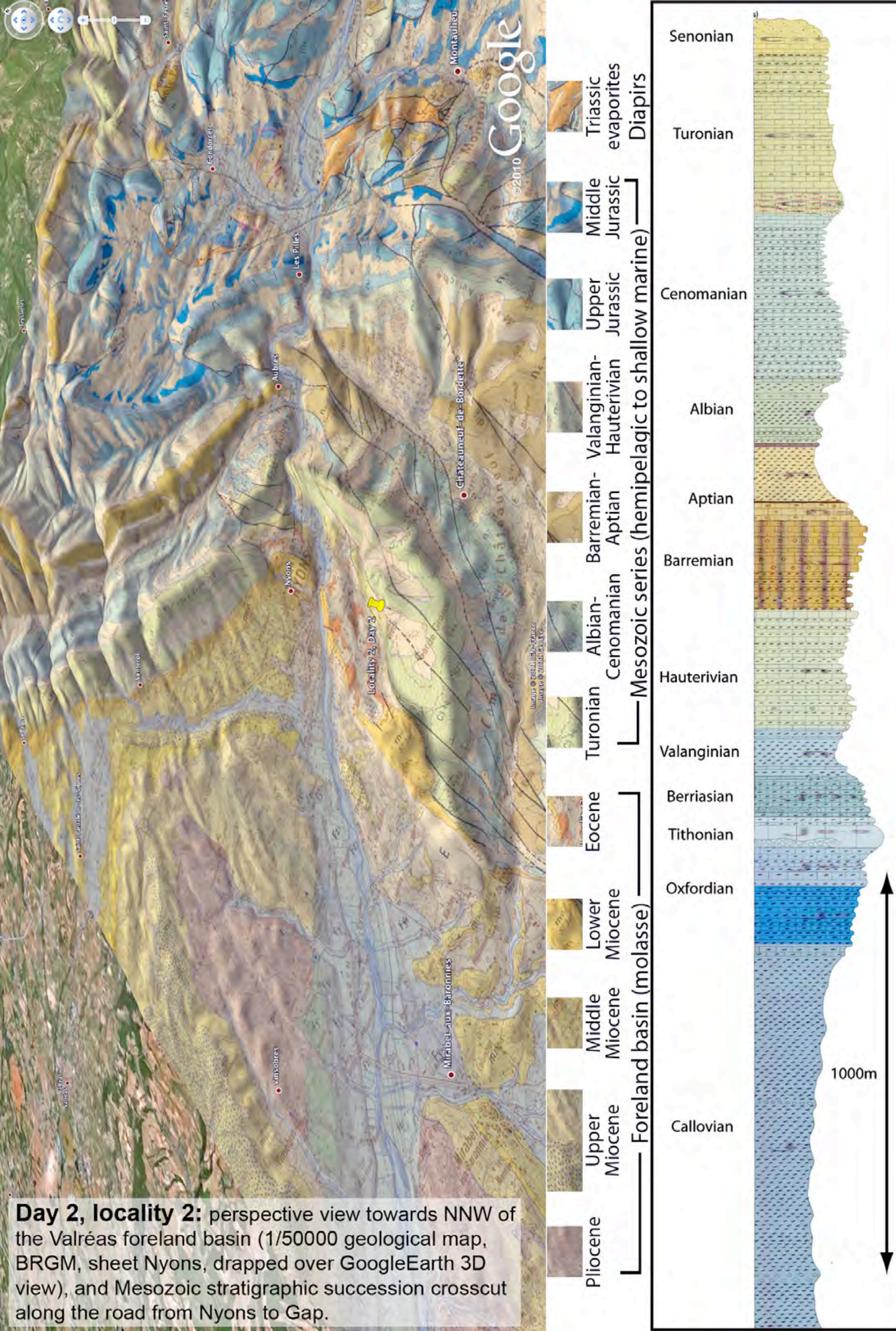
after Philippe et al., 1998



Day 2, locality 1

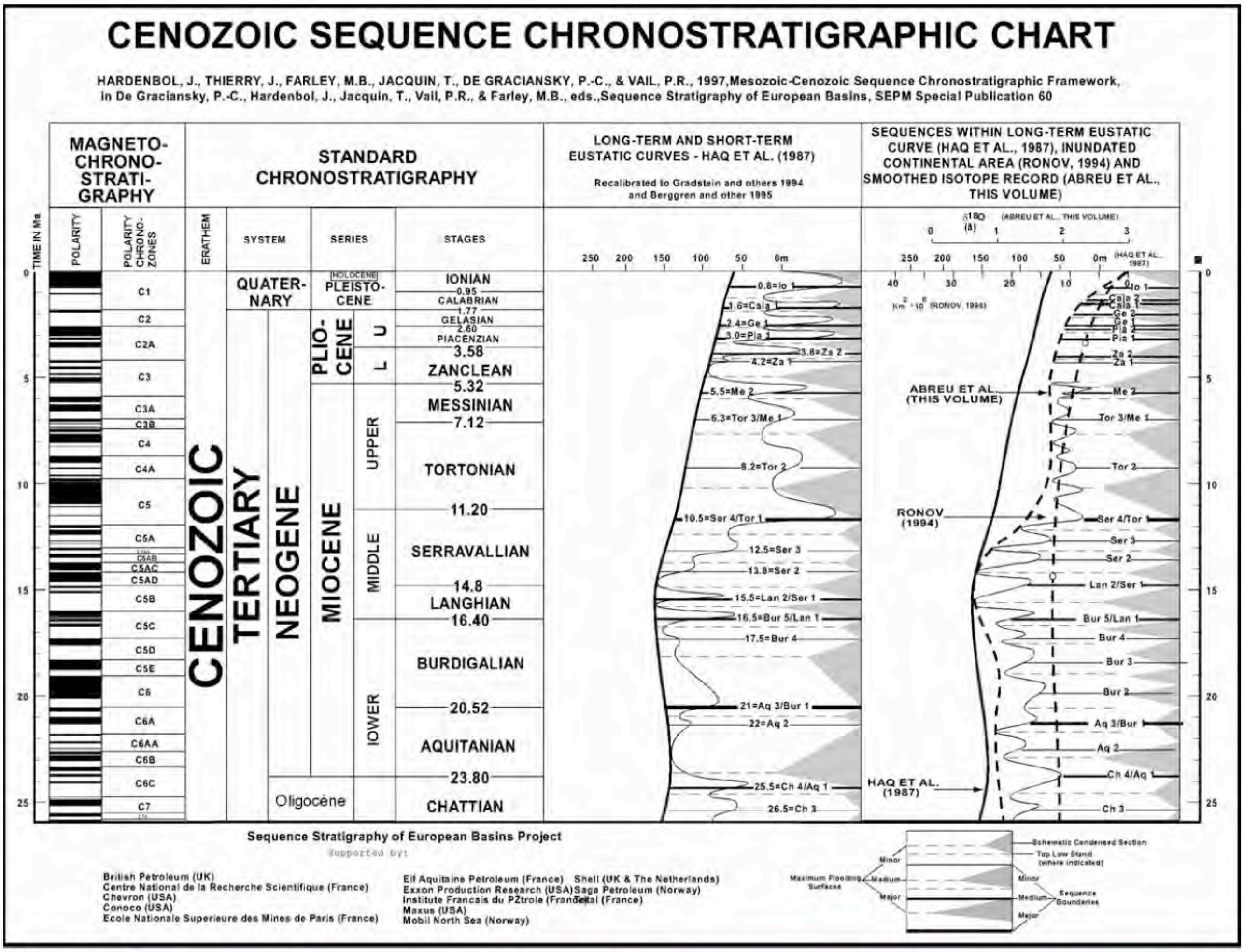


Day 2, locality 1: the West European Rift System developped during the Alpine collision. Upper map after Michon (2000). A model proposed by Merle & Michon (2001, lower part) provides a link between the Alpine collisional dynamics, the Paleogene extension in its foreland, and the Neogene volcanism in Massif Central.

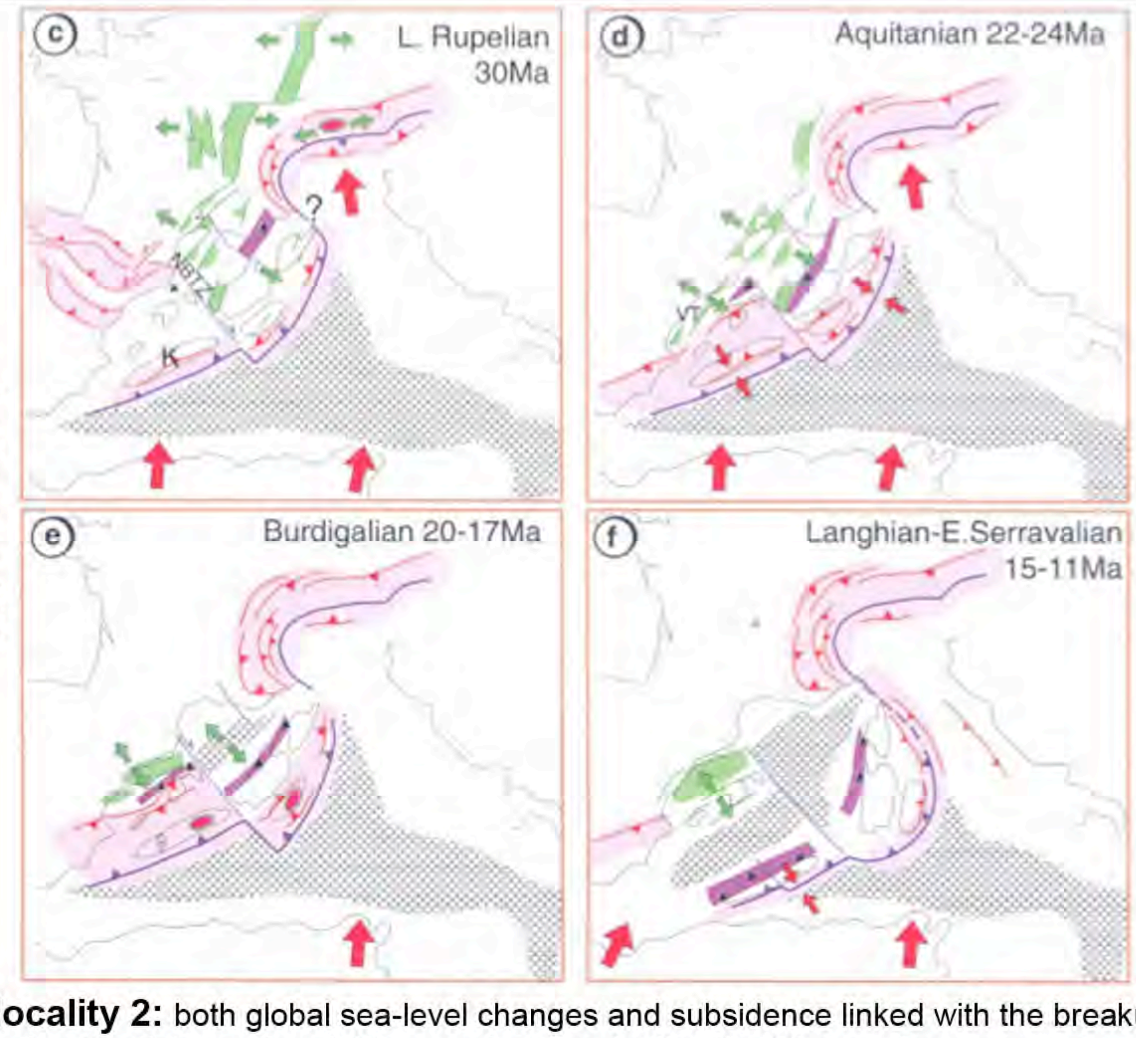


Day 2, locality 2: perspective view towards NNW of the Valréas foreland basin (1/50000 geological map, BRGM, sheet Nyons, drapped over GoogleEarth 3D view), and Mesozoic stratigraphic succession crosscut along the road from Nyons to Gap.

Day 2, locality 2:
Perspective view towards E showing the EW-trending folds having affected the subalpine mesozoic series (F1). These folds are crosscut by a NS-trending faulted zone (F2) marked by diapirs. This illustrates the interference between Pyrenean and Alpine shortening episodes.
Right: onlapping Burdigalian shallow marine limestones seen from locality 2 (black arrow above), showing an increase in accomodation possibly related with the Corsica-Sardinia breakup.

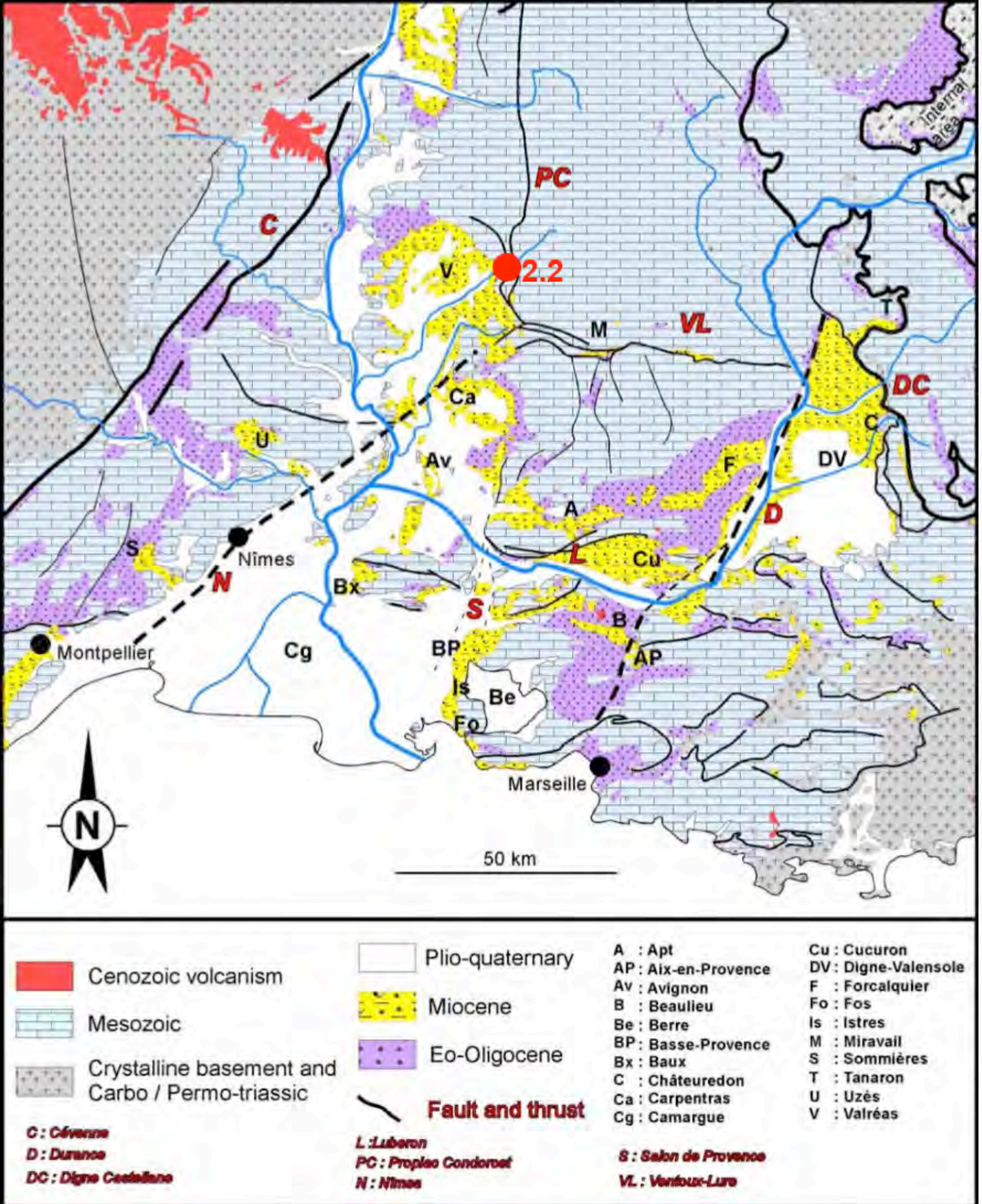


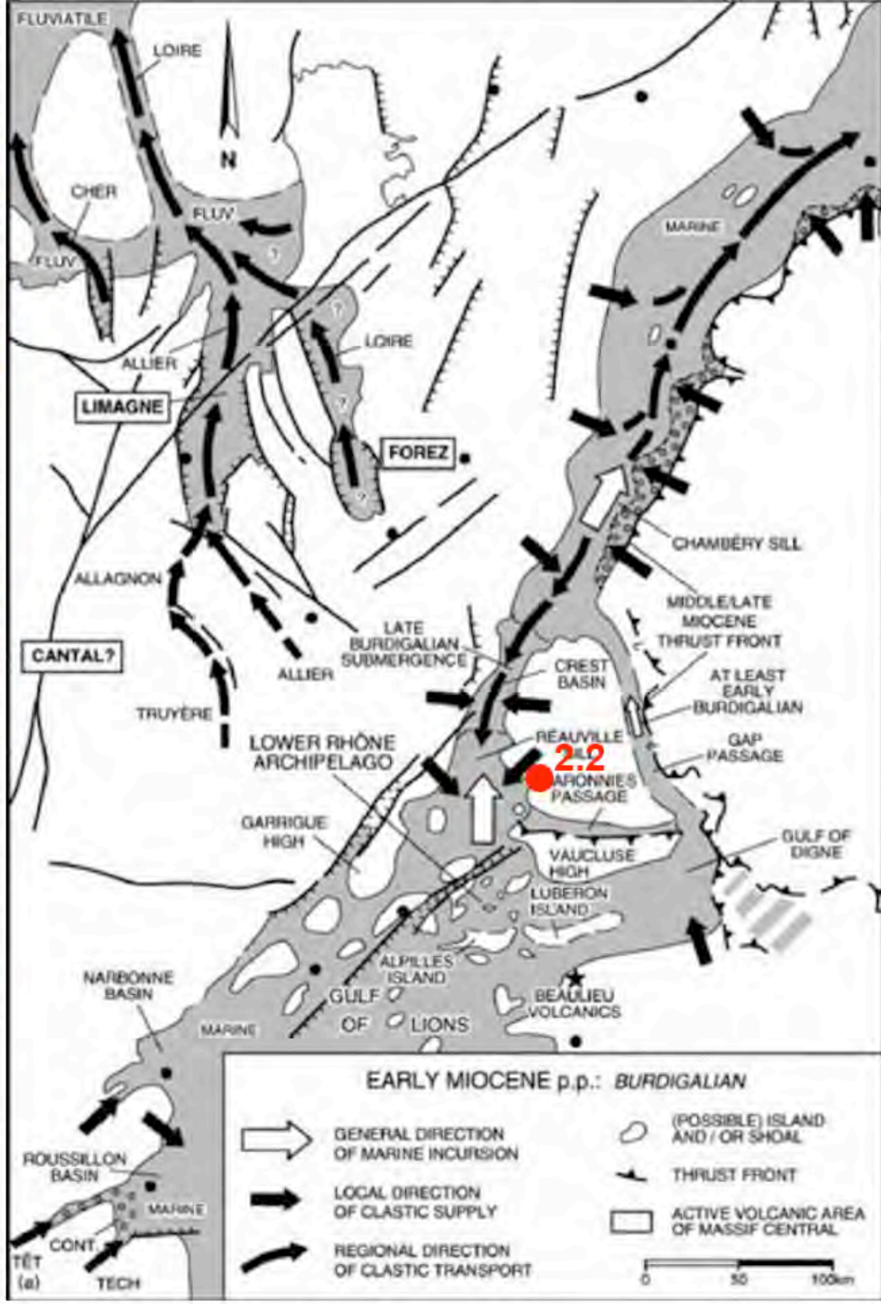
(Haq *et al.*, 1987 ; Hardenbol *et al.*, 1998)



after Seranne, 1999

Day 2, locality 2: both global sea-level changes and subsidence linked with the breakup of the Corsica-Sardinia continental fragment are controlling the Miocene transgression.

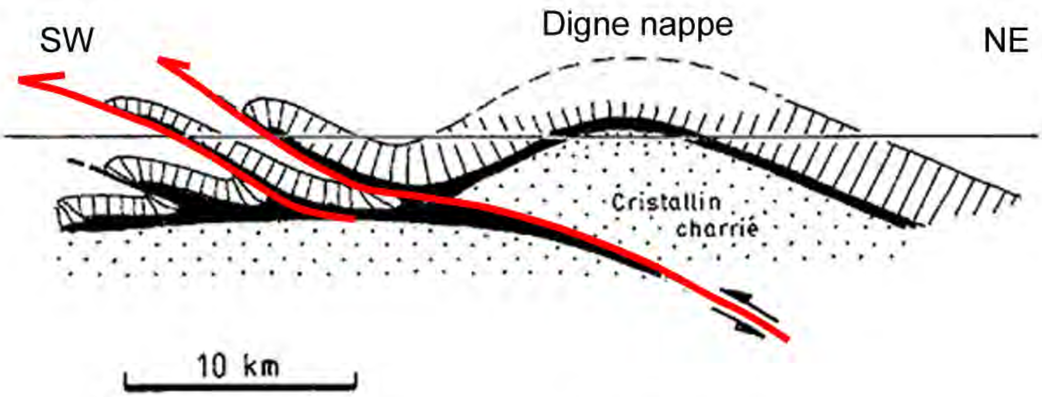


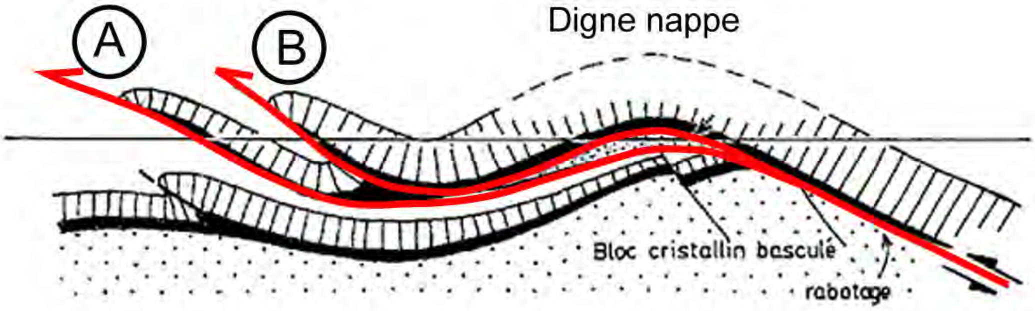


Day 2, locality 2: Tertiary outcrops in SE France (left, after Besson, 2005) and Early Miocene paleogeographic map (right, after Sissingh, 2001).

Day 2, localities 2 and 3: Perspective view towards E of the 1/250000 BRGM geological map draped over GoogleEarth DEM. The area between Nyons and Gap corresponds to a Mesozoic basin (the so-called Vocontian Basin) with thick, dominantly marly series, surrounded by the Vercors and Provence platforms (V and P) which show massive Lower Cretaceous platform limestones (here in brown). This area suffered N-S and E-W shortening because it was located in the foreland of both the Pyrenean and the Alpine orogens.

Day 3, localities 1 to 3: perspective view towards NW of the 1/250000 BRGM geological map (sheet Gap) showing the Digne nappe and its footwall, with an intermediate thrust-sheet in between (A). Exhumation and erosion of the Triassic to middle Jurassic series occurs in the hangingwall of the main thrust. Oligocene molasses occur in the footwall and are transported by the nappe, whose SW-ward displacement is estimated to ~15 km. A and B refer to stratigraphic successions presented in the next figure.

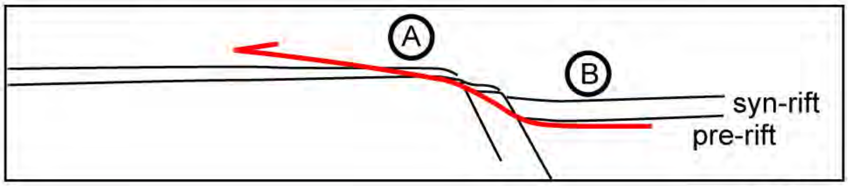


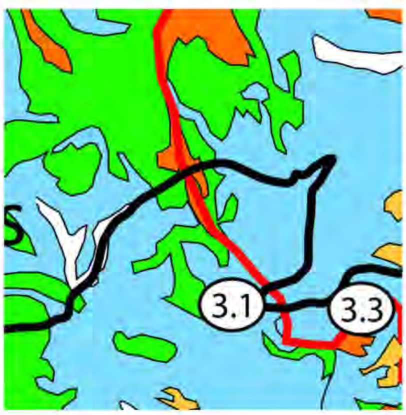


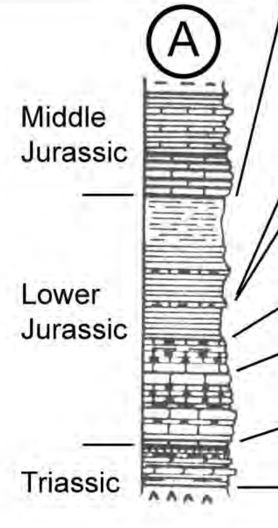
Variations of the lower to middle Jurassic series across the Digne thrust:

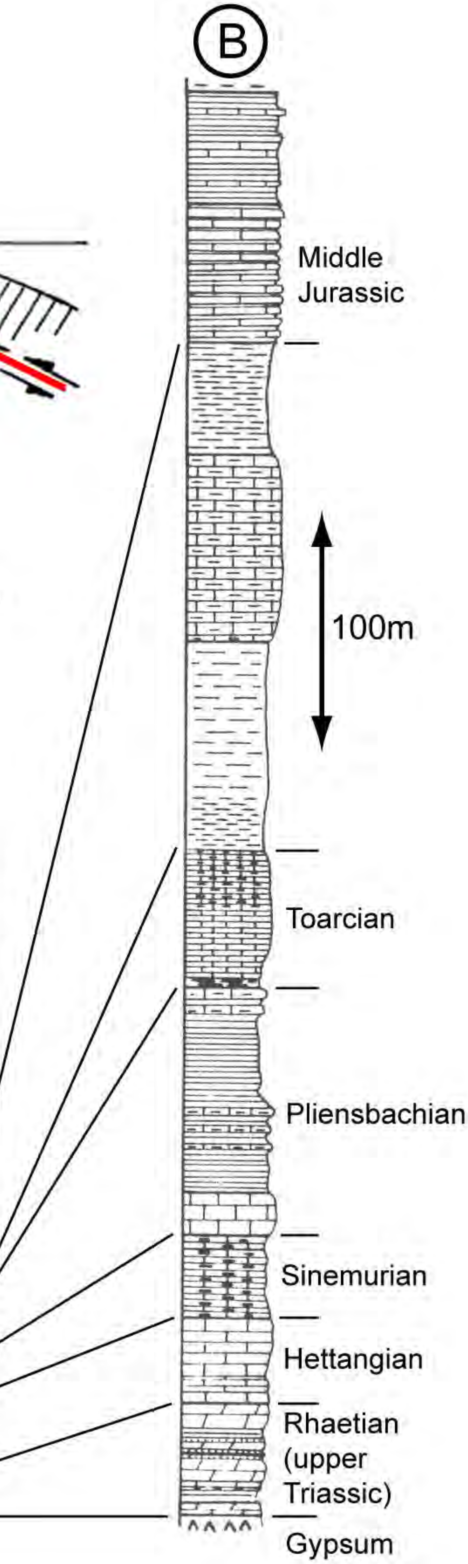
Right: stratigraphic successions after Etechamzadeh-Afchar (1973).
A: Pey Rouard series (lower thrust sheet), shown at outcrop 3.1.
B: La Saulce series (upper thrust sheet).

Above: two interpretative cross-sections after Gidon (http://www.geol-alp.com). The lower one, which involves shortcutting of a Tethyan half-graben, would be restored as follows:



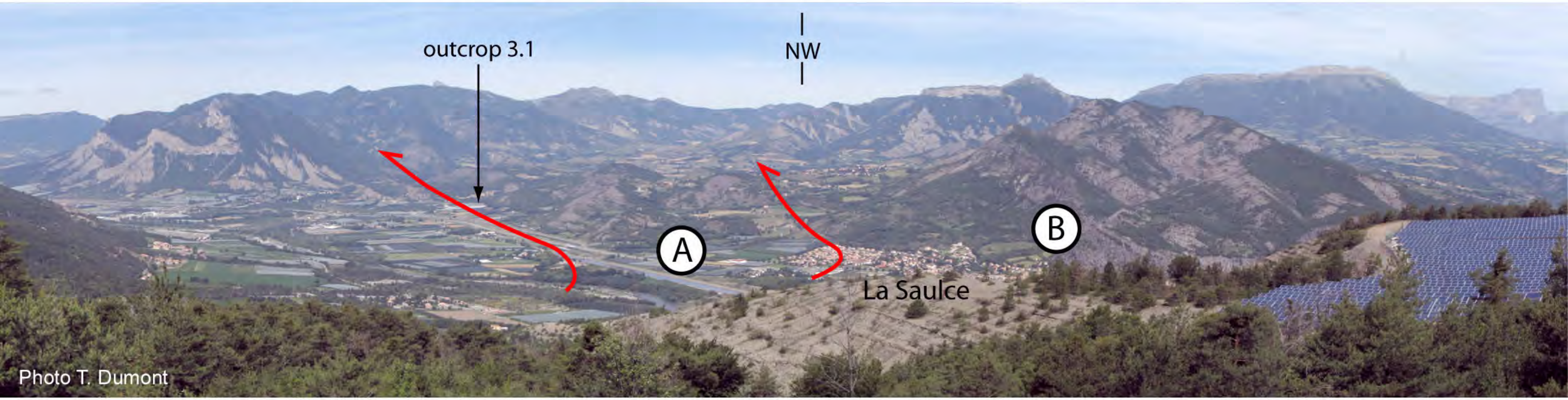




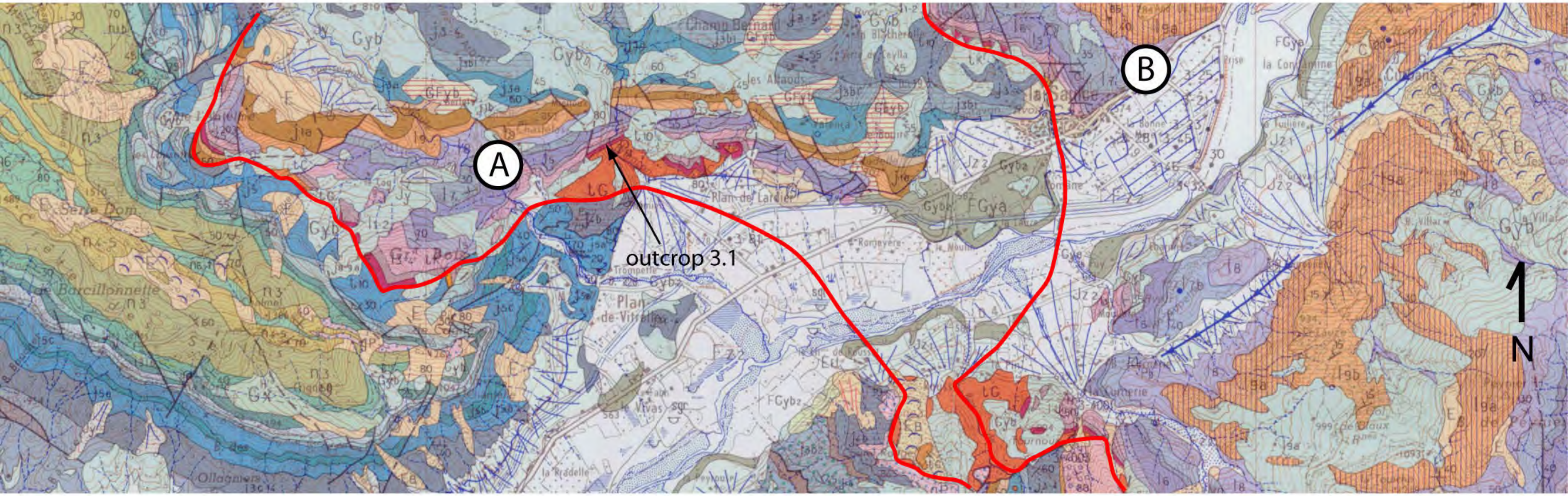


Day 3, locality 3

Structure and stratigraphy along the Digne thrust, Durance valley, SW of Gap city.

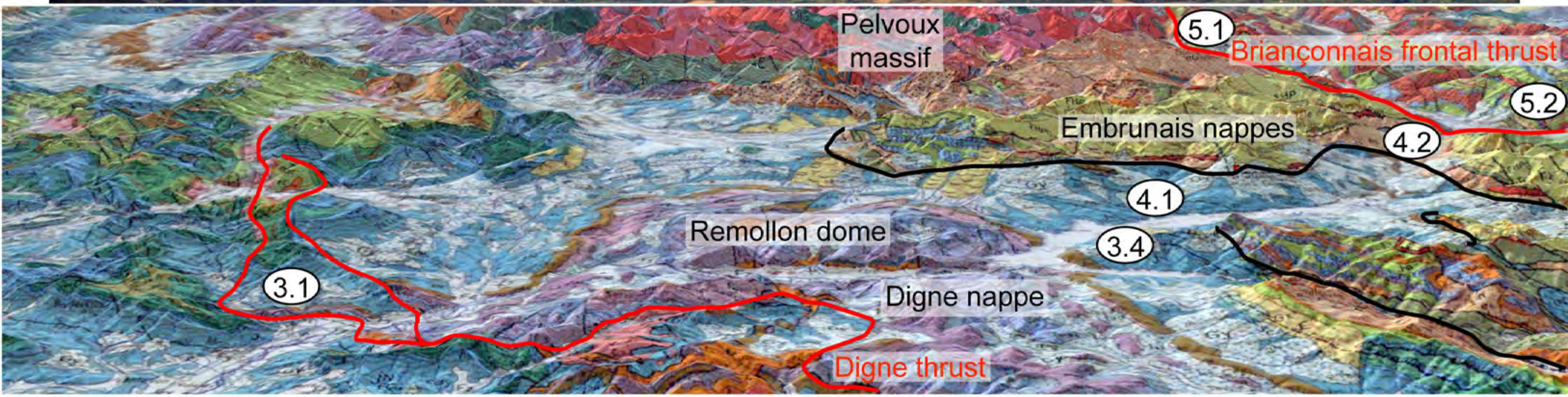


Panoramic view towards NW from locality 3, day 3. The Jurassic series of the Digne nappe (thrust sheet B) is much thicker than A.

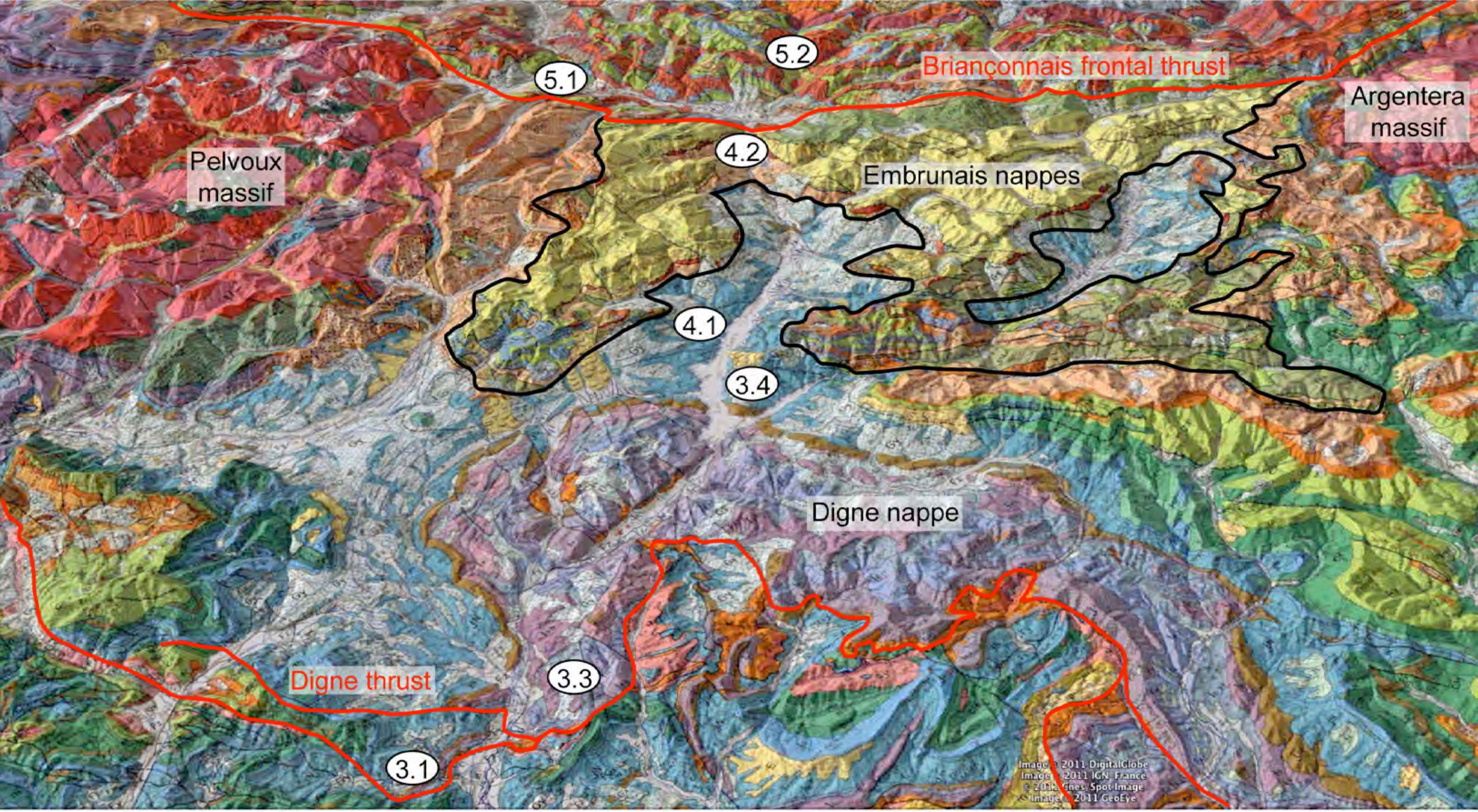


1/50000 geological map (sheet Laragne). A: Pey-Rouard thrust-sheet; B: La Saulce thrust-sheet (~Digne nappe).

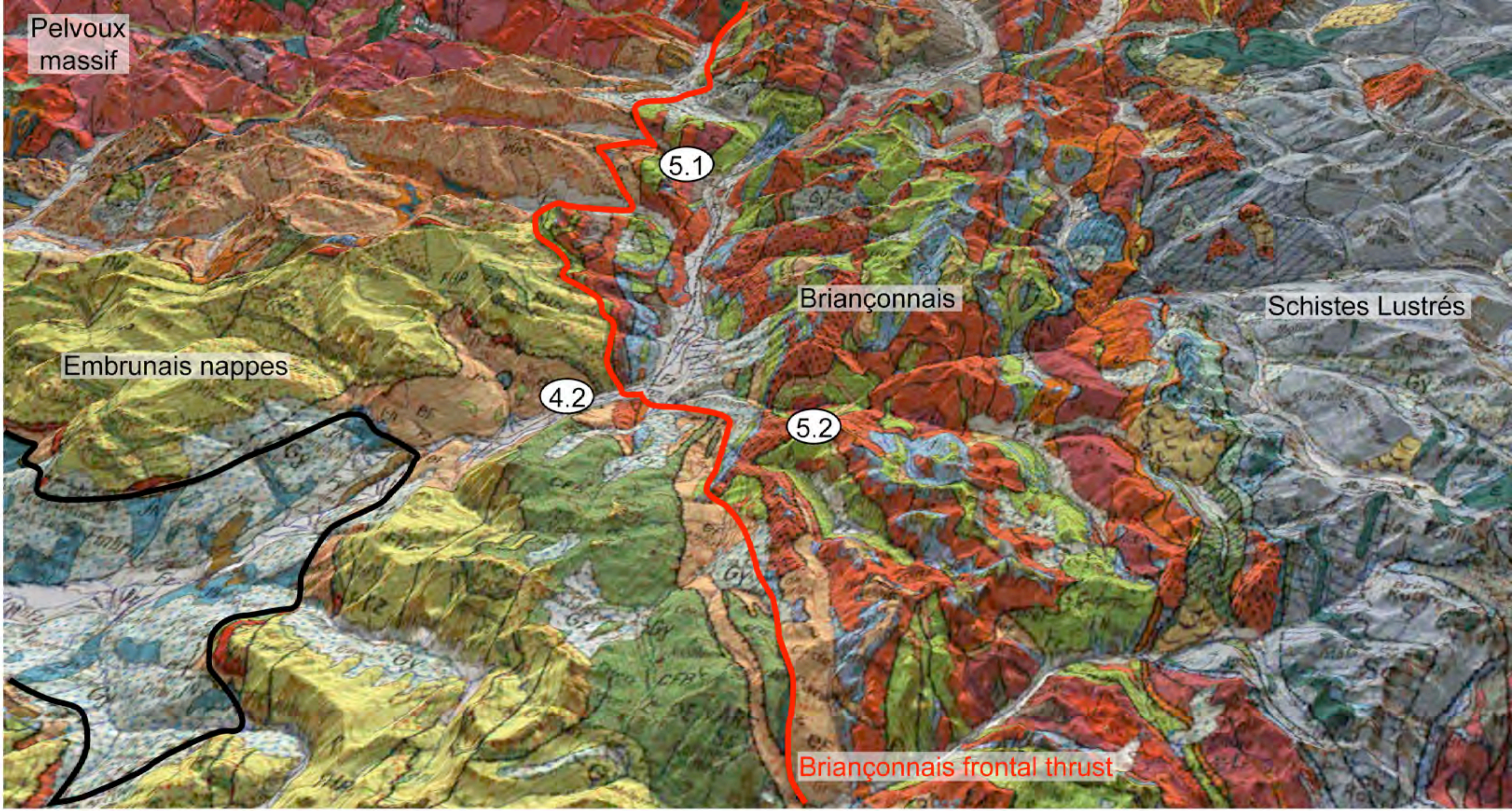
Day 3, locality 4: panoramic view of the Remollon dome from Le Sauze, Serre-Ponçon artificial lake.

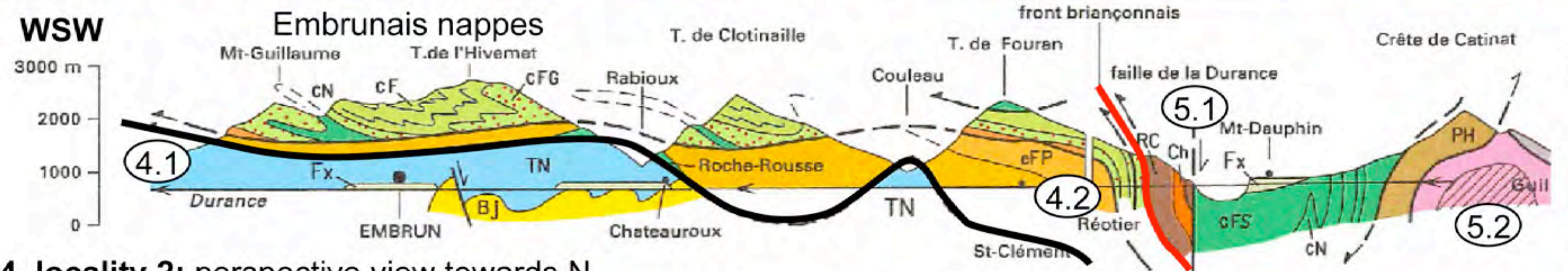


Day 3 to 4: aerial view and perspective geological map towards N, showing the Remollon dome (Digne nappe) with early Alpine, thin-skinned nappes (so-called Embrunais nappes) in the background.

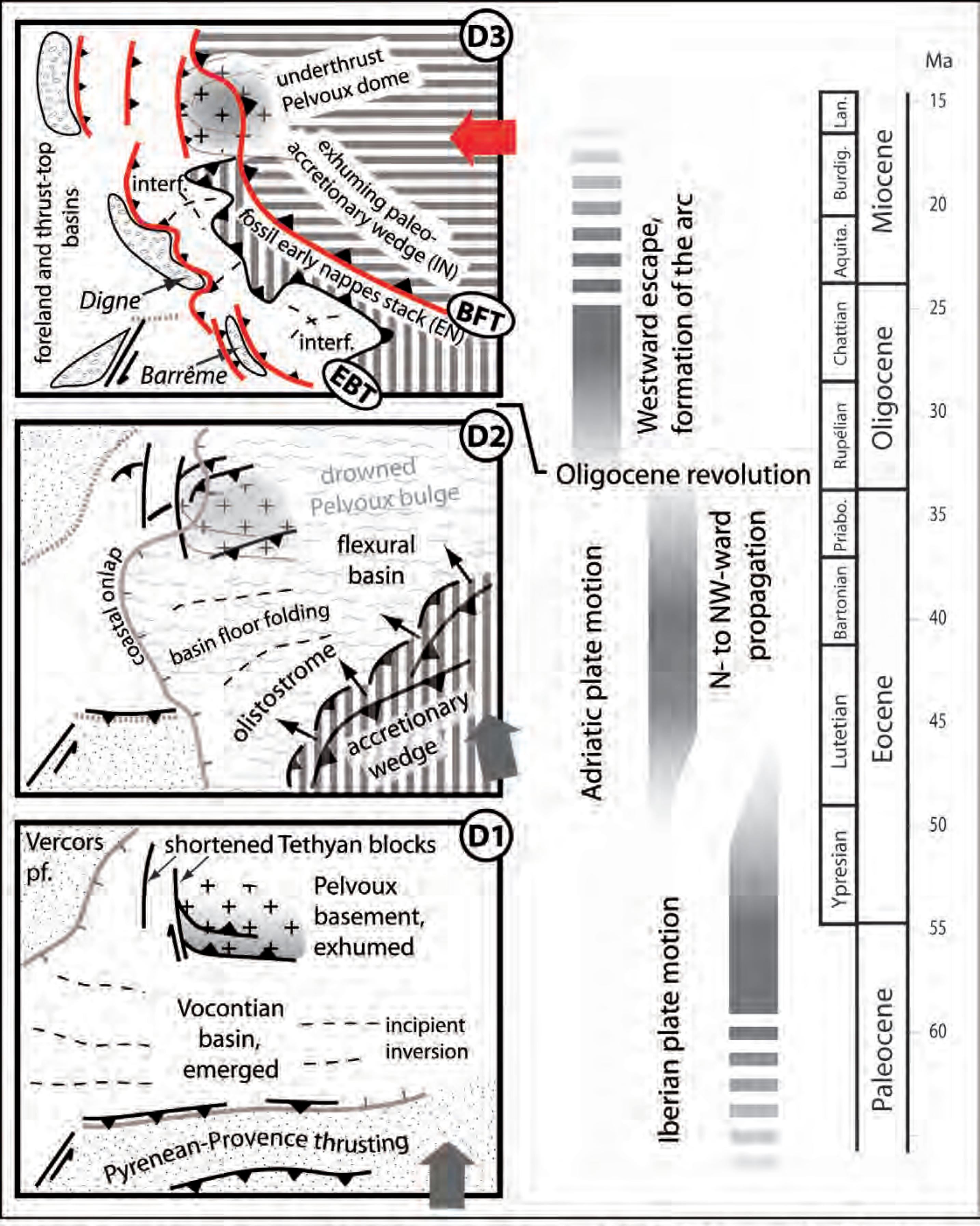


Day 4: perspective view towards NE of the 1/250000 BRGM map draped on GoogleEarth DEM. An early Alpine, thin-skinned set of nappes (so-called Embrunais nappes, emplaced during late Eocene to earliest Oligocene) is folded and crosscut by the crustal Briançonnais Frontal Thrust (early to middle Oligocene). The SW-ward propagation of the Internal Nappes in the hangingwall of the Briançonnais Frontal Thrust caused the detachment and SW-ward transport of the Digne nappe.

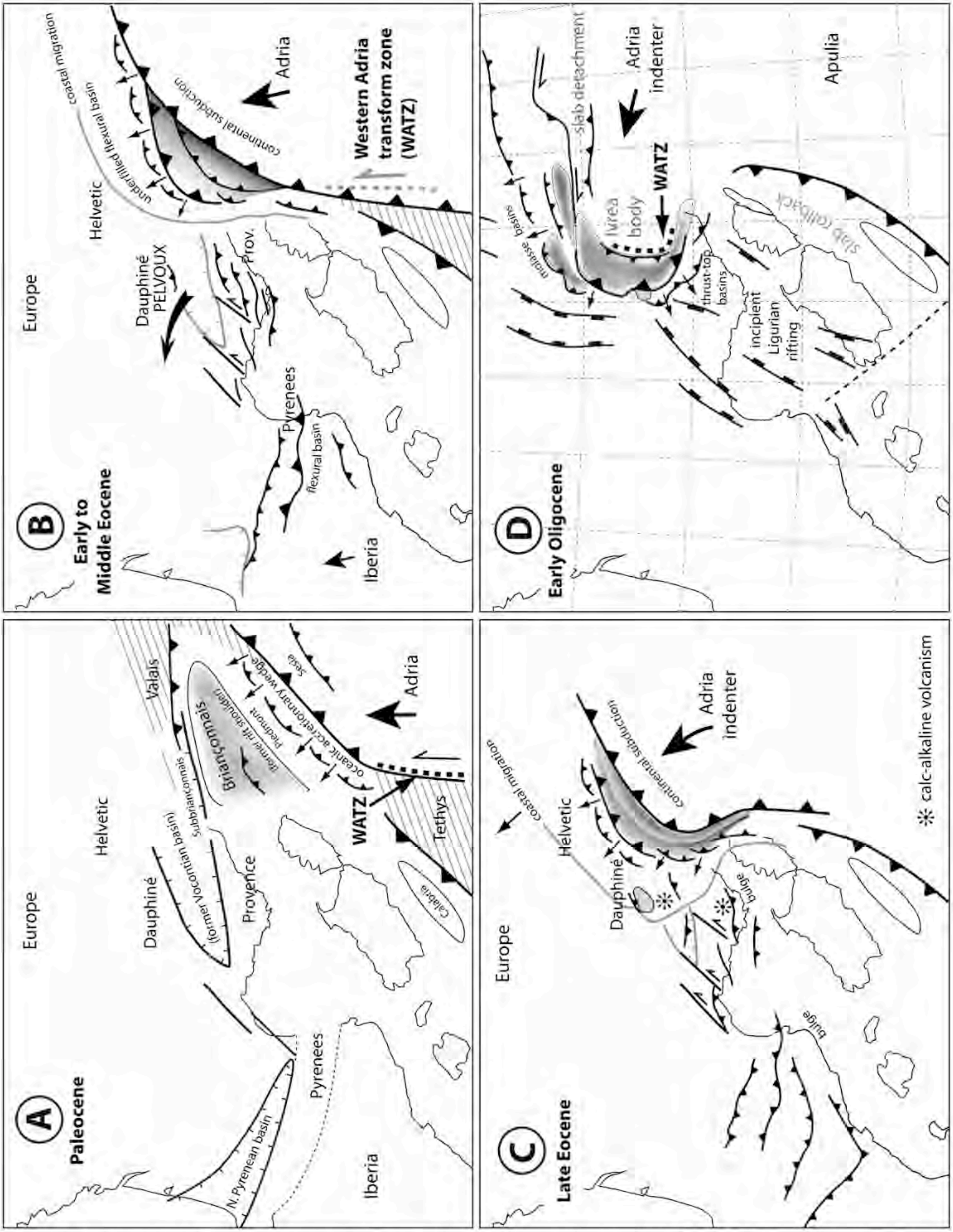




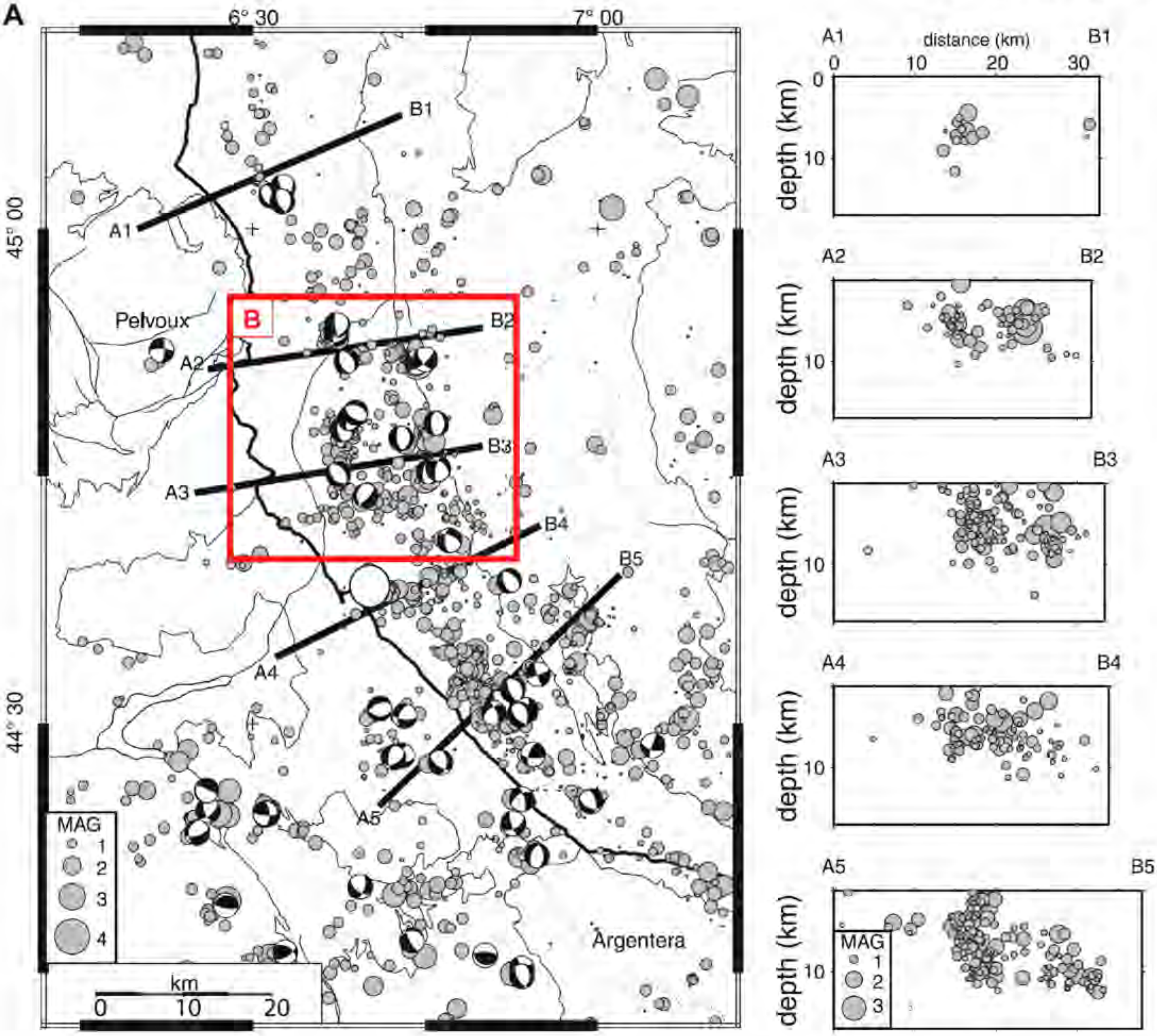
Day 4, locality 2: perspective view towards N
and cross-section (after BRGM geological map 1/50000, sheet Embrun) across the Briançonnais Frontal Thrust

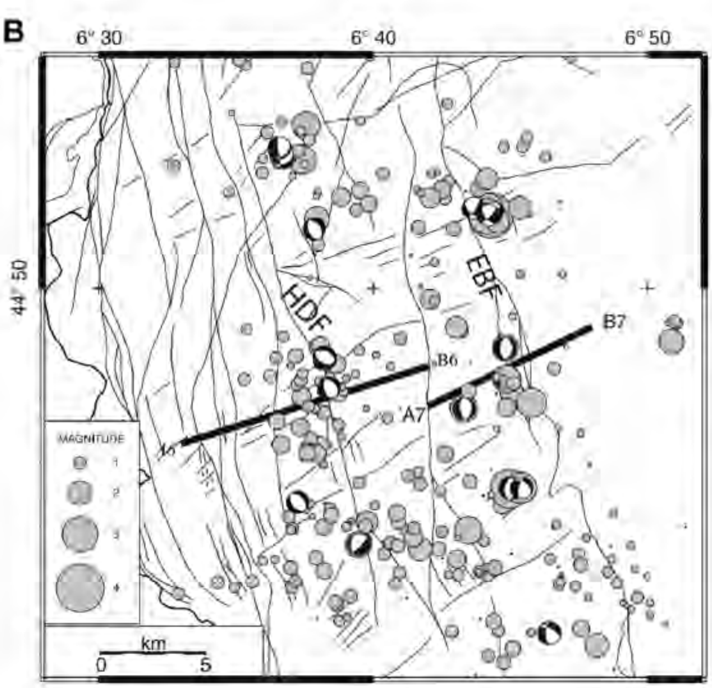


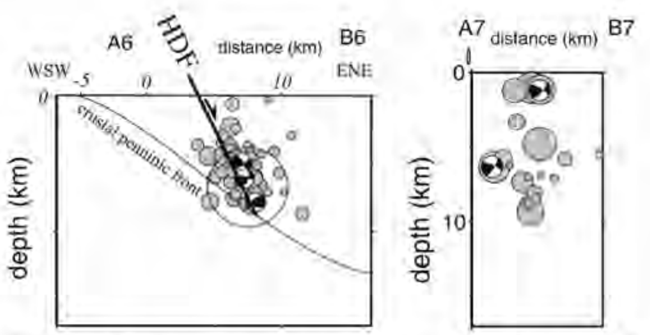
Day 4: proposed paleogeographic scenario during the Paleogene, after Dumont et al. (submitted). A sharp kinematic change occurred during lowermost Oligocene (~32Ma), which corresponds to the onset of westward escape in the Western Alps. This allowed the D3, west- to SW-directed thrusts (e.g. BFT, Briançonnais Frontal Thrust) to crosscut the early (D2) Alpine nappe stack and exhume the paleo-accretionnary wedge.



Day 4: proposed paleogeographic evolution since the onset of Adria-Europe collision, after Dumont et al, Tectonics, in press. The shift from continental subduction to collision with westward escape occurred in earliest Oligocene times.

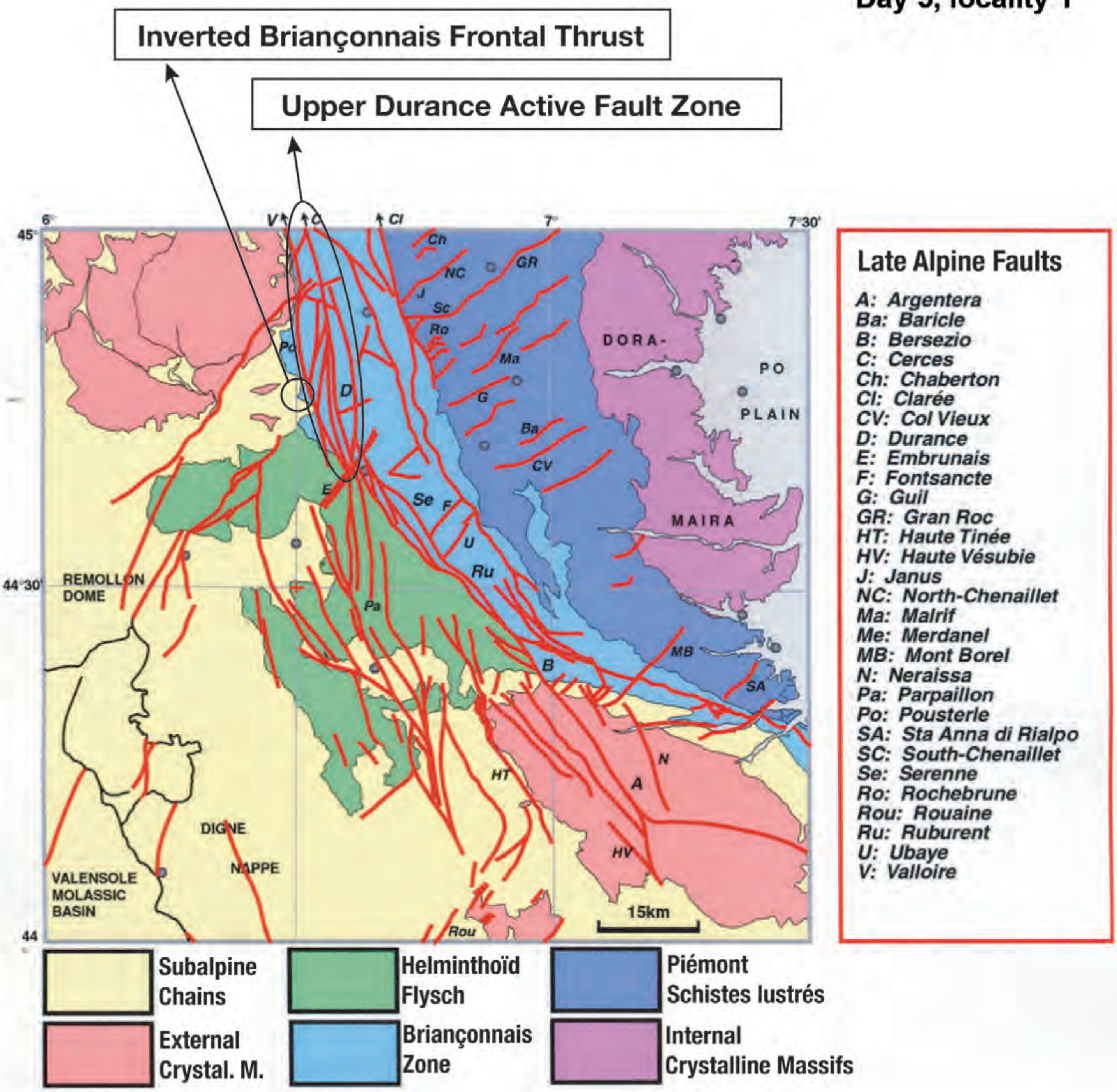






Seismotectonic maps and cross-sections in the Southwestern Alps, across the Briançonnais and Piedmont seismic arcs (Sue et al., 2007). The relationships between inherited crustal structures (crustal Penninic front and Ivrea Body) and seismicity (Briançonnais and Piedmont arcs) are illustrated in A.

B-Zoom on the Briançon (c) area allows to localize the seismic activity along faults recognized in the field: High-durance fault and East-Briançonnais fault.



Fournel small valley

(Vallon du Fournel)

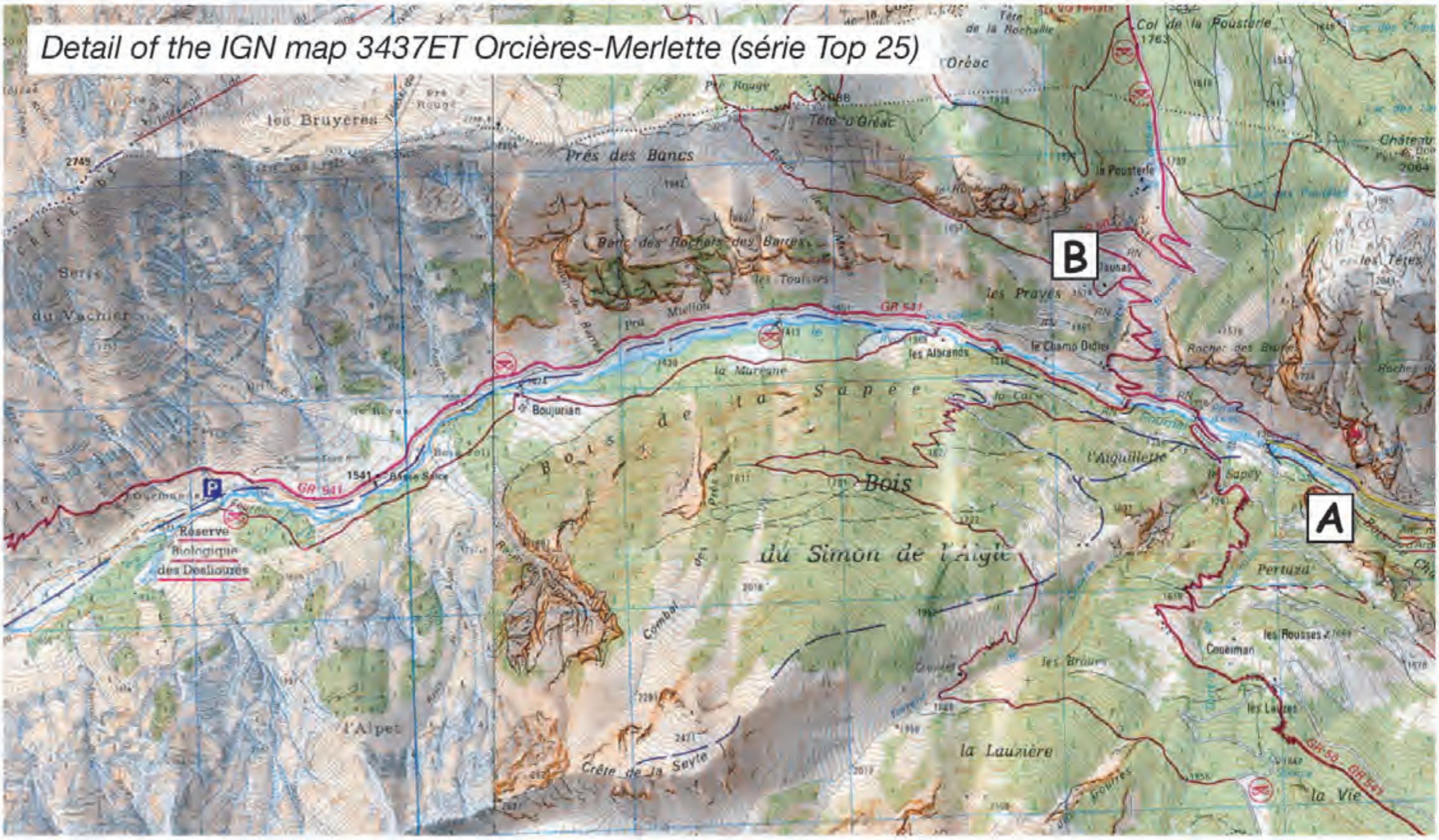
structural context

map of the late-Alpine and active faults after Sue & Tricart, 2002

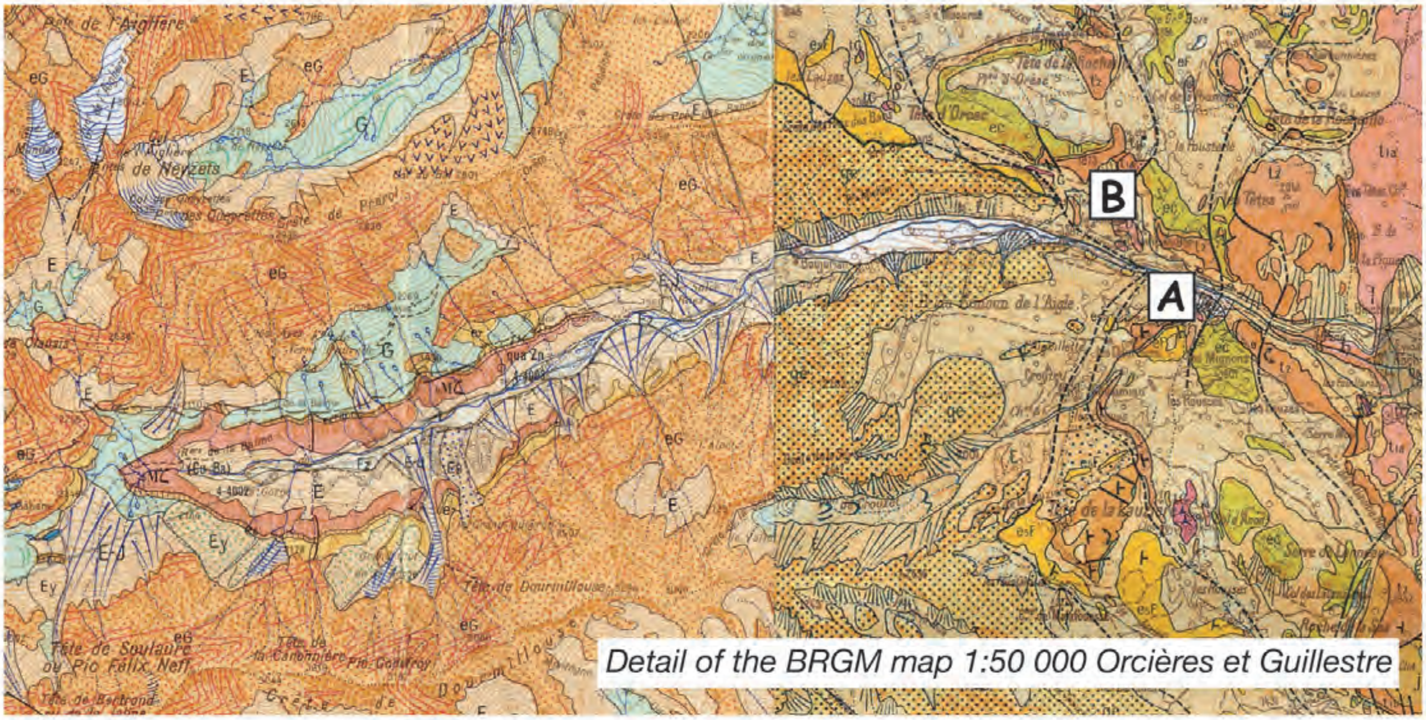
Fournel small valley : location of stops

A **Le Sapey** : general view from the Briançonnais frontal zone, onto the Upper Fournel valley, dug in the Champsaur Sandstones (internal fringe of the External Zone: Nummulitic flexural basin)

B **Oréac** : analysis of the Briançonnais Frontal Thrust, inverted as an extensional detachment during the general extension in the internal metamorphic zones



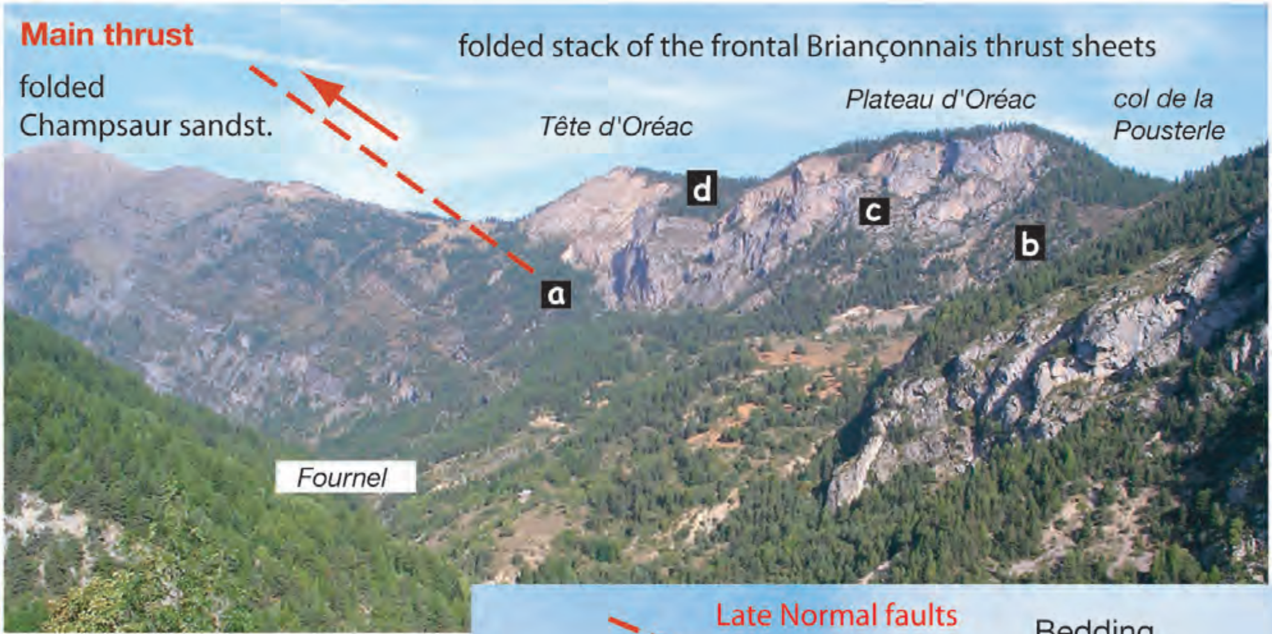
Detail of the IGN map 3437ET Orcières-Merlette (série Top 25)

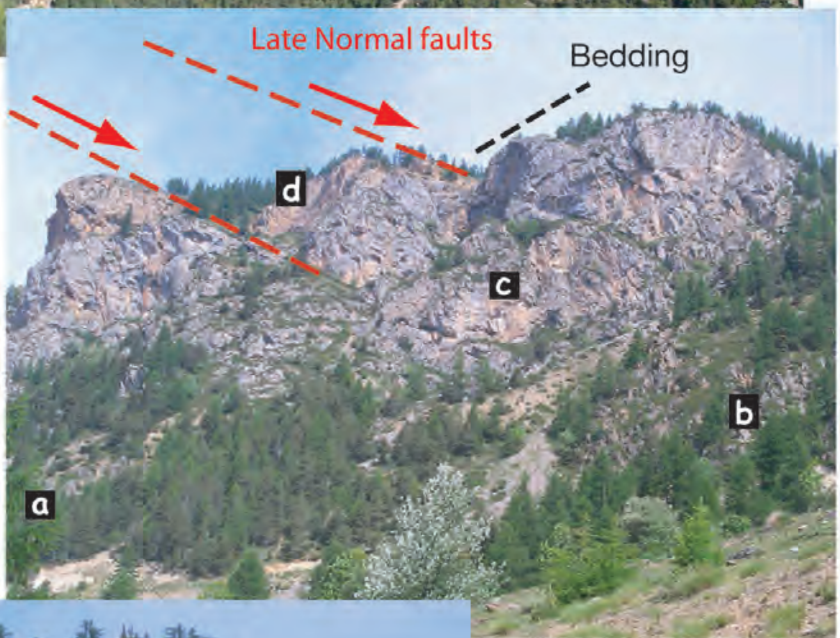


Detail of the BRGM map 1:50 000 Orcières et Guillestre

Fournel small valley : stop *A* - Le Sappey

General view towards the NW onto the Frontal Briançonnais Zone and its main thrust onto the Nummulitic flexural basin (Champsaur sandstones).





In the frontal Briançonnais thrust sheets : late westward **tilted blocs,** bounded by the normal faults which are oriented parallel to the main thrust (N-S trend and eastward low angle dip)

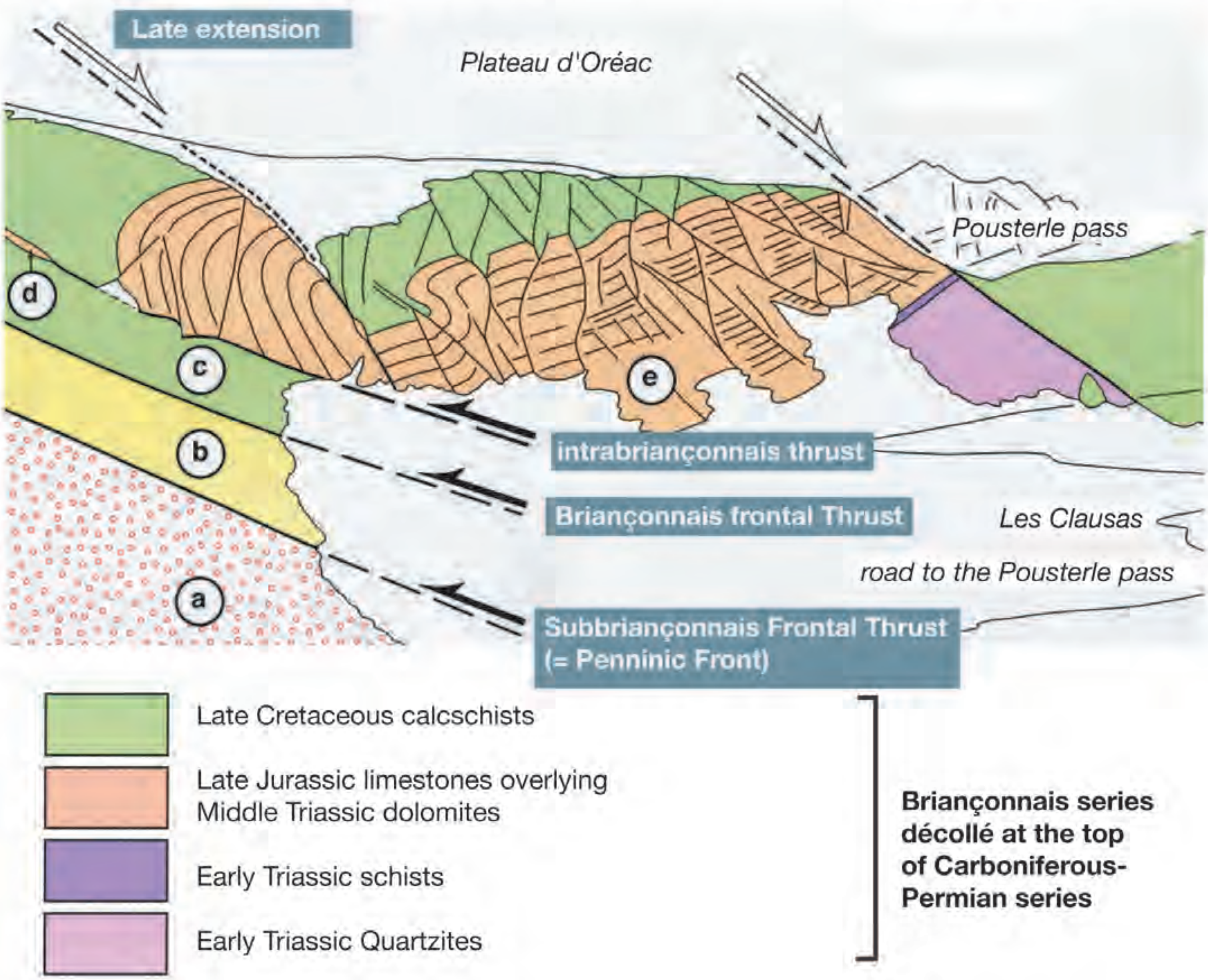
Detail: sets of conjugate normal faults sufferred westward tilting with the bedding. In consequence, primitively westward dipping normal faults now look like eastward dipping reverse faults

d Late Cretaceous : calcschists		**Briançonnais series**
c Middle Triassic & Late Jurassic: carbonates		
b Early Triassic : quartzites		
a Eocene black shales = **Subbriançonnais slice**		

(after Sue & Tricart 1999)

Fournel small valley : Stop B - Oréac

Polystage structure in the Frontal Briançonnais thrust sheets (after Sue & Tricart 1999)



tectonique pile

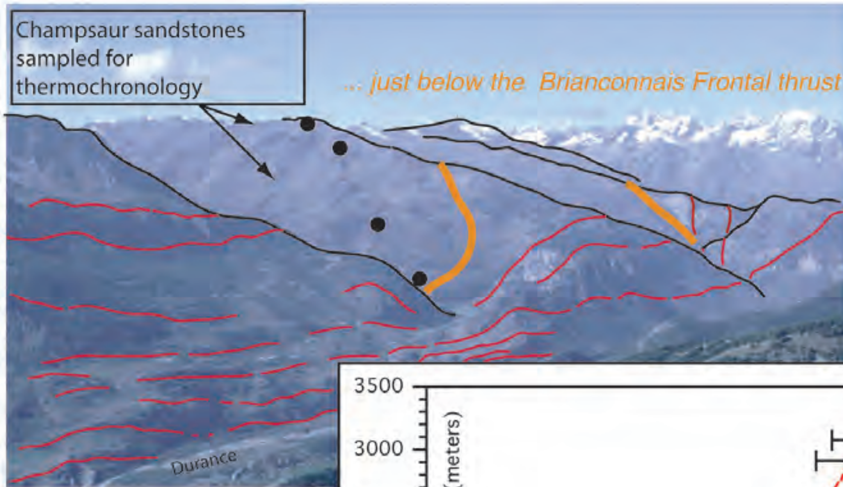
- (e) Frontal (=Western-most) Briançonnais thrust sheet
- (d) Small tectonic lenses : Briançonnais Late Jurassic / Middle Triassic formations
- (c) Tectonic slice : Briançonnais Late Cretaceous formation
- (b) Tectonic slice : Subbriançonnais black schists ("Flysch Noir")
- (a) Nummulitic flysch (Champsaur sandstones) internal fringe of External Zone

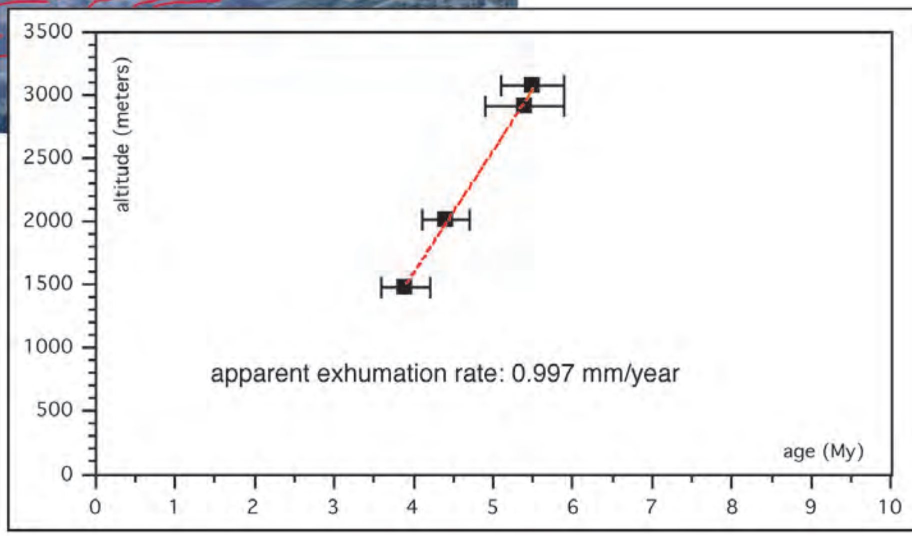
Proposed scenario (see for example: Tricart, et al., 2006)

(1) Late Eocene : synmetamorphic main thrusting phase in Briançonnais zone ; just to the West, in Eastern Dauphinois domain, formation of the Champsaur sandstones flexural basin. The front of the belt is located within the Subbriançonnais domain.
(2) Early Oligocene : refolding and new thrusting in the briançonnais stack of thrust sheets and thrustin of this stack onto the flexural basin, it self folded and décollé in the same top to-the-West movement.
(3) Miocene (?) - Present time: brittle extension in the briançonnais stack of thrust sheets, extensional reactivation("negative inversion") along the front of this stack.

Fournel small valley

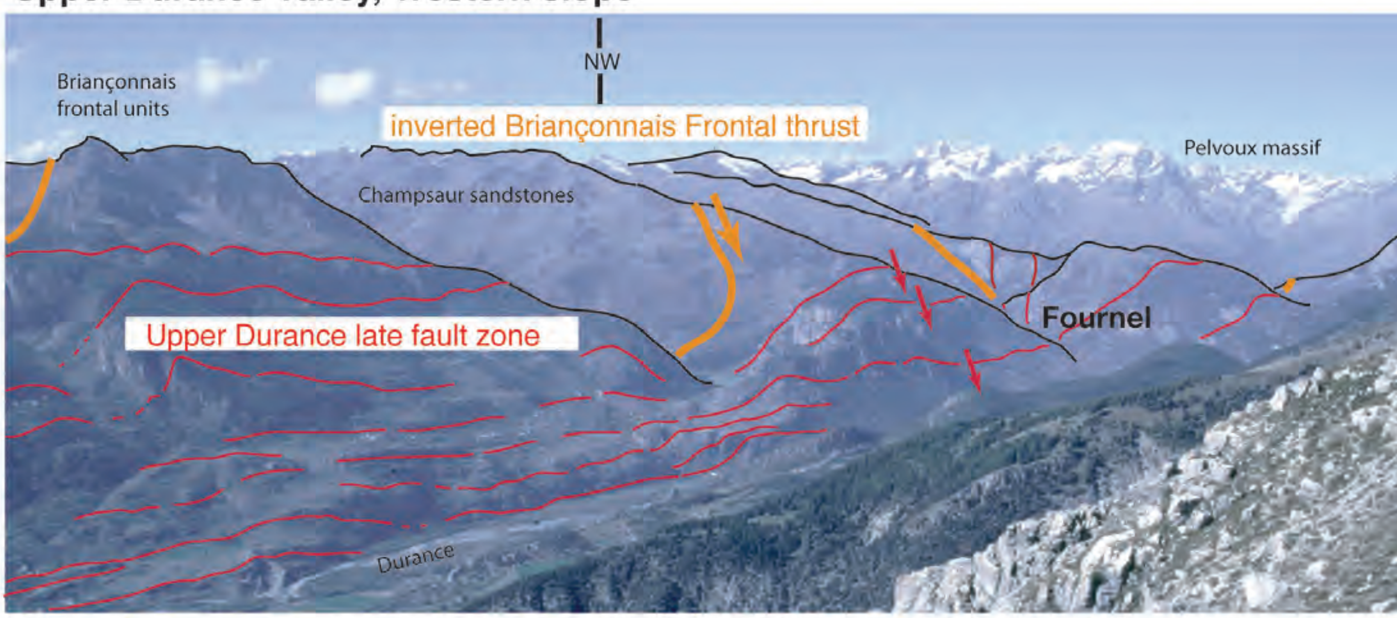
western tributary of Durance river

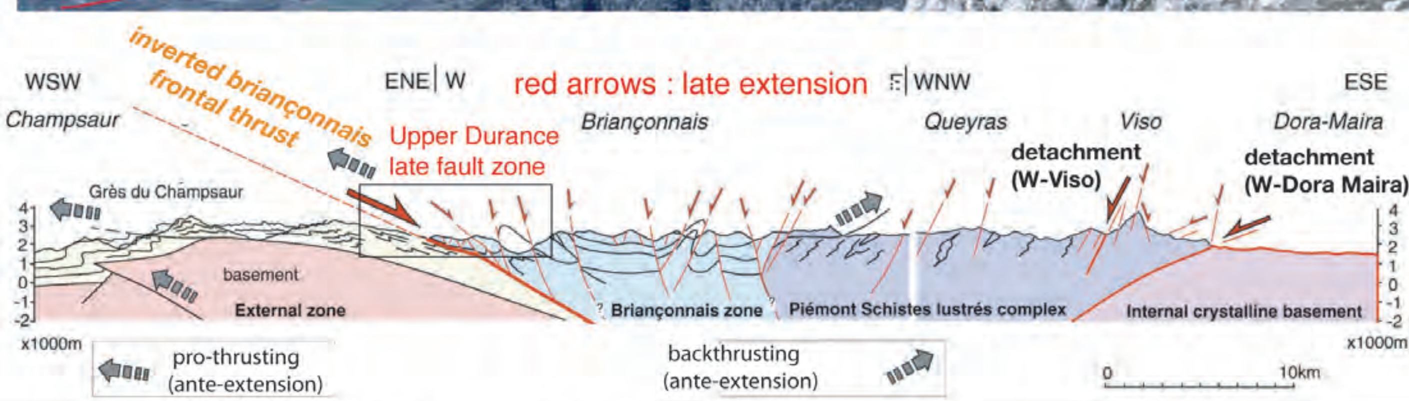




Apatite Fission Tracks ages : vertical section across the Champsaur sandstone pile

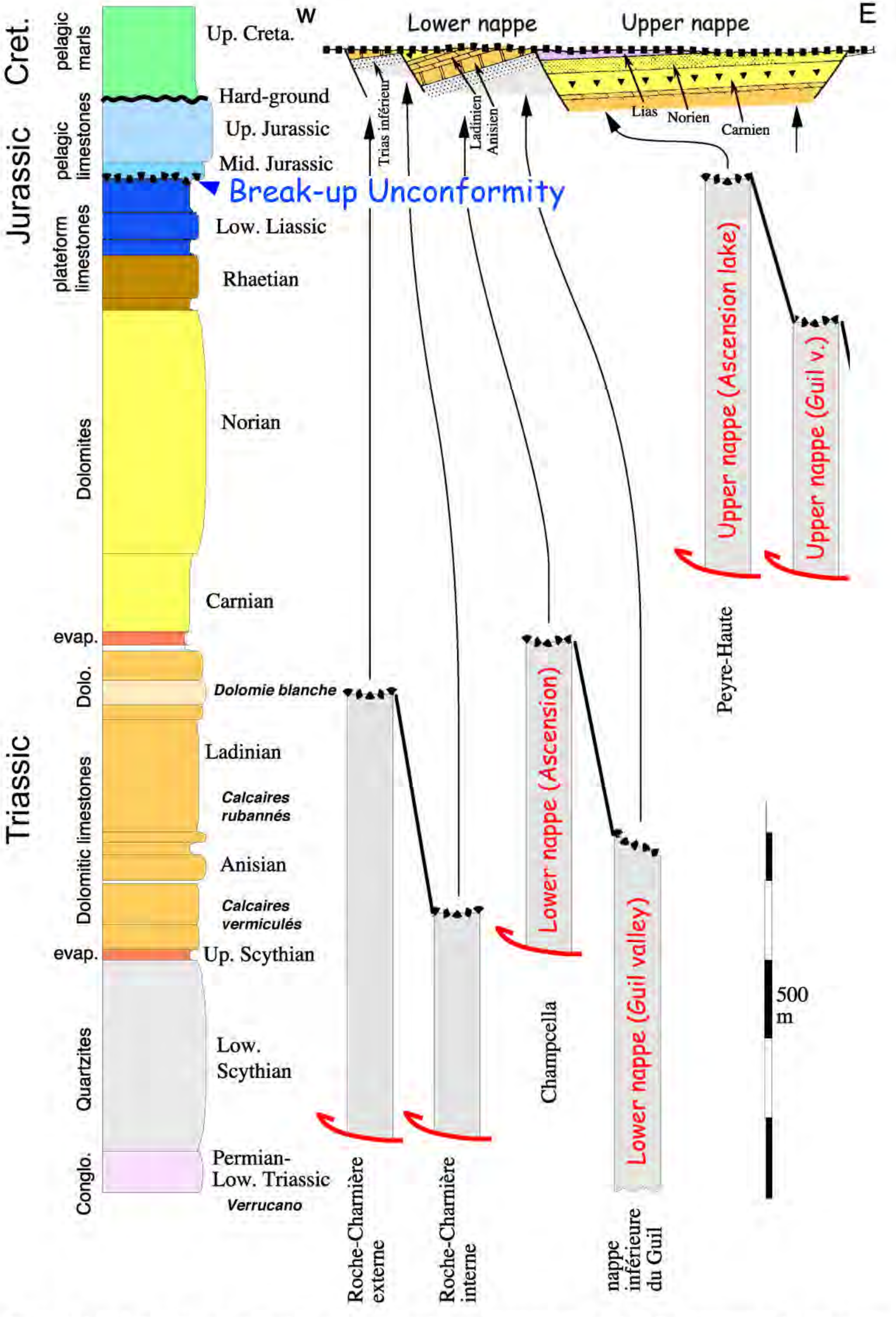
Upper Durance valley, Western slope



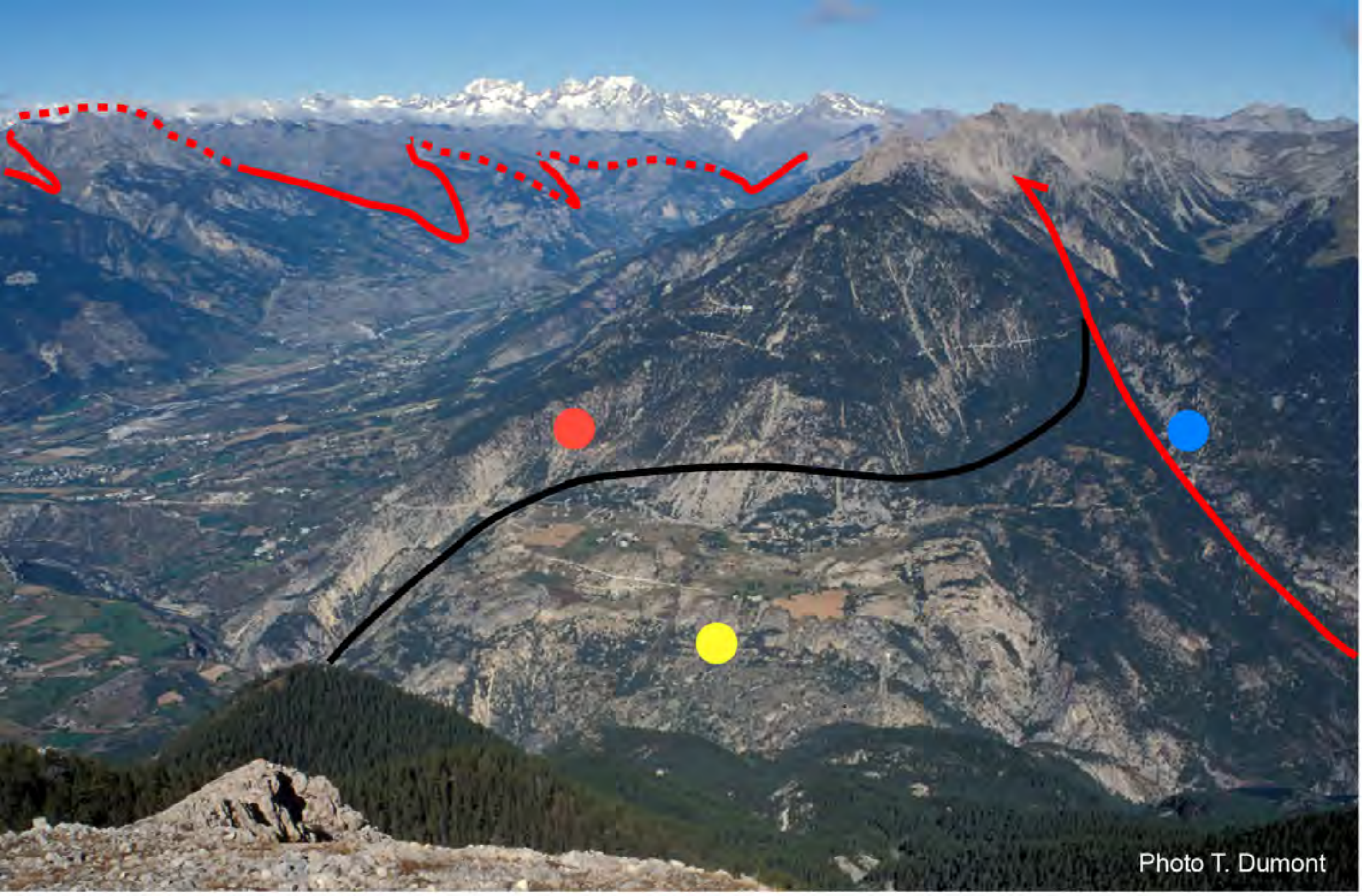


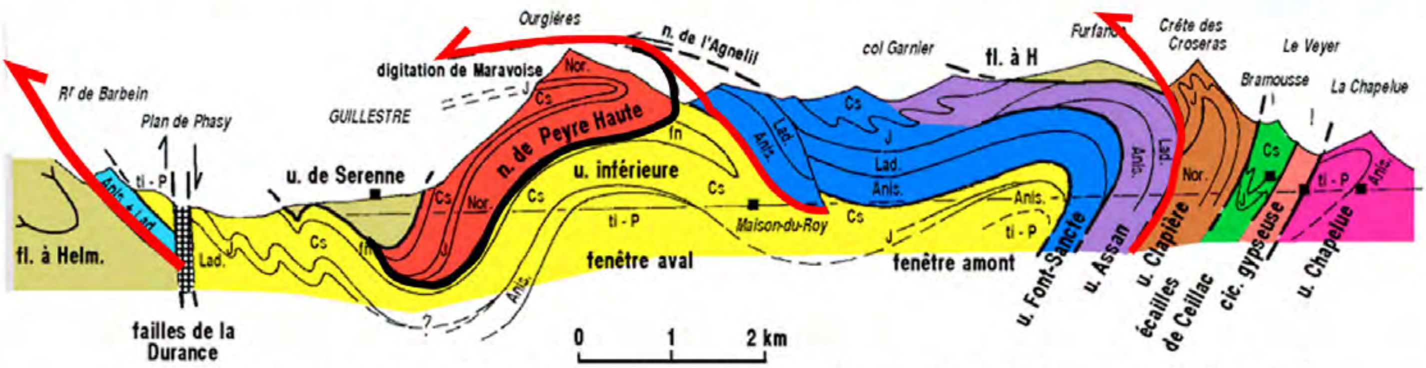
Champsaur - Dora-Maira general section

(after Tricart, Schwartz et al., 2001 et 2004 ; Tricart, 2004)



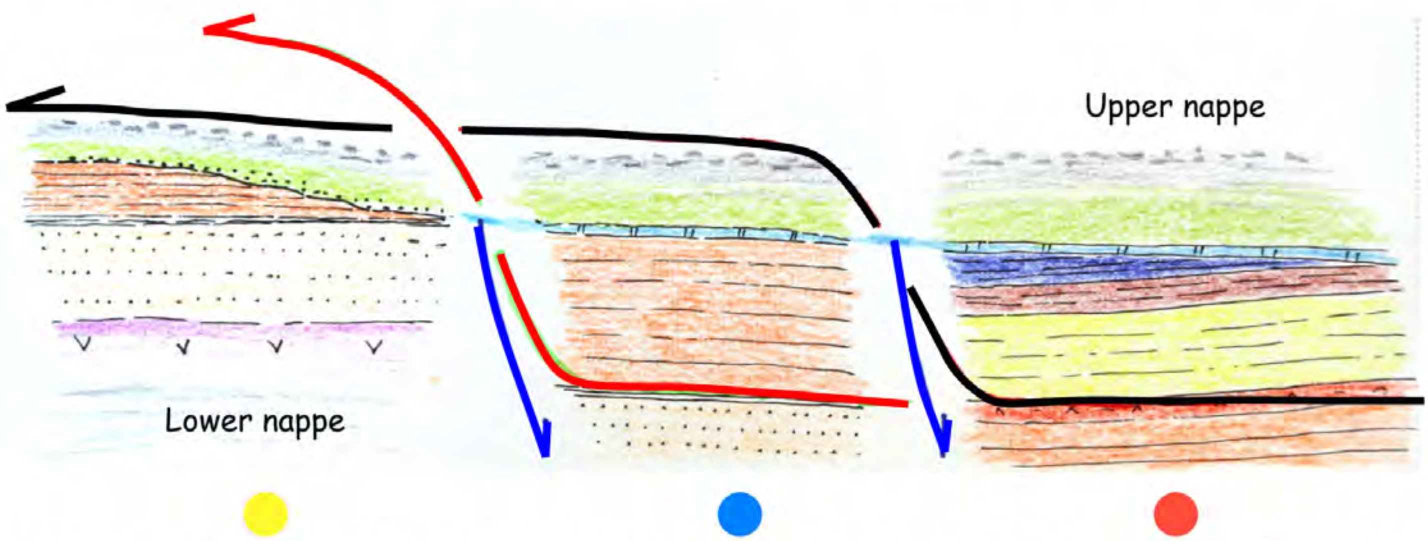
Day 5, locality 2: synthetic stratigraphic succession of the Briançonnais nappes.



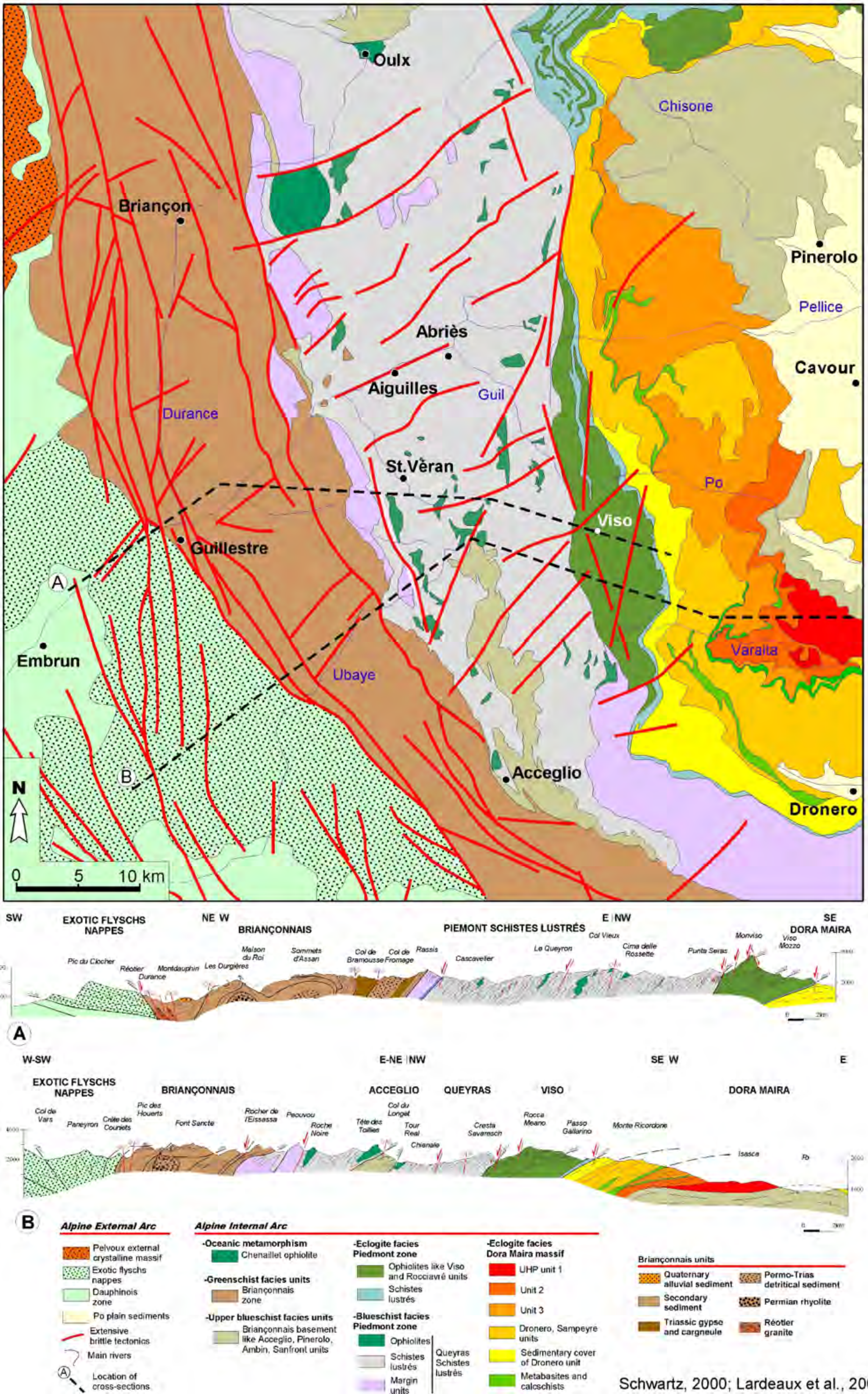


SW-NE cross-section of the Guil valley, after Gidon M. (http://www.geol-alp.com)

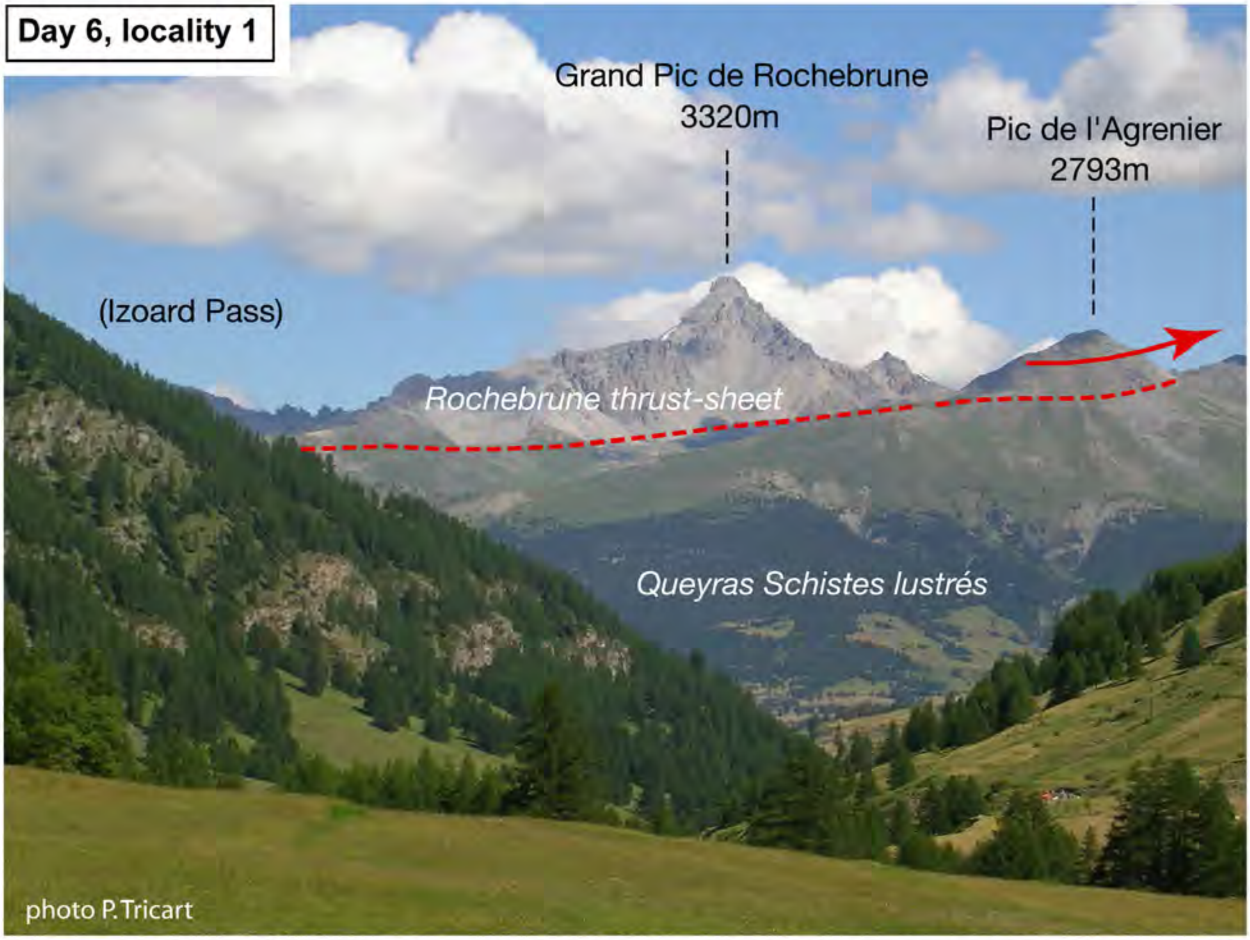
Day 5, locality 2: cross-section and panoramic view towards NW of the Guil anticline



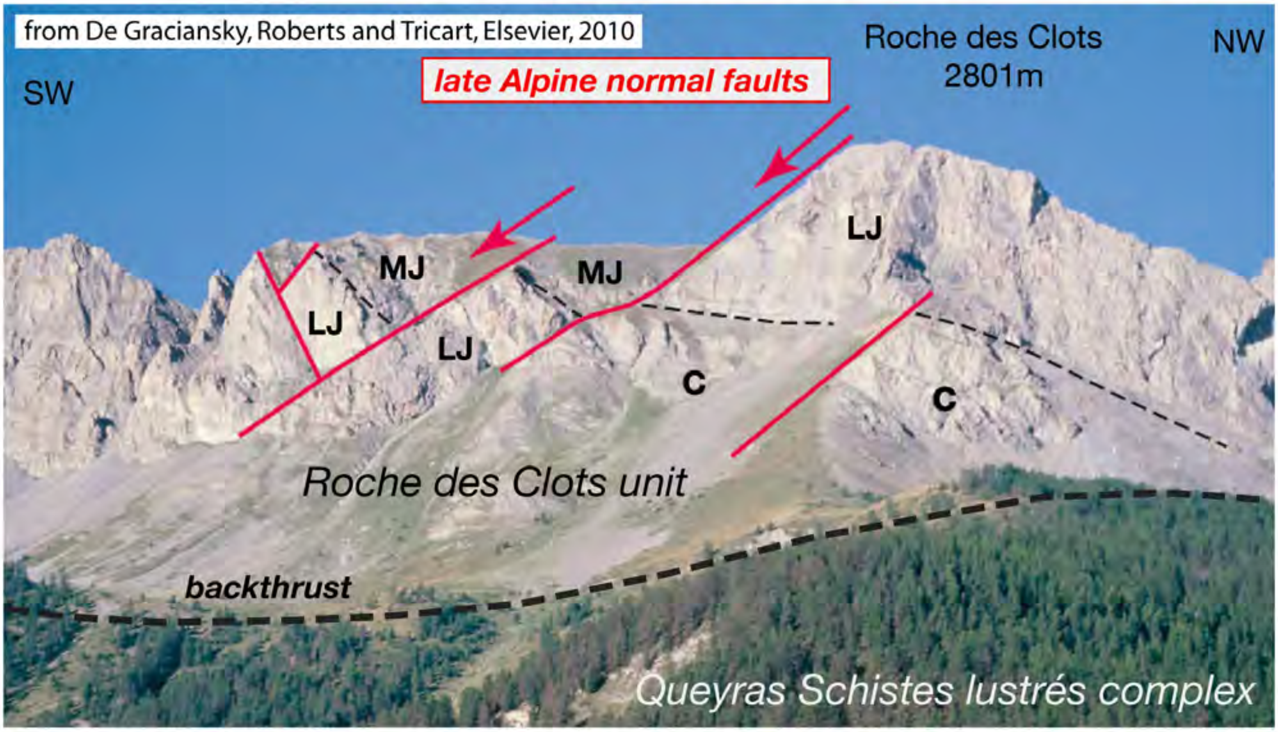
Proposed restoration of the multistage Alpine thrusting (legend of stratigraphic formations: see the previous fig.): each nappe is issued from tilted blocks of the Tethyan paleomargin.



Schwartz, 2000; Lardeaux et al., 2006



Viewing Northward : backthrust (i.e. East directed thrust) of Rochebrune unit (distal margin derived thrust-sheet) onto the Queyras Schistes lustrés complex (imbricated ocean derived thrust sheets)



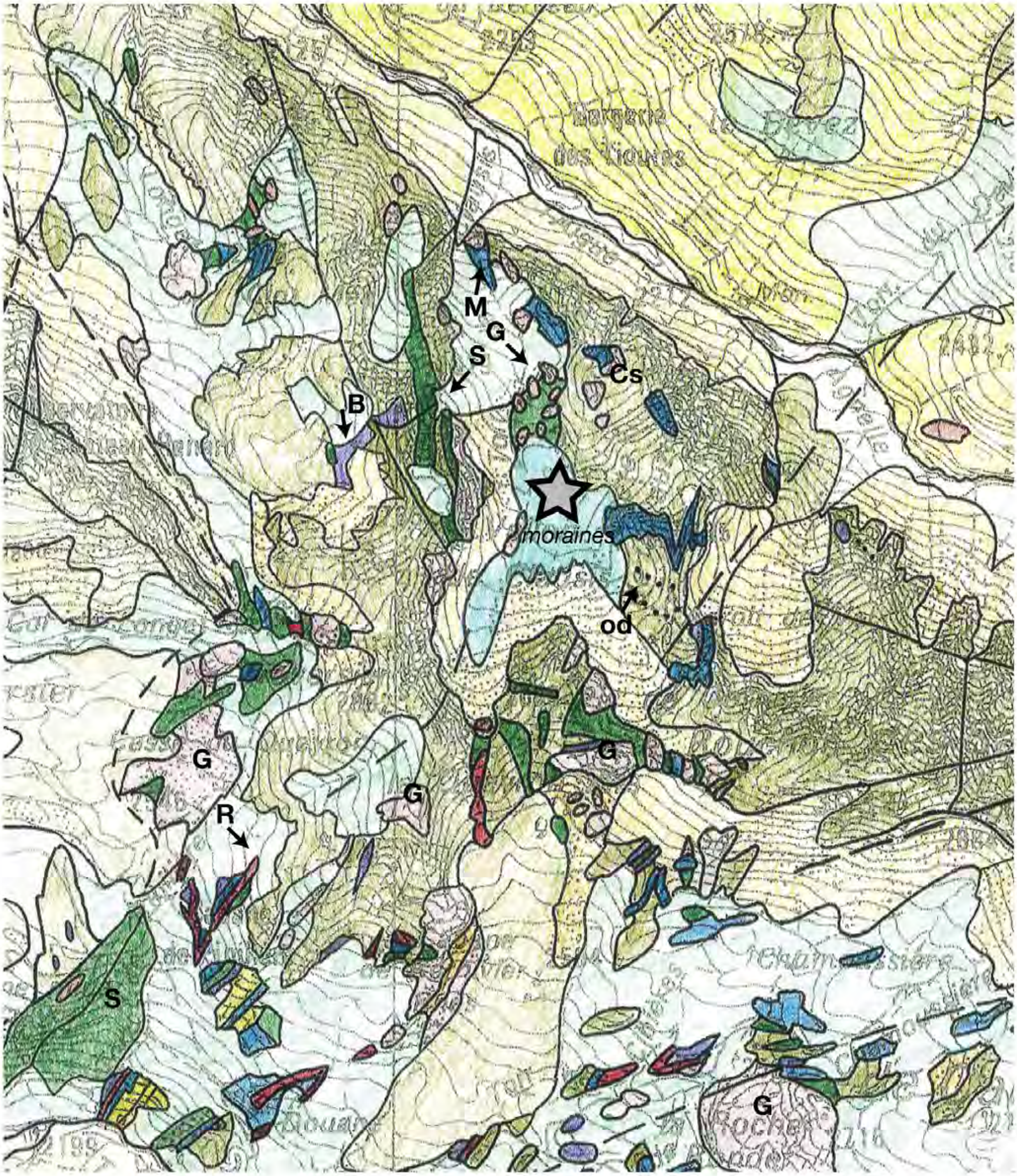
Viewed Westward, the backthrust (i.e. East directed thrust) of Roche des Clots unit onto the Queyras Schistes lustrés complex. Like Rochebrune unit, Roche des Clots unit originates from the distal margin. The Queyras Schistes lustrés complex originates from an imbricate of ocean derived thrust sheets. The backthrust surface contains slivers of gypsum coming from Triassic formations in the margin. In the hangingwall of this backthust, reactivated as an extensional detachement, an important late brittle extension is accomodated by kilometric tilted blocs.

Age of the main formations in the Roche des Clots unit :

MJ : Middle Jurassic ; **LJ :** Late Jurassic ("Tithonian" limestones) ; **C :** Cretaceous.

Carte Géologique de la France à 1/50 000, sheet "Aiguilles-Col St Martin", BRGM, 2003 : *preliminary drawing, P. Tricart*

Detailed geological map around Clausis small valley



Piémont Schistes-lustrés complex

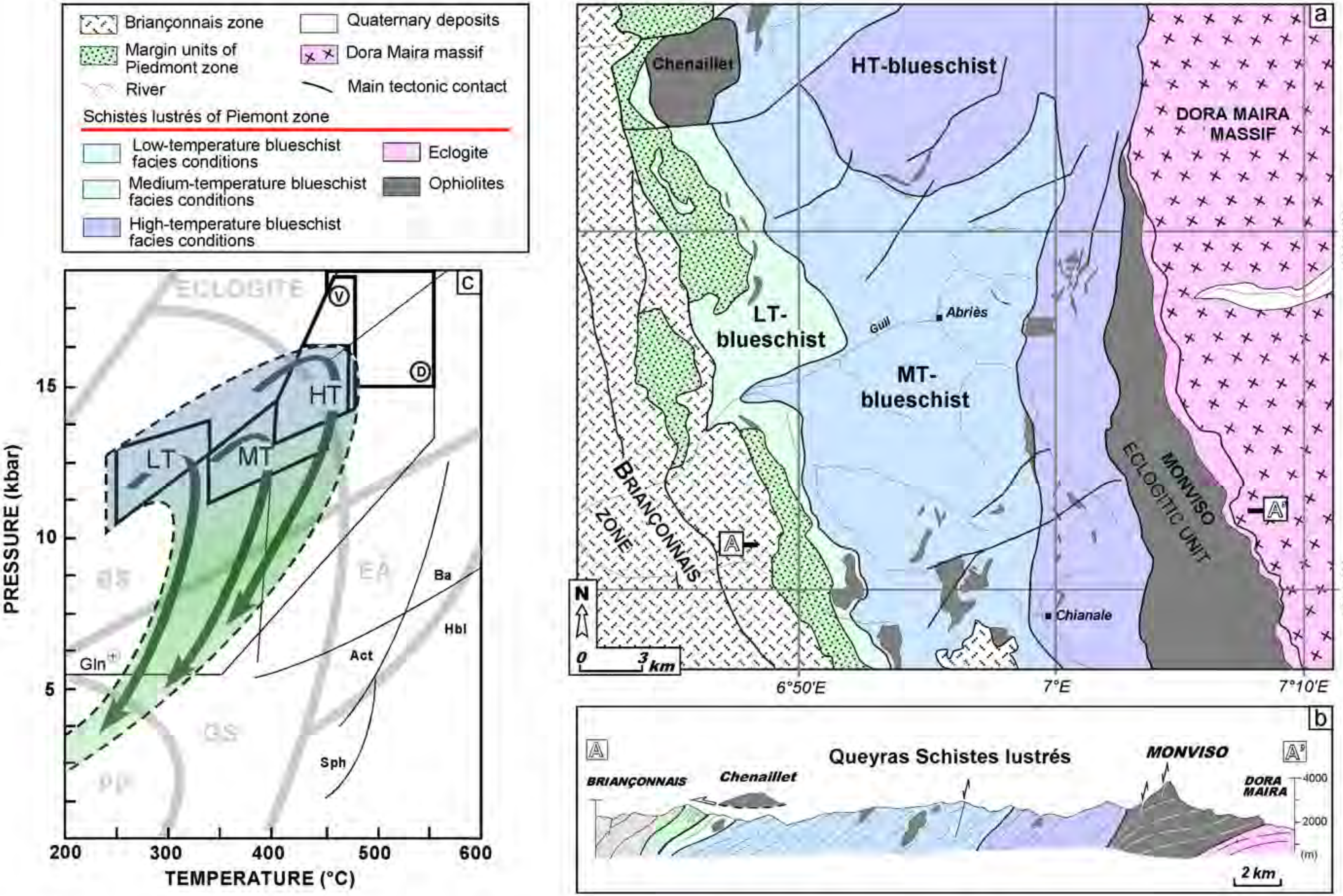
- **Cs** **calcschists** : Cretaceous oceanic marls with **ophiolite derived detritus (od)**
- **M** **"marbles"** : Tithonian limestones
- **R** **radiolarian cherts**
- **B** **meta-basalts** (massive, brecciated or pillowed)
- **G** **meta-gabbros** (primitively intruded within the peridotites)
- **S** **serpentinites** derived from mantle peridotites

Many blocs isolated within the Cretaceous calcschists are of sedimentary origin : they represent olistoliths fallen from normal fault scarps linked with seafloor spreading in Cretaceous times. This "mélange" aspect was greatly enhanced by tectonic boudinage within the growing accretionnary wedge (subduction stage) and subsequently when this wedge was severely refolded (collision stage).

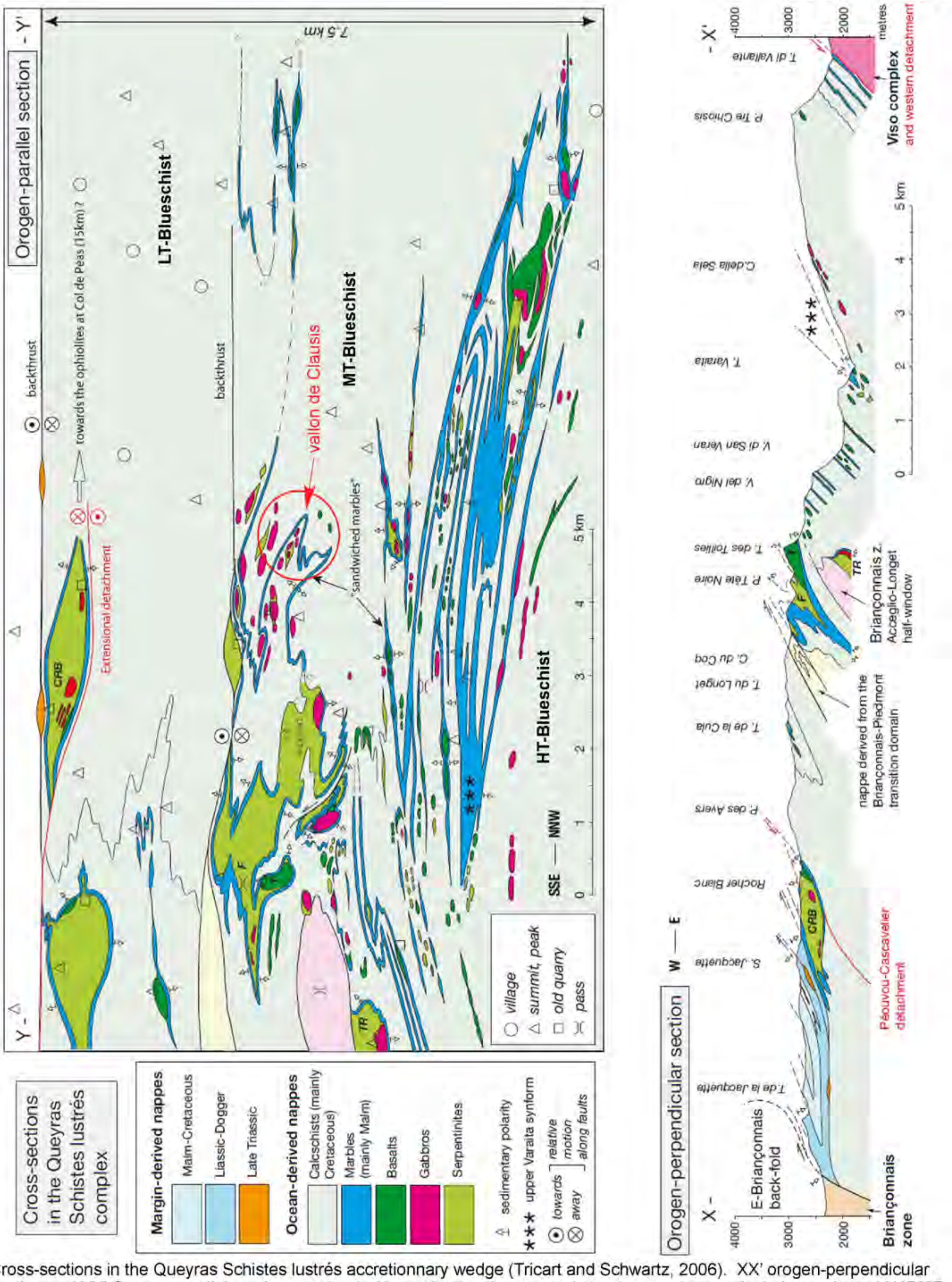
Day 6, locality 2

detail of the French topo map by I.G.N., original scale 1:25 000

Clausis small valley (Vallon de Clausis) in central Queyras



A-simplified metamorphic map of the Schistes lustrés accretionary wedge (Schwartz et al. submitted). B-west-east cross section through the Schistes lustrés, Monviso massif and the western part of Dora Maira massif (Schwartz, 2000). C-*P-T* conditions in the Queyras Schistes lustrés. The eclogitic conditions in the Monviso ophiolitic unit and the Dora Maira crystalline massif are included for comparison.



Cross-sections in the Queyras Schistes lustrés accretionnary wedge (Tricart and Schwartz, 2006). XX' orogen-perpendicular section and YY' Orogen parallel section constructed by projecting the mapped structures onto a vertical plane oriented N170°E. The Queyras Schistes lustrés derived from Mesozoic oceanic sediments strongly deformed and metamorphosed during alpine subduction and they outcrop today as foliated and polydeformed calcschists enclosing boudinaged decametre-to-kilometresized ophiolitic bodies. At the regional scale, the main structure is a pile of thrust sheets imbricated within an accretionary wedge during the Palaeogene. This pile has undergone repeated and severe refolding under metamorphic conditions grading up eastwards from blueschist to blueschist-eclogite transitional facies.

Day 6, locality 3

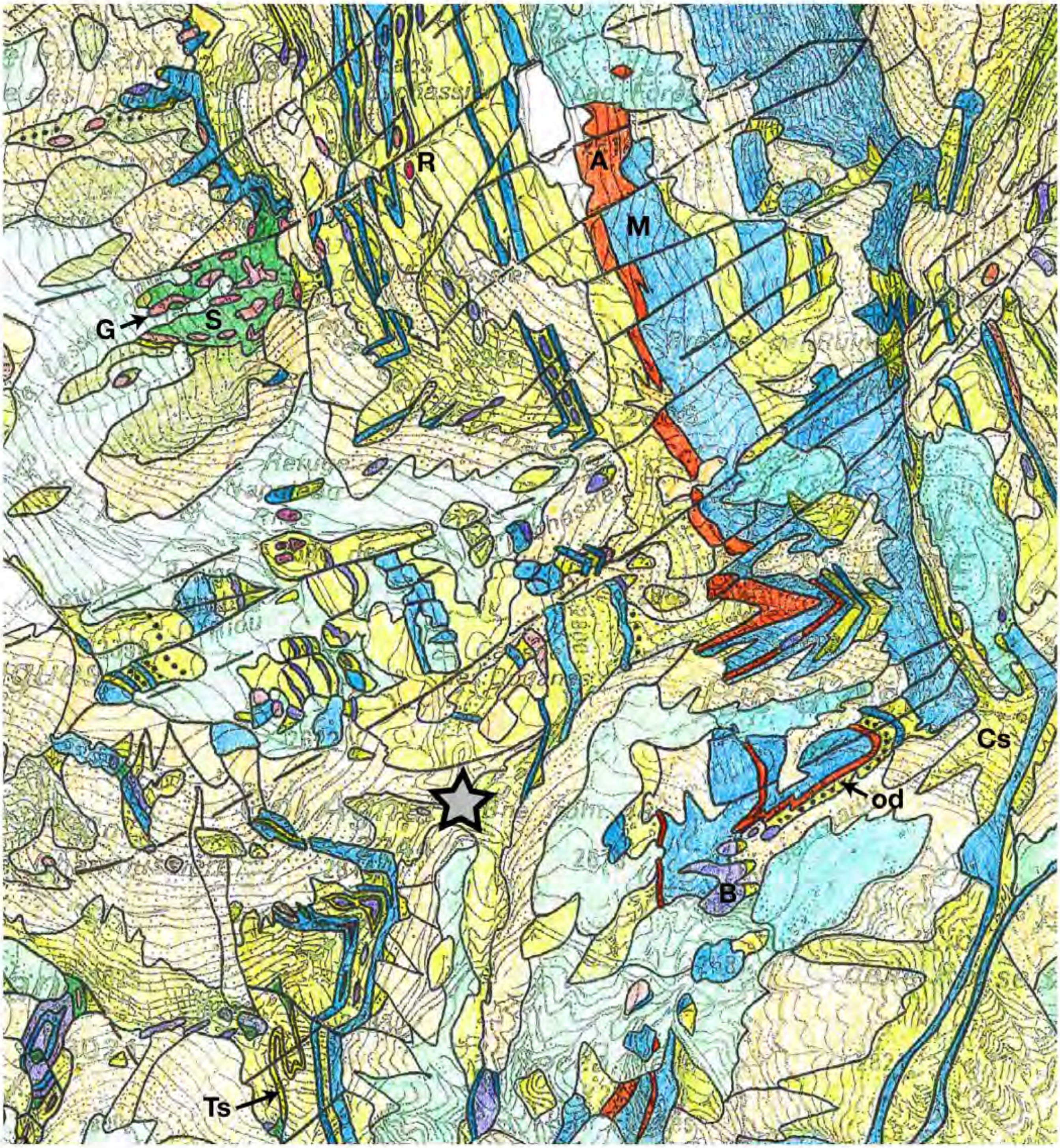
detail of the French topo map by I.G.N., original scale 1:25 000

☆ **Agnel Pass** (Col Agnel) : 2744 m

Day 6, locality 3

Carte Géologique de la France à 1/50 000, sheet "Aiguilles-Col St Martin", BRGM, 2003 : *preliminary drawing, P. Tricart*

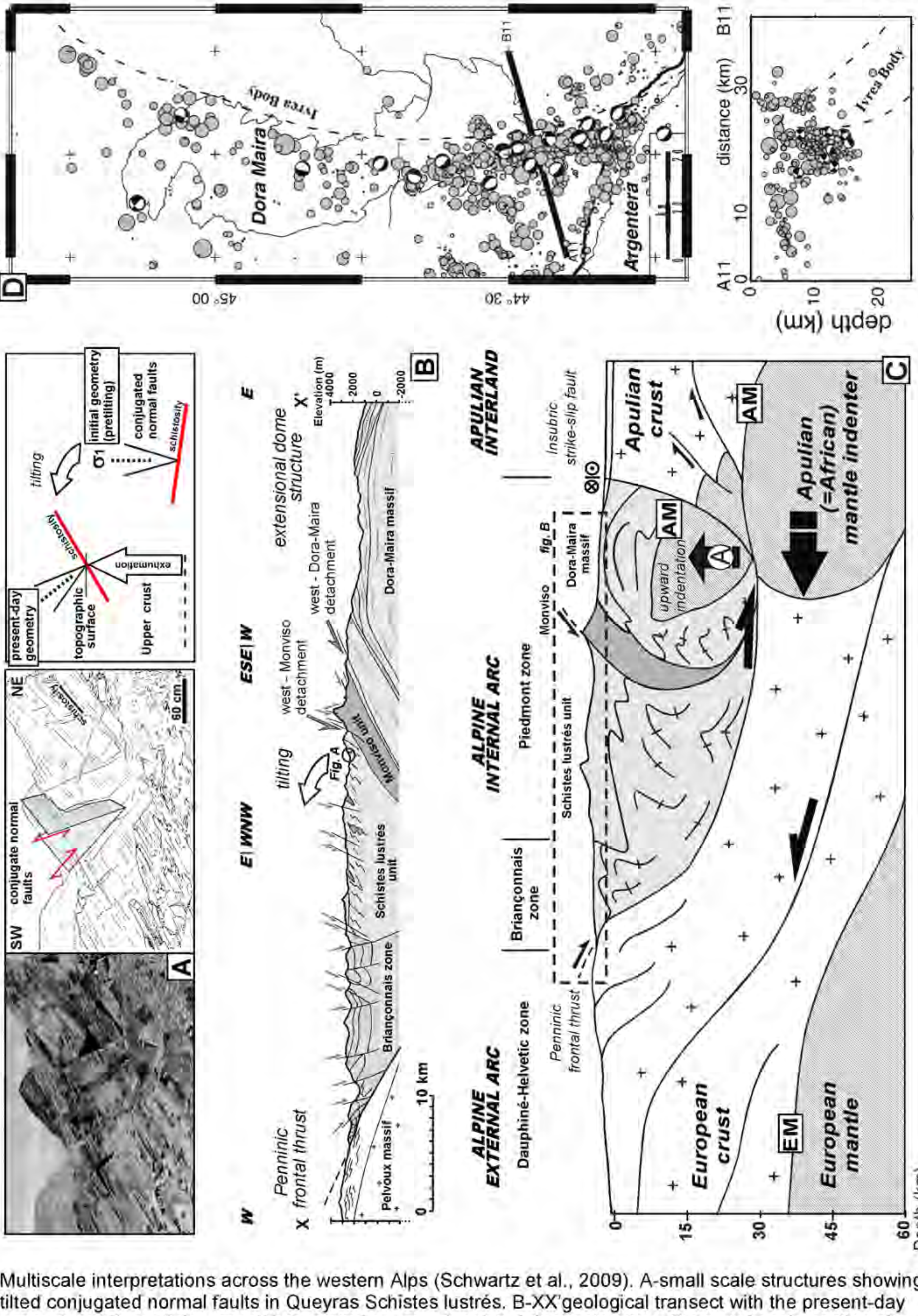
Detailed geological map around Agnel Pass



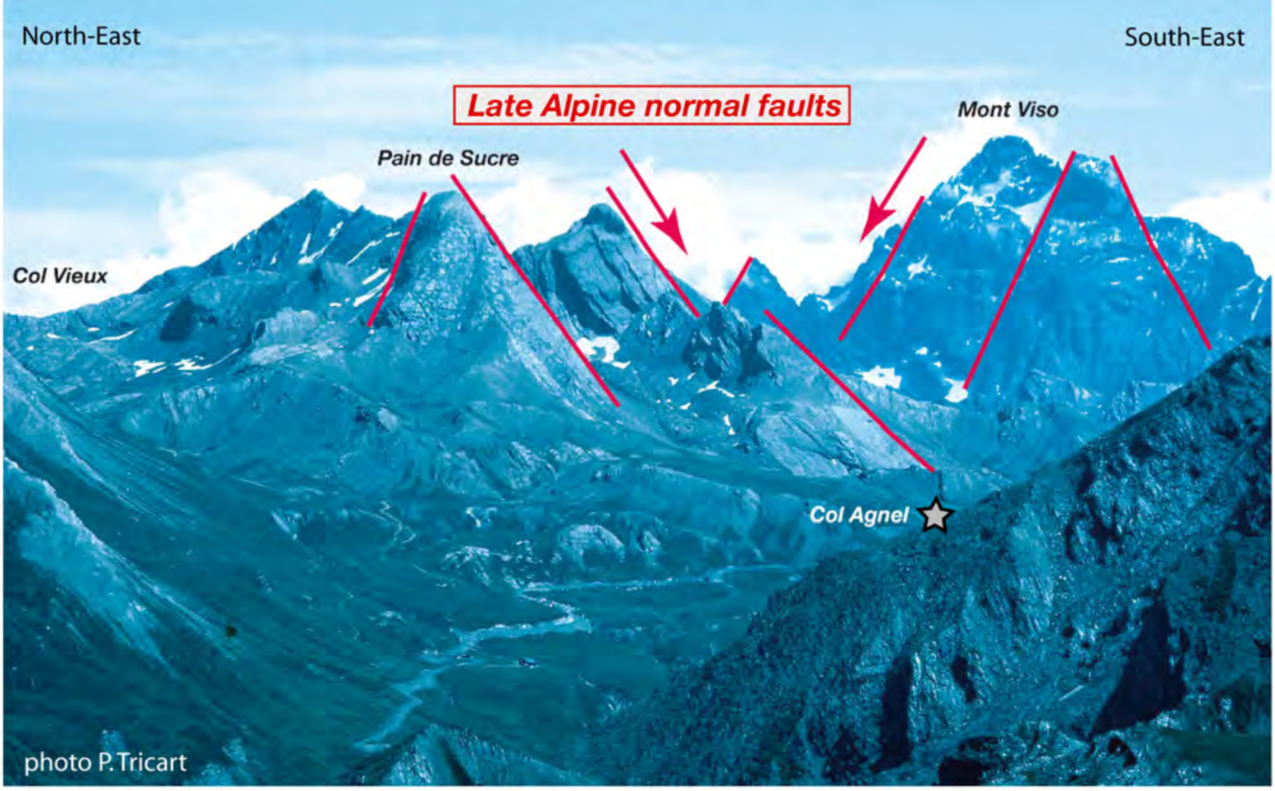
Piémont Schistes-lustrés complex	**Cs**	**calcschists** : Cretaceous oceanic marls with **ophiolite derived detritus (od)**
	A	**meta-arkoses** : old continental crust derived detritus
	M	**"marbles"** : Tithonian limestones
	R	**radiolarian cherts**
	B	**meta-basalts** (massive, brecciated or pillowed)
	G	**meta-gabbros** (primitively intruded within the peridotites)
	S	**serpentinites** derived from mantle peridotites
	Ts	**talc-schists** in alpine shear zones

late Alpine fault (postorogenic collapse)

Agnel Pass



Multiscale interpretations across the western Alps (Schwartz et al., 2009). A-small scale structures showing tilted conjugated normal faults in Queyras Schistes lustrés. B-XX'geological transect with the present-day geometry of Dora Maira massif interpreted as an extensional dome structure. C-Crustal-scale section showing the depth of the European Moho (EM) and Apulian lithospheric mantle indenter (AM). D-seismic map and cross section through the piedmont seismic arc (Sue et al., 2007)

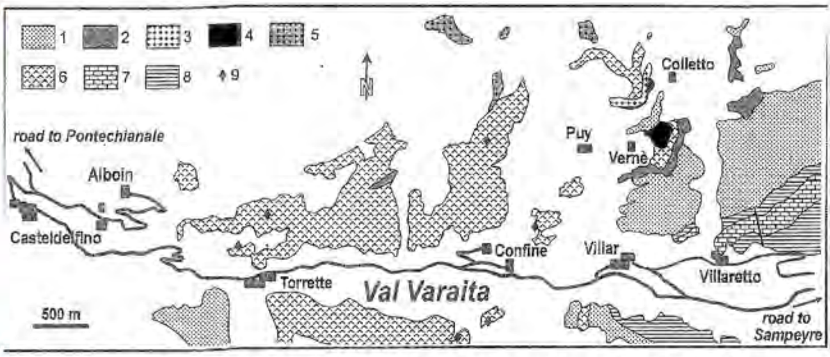


In Col Agnel - Mont Viso area, spectacular development of late normal faults trending NE-SW to E-W. They are closely associated with N-S normal faults less visible in the landscape. Both families oriented respectively transverse and parallel to the fold-thrust belt accomodate a radial brittle extension.

Day 6, locality 3

Viewed Eastward from the main crest between France (Queyras) and Italy: the Western steep face of Mont Viso pyramide in eclogitized ophiolites. The geometry of the pyramide is controled by conjugate late normal faults. In the foreground, the internal part of the Piémont Schistes lustrés complex.

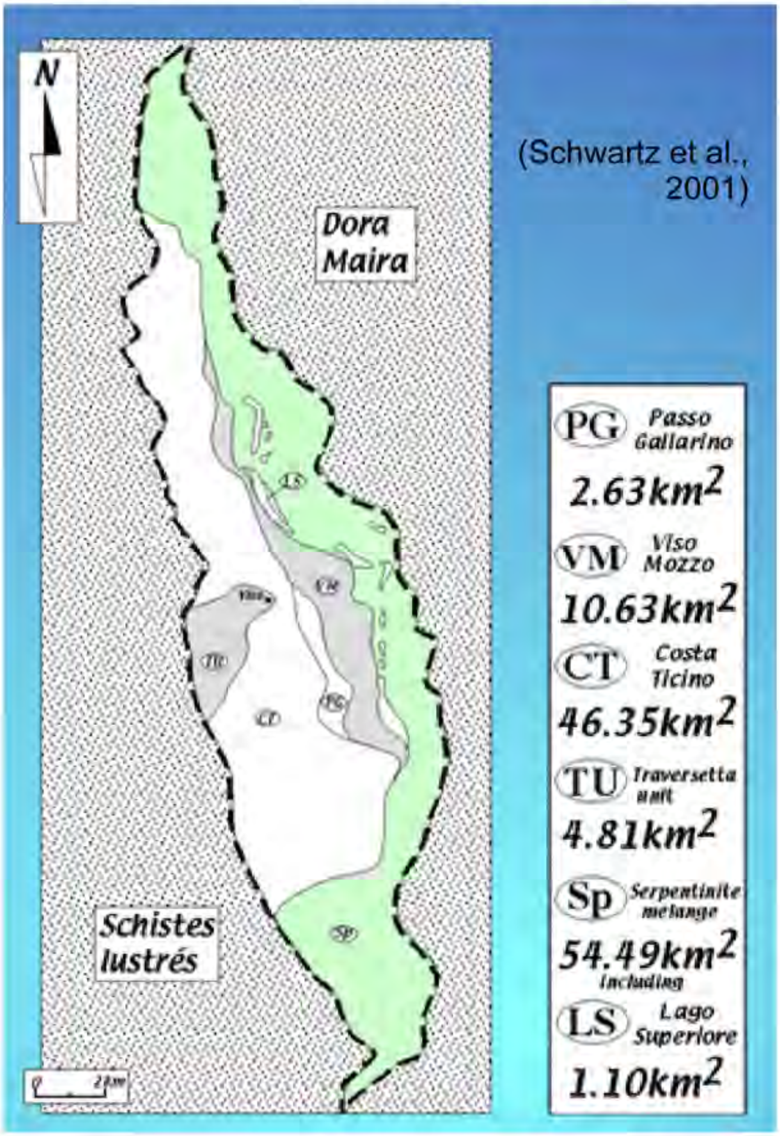
Location map



Geological map of the Monviso along the Val Varaita
1 calc-schist, 2 metabasite, 3 plagiogranite, 4-5 metagabbro,
6 serpentinites, 7 marbles, 8 Quartzites. (Lombardo et al., 1992)

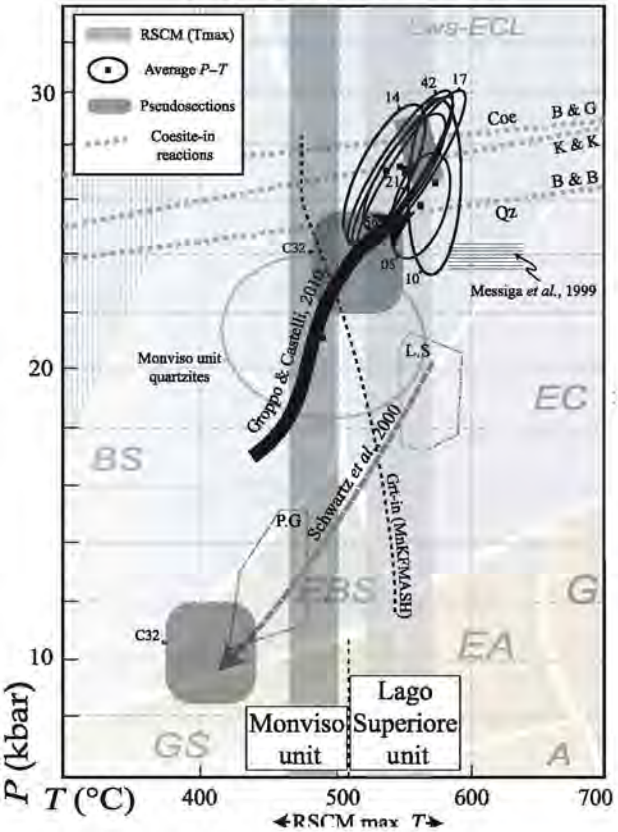
Lithological map of the Monviso Massif

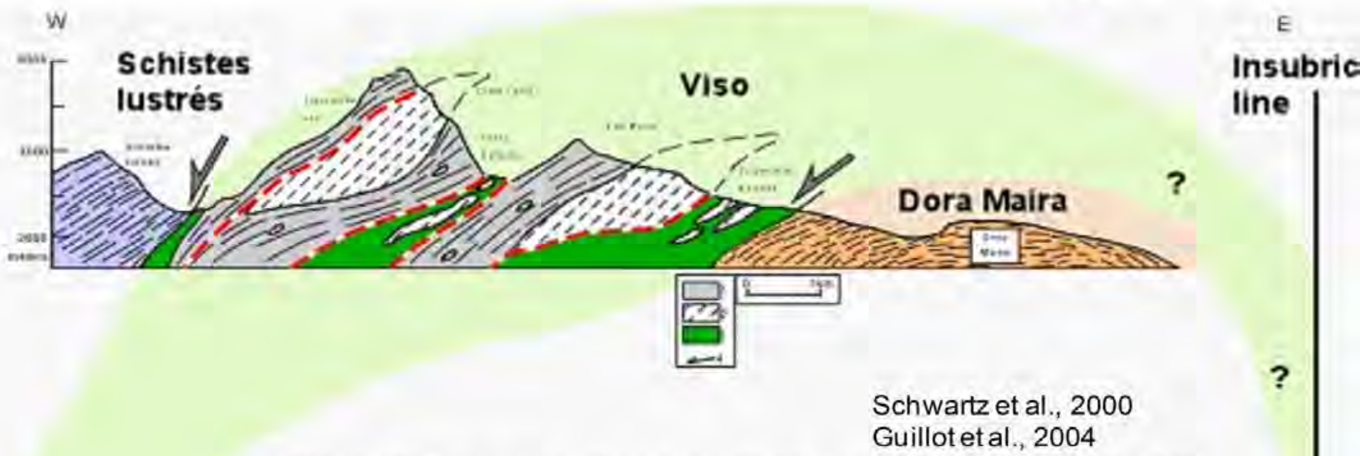
Notice that 50% is represented by ultramafic rocks



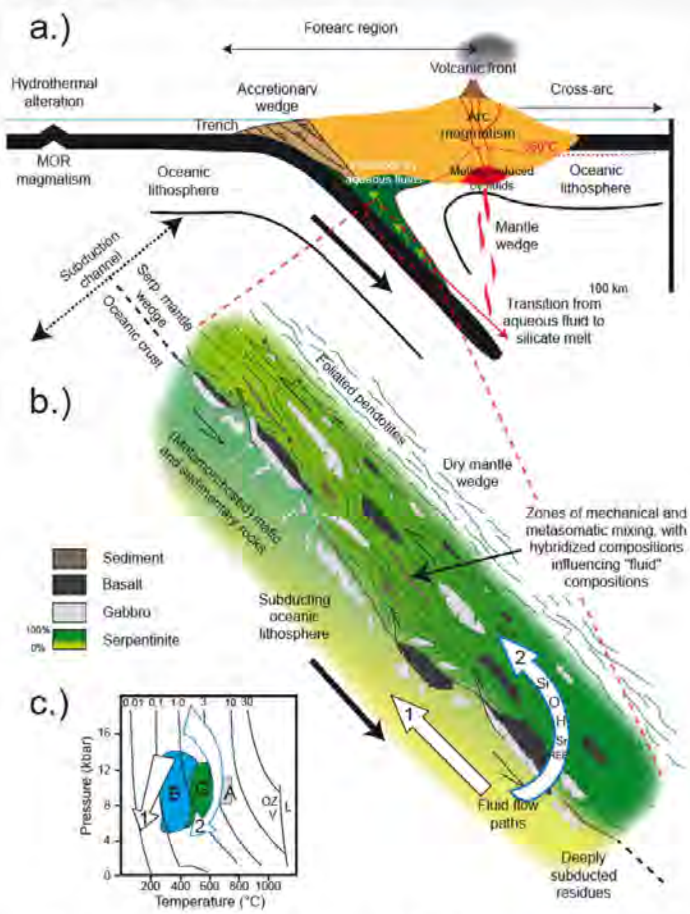
P-T path of the Monviso

(after Schwartz et al., 2000, Angiboust et al., 2011)





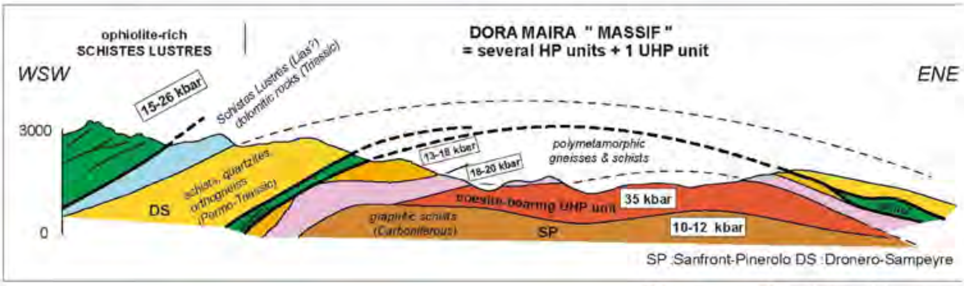
Cross section of the Monviso ophiolite showing the different units with eclogitic lenses embedded within the serpentinite. The tectonic contact between the different units correspond to normal shear zones under greenschist facies conditions. 1: Greenschist foliated metabasalts (prasinites); 2: eclogitic lenses composed of undifferentiated metagabbros, massive metabasalts and pillow lavas; 3 serpentinites. The shaded envelop corresponds to the geometry of the Monviso unit rooted below the Schistes Lustrés (Paul et al. 2001) and possibly rooted east of the Dora Maira massif, along the Insubric line.



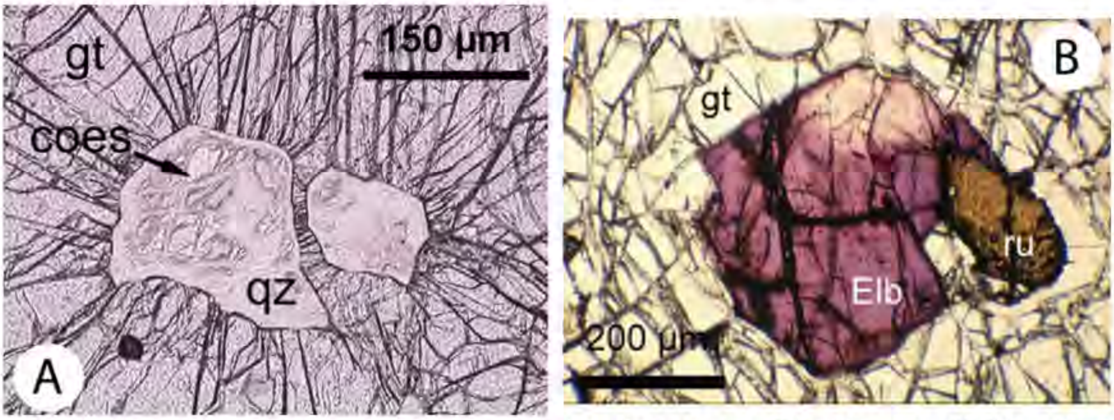
Schematic relationship between accretionary wedge and serpentinite subduction channel. (b) Detail of the serpentinite subduction channel. It forms a ~60 km long (from 40 to 100 km depth) soft channel between the dry (rigid) subducted oceanic lithosphere and the dry (rigid) mantle wedge. It is made of a melange of serpentinites deriving the hydrated oceanic lithosphere and from the hydration of the mantle wedge and contains exotic blocks of metabasalts, metasediments and metaggabros, mainly derived from the subducting oceanic lithosphere but also from the above arc system. Due to the low viscosity and low density of serpentinite mineral and the triangle shape of the serpentinite channel, the dowgoing material is progressively entrained upward (Guillot et al., 2009)

Day 7, locality 2

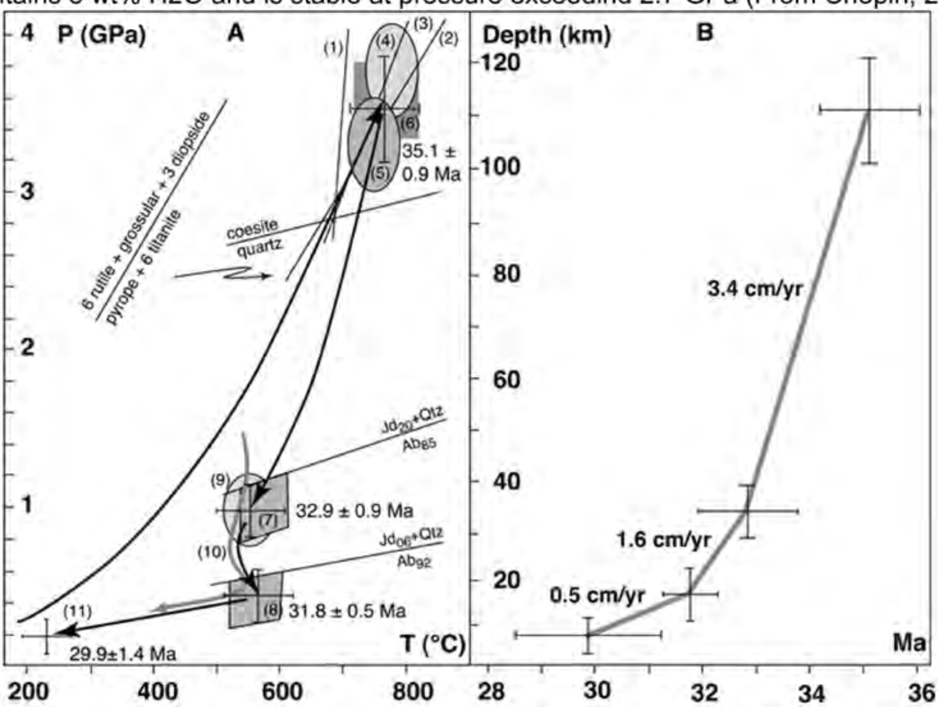
UHP Dora Maira massif



Cross section from Henry et al., 1993

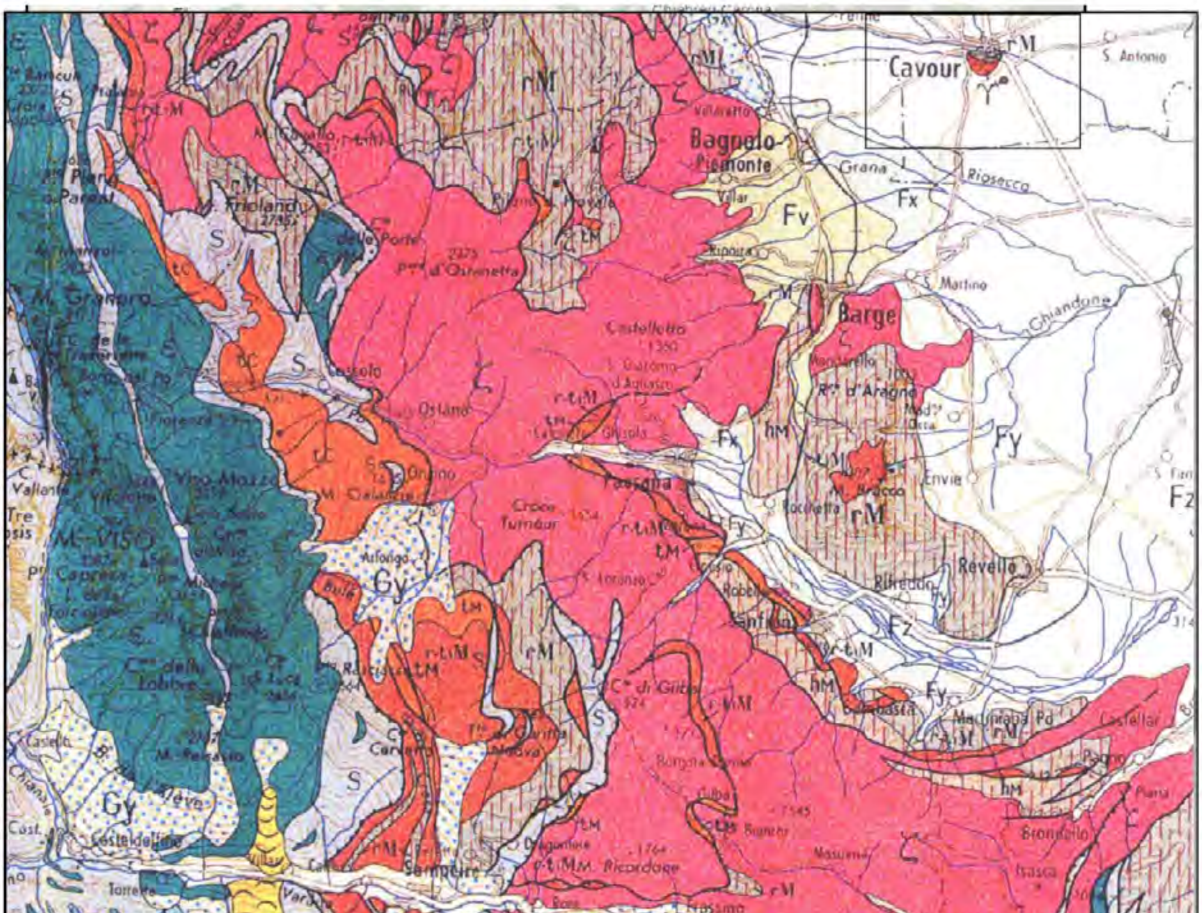


A coesite inclusion within pyrope garnet and B Ellenbergite inclusion. This Mg---Al---(Ti,Zr)---silicate contains 8 wt% H2O and is stable at pressure exceedind 2.7 GPa (From Chopin, 2003)



P-T-t path of the UHP continental eclogites (from Schertel and Schreyer, 2008)

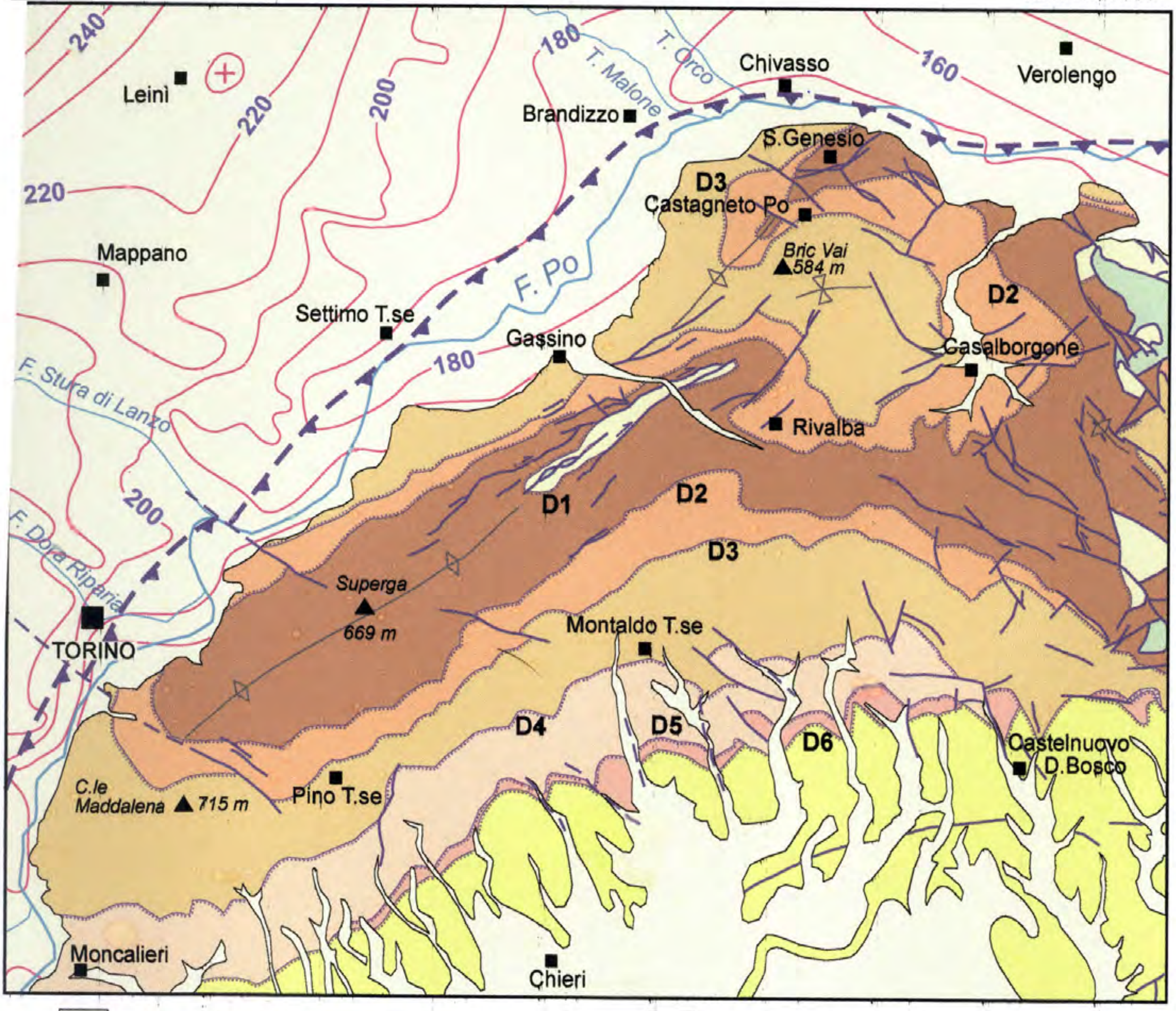
Rocca Cavour



A small outcrop of Permian granite belonging to the Dora-Maira massif, isolated within the Po plain sediments.

8.1a **Torino Hills** **SCHEMA STRUTTURALE**

scala 1:200.000



- Depositi quaternari
- Sintema VI (Pliocene inf.-medio)
- Sintema V (Messiniano sup.)
- Sintema IV (Tortoniano - Messiniano)
- Sintema III (Langhiano - Serravalliano)
- Sintema II (Burdigaliano sup. - Langhiano *p.p.*)
- Sintema I (Oligocene *p.p.* - Burdigaliano *p.p.*)
- Marne di Monte Piano (Eocene sup.)
- Unità Liguri
- D3 — Discontinuità stratigrafiche
- Faglie affioranti e sepolte o incerte
- Thrust Frontale Padano
- a, b — Pieghe: traccia di superfici assiali (a: anticlinali; b: sinclinali)
- 240 — Isobate (m s.l.m.) della superficie di appoggio dei depositi quaternari

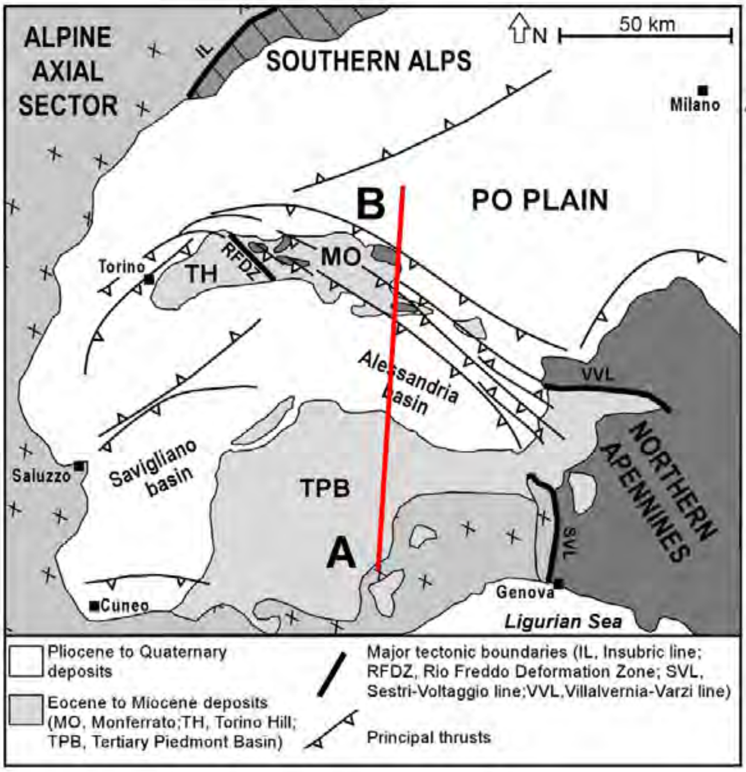


Fig. 1: Geological map of the Pô plain showing the Tertiary Piedmont Basin and associated active structures

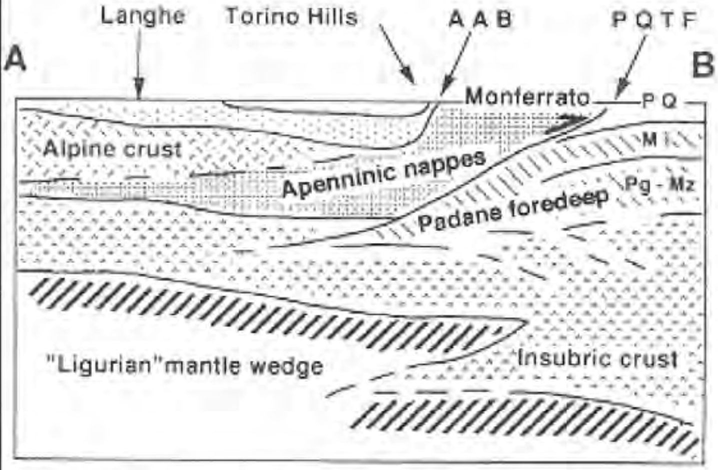


Fig. 2 : N-S Cross-section showing the crustal configuration of the Alps/Apennines junction zone (Piana and Polino 1995). AAB: Alps/Appenines boundary. PQTF : Plio-Quaternary Deformation zone. PQ: Plio-Quaternary deposits, Mi: Miocene, Pg-Mz: Paleogene-upper Mesozoic.

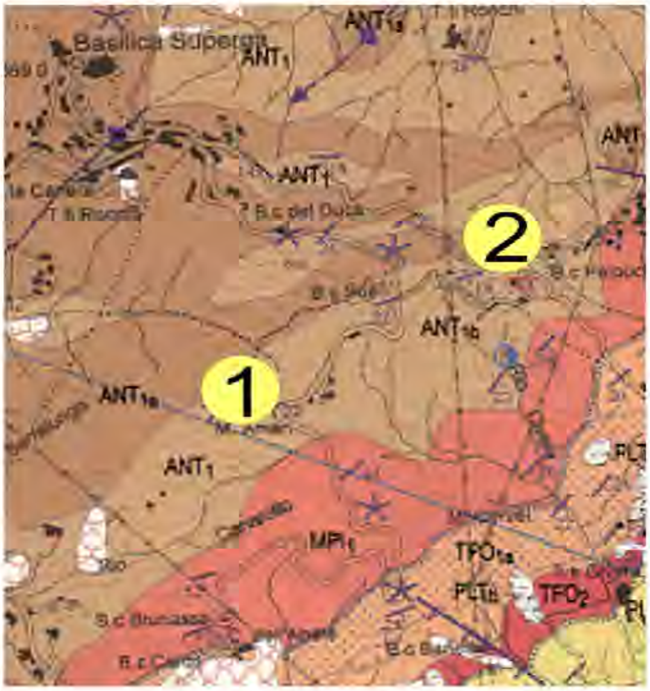


Fig. 3 : Oligo-Miocene deposits - 1 Blueschists derived conglomerates including metric blocs - 2 serpentinite derived congomerates

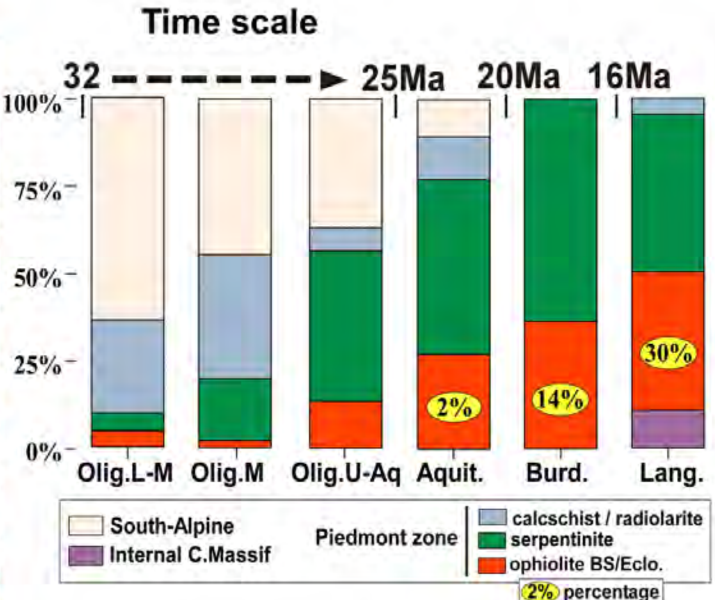
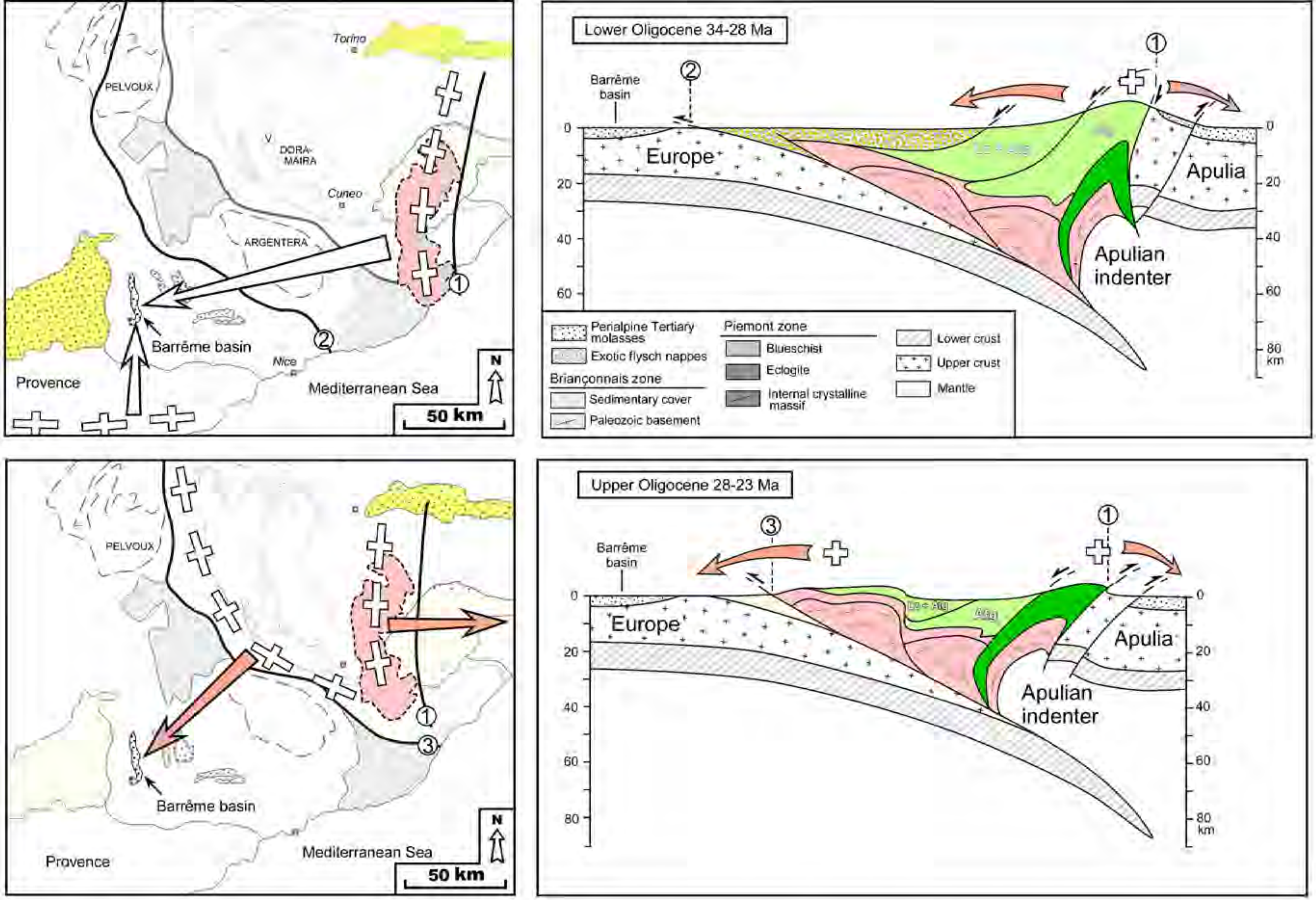
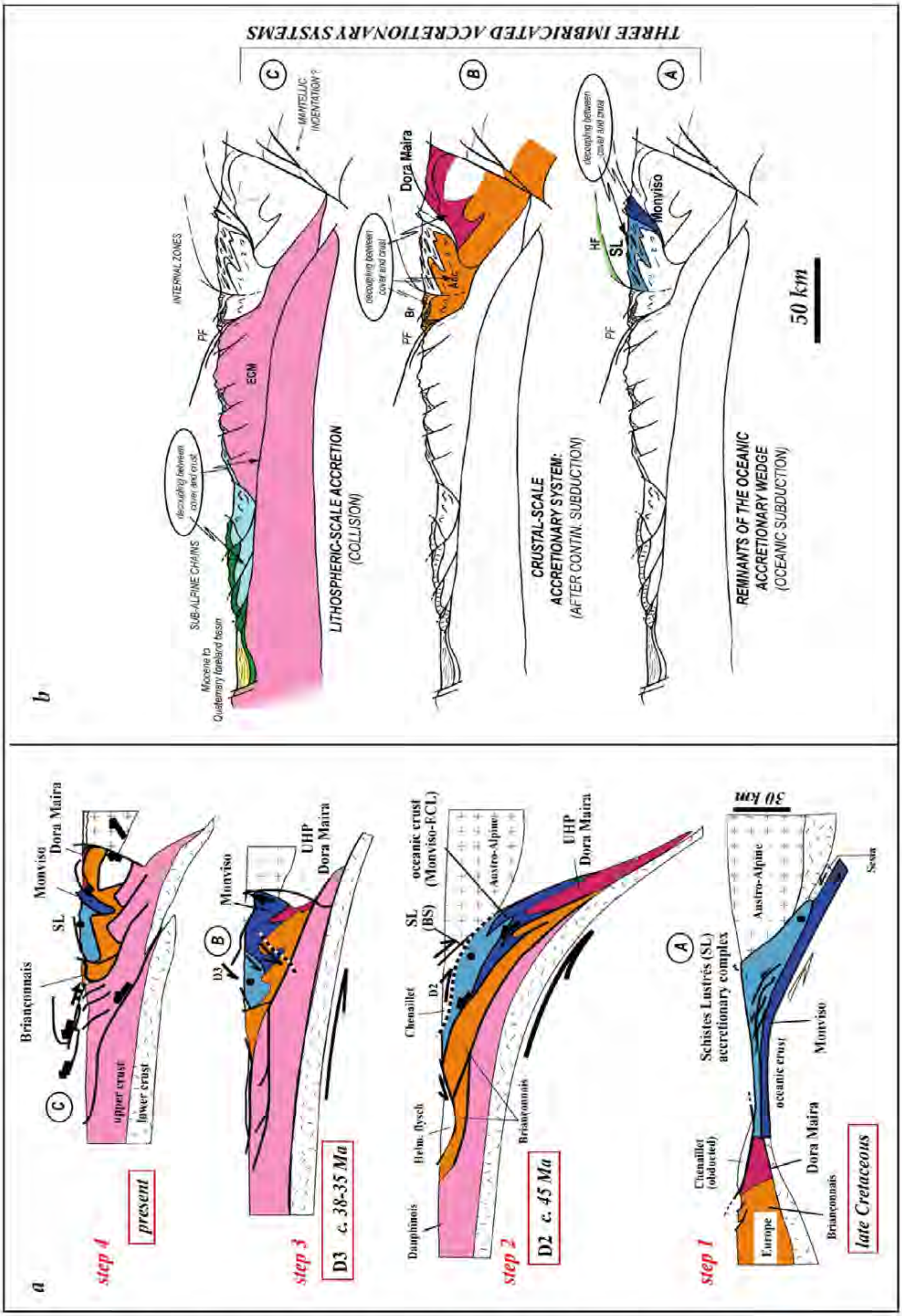


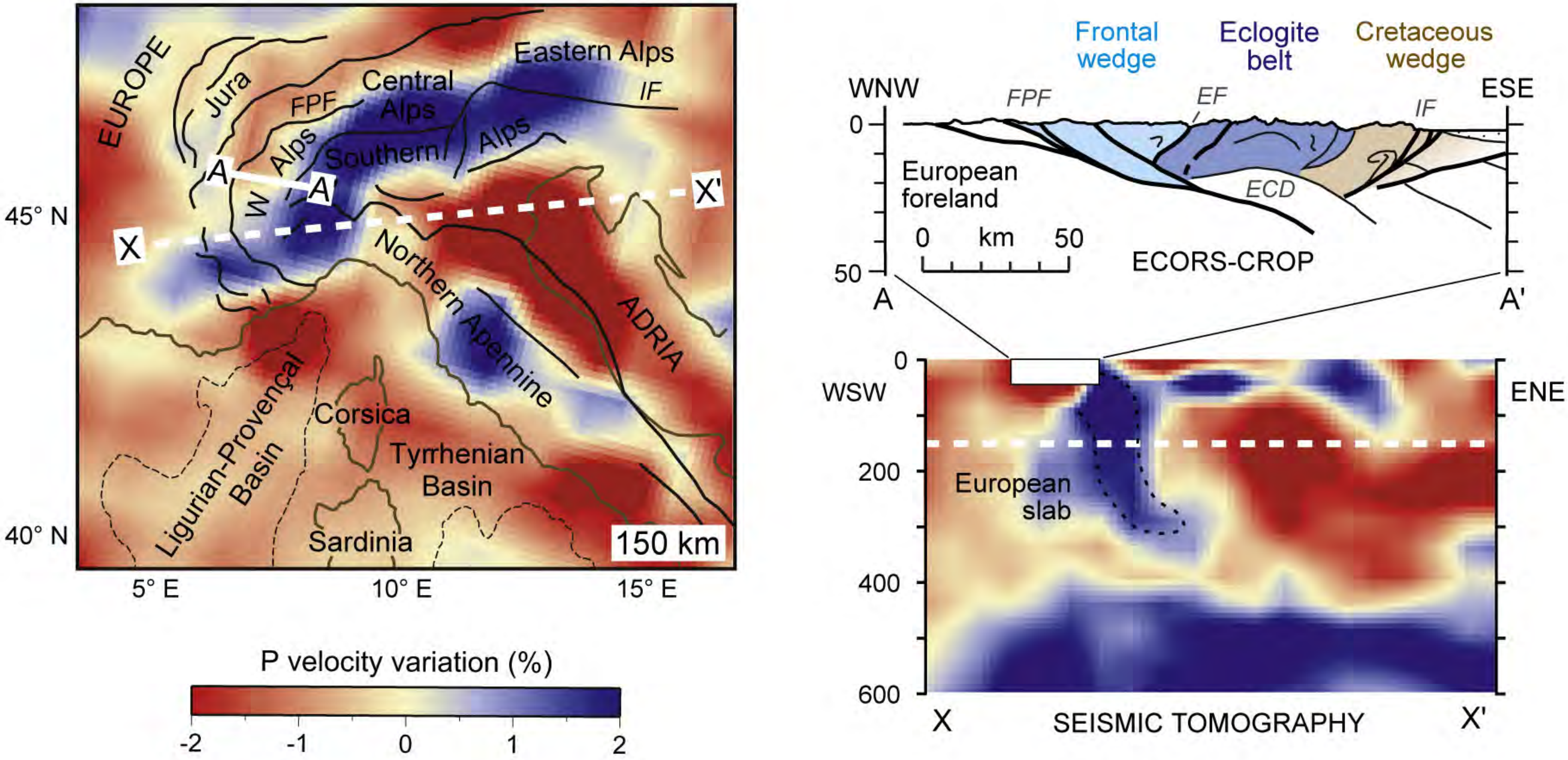
Fig. 4: Evolution of the lithology of the clasts trough time within the Torino Hills sediments. The increasing perecentage of blueschists, then eclogitic derived clasts record the exhumation/erosion of the deepest part of the Internal Alps Zone

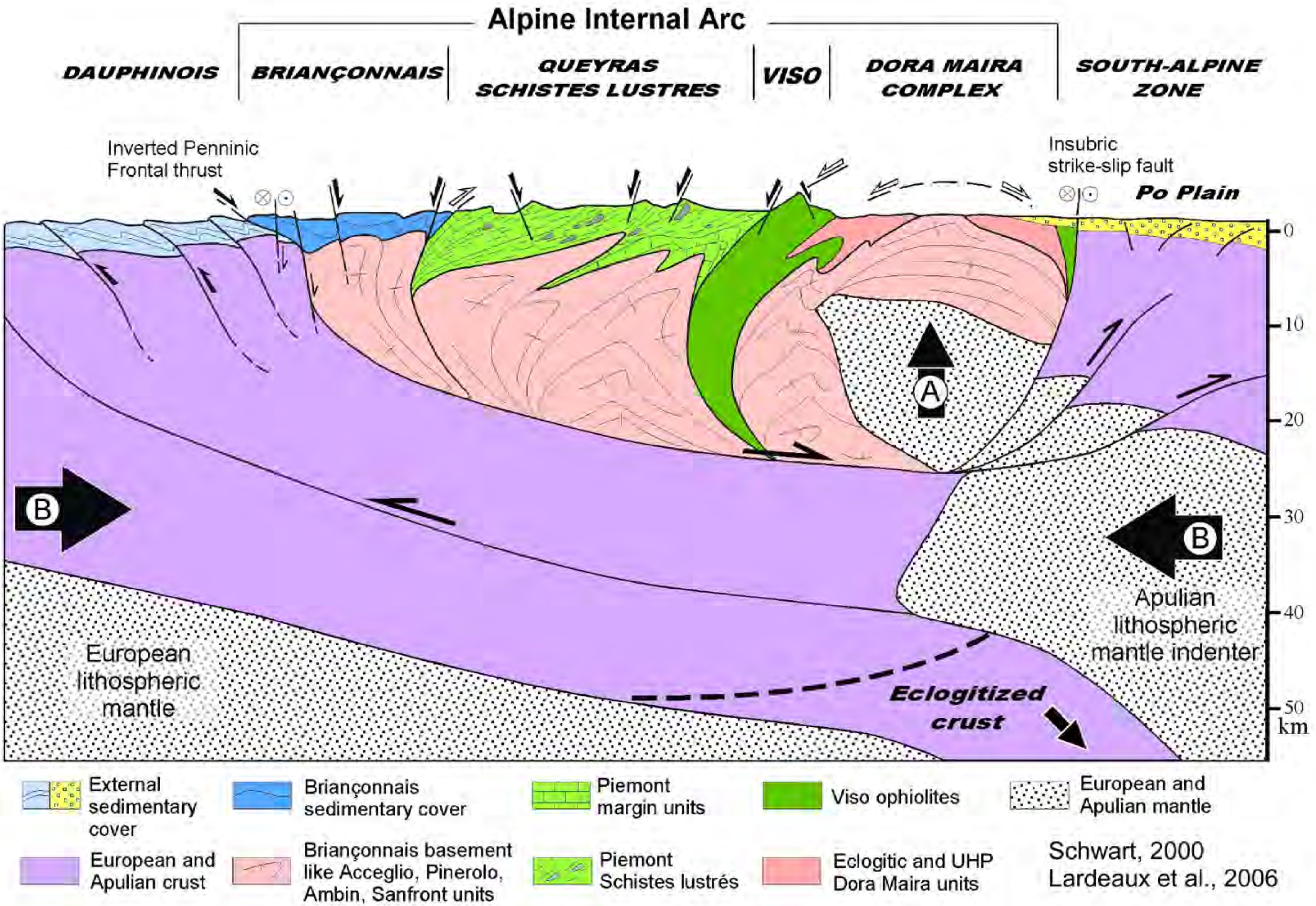


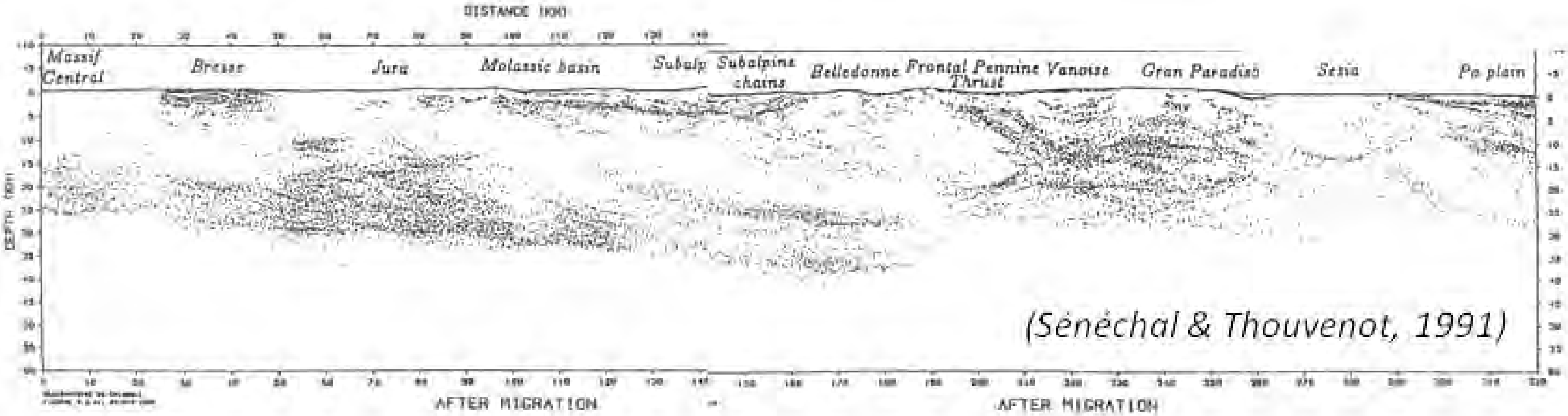
Palinspastic maps and cross sections reconstructions showing the evolution of the relief zones from lower to upper Oligocene. a) during the lower Oligocene, the main relief zone (White cross) were located above the Dora Maira massif and in Provence. These reliefs zones feed the local foreland bassins. b) During the upper Oligocene the activation of the Briançonnais thrust front allows the formation of a westward relief while in the internal zone, the persistence of high reliefs feeds the Torino Hills in eclogitic clasts. (Schwartz et al., Geol Mag. in press)



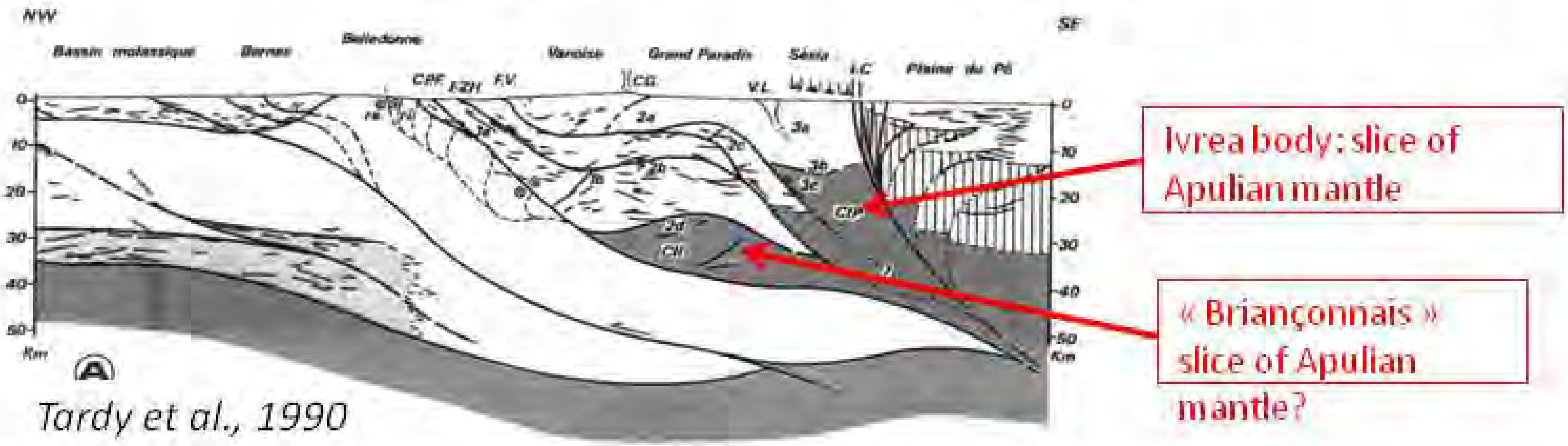
Evolution od the Western Alps (after Agard et al., 2009)


EUROPE
Jura
FPF
W Alps
A
A'
Central Alps
Southern Alps
Eastern Alps
IF
X
X'
Northern Apennine
ADRIA
Ligurian-Provençal Basin
Corsica
Sardinia
Tyrrhenian Basin
150 km
45° N
40° N
5° E
10° E
15° E
P velocity variation (%)
-2
-1
0
1
2
Frontal wedge
Eclogite belt
Cretaceous wedge
WNW
ESE
FPF
EF
IF
ECD
European foreland
0 km 50
ECORS-CROP
0
50
WSW
ENE
European slab
200
400
600
SEISMIC TOMOGRAPHY


Alpine Internal Arc
DAUPHINOIS
BRIANÇONNAIS
QUEYRAS SCHISTES LUSTRES
VISO
DORA MAIRA COMPLEX
SOUTH-ALPINE ZONE
Inverted Penninic Frontal thrust
Insubric strike-slip fault
Po Plain
0
10
20
30
40
50
km
A
B
B
European lithospheric mantle
Apulian lithospheric mantle indenter
Eclogitized crust
External sedimentary cover
Briançonnais sedimentary cover
Piemont margin units
Viso ophiolites
European and Apulian mantle
European and Apulian crust
Briançonnais basement like Acceglio, Pinerolo, Ambin, Sanfront units
Piemont Schistes lustrés
Eclogitic and UHP Dora Maira units
Schwart, 2000
Lardeaux et al., 2006

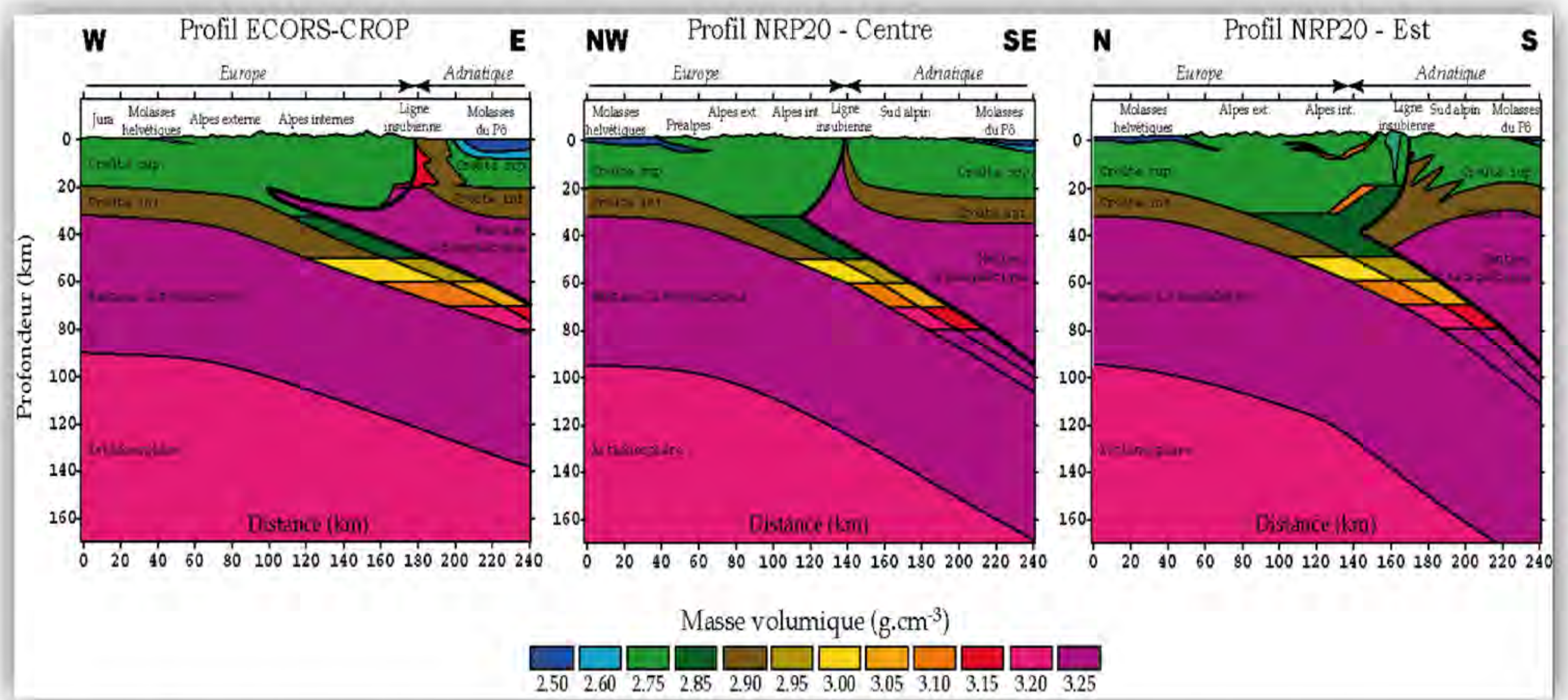


(Sénéchal & Thouvenot, 1991)

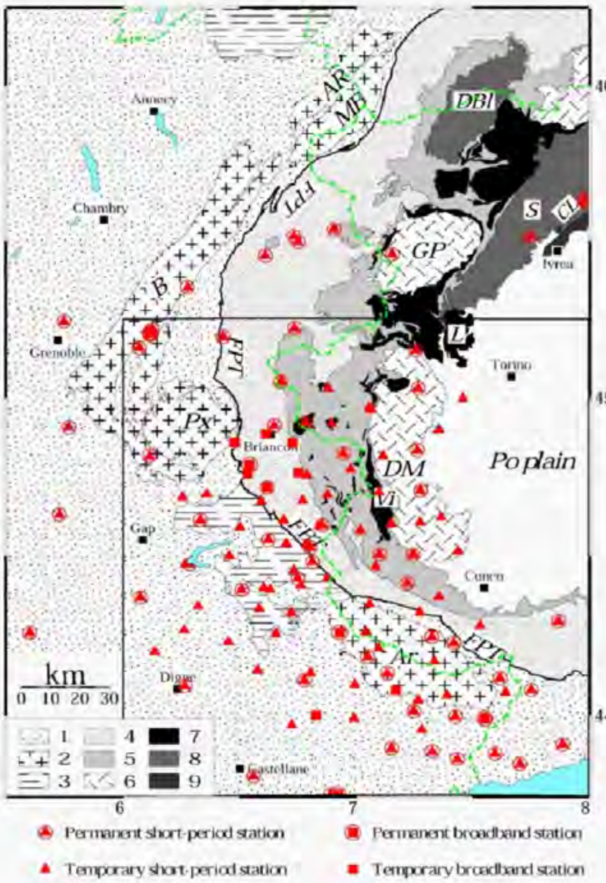


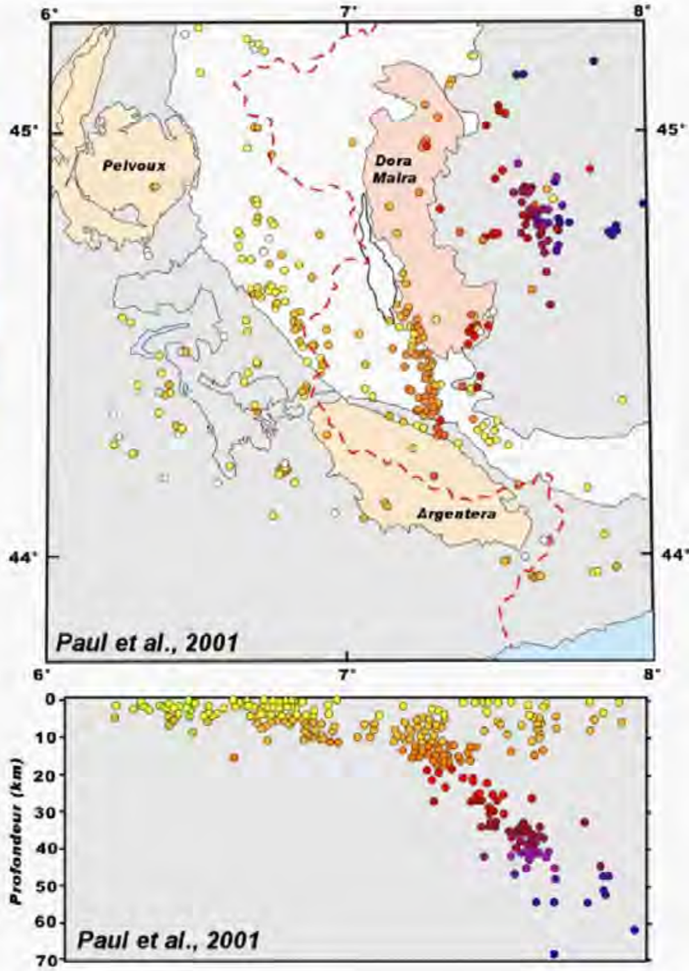
Tardy et al., 1990

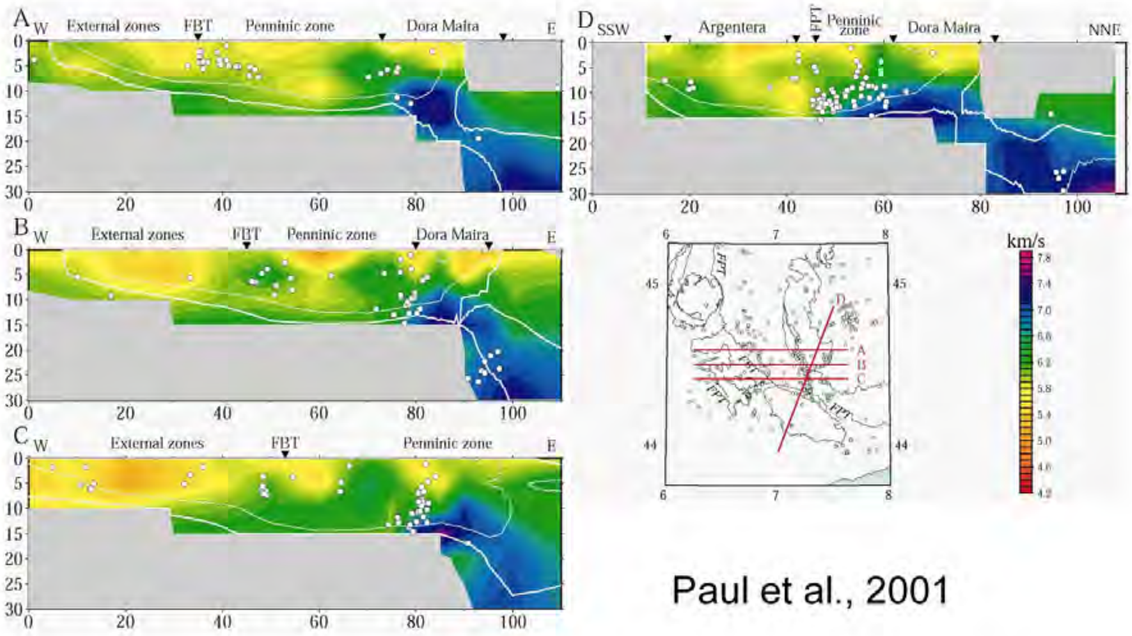
Schmid & Kissling, 2000



Density estimation across the main geophysical profile
notice the dense body at shallow level within the suture zone in the Ecors Crop profile interpreting as partially hydrated ultramafic rocks : the Ivrea body (After Marchant and Schmidt, 1997).





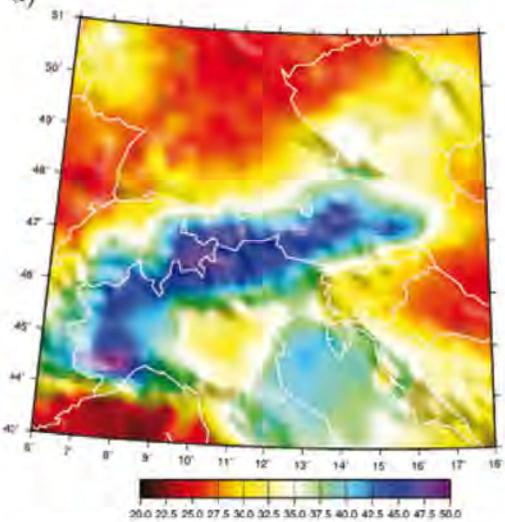


Paul et al., 2001

Local earthquake tomography in the SW Alps

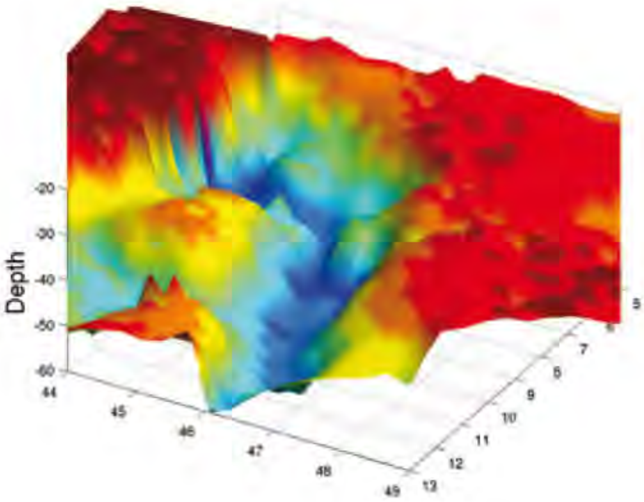
The IVREA BODY

a)

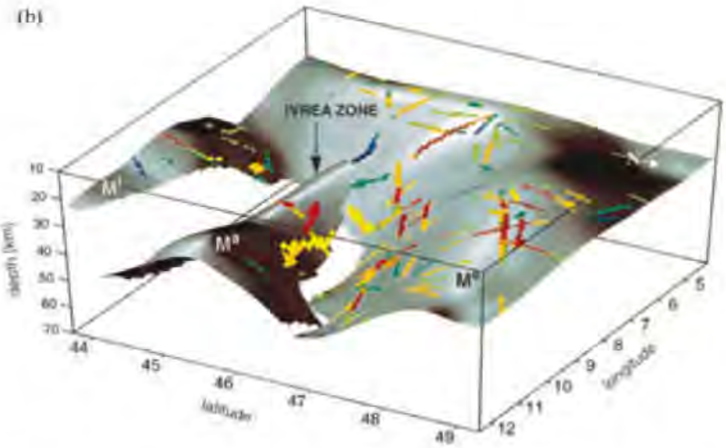


Map of the Moho depth (Stehly et al., 2009)

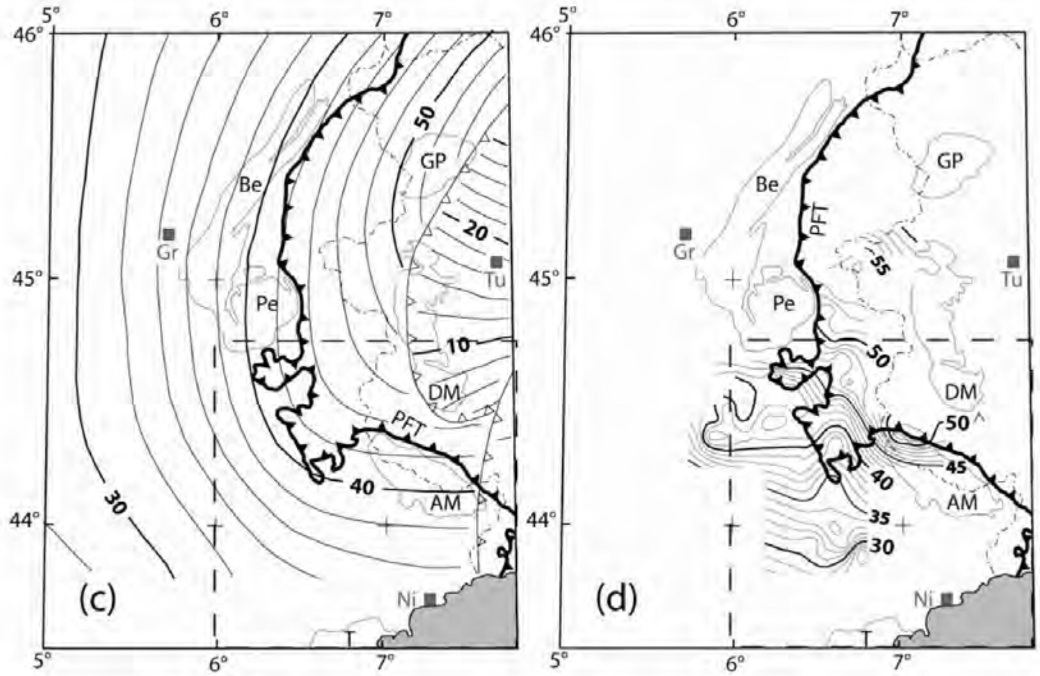
a)



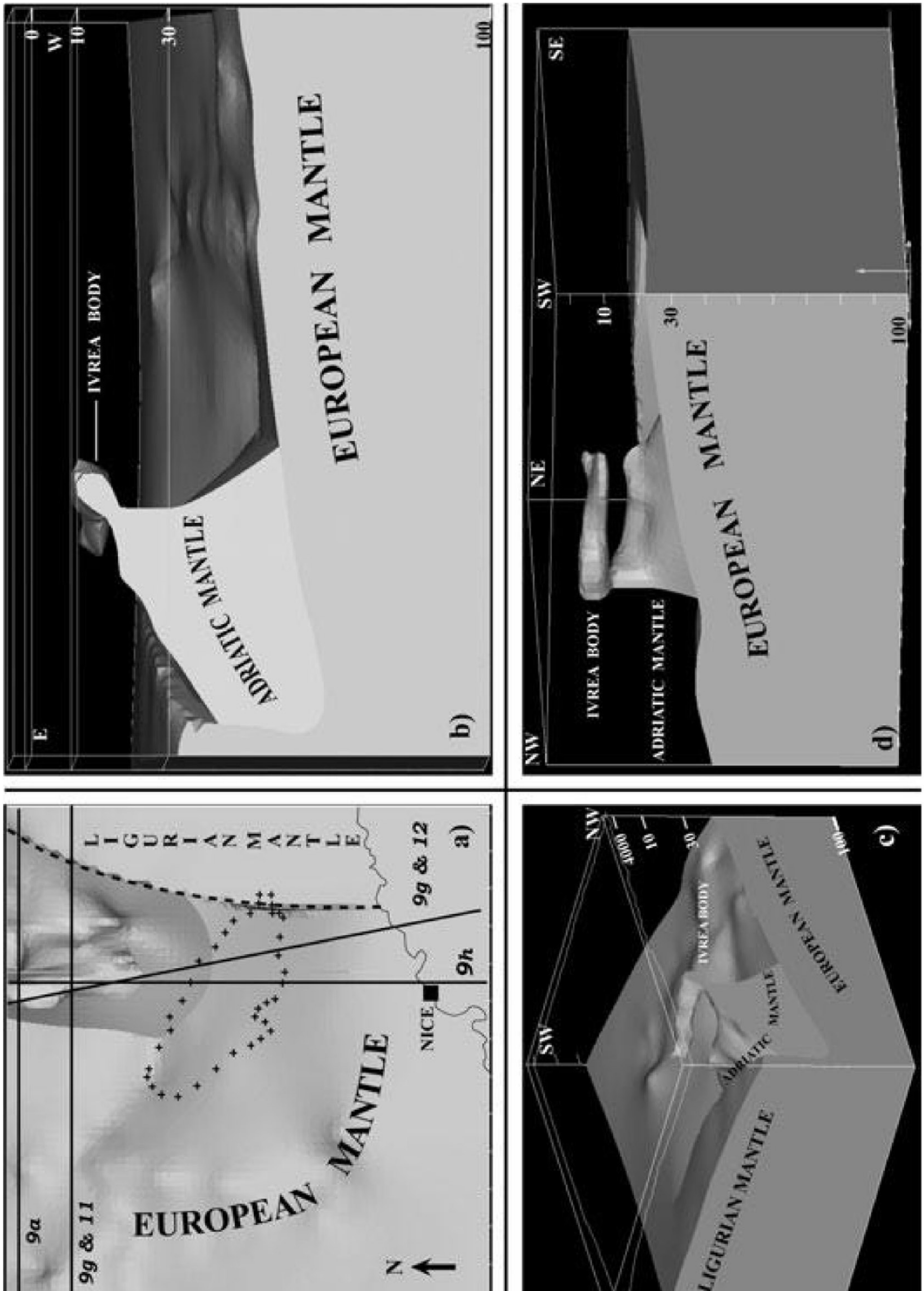
b)



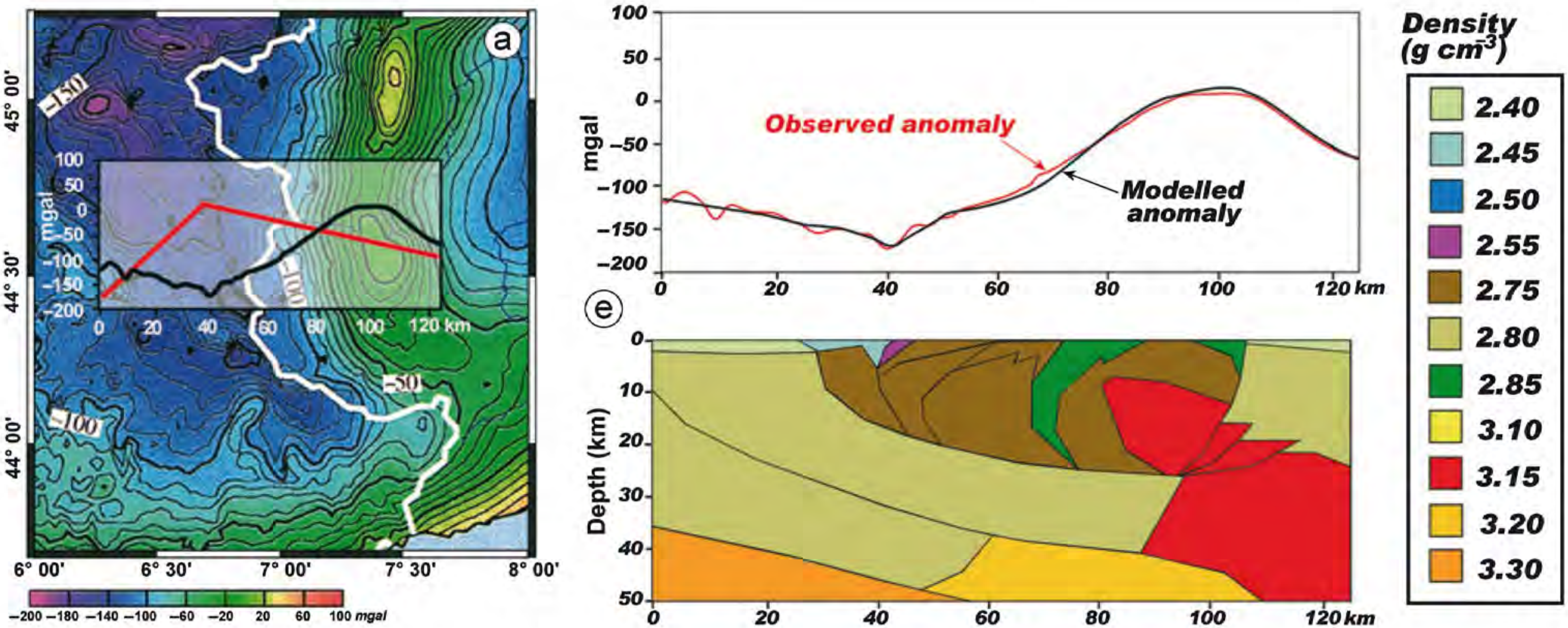
3D view of the Moho depth. a) Stehly et al., 2009,
b) Waldhauser et al., 1998.



Map of the Moho benath the Western alps. C) Whaldauser et al., 1998
d) Thouvenot et al., 2007



3D model of the Ivrea Body (Schreiber et al., 2010)



Models of the gravity effect calculated for the interpretative cross-section. Three models with different rock density values are presented. The model showing the best fit between the observed and the modelled anomaly is presented in the enlarged picture. The studied geotransect (red line) is located on the Bouguer gravity map of Masson *et al.* (1999). The black line represents the gravity profile along the geotransect.