Field Trip post - Pata days 2022

Historical seismicity, active tectonics and gravitational deformations in the south-western Alps (Barcelonette Area, France)

1 – 3 October 2022

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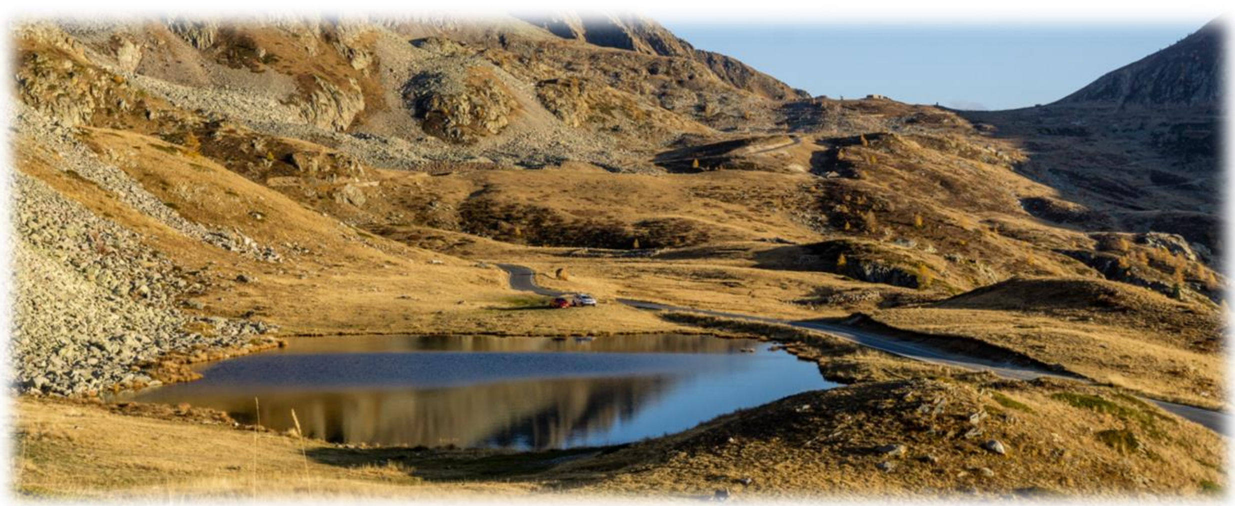

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Overview of the Field Trip

Oct. 1st - Epicentral area of the 1959 Ubaye earthquake, High Durance and Serenne fault systems

Road to Barcelonette, Séolane center.

Oct. 2nd – Gravitational deformation at the North western edge of the Argentera massif, Visit of the Bersezio Fault in the Orgials valley

Restaurant in Vinadio (Italy), overnight in Barcelonette

Oct. 3d Road back to Aix-en-Provence

Important remarks and advices

Each attendee should be adequately equipped for walking. We will have short walks at relatively high elevation (up to 2,900 m above sea level). Even in early October, the sun may hits strong and you should protect your skin and head. Storms are rare at this season but rain showers are frequent; you should have waterproof clothes in you backpack. In any case, please pay attention to the recommendations of the guides who know the visited sites.

Some stops are located along the roads. You must be cautious and respect the highway code.

Lunches will be provided by the organizers (Saturday/Sunday)

All payments will be made on site, please refer to the details sent by email this summer. And….don't forget to bring your own towel at the Séolane center!

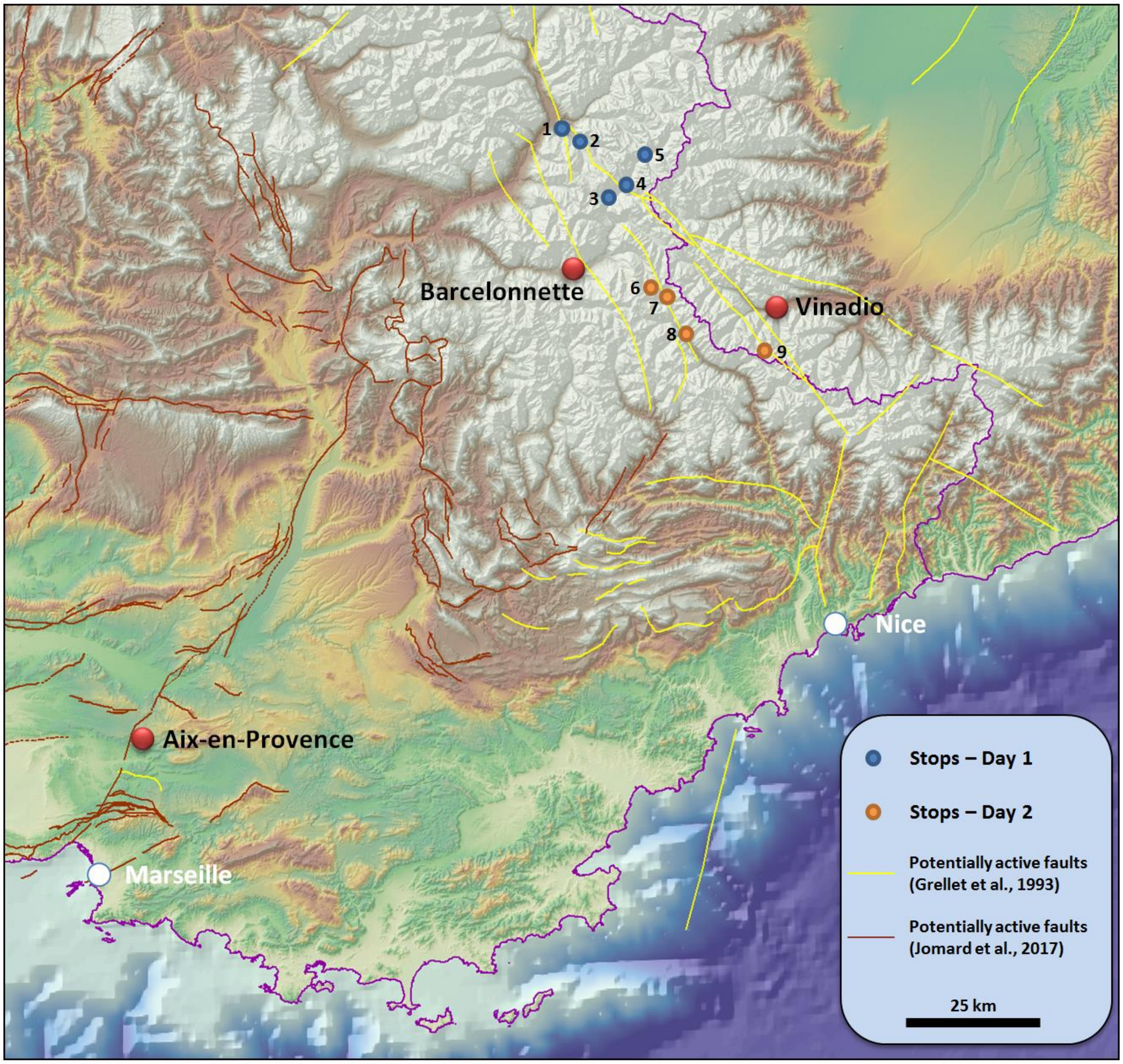

Figure 1 : Planned stops and their approximate locations (see google earth kml file for more details)

Tectonic settings, a summary

The Barcelonette area belongs to the southwestern termination of the Alpine belt, extending from Slovenia/Austria to south-eastern France.

In a few words (e.g. De Granciansky et al., 2010 and references therein), the Alpine belt results from the closure of the Tethys Ocean, bounded by the Eurasian and Adria continents (Fig. 2). In the Western Alps, the oceanic subduction started during Cretaceous times and lasted until early Eocene times, followed by continental collision during the Tertiary Collision gave birth to a crustal scale orogenic acrretionary prism (internal domain), but also to nappes overthrusted onto the paleo-European continental margin (ie. the external domain). Marking the boundary between the internal and external domains along the Western Alpine arc, the Frontal Penninic Thrust (FPT or PF in Fig.2) is the main compressional structure of Oligocene age (Fig. 2, 3, 4).

From Miocene to Pliocene times, the compressive deformation front propagated toward the external domains, giving room for orogen-parallel extension, crosscutting earlier compressional structures of the internal domain, and ultimately leading to the extensional reactivation of the FPT (Sue and Tricart, 2003). Persistence of tectonic activity during the Quaternary is less obvious to characterize, so that the origin of the ongoing seismotectonic activity is interpreted by some authors as being associated with far field tectonics, and by others as associated with other internal (buoyancy forces) or external (GIA, erosion…) deformation processes.

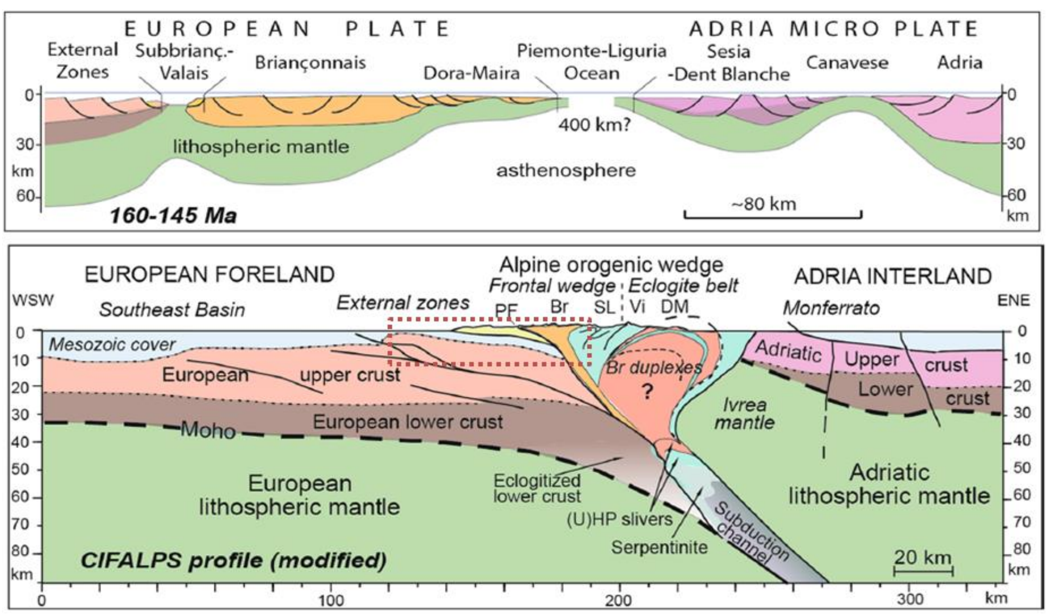

Figure 2 : Simplified cross sections across the South Western Alps. On top: before convergence. Below: actual geometry along the CIFALPS project. (Modified after Michard et al., 2022). Location of the Ubaye valley is marked by a red rectangle.

During the field trip, we will drive through the external domain toward more internal zones where Alpine deformations are more intense. The Ubaye valley of Barcelonette lies at the boundary between external and internal domains. The city of Barcelonette is located in an erosional window opened into the internal nappes of Flyschs, overthrusted over the sedimentary cover of the European basement. While driving to the upper Ubaye valley, we will cross the FPT and access to internal zones (Fig. 3 and 4). Major faults affecting the area are the High Durance (D), the Serenne-Bersezio (S) and the Jausiers-Tinée (JT) fault systems (Fig. 3).

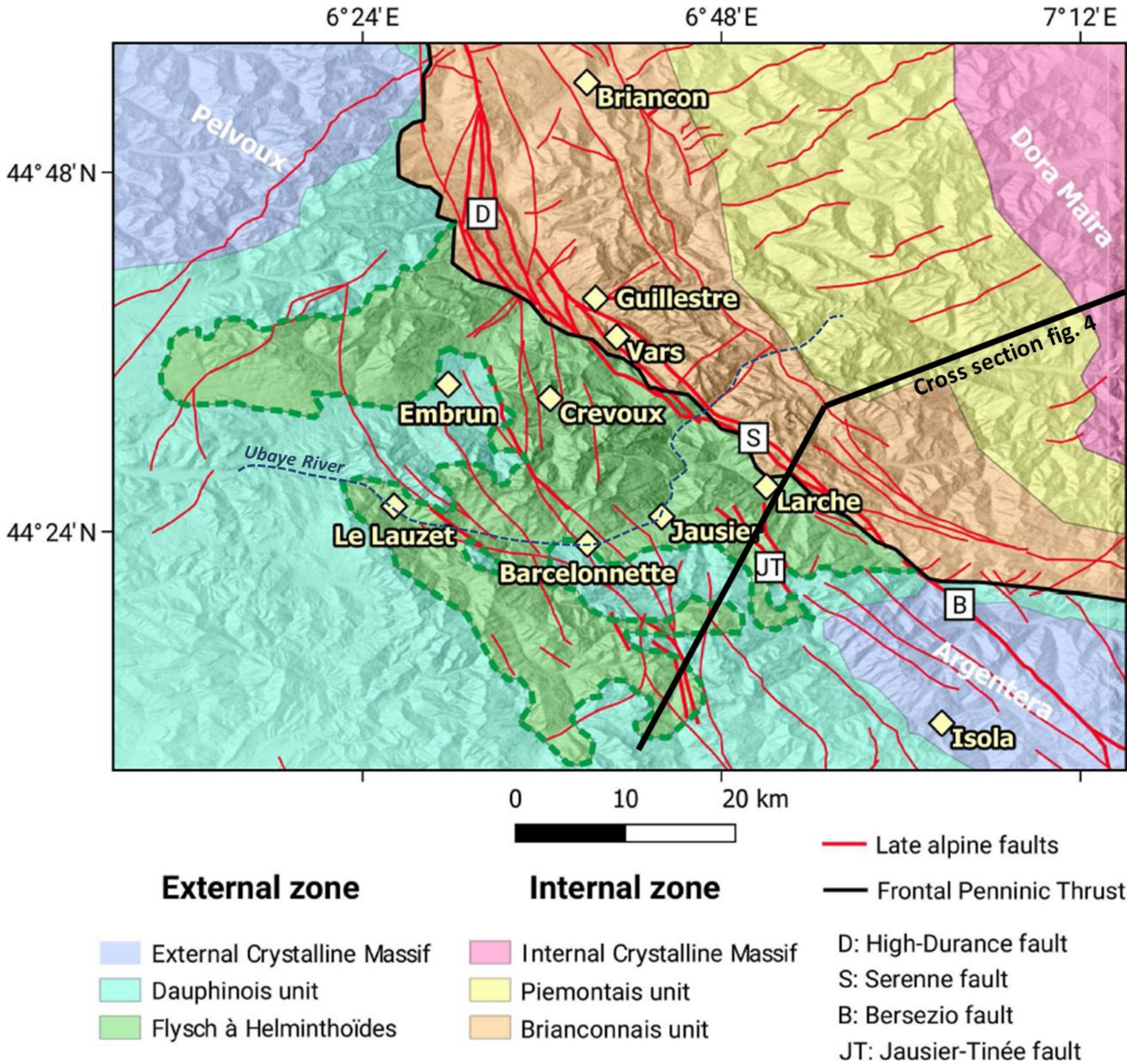

Figure 3 : Simplified geological map of the Ubaye valley area, with location of cross section reported in fig.4. (Adapted from Baques et al., 2021)

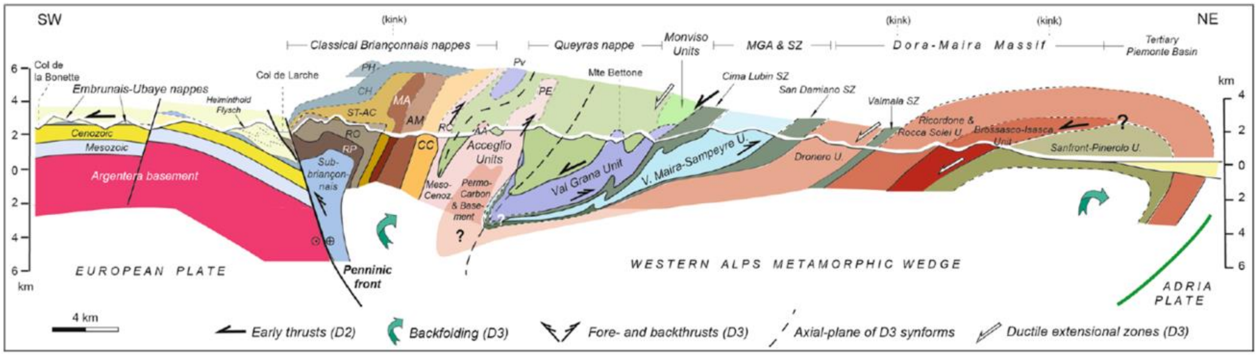

Figure 4 : cross section of the upper Ubaye valley area (Michard et al., 2022).

The Ubaye/high Durance area is the most seismically active in the Western Alps. It has been regularly struck by classical mainshock-afterchock sequences, but also by many earthquake swarms (Bacques et al., 2021 and Larroque et al., 2021 for synthesis, Fig. 5 and supp. mat.).

Historical seismicity (see www.sisfrance.net, Jomard et al., 2021) in this region is rather poorly known in comparison with other regions in France, mainly due to the rural character of the area prior to the XIXth century. For instance, the oldest known event reported in the Ubaye valley dates back to 1844. The main historical events, with epicentral intensities over VII (MSK-64 scale), are those that occurred in 1935, 1938 and 1959 (estimated magnitudes between 5 and 5,5, Manchuel et al., 2018).

The instrumental seismicity (1962 -> 2020) shows different behavior: (1) very low levels of seismicity are recorded in the basement (Argentera and Ecrins massifs), (2) swarms located on well delimited faults are registered in the lower Ubaye valley (external domain), (3) relatively high levels of diffuse seismicity are recorded in the more internal domains.

Finally, focal mechanisms are compatible with a local extensive tectonic regime, with a slight right lateral component (Bacques et al., 2021, Mathey et al., 2021).

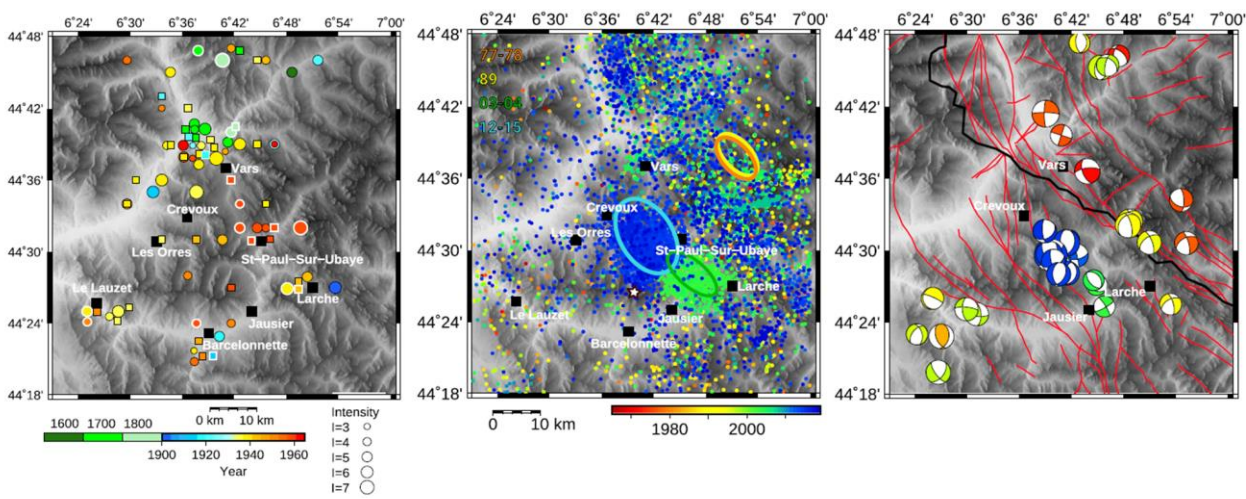

Figure 5: historical seimicity (left), instrumental seismicity with locations of seismic swarms within circles (middle), focal mechanisms (right), from Baques et al., 2021

Although the Ubaye/High-Durance area is one of the most seismically active in the French Alps, active faults are in detail relatively poorly known and characterized. This is mainly due to the difficulty of mapping the structures, the difficulty of associating seismicity to particular structures, but also to find geological evidence of recent deformation.

The only large-scale mapping of potentially active faults dates back from 1993 (Fig. 1, Grellet et al., 1993). The structures highlighted at that time were chosen based on a geometric criteria (orientation of faults) with respect to a stress field considered to be oriented North-South, and without taking into account geological argument.

More recently, work focused on more specific areas allowed to establish the activity of the three main fault systems: the High Durance and Serenne-Bersezio faults (based on geological criteria and seismic activity), and the fault of Jausiers/Tinée (based on seismic activity and questionable field evidences). Two main models co-exist today to describe the geometry and activity of these late Alpine faults (Fig. 6). It is however generally accepted that these faults developed during a Miocene extensional tectonic regime, which evolved toward a right lateral transpressional regime during the Pliocene (e.g. Tricart, 2004). The current kinematics of these faults is however discussed, from pure extension to right lateral deformations. Focal mechanisms computed in the area (Baques et al., 2021, Fig. 5) present both normal and strike-slip components.

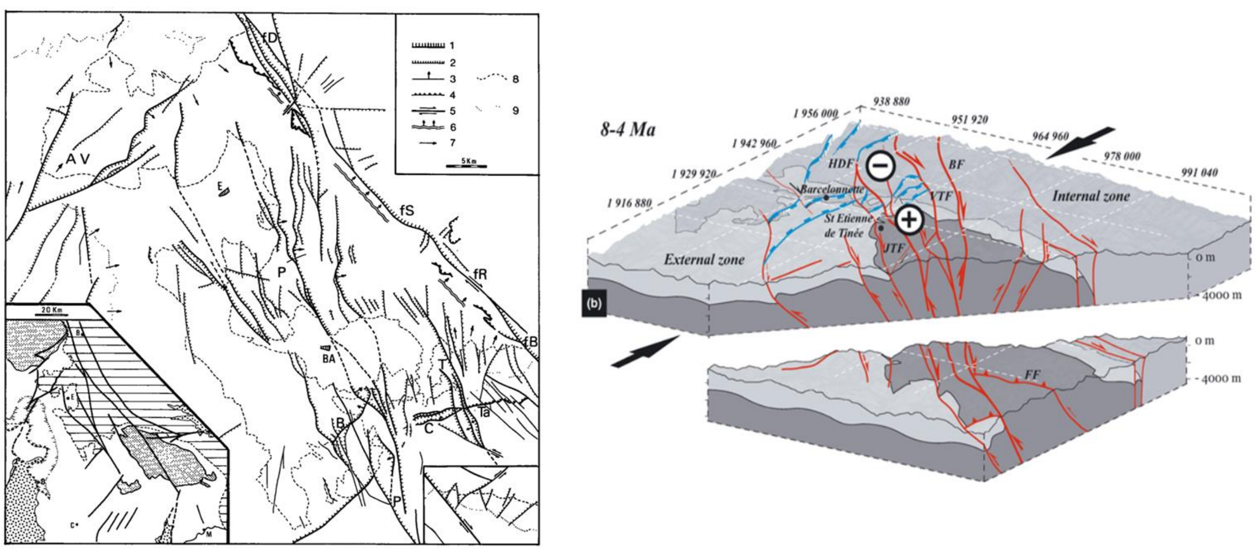

Figure 6: Geometry of the late alpine fault systems as proposed by Kerckhove (1969) and Sanchez et al., (2011)

List of stops

1st of October

Start from Aix en Provence city (9h – 9h30), and road to the Guillestre area (2h)

- **Stop 1** : quick stop at the “plan de phazy” hot spring, located along the Higher Durance fault system (15-20mn)
- **Stop 2 :** Panoramic view of the high Durance valley and active faults on the road to Vars (30mn)
- Lunch near the Col de Vars Pass, depending on the weather conditions (1h)
- **Stop 3 and 3’:** visit of the Saint-Paul sur Ubaye city and the Grande Serenne hamlet, where many evidences of the 1959 earthquake are preserved (1h – 1h30)
- **Stop 4** : visit of the Pont-du-Châtelet (bridge) area, located along the Serenne active fault system and the Peninic front (1h30)
- **Stop 5** : depending on the timing, optional walk toward two major valley-blocking landslides, potentially triggered by earthquakes (1h30 – 2h walk)

Overnight in Barcelonette, in the Séolane center

2nd of October

Departure from Séolane at 9h

- **Stop 6 :** Road to the La Bonnette-Restefond pass and short walk (5mn) to the Bonette peak (2860m). Panoramic of the overall area, encompassing internal and external alpine domains. (1h)
- **Stop 7 :** Walk from the “camp des fourches” to the Mt des Fourches (2342m). View on the northwestern edge of the Argentera crystalline massif, faults and active large scale gravitational deformations. Lunch on site 7 depending on the weather conditions. (2h)
- **Stop 8 :** Village of St Etienne de Tinée, in front of the La Clapière landslide, one of the biggest active deep seated landslide in the Alps. (30mn)
- **Stop 9 :** Walk along the Bersezio fault at the Lombarde pass (2350m, boarder between France and Italy). View on active faulting morphologies affecting glacial and post-glacial deposits (3h)

Dinner in the Italian village of Vinadio (Hotel Ligure)

Overnight in Barcelonette and return to Aix en Provence the 3rd of October early in the afternoon.

Saturday October 1st

1. Plan de Phazy hot springs (short stop – 15-20mn)

The three hot springs (26-28°C all the year) are known at least since the Roman period, located alongside the Via Domitia build 200 B.C. The therapeutic virtues of the springs have been exploited since the 17th century. Today it feeds mainly agricultural greenhouses.

The water infiltrates through the neigbooring slopes, reaching a depth estimated around 1km, and then reaches the surface, drained along the Upper Durance active fault system. The water is enriched in iron oxides, chlorides and sulfates given the presence of Triassic evaporitic deposits.

The Rotunda was built in 1824 for thermal purposes where the hot springs flowed. In 1935 (March 19th), following an earthquake of epicentral Intensity Io = VII, the source stopped a while and reappeared finally several meters outside the building.

Today it gushes out of a pink marble rock from a quarry close to Guillestre, erected in front of the Rotunda, and flows into 4 pools built in the 1980s.

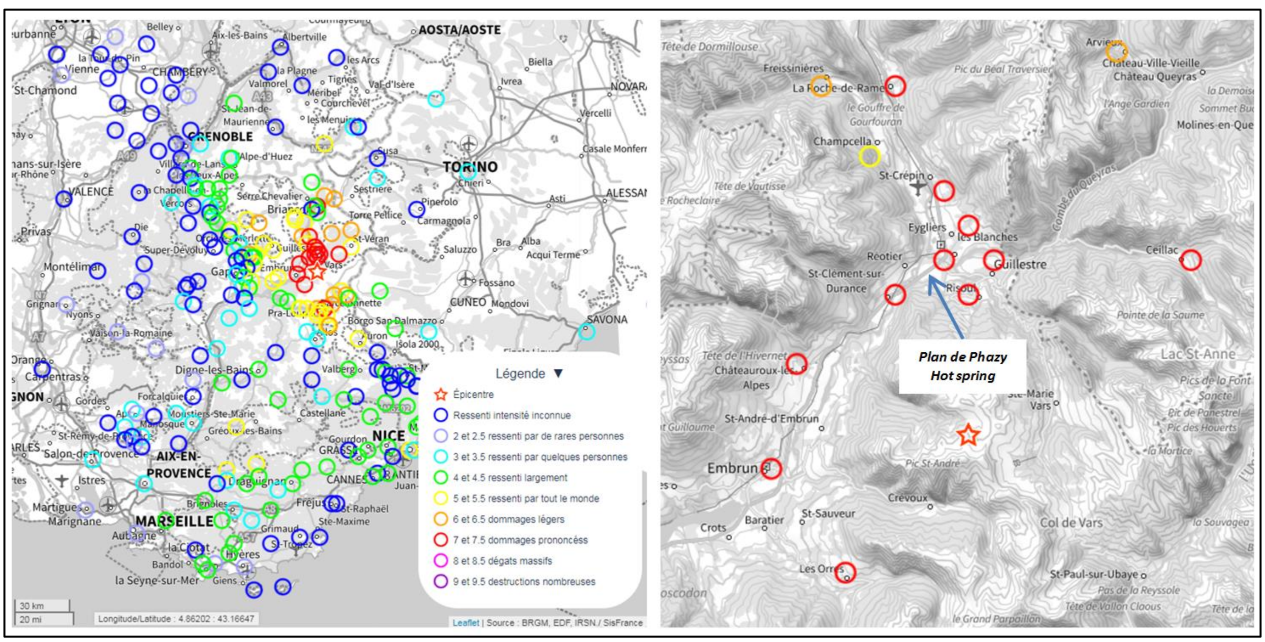

Figure 7 : Macroseismic field related to the 1935 earthquake of "St Clément" (source www.sisfrance.net)

2. Panoramic view on the High Durance valley (30mn)

We will stop at the orientation table of Peyre Haute, on the road to the 'Col de Vars' pass (44.6434°N, 6.6605°E). Here, we'll have a panoramic view from the Ecrins-Pelvoux basement massif to the West, the high Durance fault system (in the center), toward the Briançonnais area to the East.

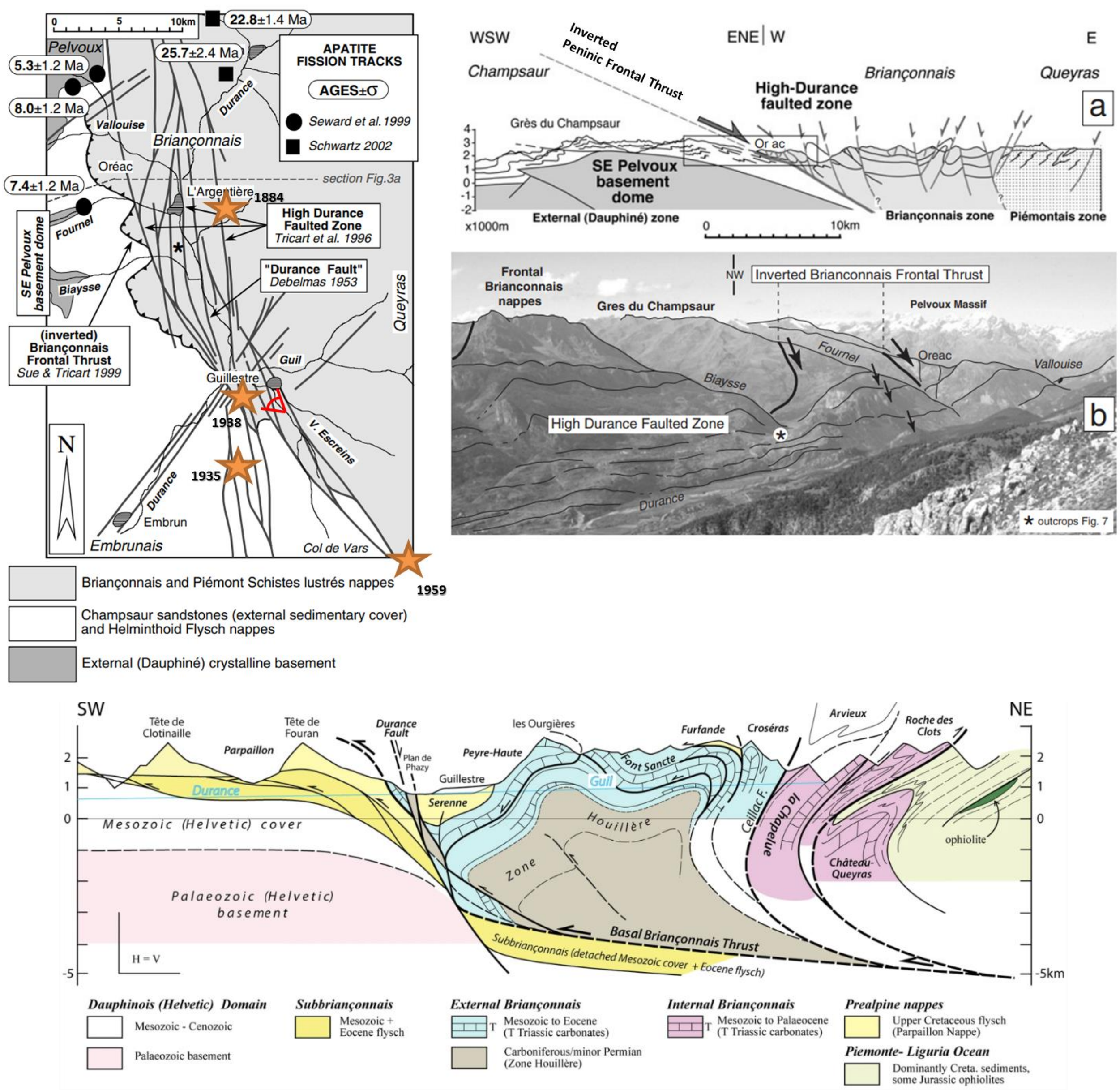

Figure 8: The High Durance fault system in map and cross section. The estimated epicentral location and the date of historical earthquakes with Io>=7 are reported, as well as the location of the Peyre Haute viewpoint in red (adapted from Tricart, 2004 and Ballèvre et al., 2020)

Given 20 years of GPS data (campaign and permanent datasets), Mathey et al. (2020) were able to derive a GPS velocity field for the High Durance / Briançonnais area, and to model a synthetic slip rate for the High Durance fault system, around 2mm/yr (Fig. 9). However, the authors state that such a slip rate corresponds to ~1 Mw 4 event each year. Such an earthquake rate is higher than observed, but could potentially be explained by aseismic deformation in the area.

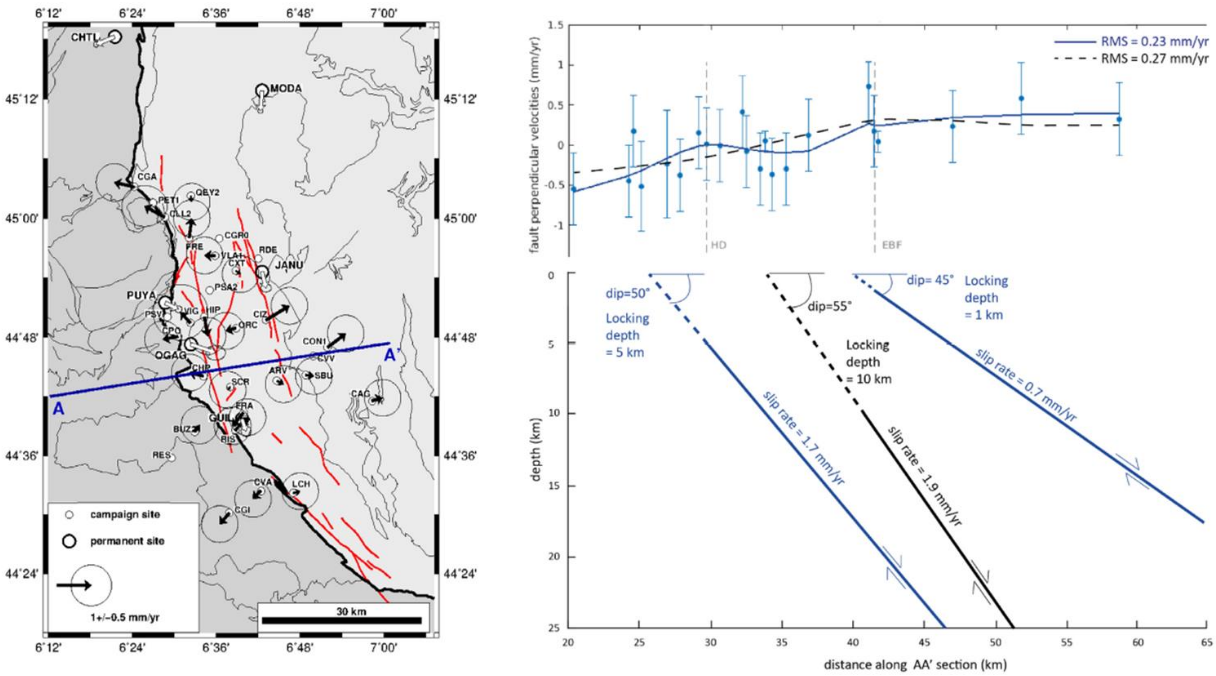

Figure 9 : GPS data (velocity field with respect to Eurasia) and best fitting fault models corresponding to the observed velocities model (Mathey et al., 2020)

3. Epicentral area of the 1959 earthquake, Saint-Paul-sur-Ubaye and La Grande Sérenne (1h – 1h30')

Because this region of the Alps has long been a rural area with few military issues, our knowledge concerning the historical seismicity is limited. Therefore, if St-Paul-sur-Ubaye suffered many earthquakes during the last two centuries, few of them have caused significant damage.

Among them, earthquakes having generated intensities higher than VI are the events of 1938 (I = VI-VII) and 1959 (I= VII-VIII), and probably that of 1935, even if the information is not available (Fig. 10).

More recently the Barcelonnette earthquakes of 2012 and 2014 have generated some slight damage with intensities between V and VI to the municipality.

The 5th of April 1959, around noon, the upper Ubaye Valley was struck by an earthquake of magnitude Mw = 5.1 ± 0.2 (Manchuel et al, 2018), felt in the major part of southeastern France. This earthquake is among the strongest recorded in the French Alps for 100 years. The epicentral area of the earthquake is thought to be close to the city of St Paul, which suffered strong damages. It happened just after the Sunday mass, which contributed to the fact that the event did not cause any fatalities.

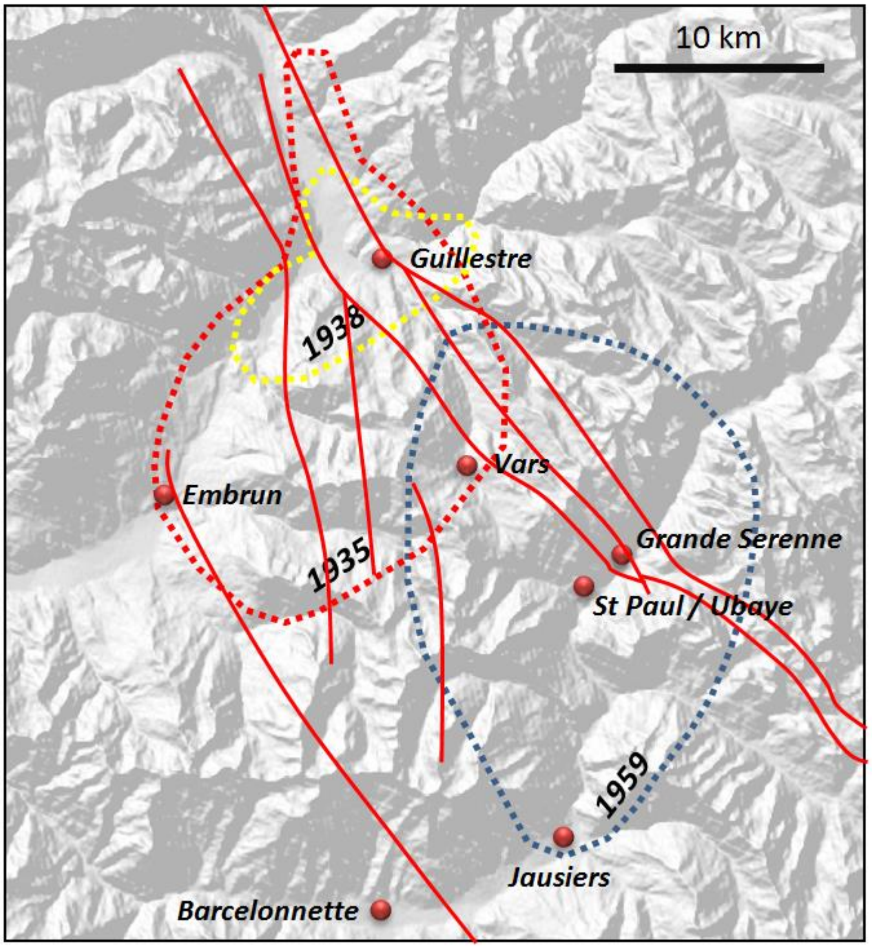

Figure 10 : Isoseismal lines of macroseismic intensity >= VII and simplified traces of faults (from Kerckhove, 1959)

In St-Paul, 227 houses over 250 were damaged, 60 of them being declared uninhabitable. Vaults of the church and school partly collapsed. The earthquake also triggered environmental effects (landslides and rockfalls, a seiche effect within a lake near the Col de Vars). Various ground cracks were also observed in some places, most probably linked to gravitational effects.

In La Grande Serenne, damages were even more important, in particular because the vulnerability of the buildings of this small hamlet was higher.

Reinforcement and renovation works took several years and are still visible today, as well as some effects on the building, which we will be able to look for while walking in the village.

Figure 11 : Pictures after the 1959 earthquake in St Paul and Grande Serenne (pictures from www.azurseisme.com)

Figure 12 : La grande Serenne as seen today

4. The Serenne fault at “pont du châtelet” (1h30’)

The bridge was built by the end of the 19th century to create a road toward the hamlet of Fouillouse. It overhangs the Ubaye River by about 110 m, in a narrow passage incised in the Jurassic limestone.

Figure 13 : The bridge, damaged after the 1959 earthquake (www.azurseisme.com)

The incision is thought to be subglacial in origin but had never been dated or quantified. The top of the Jurassic limestones however highlight typical glacial landforms such as stoss and lees.

The Jurassic slice that closes the valley (Fig 14) marks the passage of a segment of the Serenne Fault system, which continues in the landscape on both sides of the valley. While the long-term activity of the fault is well marked in the morphology, evidence of Holocene activity is not readily apparent.

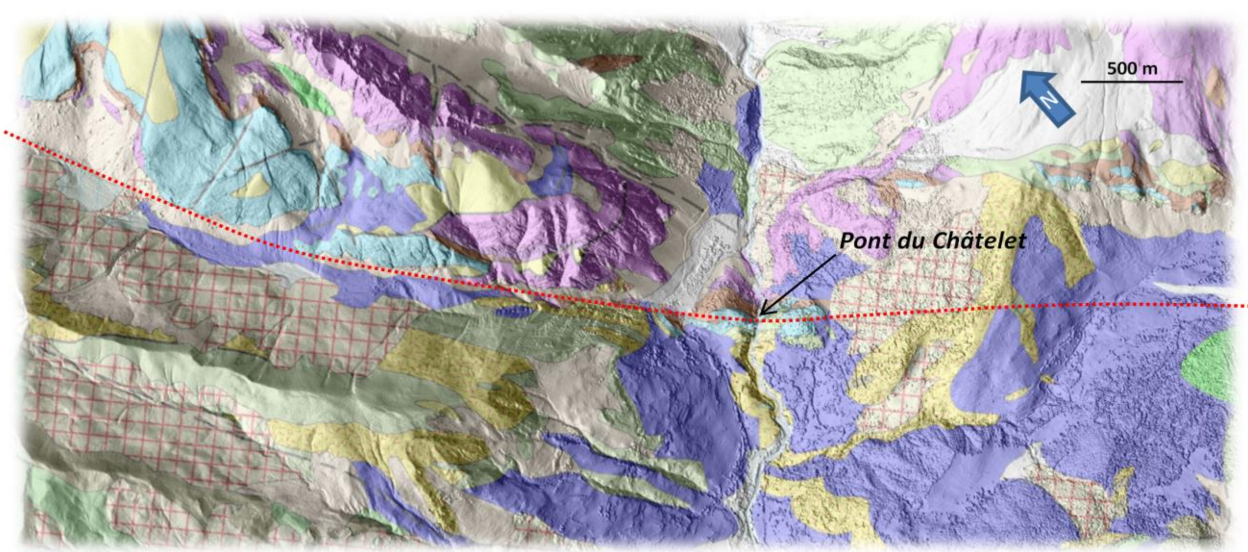

Figure 14 : Geological map (BRGM) draped onto a photogrammetric DEM

Instrumental seismicity in the vicinity of the Serenne fault appears mostly diffuse (Bacques et al., 2021, Fig. 5), with focal mechanisms showing a major normal tectonic regime with a slight dextral motion. Nodal planes are compatible with the orientation of the faults (Fig. 15, Sue et al., 2007).

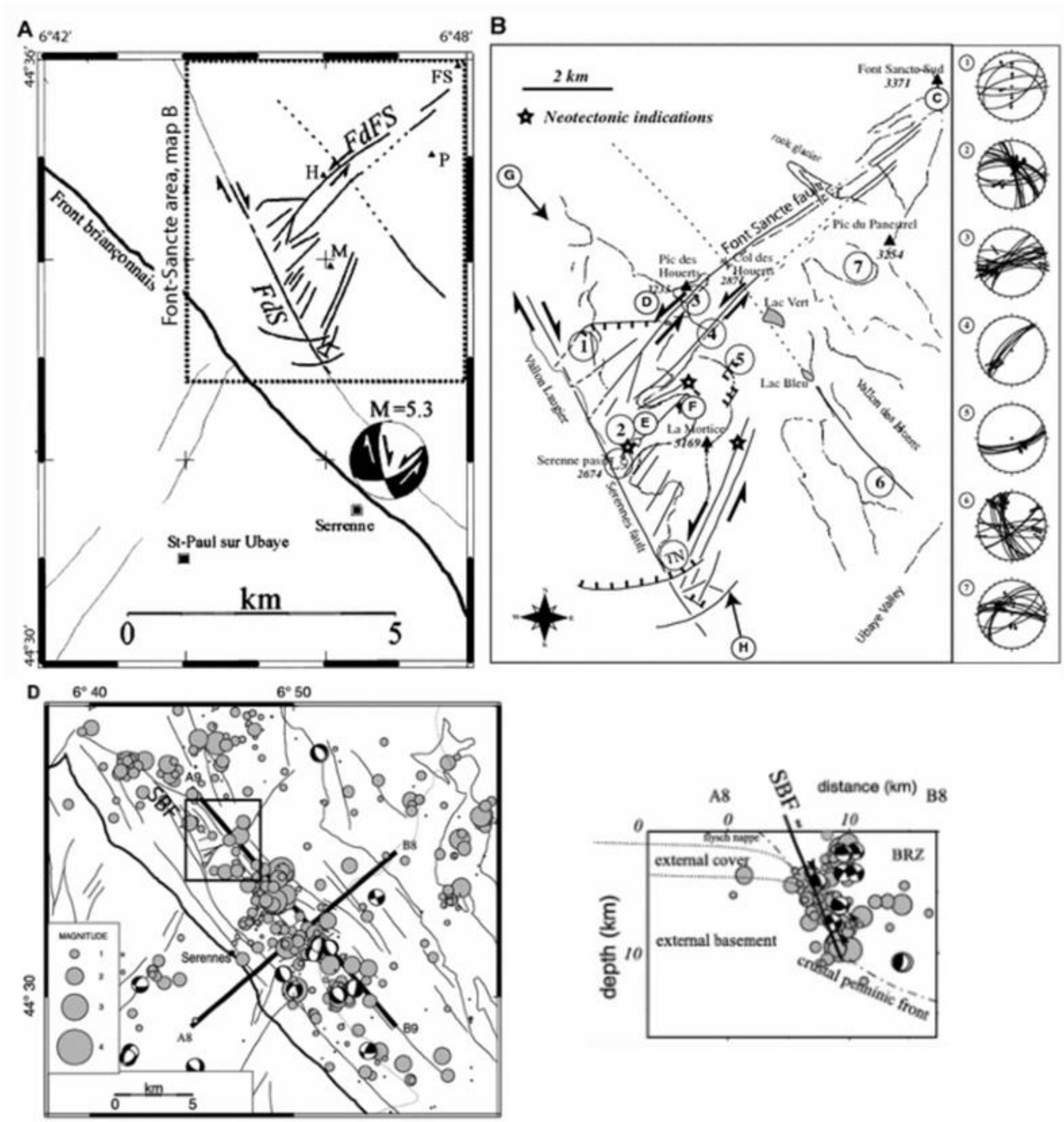

Figure 15 : The Serenne fault system mapped on the slope located on the right bank of the bridge. Instrumental seismicity from Sismalp data (Sue et al., 2007)

5. Valley blocking rockslides at ‘plan de Paroirt’ (2h)

Two major valley-blocking rockslides are present few kilometers north-east of the Serenne fault. These rockslides formed a lake called “Paroirt Lake” (or Prarouard), which dried up in the mid 40's, giving birth to the ‘plan de Paroirt’.

The age of these rockslides is unknown. However, their very fresh morphology and the rapid drying of the lake lead us to think that they are relatively recent, and possibly synchronous. This is coherent with regional knowledge which supposes their occurrence during the middle Ages.

These landslides are probably the result of the long-term post-glacial evolution of the slope, which is supported by the presence of gravitational morphostructures expressed outside the landslide areas. However, the triggering of such rockslides could be seismic in origin.

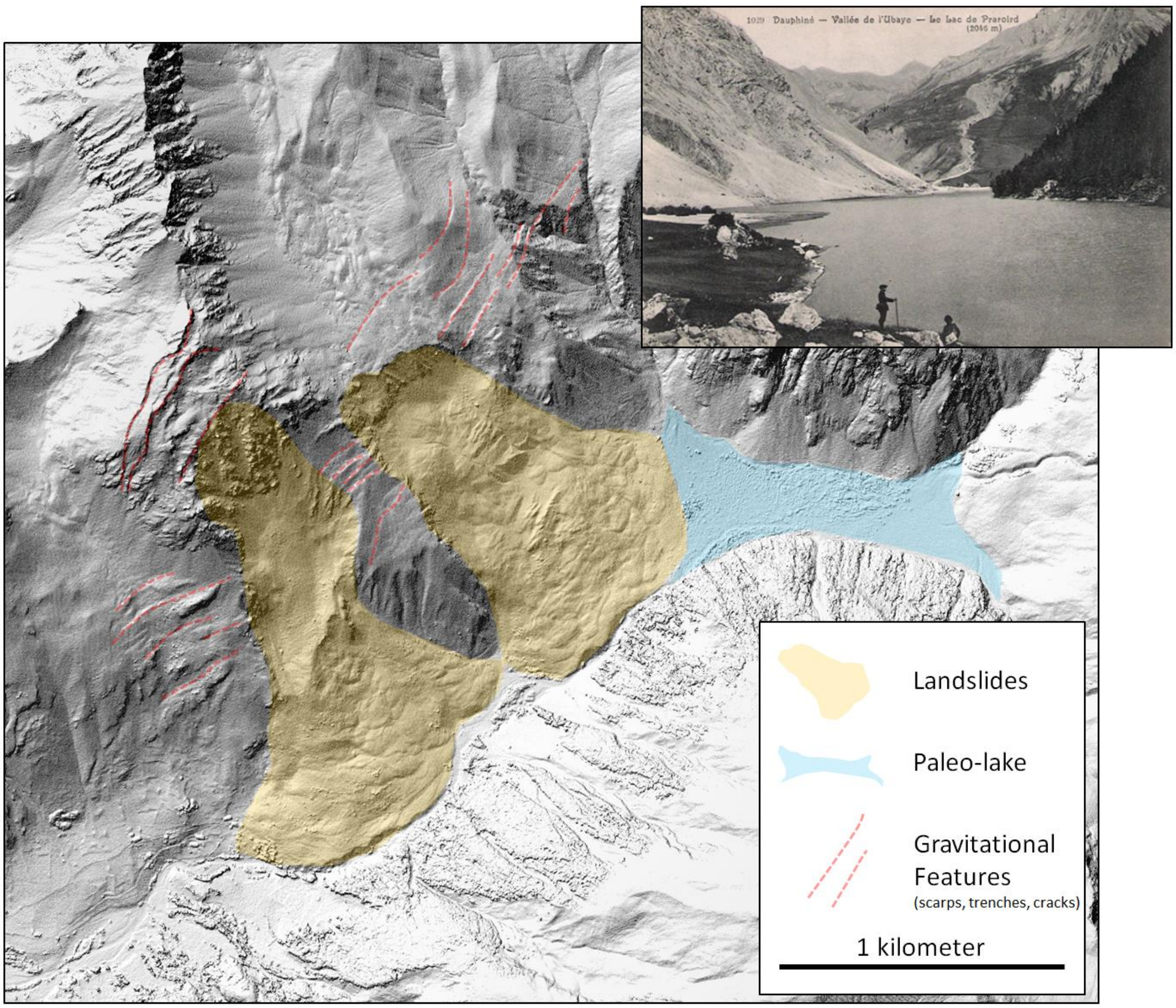

Figure 16 : photogrammetric DEM of the Rockslide area. Top right, early XX^th^ century postcard of the former lake.

Sunday October 2nd

1. Cime de la Bonnette (1h)

Overlooking the Restefond pass by a few dozen meters, the ‘Cime de la Bonette’, with its 2860m, is a wonderful panorama of the south-western Alps. The view encompasses an area going from the northern end of the external crystalline massif of Argentera-Mercantour and its detached sedimentary cover, to that of the massif of Pelvoux-Ecrins, passing through the internal and external sedimentary domains crossed the previous day.

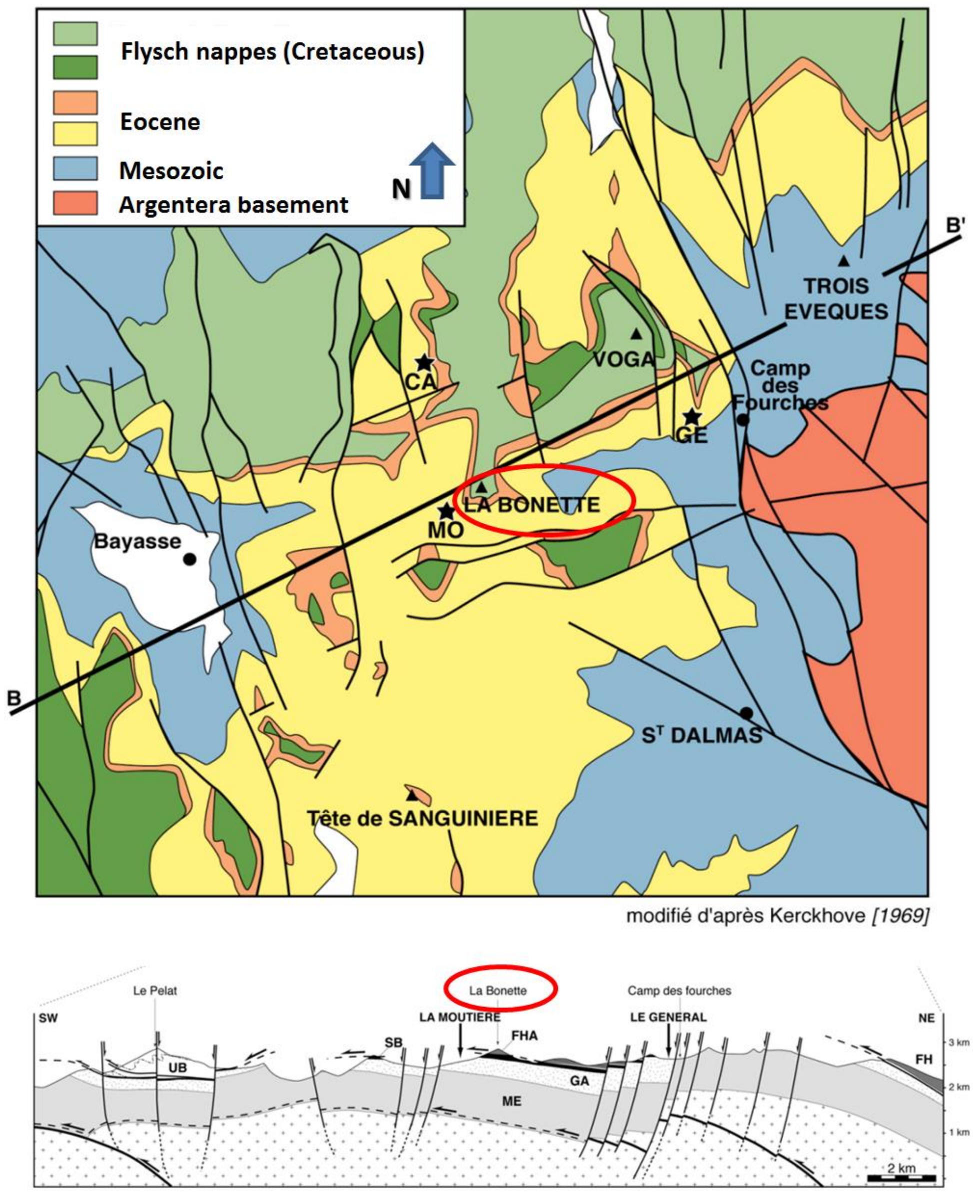

Figure 17 : Structural map of the La Bonette area (adapted from Du Bernard, 2002)

The Bonette summit itself constitutes a klippe of Cretaceous flysch, overthrusting Eocene sediments of the autochthonous series (Fig. 17). This structure, resulting from the Alpine compression during the Eocene, is crosscut by a series of late Alpine normal and strike-slip faults (Fig. 17), some of which being considered active today, such as the Jausiers-Tinée and Sérenne faults (Fig. 3).

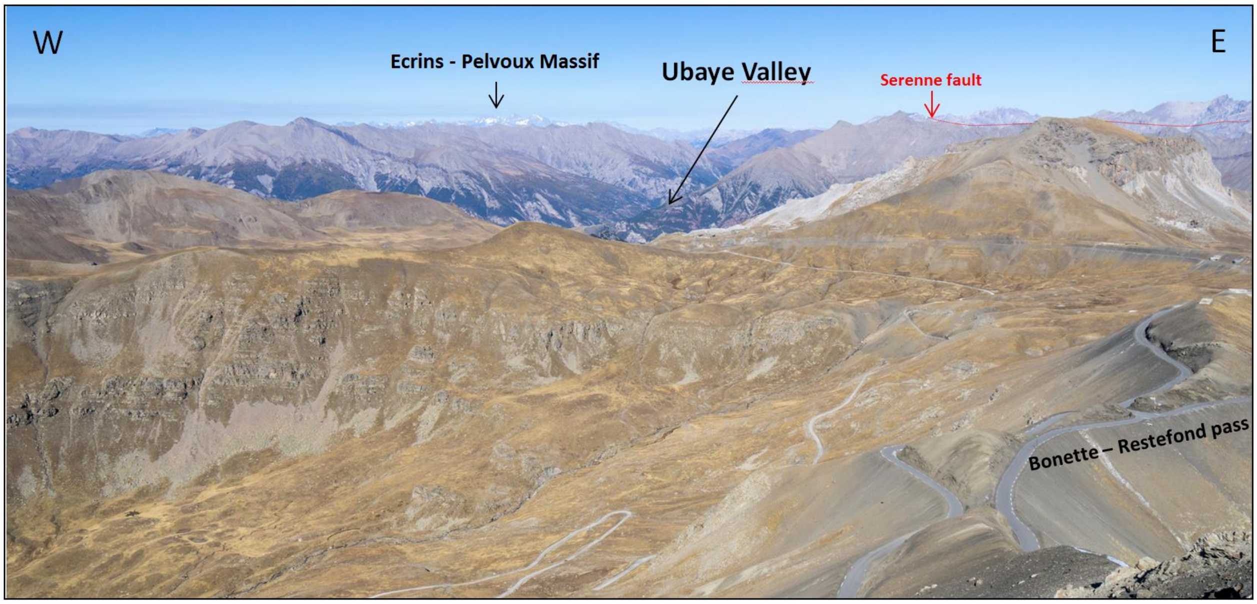

Figure 18 : View from the Cime de la Bonette toward the North

2. From 'Camp des Fourches' to 'Mt des Fourches' (2h)

A short hike brings us from the camp to the Mont des Fourches, from where we will have a view of the northwestern termination of the Argentera-Mercantour massif.

In this area, the basement, which is globally structured along a N140 direction, more or less parallel to the axis of the valleys, is affected by numerous diffuse (i.e. DSGSD – Deep Seated Gravitational Deformations) and more localized (i.e. DSL – Deep Seated Landslides) gravitational deformations (Fig. 19).

The initiation of gravitational deformations on top of the Pra DSL has been dated (Be10, Sanchez et al., 2010) between 5,6 and 4,5 ka B.P, highlighting the long term evolution of slopes toward a well individualized rockslide (Fig. 20).

In parallel, Sanchez et al., (2010) dated nearby fault scarps showing apparent-right lateral motions with up to 15m horizontal offset (Fig. 20). They proposed that this offset was produced by earthquakes occurring during a time span comprised between 11ka (i.e.

glacier retreat) and 7,8ka. They conclude that a tectonic control of gravitational deformations in the area is possible.

However, the origin of fault scarps (Fig. 20) attributed to a Holocene fault activity along the Jausiers-Tinée fault is debated. Indeed, the relative influences of the (1) structural inheritance, (2) post-glacial erosion and (3) large-scale gravitational deformations, are likely to complicate the proposed interpretations.

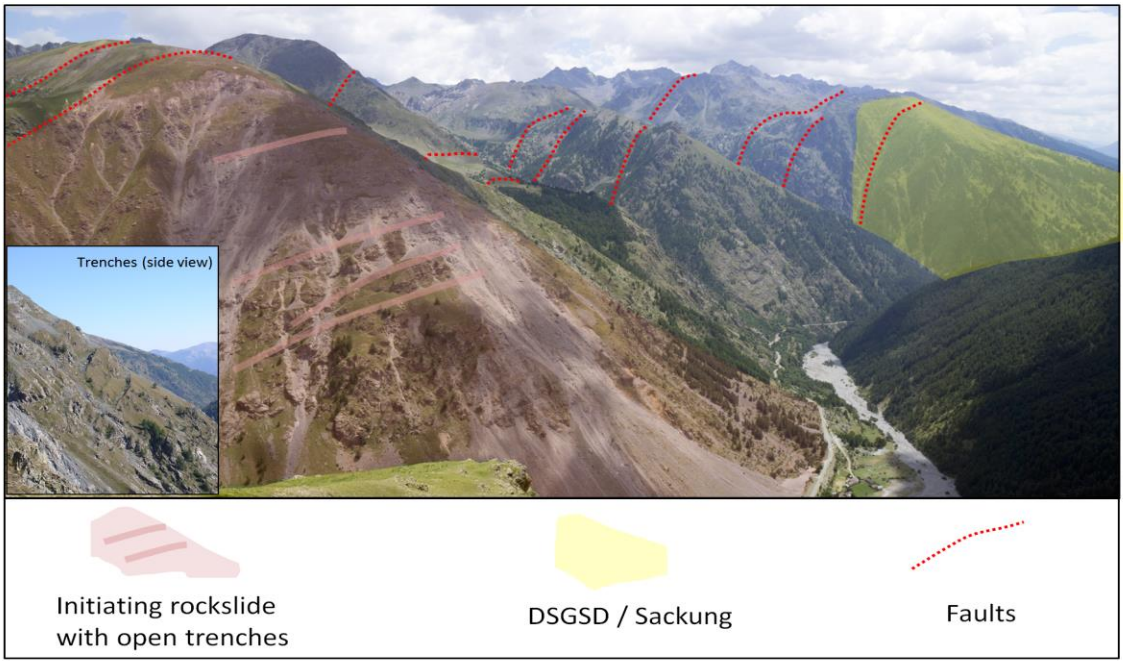

Figure 19 : Interpreted picture from the Mt des Fourches toward the South-East (Le Pra)

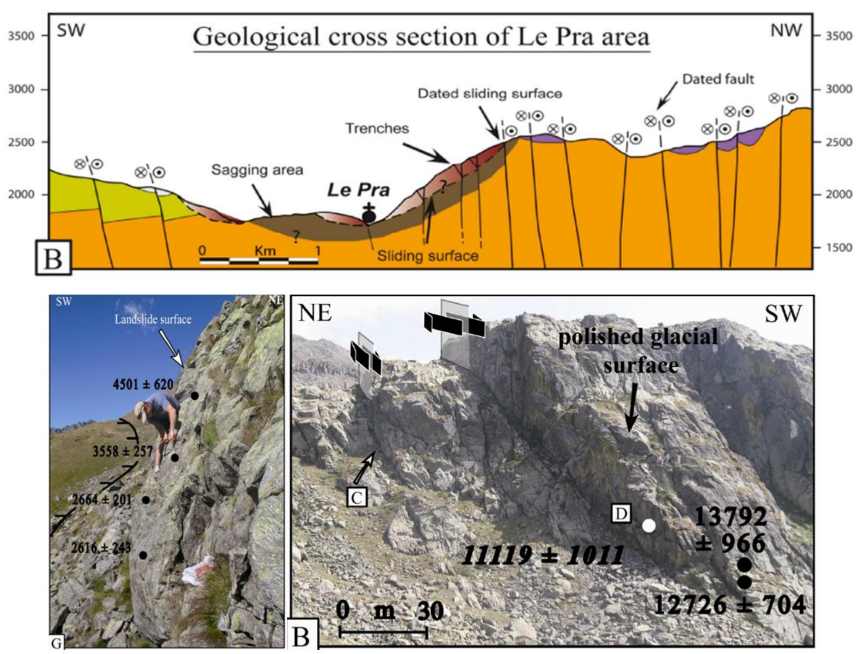

Figure 20 : Cross section of Le Pra area and Be10 dating of gravitational scarps (left) and faults (right). (Sanchez et al., 2010)

On the way back to the vehicles, a view of the ‘Salso Moreno’ valley (Fig. 21) allows to highlight the interface between the metamorphic basement and its Mesozoic sedimentary cover. But also to have a view on the 'Camp des Fourches' fault, highlighting a vertical throw estimated at more than 1km.

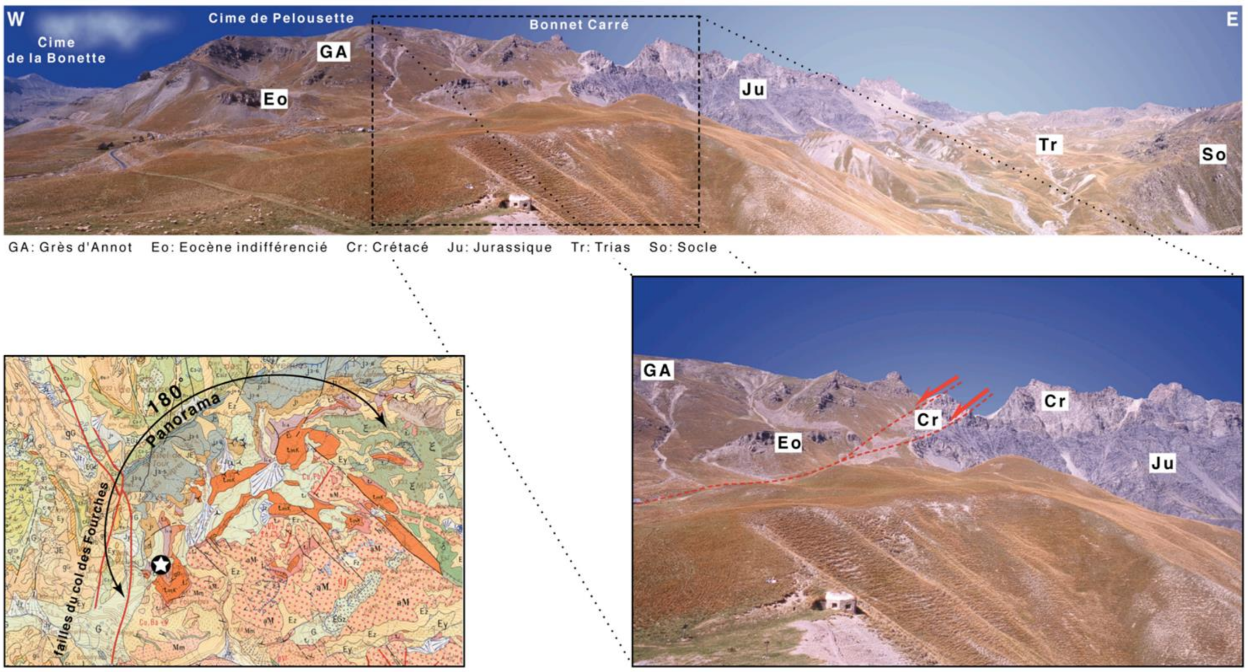

Figure 21 : Panoramic view of the 'Salso Moreno' area (from Du Bernard, 2002)

3. La Clapière Deep Seated Landslide (30 – 45 mn)

This active DSL is one of the most important in the Alps. It presents an estimated volume of 50 to 60.10^6 m^3 affecting an area 1km wide / 700m high over a thickness up to 100 m.

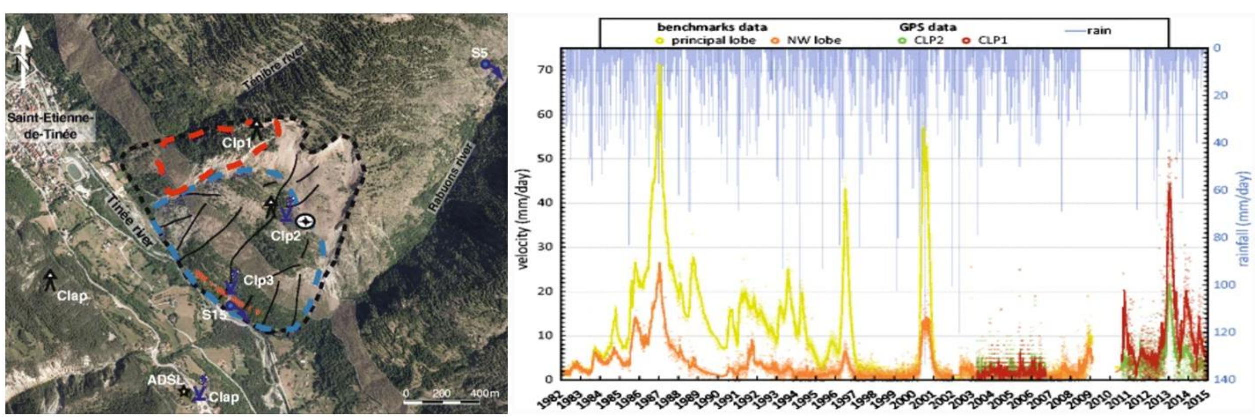

Figure 22 : Recorded internal deformations 1982 – 2015 (Palis et al., 2017)

As observed at the Pra area, the DSL results from the long term evolution of slopes covering a time span of 10ky after glacial retreat (Fig. 23). However the La Clapière slope is a later stage of evolution compared to the Pra, prefiguring its evolution in the next decades.

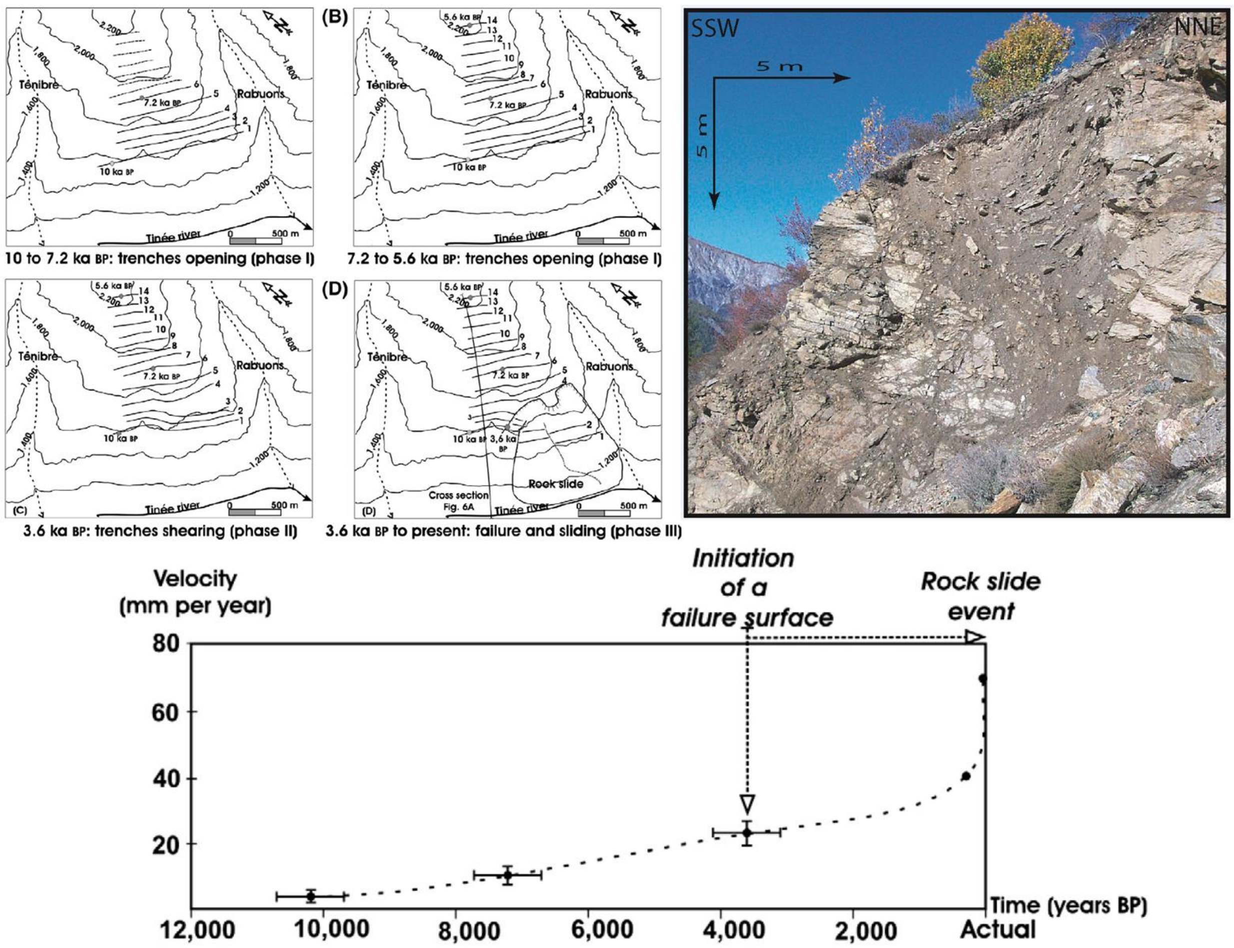

Figure 23 : evolution of the La Clapière slope inferred through morphological mapping and cosmogenic nuclide dating. View of an opened trench in cross-section (adapted from El Bedoui et al., 2009 and Jomard et al., 2014)

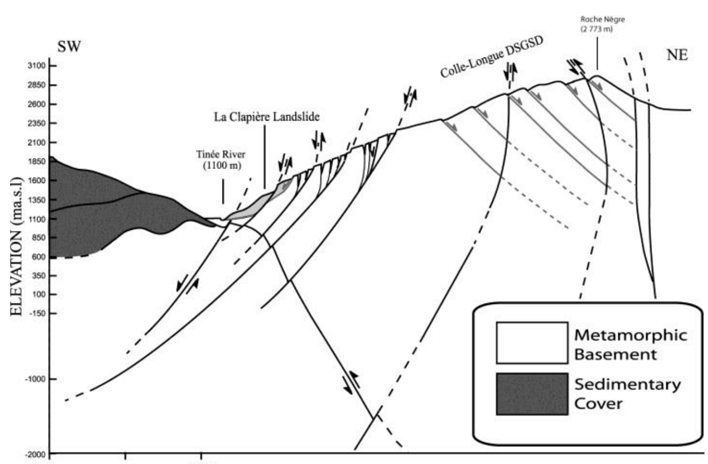

Figure 24 : cross section through the La Clapière slope (Jomard et al., 2014)

At wider scale, this DSL develops in a much wider area affected by diffuse gravitational deformations, called the Colle-Longue DSGSD (Fig. 24 and 25, Jomard 2006; Jomard et al., 2014) and highlighting typical morphologies such as counterslope-scarps, scarps and open trenches over a ±10km length. The inherited structure (faults, foliation) plays a major role in localizing gravitational deformations. However questions about a possible tectonic control remain unsolved (see Fig. 26, Darnault et al., 2012).

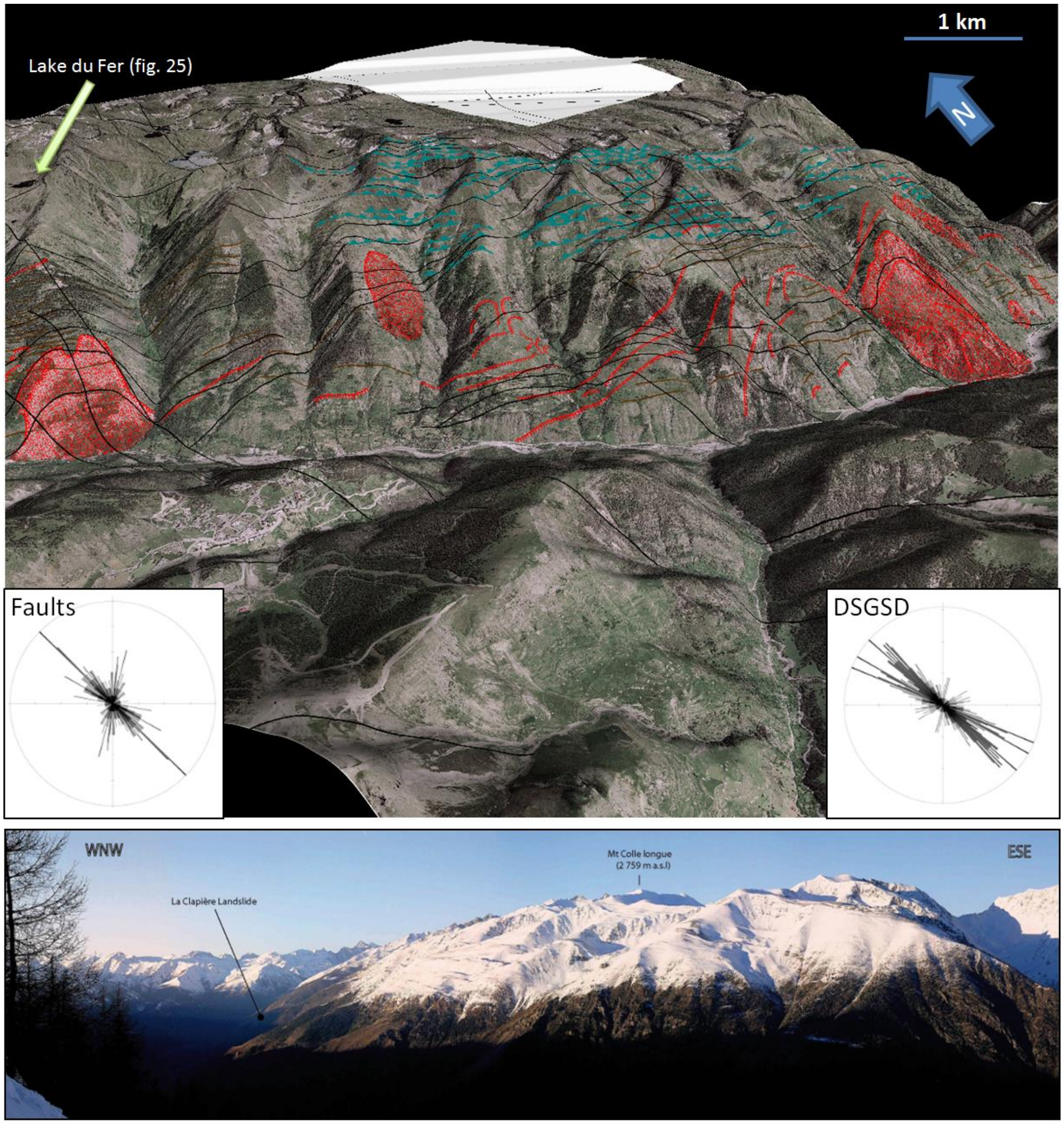

Figure 25 : Oblique 3D view over the Colle-Longue DSGSD and La Clapière with counterscarps (in green), scarps (in red), trenches (in brown) and faults (in black). Stereograms represent field measurements along faults and DSGSD morphologies (adapted from Jomard et al., 2014)

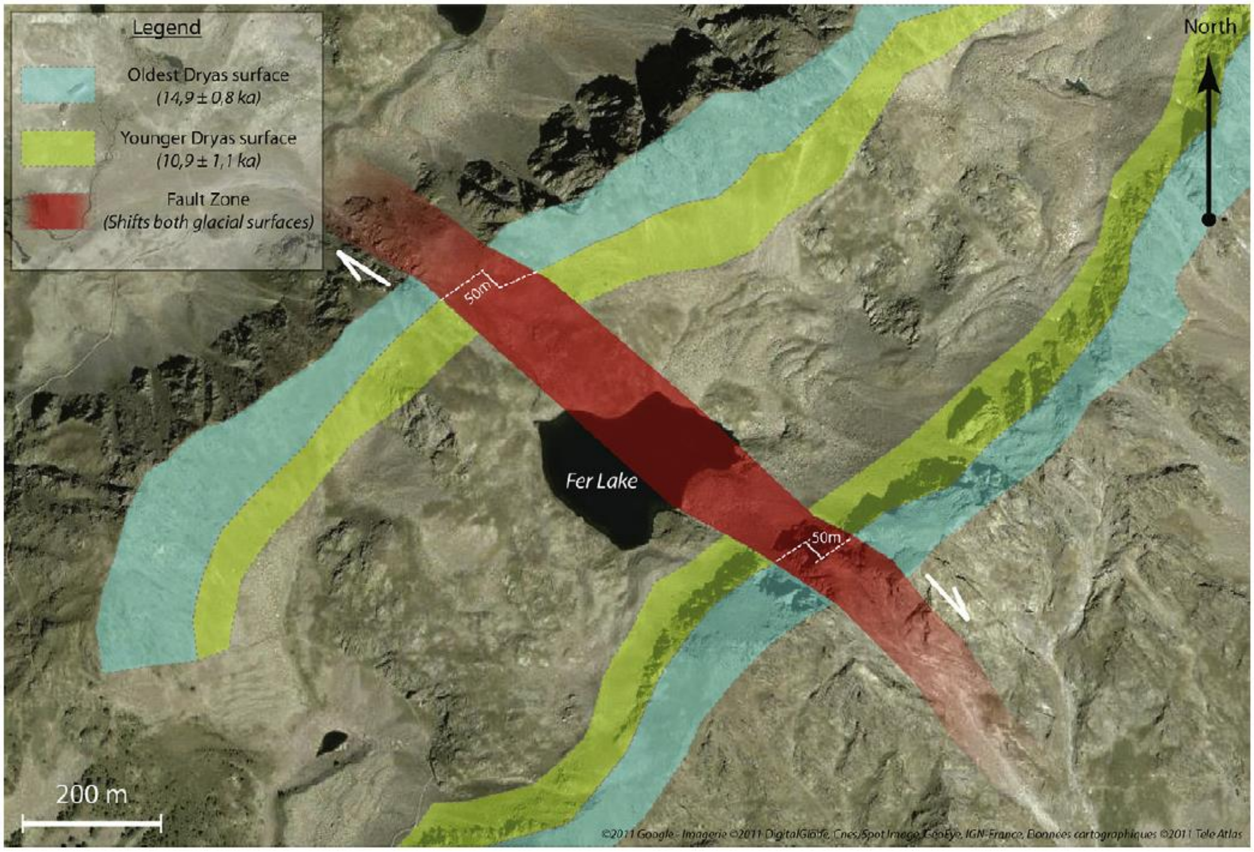

Figure 26 : Right-lateral motion along a fault, interpreted as possible marker of Holocene active faulting occurring in between 10,9ky and 7,9 ky (Darnault et al., 2012)

4. The Bersezio fault in the Orgials valley (2 – 3h)

The Bersezio fault, which outcrops near the Lombarde Pass, certainly represents the clearest active fault morphology available in the region. The Bersezio fault is the southern continuation of the Serenne fault seen yesterday, which then corresponds to a structure with a global length of more than 70 km long. However, the 2km that we are covering today are the only ones presenting a continuous scarp characterized by tectonic-morphologies that are sufficiently well expressed to allow for a paleoseismological analysis.

The Bersezio fault has a long and polyphased history, with its most recent major expression corresponding to transpressional motions registered during the uplift of the Argentera massif in Pliocene times (Fig. 27).

Few earthquakes have been registered in the area, in comparison with much higher seismicity rates observed in the Ubaye valley. These events are mostly representative of normal faulting with a slight right lateral component (Larroque et al., 2009).

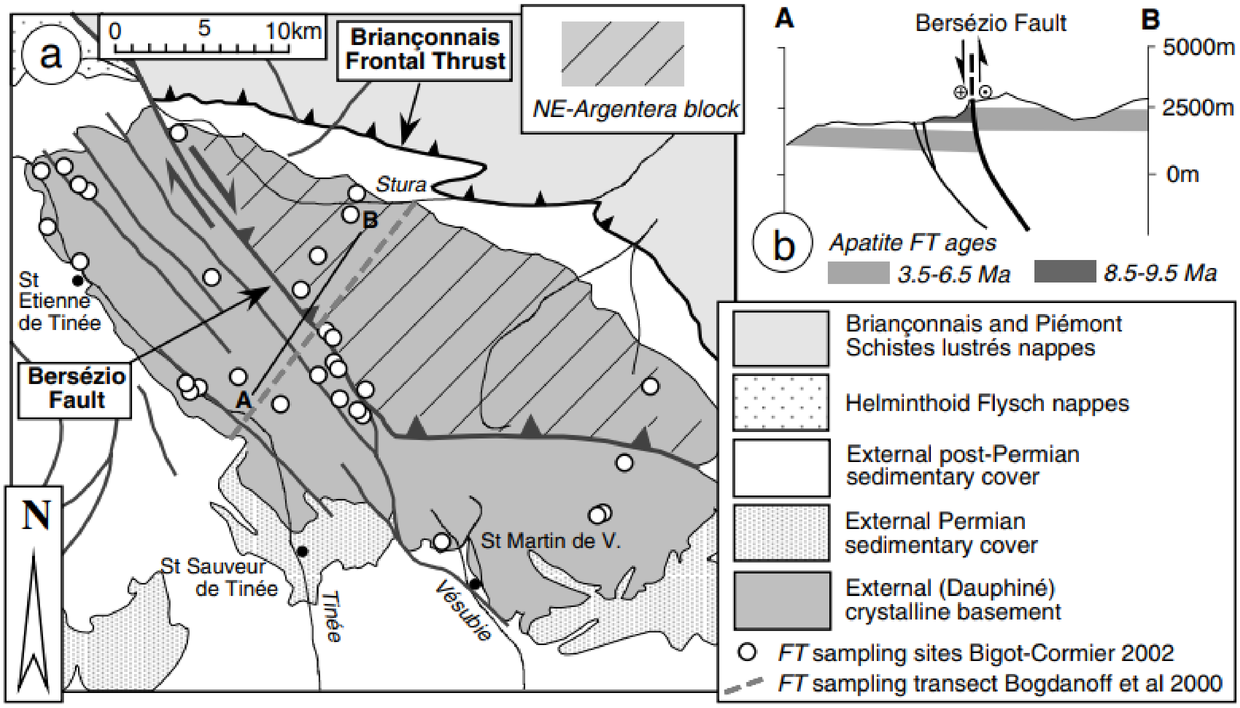

Figure 27: location of the Bersezio fault within the Argentera Massif, and Pliocene (to present?) kinematics (Tricart, 2004)

In the early 90's, a first paleoseismological study in the area led Ghafiri et al., (1995) to trench the fault in its French side (near the Isola 2000 ski resort, fig. 28), without success. However the Italian side (Orgials valley) has never been studied in details. Results presented here are part of an ongoing research along the Italian part of the fault.

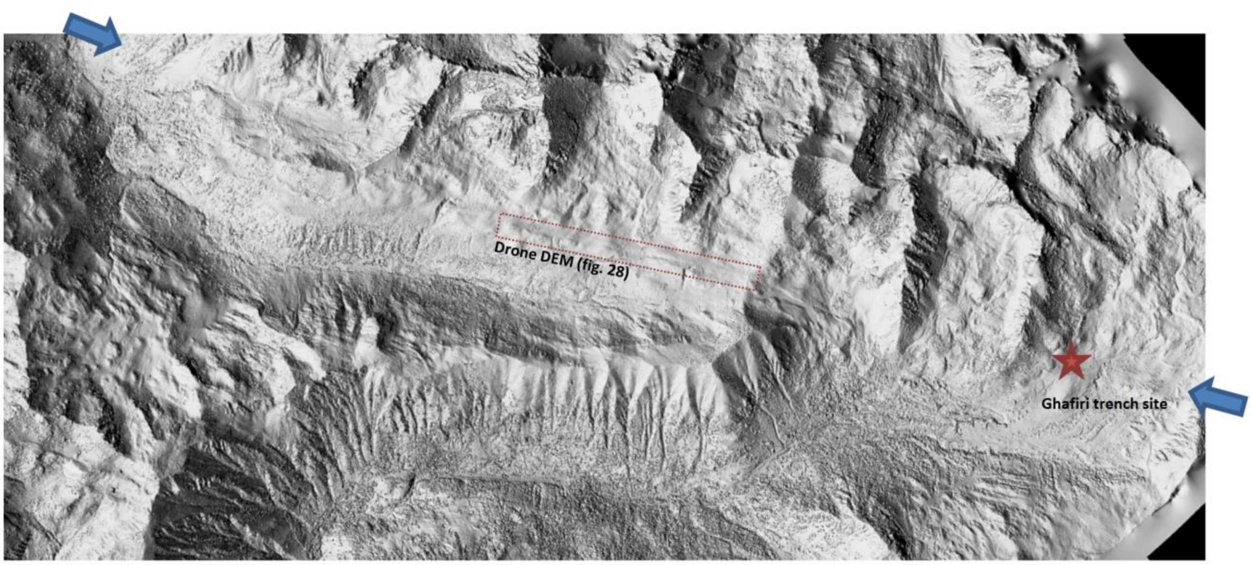

Figure 28 : Photogrametric DEM derived from 1968 air photo. With the fault axis (blue arrows), location of high resolution drone DEM (red) and location of trenches dug by Ghafiri (1995, red star)

We will walk along the 2km long fault segment, along which several points of interest are reported in Fig. 28 and 29. Basement outcrops as well as linear scarps affecting glacial and postglacial morphologies will be discussed in terms of active tectonics significance. At point 5, a short trench exposes lacustrine sediments potentially affected by the fault (Fig. 31).

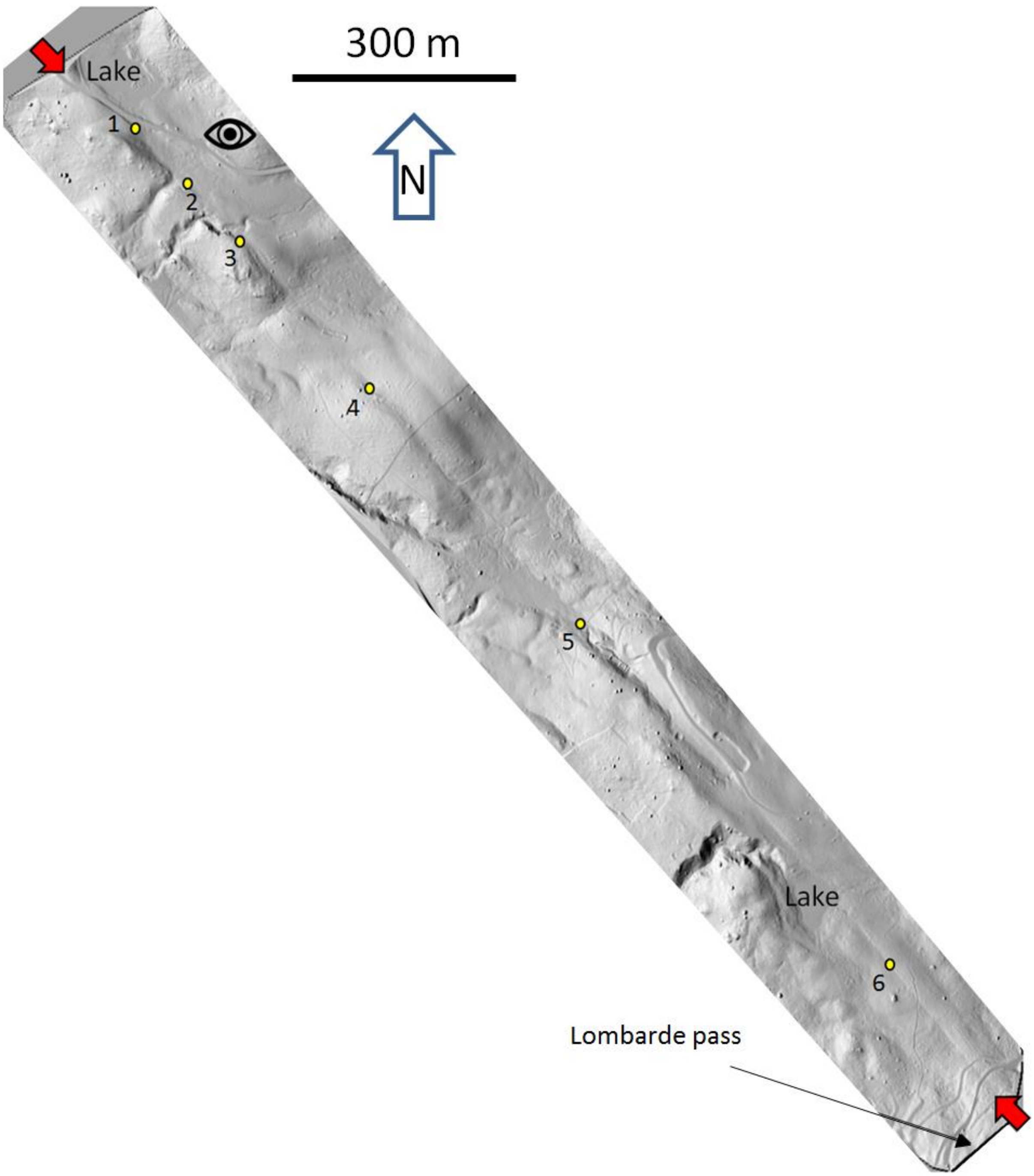

Figure 29 : Drone DEM of the 2km length Bersezio fault segment, and location of points of interest 1 to 6 (Vassallo et al., 2022)

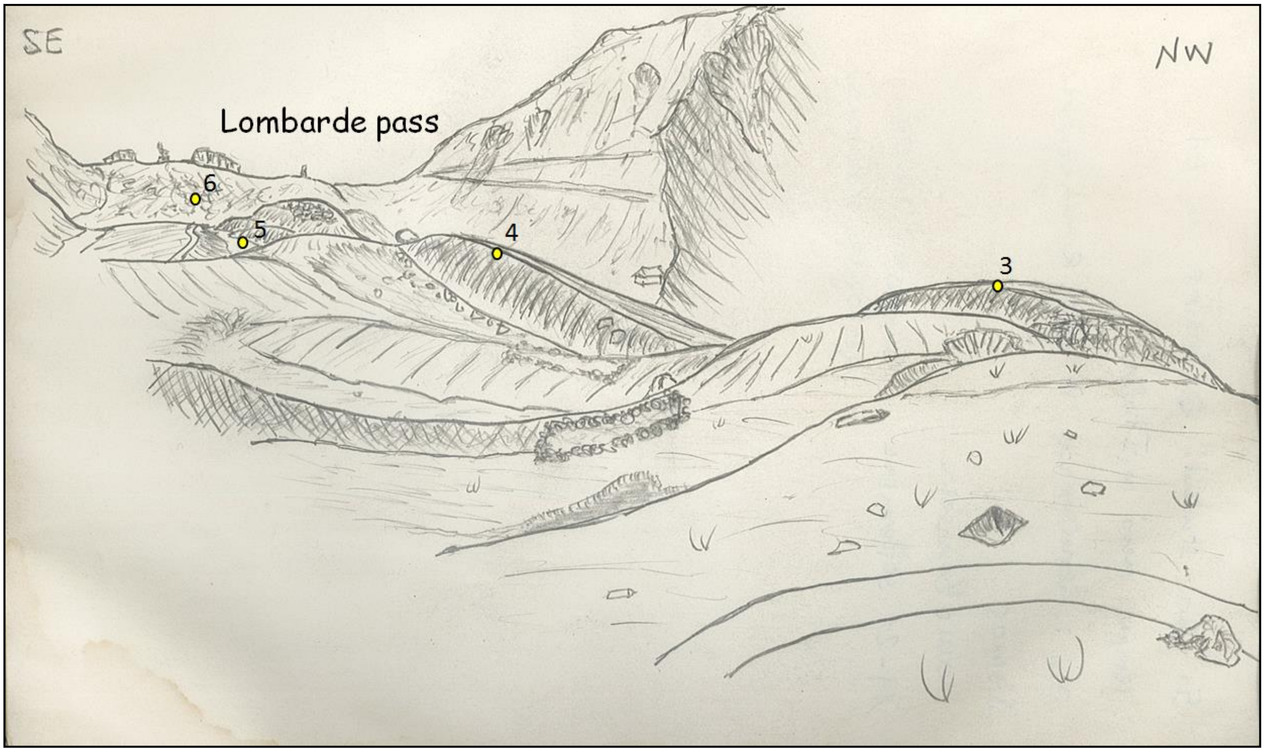

Figure 30 : hand-sketch of the bersezio fault and location of points of interest (location of the viewpoint in fig. 28)

Figure 31: Pictures at POI 1 (general view along the fault scarp) and POI 5 (trench excavated by hand)

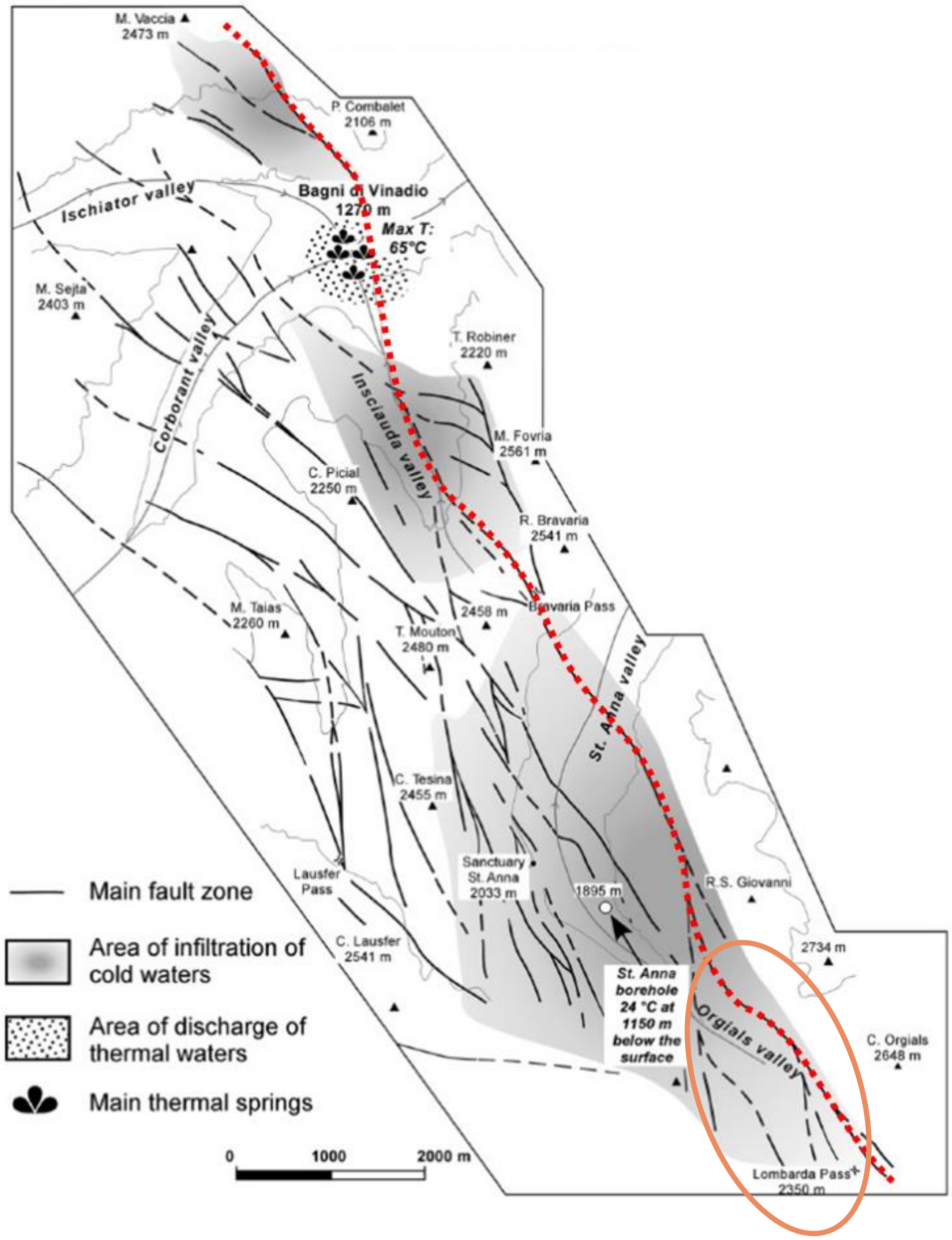

Figure 32 : Detailed map of faults around the principal Bersezio fault system (red dots) north of the Orgials valley (orange circle); greyish zones represent areas of cold water infiltration, drained in faults and flowing as hot springs in Bagni di Vinadio (Tmax: 65°C) – Adapted from Baietto et al., 2009

Supplementary material

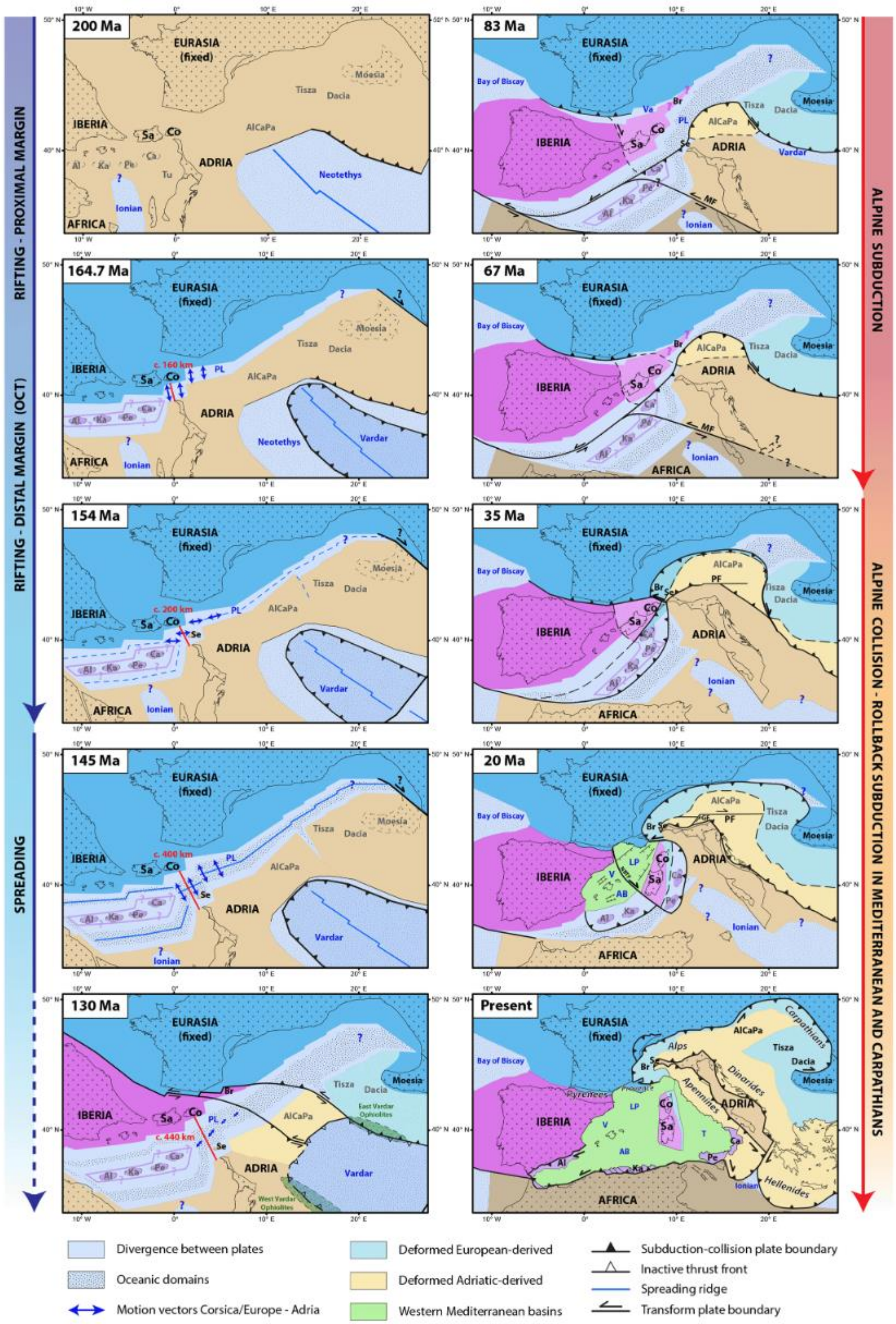

Figure 33 : Simplified tectonic reconstruction maps at the Alpine scale (Le Breton et al., 2021)

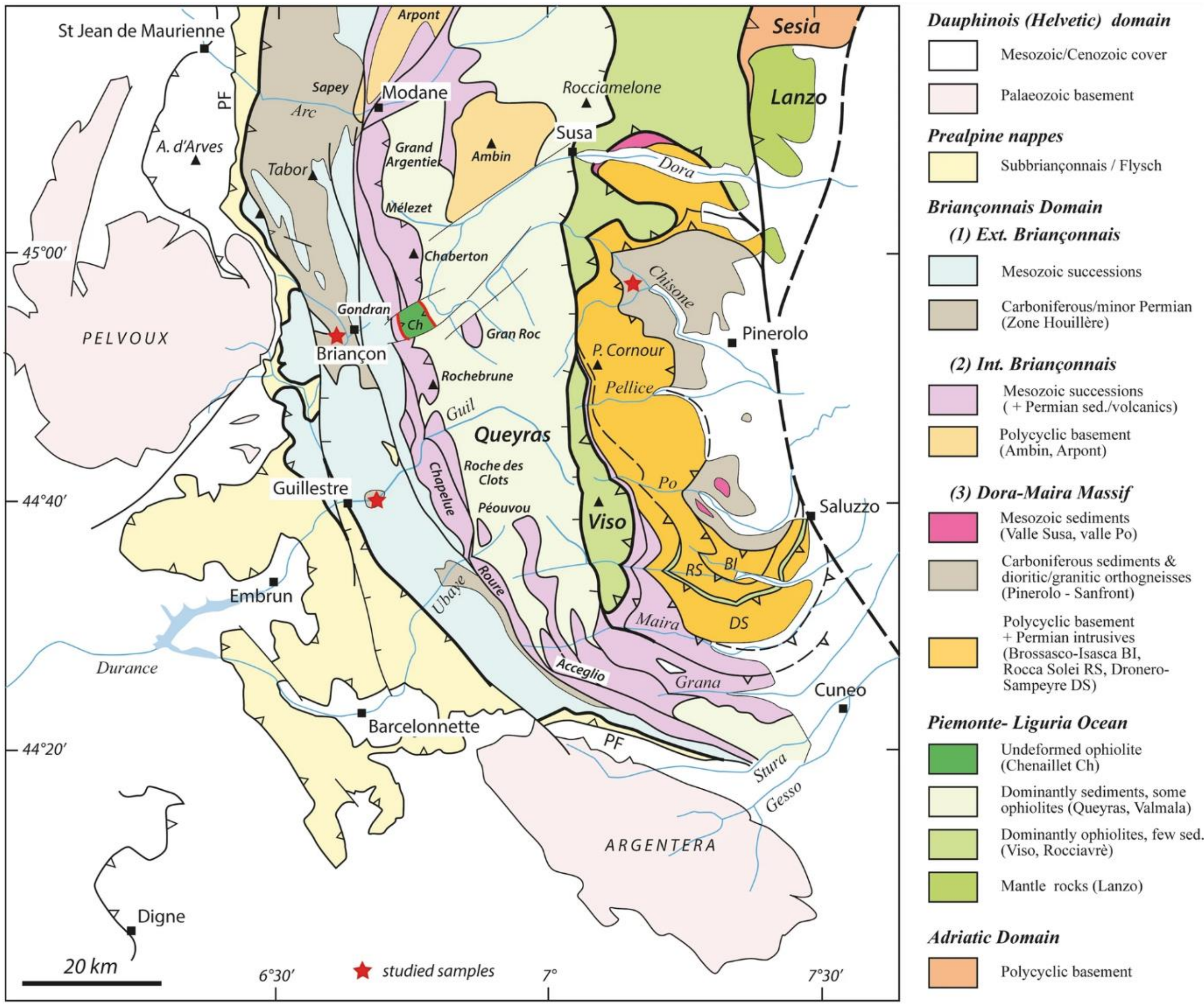

Figure 34: simplified geological map of the south-western Alps (Ballevre et al., 2020)

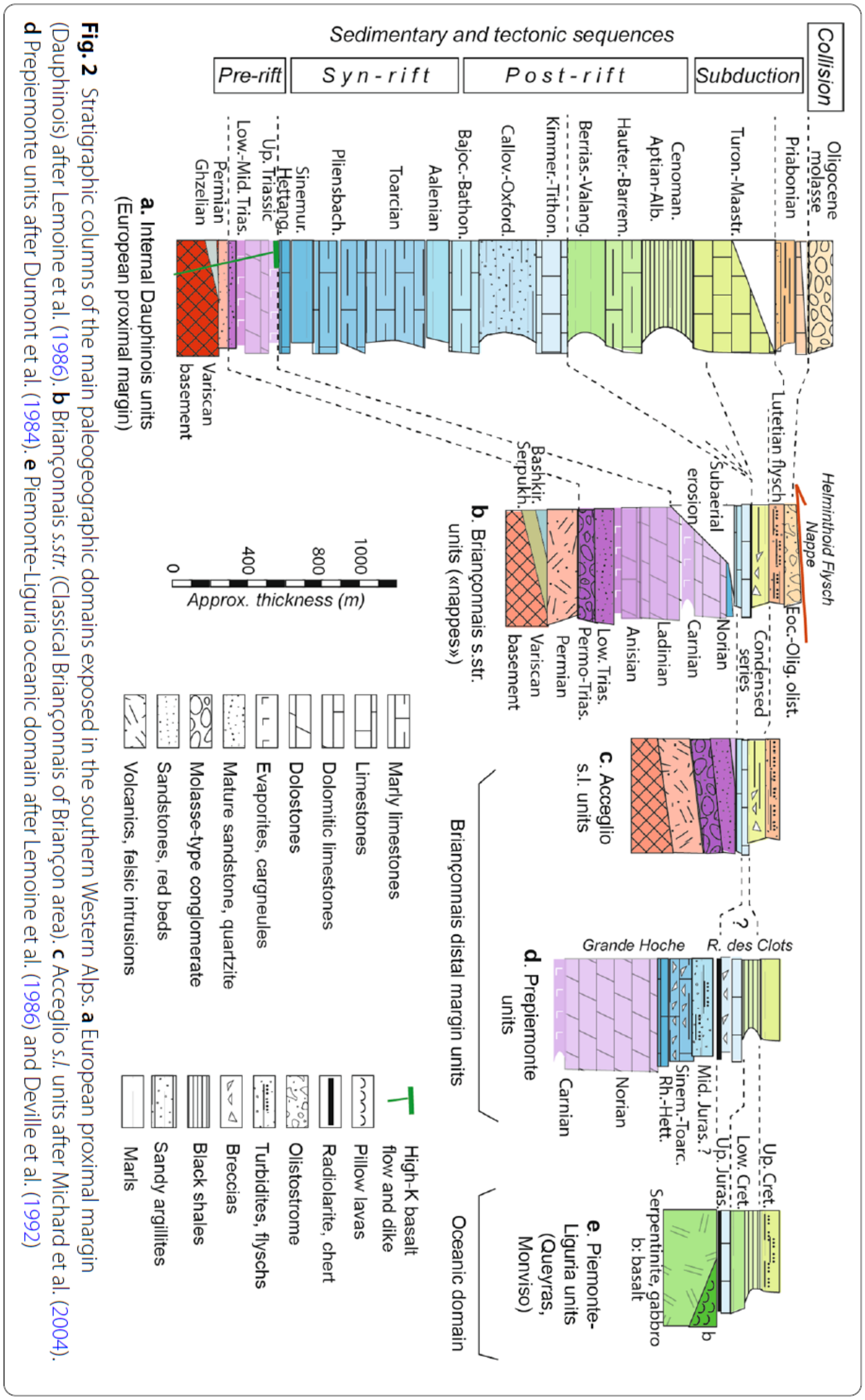

Figure 35: Simplified stratigraphy of the external (a) and internal (b, c, d, e) alpine domains (Machard et al., 2022)

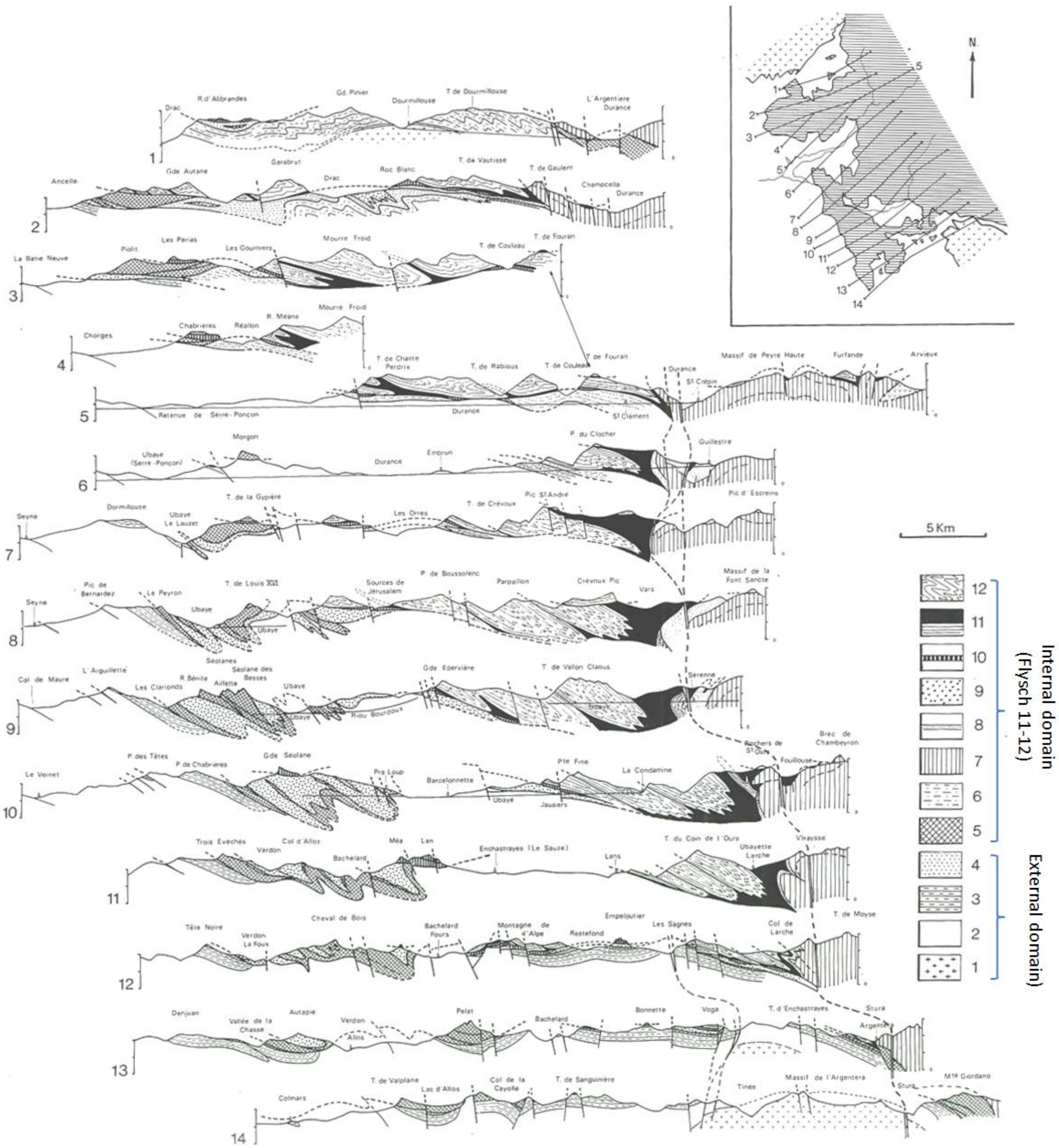

Figure 36: Serial cross sections of the Embrunnais-Ubaye nappes (Kerckhove, 1970)

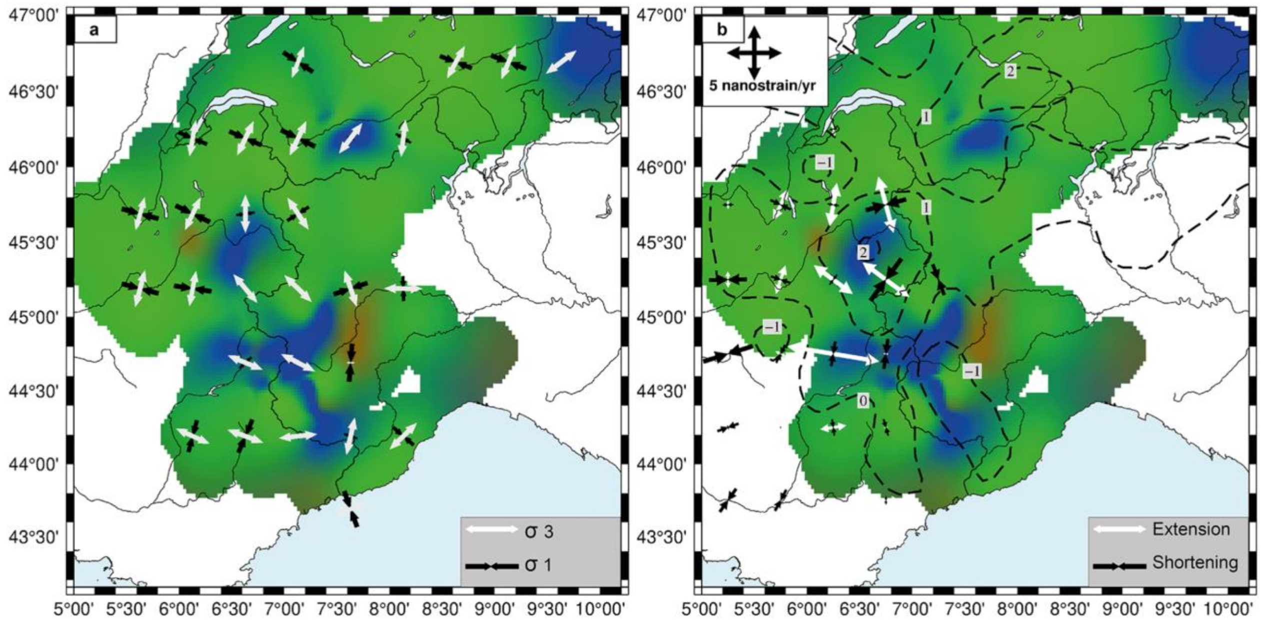

Figure 37 : Left: Stress orientation using focal mechanisms and smoothed interpolation (in red : compression, in blue : extension, in green : strike slip), Right: GNSS strain rates from Walpersdorf et al. (2018). Dashed lines represent contours of vertical velocities (in mm yr−1) from Sternai et al. (2019). Figures from Mathey et al., 2021

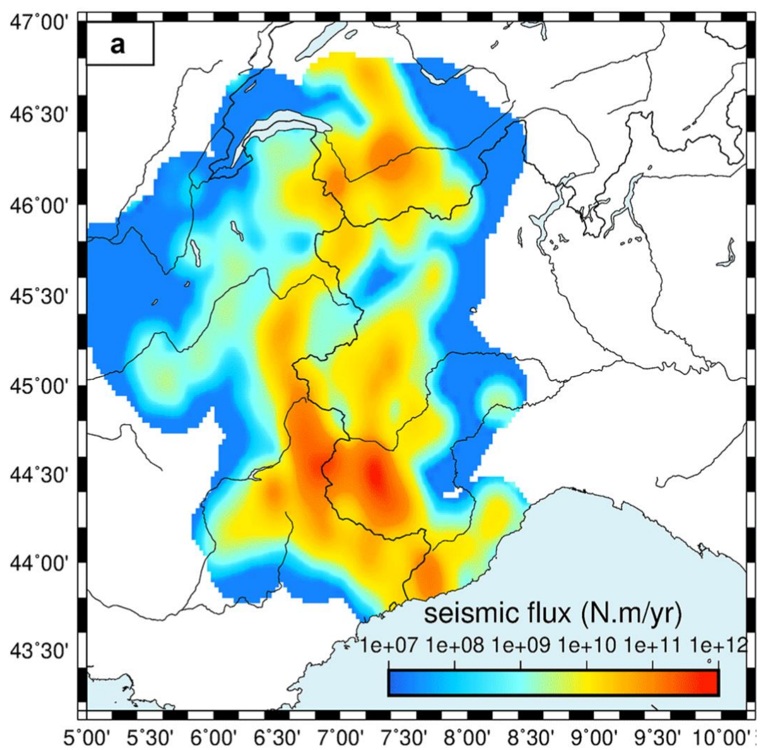

Figure 38 : Smoothed seismic flux over the western Alps (computed using annualized seismic moment for the period 1989 – 2014; Mathey et al., 2021)

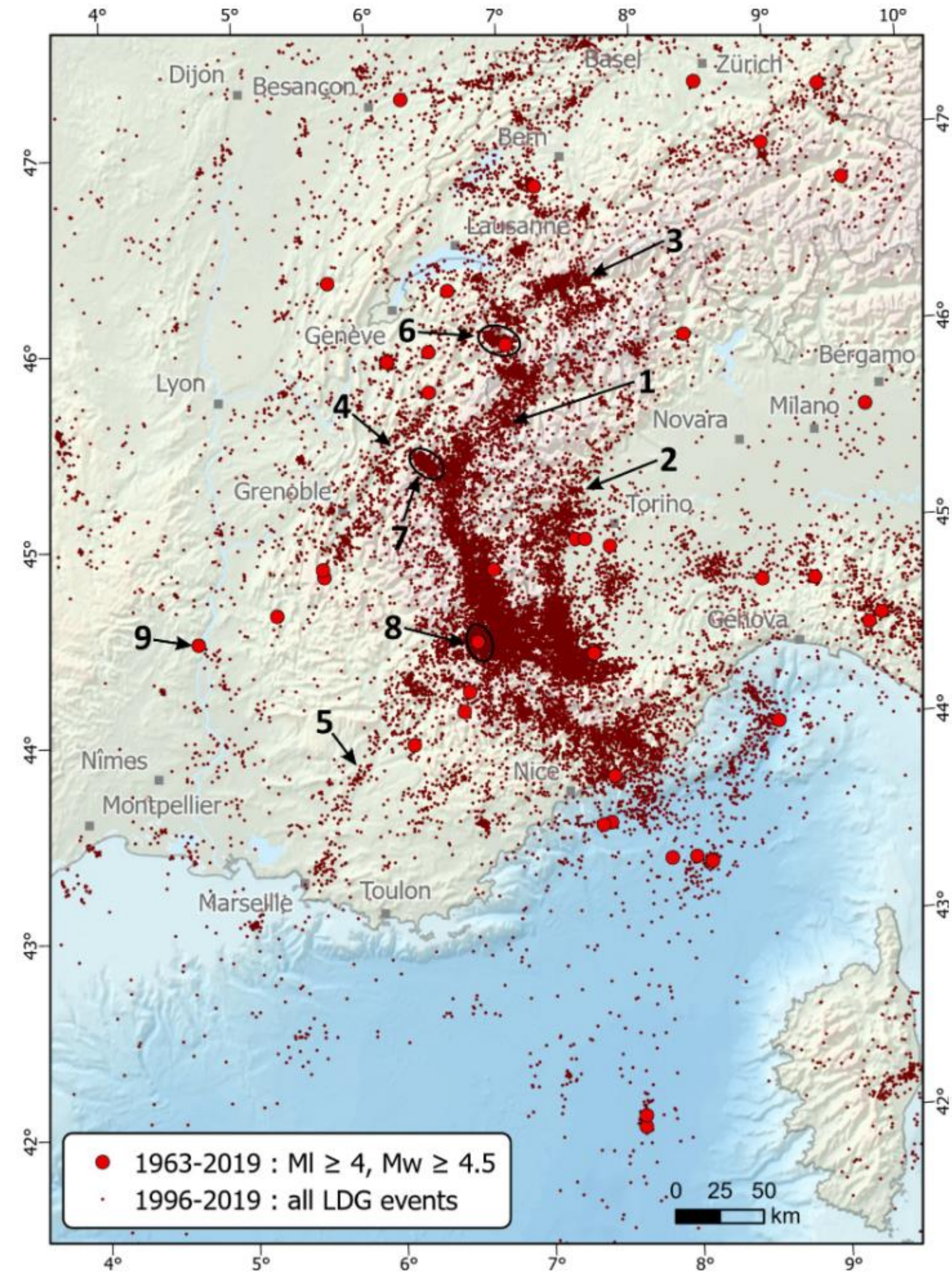

Figure 39 : Seismicity map from the CEA_1996–2019 catalog supplemented by earthquakes of ML⩾4.5 or Mw⩾4.0 from the CEA and the Si-Hex catalogs for the period 1963–1996. 1, 2: Briançonnais and Piemontais seismicity arcs respectively; 3–5: Rhône, Belledonne and Durance seismic alignments respectively; 6: Vallorcine cluster; 7: Maurienne cluster; 8: Ubaye cluster; 9: Epicenter of the Le Teil earthquake (Mw 4.9, 2019/11/11). From Larroque et al., 2021.

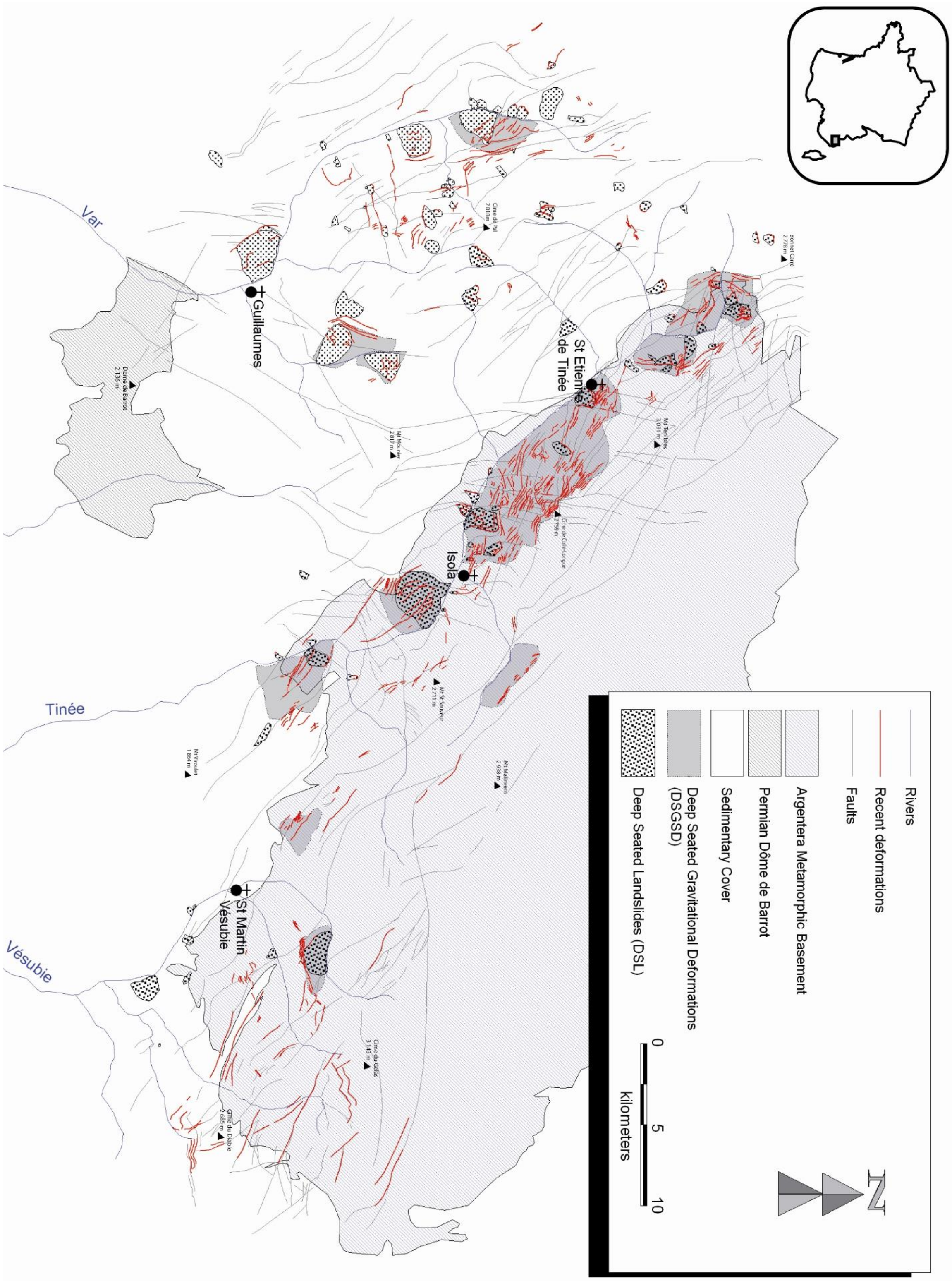

Figure 40 : Map of gravitational deformations and faults observed within and near the Argentera-Mercantour massif (Jomard et al., 2014)

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