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Geological map of the External Ligurian Units in western Monferrato (Tertiary Piedmont Basin, NW Italy)

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ABSTRACT
The External Ligurian Units in western Monferrato (NW-Italy) have been always described as an undifferentiated chaotic complex. This map, at 1:10,000 scale, describes in detail the tectono-stratigraphic setting of these Units in the sector of the Alps-Apennines junction. Here, the External Ligurian Units represent the northwestern prolongation of Northern Apennines and consist of a Late Cretaceous chaotic succession represented by the *Argille varicolori* and the overlaying Monte Cassio Flysch. The late Eocene – Miocene episutural succession of the Tertiary Piedmont Basin rests unconformably on the External Ligurian Units. The mapped crosscutting relationships between stratigraphic unconformities and faults allow to describe a complex tectono-stratigraphic setting that is the product of four tectonic stages. Layer-parallel extension related to Late Cretaceous – early Eocene deformation occurred in the internal sector of the Alpine accretionary wedge is preserved within the External Ligurian Units and it is sealed by the late Eocene deposits of the Tertiary Piedmont Basin. The unconformity at the base of the Oligocene succession records the drowning of shelf sediments controlled by NW-striking left-lateral transtensive faulting. A WNW-striking and NE-verging thrust superposes the External Ligurian Units onto the late Eocene – Oligocene deposits and it is sealed by the gravitational emplacement of late Oligocene Polygenetic argillaceous breccias. Both the WNW-striking thrust and the Polygenetic argillaceous breccias are cut by NW-striking right-lateral transpressive faults that are, in turn, sealed by the Tortonian unconformity.

1. INTRODUCTION

The understanding of the tectono-stratigraphic evolution of a sector is strictly related to the outcrop condition. Good outcrop condition and excellent rock exposures attract geologists with different backgrounds facilitating a complete understanding of the geology of that sector. On the contrary, a sector with poor rock exposures and very low outcrop percentage is commonly not or poorly studied with a consequent lack of geological informations on its tectono-stratigraphic evolution. In most of these cases, detailed geological mapping represents the most useful approach in covering the lack of geological information, thus in better understanding the tectono-stratigraphic evolution of a sector. This is the case of the western Monferrato in NW Italy (Fig. 1), where the Late Cretaceous - Eocene unmetamorphosed External Ligurian Units (i.e., "undifferentiated complex" *sensu* Bonsignore *et al.*, 1969; "la Pietra chaotic complex" *sensu* Dela Pierre *et al.*, 2009b) have never been mapped and studied in detail because of the poor outcrop condition and the extensive unconformable cover of the late Eocene – late Miocene episutural succession of the Tertiary Piedmont Basin.

In this paper, we present a new geological map (1:10,000 scale) of a sector of the westernmost Monferrato (South of Lauriano village) that, although it covers a limited area, represents the northwesternmost sector of Northern Apennines were the External Ligurian Units crop out. This sector is also crucial for better understanding both the Late Cretaceous – Eocene tectono-stratigraphic evolution of the internal sectors of the Alpine accretionary wedge and the relationships between the External Ligurian Units and the overlying Tertiary Piedmont Basin succession in the sector of Alps-Apennines junction (e.g., "Ligurian knot" of Laubscher *et al.*, 1992; Schumacher and Laubscher, 1996; Rossi *et al.*, 2009; Mosca *et al.*, 2010).

2. METHODS

The geological map has been realized in about three years (2009-2011) of field work by means of a geological mapping at 1:10,000 scale and detailed stratigraphic and structural analyses. Areas of particular complexity or interest have been mapped with a 1:1,000 scale detail (e.g., North of Moglietto, South of "la Giustizia", West of Novarese and South of "la Pietra"; see Geological Map). Progressive acquisition and interpretation of data have been documented in the attached geological-structural map at 1:10,000 scale using sections 156040 and 157010 of the topographic map "CTR - Carta Tecnica Regionale, Regione Piemonte". The map includes a regional-structural scheme, three geological cross sections, and a stratigraphic column describing the characteristics of the lithostratigraphic succession.

3. REGIONAL SETTING

The Tertiary Piedmont Basin (Fig. 1A) is a large episutural basin developed, since late Eocene onward, in the internal sector of the Western Alps (e.g., Gelati & Gnaccolini, 1988; Castellarin, 1994; Mutti *et al.*, 1995; Roure *et al.*, 1996; Mosca *et al.*, 2010). This basin has been unconformably deposited on the Alps - Apennines junction (e.g., "Ligurian knot" of Laubscher *et al.*, 1992; Schumacher & Laubscher, 1996) that corresponds to a complex tectonic jigsaw including the buried metamorphic Western Alpine units, the SE-verging front of the South Alpine thrust system, and the northeast-verging External Ligurian Units of the Northern Apennines (e.g. Biella *et al.*, 1988; 1997; Laubscher *et al.*, 1992; Castellarin, 1994; Mutti *et al.*, 1995; Roure *et al.*, 1996; Schumacher & Laubscher, 1996; Piana, 2000; Mosca *et al.*, 2010; Molli *et al.*, 2010). The External Ligurian Units consist of a non-metamorphosed succession deposited on the ocean-continent transition zone (OCT) of the rifted Adria continental margin (e.g., Marroni *et al.*, 2010 and reference therein). They are classically differentiated from the Internal Ligurian Units (Fig. 1A) that represent an "incomplete" ophiolite sequence and overlying Jurassic-Eocene sedimentary cover deposited on the Jurassic oceanic crust of the Ligurian Ocean (e.g., Elter, 1975; Abbate *et al.*, 1986; Castellarin, 1994; Lucente and Pini, 2003; Marroni *et al.*, 1998, 2001, 2010; Festa *et al.*, 2010; Molli *et al.*, 2010; Vezzani et al., 2010; Dilek and Furnes, 2011).

The Torino Hill and Monferrato, which are separated by the NW-striking Rio Freddo Deformation Zone (*sensu* Piana & Polino, 1995), represent the northern part of the Tertiary Piedmont Basin (Fig. 1A). The Torino Hill succession rests unconformably on a metamorphic basement and Mesozoic sedimentary cover of South Alpine pertinence (Festa *et al.*, 2005, 2009b; Mosca *et al.*, 2010), buried at a depth of 2–3 km (Bonsignore *et al.*, 1969; Miletto & Polino, 1992; Mosca *et al.*, 2010). The Monferrato succession unconformably overlies the Cretaceous-to lower Eocene, non-metamorphic undifferentiated Ligurian units (Bonsignore *et al.*, 1969). Its magnetic basement is buried at a depth of 8–10 km (Cassano *et al.*, 1986; Miletto & Polino, 1992).

Although Elter *et al.* (1966) and Bonsignore *et al.* (1969) suggested that part of the Ligurian Units of Monferrrato (i.e., the "Lauriano complex" of Albian–Cenomanian age and the "Monteu da Po Flysch" of Maastrichthian age) should be correlated with part of the "basal complex" and the Monte Cassio Flysch of the External Ligurian Units, respectively, these units have been commonly described and mapped as an undifferentiated chaotic complex ("undifferentiated complex" *sensu* Bonsignore *et al.*, 1969; "la Pietra Chaotic Complex" *sensu* Dela Pierre *et al.*, 2003a, 2003b) of Late Cretaceous–middle Eocene age. Only Sacco (1908), in the first edition of the Geological Map of Italy, and Beets (1940) distinguished in map varicolored shale and a calcareous flysch succession but they did not correlate in detail these units with those of the Northern Apennine succession.

By contrast, the late Eocene – late Miocene succession of the northern part of Tertiary Piedmont Basin has been described (e.g., Clari *et al.*, 1987; Dela Pierre *et al.*, 2003b, 2007; Festa *et al.*, 2009b, Festa, 2011) and mapped in detail during last decades (Piana, 2000; Dela Pierre *et al.*, 2003a; Festa *et al.*, 2009a) allowing to subdivide the tectono-stratigraphic evolution of the Torino Hill and Monferrato into four contractional faulting stages dated as Rupelian, Burdigalian, Serravallian, and –Messinian, respectively(Piana, 2000; Dela Pierre *et al.*, 2003a, 2003b, 2007; Festa *et al.*, 2005, 2009a, 2009b, Festa, 2011).

4. DATA

4.1. Stratigraphy

The stratigraphic succession (Fig. 2) is characterized by the unconformable deposition of the late Eocene – middle Miocene succession of the Tertiary Piedmont Basin onto the Cassio Unit of the Late Cretaceous External Ligurian Units, former described as "undifferentiated complex" (*sensu* Bonsignore *et al.*, 1969) and "la Pietra chaotic complex" (*sensu* Dela Pierre *et al.*, 2003b).

The lower part of the Cassio Unit consists of the chaotic succession of the Late Cretaceous (Santonian – Campanian) *Argille varicolori* (Varicolored Scaly clays). The latter, correspond to the upper part of the "basal complex" *Auct.* of the External Ligurian Units (e.g., Marroni *et al.*, 2010; Codegone *et al.*, 2012). The *Argille varicolori* are characterized by highly disrupted and chaotic rocks lacking layer-continuity and displaying a block-in-matrix fabric (Fig. 3A). The matrix consists of alternating cm-dm layered varicolored (mainly gray, red and purple) deformed beds of clay and shale (Fig. 3B). The blocks, which represent the product of intense disruption and fragmentation of the originally coherent succession, consist of Upper Cretaceous limestone, sandstone and manganiferous siltstone. These blocks are of intra-formational origin, thus the *Argille varicolori* represent a broken formation (*sensu* Hsü, 1968; see also Festa *et al.*, 2012). Tens of meters thick and hundreds of meters long lenticular body of Campanian conglomerates ("Salti del Diavolo" conglomerates *Auct.*) is also enveloped within the *Argille varicolori* (Figs. 2 and 3C). The occurrence of not-mappable slices of Cenomanian(?) – early Campanian Scabiazza sandstones and early Cretaceous Palombini shales, tectonically included in the *Argille varicolori* along the thrust shear zones (see below), suggests that such lithostratigraphic units represent the stratigraphic base of the *Argille varicolori* (Fig. 2) as well as in Northern Apennines (e.g., Marroni *et al.*, 2010 and reference therein).

The *Argille varicolori* grade upward to the late Campanian(?) – Maastrichtian Monte Cassio Flysch that consists of a thick (up to 400 m) and highly disrupted succession of calcareous turbidite (Figs. 3D and 3E) alternating with grayish and light brow-yellowish hybrid calcarenite (Fig. 3F) and grayish micritic limestone, decimeters to about one meter thick, and up to decimeter thick horizons of gray marl and clay. The External Ligurian Units are followed unconformably by the late Eocene hemipelagic Monte Piano marls (Figs. 2 and 4A) that represent the stratigraphic base of the Tertiary Piedmont Basin succession (see also Dela Pierre *et al.*, 2009b; Festa *et al.*, 2009a). The shallow water coarse-grained sediments of the Cardona Formation (early Oligocene; see Fig. 4B) rest unconformably onto the Monte Piano marls and grade upward to the slope fine-grained deposits of the Antognola Formation (late Oligocene – Aquitanian; see Fig. 4C) and siliceous marls of the Lower Pteropodi marls (early Burdigalian; see Fig. 4D) (see also Clari *et al.*, 1987; Dela Pierre *et al.*, 2009b; Festa *et al.*, 2009a).

Polygenetic argillaceous breccias of late Oligocene age, firstly described in Monferrato, have been differentiated within the "undifferentiated complex" *sensu* Bonsignore *et al.* (1969) or "la Pietra Chaotic Complex" *sensu* Dela Pierre *et al.* (2003b). These breccias (Figs. 2, 4E and 4F) consist of a highly disrupted polygenetic assemblage of both native and exotic blocks (centimeters to decimeters in size) sourced from the "basal complex" *Auct.* (i.e., *Argille varicolori*, Scabiazza sandstones, Palombini shales), older stratigraphic succession (Maiolica limestones and reddish limestone) of the External Ligurian Units, Monte Cassio Flysch, and late Eocene – late Oligocene Tertiary Piedmont Basin succession (Monte Piano marls, Cardona Formation and Antognola Formation). The blocks are randomly distributed and oriented within a brecciated, almost isotropic, shaly matrix (Figs. 4E and 4F). The Polygenetic argillaceous breccias correspond to an upper Oligocene sedimentary mélange (i.e., olistostrome).

The Antognola Formation is followed unconformably by the Sciolze Group (*sensu* Festa *et al.*, 2009a, 2009b) that includes shallower and coarser shelf deposits of the Moransengo sandstones (Burdigalian *p.p.* – Langhian *p.p.*; see Clari *et al.*, 1994a, 1995b; see Fig. 5A) and the whitish calcareous marls (Fig. 5B) of late Burdigalian age, corresponding to the Pietra da Cantoni Formation (see also Dela Pierre *et al.*, 2009b; Festa *et al.*, 2009a).

The Langhian succession is introduced by a regional unconformity bounding at the base whitish hybrid arenite (Fig. 5C) of the Tonengo sandstones (Pino Torinese Group *sensu* Festa *et al.*, 2009a, 2009b) that represent outer platform deposits (see also Clari *et al.*, 1994a).

Alluvial deposits of Holocene to Quaternary age drape the base of the foothills.

4.2. TECTONIC SETTING

The tectonic setting is described in the following through the crosscutting relationships between faults and stratigraphic unconformities, or between different mesoscale deformation features.

The unconformity at the base of the late Eocene Monte Piano marls constrains to the Late Cretaceous – early Eocene the deformation affecting the External Ligurian Units. This deformation is not shown at map scale because of the overprinting of later deformation (see below). However, at the mesoscale the *Argille varicolori* are characterized by a layer-parallel extensional fabric (Figs. 6A and 6B), mainly WNW-striking (Fig. 7A), resulting from progressive bedding-parallel boudinage typical of broken formations (*sensu* Hsü, 1968; see also Festa *et al.*, 2012). Pinch-and-swell structures and boudinage are mainly asymmetric (Fig. 6A) and define a planar alignment mainly along WNW-ESE direction. Elongated intra-formational blocks show irregular flat-to ellipsoidal shape corresponding to different degrees of extension accompanied by R and R' shears (Figs. 6A and 6B). Decimeters wide, ESE-verging noncylindrical flattened and intralayered asymmetrical folds uniformly occur in the *Argille varicolori* (Fig. 6C). These are commonly rootless and transposed with mainly NNE-striking fold axes (Fig. 7B). The unconformity at the base of late Eocene Monte Piano marls constrains to Late Cretaceous – early Eocene the first tectonic stage preserved in the studied sector (see Geological Sections 1, 2 and 3).

The unconformity at the base of the Cardona Formation records the drowning of Early Oligocene shelf sediments controlled by NW-striking left-lateral transtensive faults (see also Piana, 2000; Dela Pierre *et al.*, 2003b; Festa *et al.*, 2005, 2009b). These faults, that are well preserved at the mesoscale (Fig. 1A), show meters-to tens of meters wide "tulip type" flower structures such as, for example, along the NW-striking fault located to the South of Piazzo (Fig. 6D). At regional scale, transtensive faulting defined localized NW striking pull-apart basins that controlled the drowning of early Oligocene sediments (see Mutti *et al.*, 1995; Piana, 2000; Dela Pierre *et al.*, 2003b; Festa *et al.*, 2005, 2009b; Rossi *et al.*, 2009; Mosca *et al.*, 2010). The tectonic activity of these faults corresponds to the Rupelian tectonic stage of Piana (2000) and Festa *et al.* (2005, 2009b).

The Cardona Formation (Oligocene *p.p.*) and the lower part of the Antognola Formation (late Oligocene – early Miocene) are overthrust by the Late Cretaceous External Ligurian Units (Monte Cassio Flysch and *Argille varicolori*) along a NW-striking and NE-verging thrust (see Geological Sections 1, 2 and 3). SW and NE-dipping splays develop from the main thrust surface as in the sectors ESE of Novarese (see also Geological Section 3) and NNE of Moglietto (see also Geological Section 2), respectively. In this last sector, the NE and SE-dipping thrusts depict a NW-striking pressure ridge along which the *Argille varicolori* are pushed up (see Geological Section 2).

In the hangingwall of the main NE-verging thrust, the *Argille varicolori* are deformed by contractional shearing to form a narrow (up to tens of meters thick) NW-striking-tectonic mélange (Fig. 6F and 7C). Shear deformation cuts and completely overprints the above described layer-parallel extensional fabric of the *Argille varicolori* (i.e, broken formation) forming a scale independent "structurally ordered" (*sensu* Festa, 2011; Festa *et al.*, 2012) block-in-matrix fabric (Fig. 6F), and a pervasive scaly cleavage in the matrix (Figs. 6G). Here, the *Argille varicolori* tectonically include blocks of both native (e.g., limestone, sandstone and manganiferous siltstone) and exotic origin (e.g., Early Cretaceous Palombini shales, Cenomanian(?)–early Campanian Scabiazza sandstones) wrenched from the "basal complex", the older buried succession (Late Jurassic-to Early Cretaceous Maiolica), late Campanian(?)-Maastrichtian Monte Cassio Flysch, and the late Eocene – Oligocene Tertiary Piedmont Basin succession.

The emplacement of the Polygenetic argillaceous breccias (see also Geological Section 1) constrains to the early part of late Oligocene the tectonic superposition of the External Ligurian Units onto the Tertiary Piedmont Basin succession. This data better details the late Chattian – pre late Burdigalian tectonic stage described in literature (see Piana, 2000; Festa *et al.*, 2005, 2009b) constraining the thrusting to the late Oligocene (i.e., Chattian).

Contractional deformation gradually decreases up to late Burdigalian times as suggested by the progressive decreasing of bedding dipping from the upper part of Antognola Formation (Aquitanian) to the Lower Pteropodi marls (early Burdigalian), Moransengo sandstones (Burdigalian *p.p.* – Langhian *p.p.*) and Pietra da Cantoni (late Burdigalian).

NW-striking right-lateral transpressive faults, cut both the thrusts (e.g., West of Mezzana, South of Piazzo) and the unconformity at base of Antognola Formation (e.g., East of Gerbole), respectively. These faults, that in some cases show typical horse tail termination (South of Piazzo), reactivated the pre-existing left-lateral transtensive faults (Piana, 2000; Dela Pierre *et al.*, 2003a, 2003b; Festa *et al.*, 2005, 2009a, 2009b). Out of the studied area, they are, in turn, sealed by the unconformity at the base of Tortonian succession (see Piana, 2000; Dela Pierre *et al.*, 2009a, 2009b; Festa *et al.*, 2005, 2009a, 2009b).

5. CONCLUSIONS

Geological mapping allows to map and describe in detail, for the first time in western Monferrato, the tectono-stratigraphic setting of the External Ligurian Units of Northern Apennines in the sector of Alps-Apennines junction. These units, that here represent the northwesternmost outcrop exposure of the External Ligurian Units of Northern Apennines, are unconformably covered by the episutural deposits of the late Eocene – late Miocene Tertiary Piedmont Basin. The crosscutting relationships between mapped faults and stratigraphic unconformities (Fig. 8), and different types of mesoscale deformation styles, allow to define four main tectonic stages (i.e., Late Cretaceous – early Eocene, Rupelian, Chattian, Serravallian; Fig. 8) recording the transition from accretionary stages to collisional deformation occurred in the internal sector of the Alpine accretionary wedge.

6. SOFTWARE

The Map was created using Adobe Illustrator 10.

The geological map has been digitalized using the ArcView 3.1 and then edited with Adobe Illustrator 10. This latter has also been used for the drawing of the geological sections and for the arrangement of the illustrations in this paper. Structural data have been processed and drawn using the software Faultkin vs. 5.5.0 (Richard W. Allmendinger, Copyright © 2001).

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FIGURE CAPTIONS

Figure 1 - Structural sketch map (A) of the northwestern Italy (modified from Bigi *et al.*, 1983; Mosca et al., 2010; Codegone et al., 2012). (B) Location of Fig. 1A.

Figure 2 - Stratigraphic columns of the External Ligurian Units, Epiligurian Units and Tertiary Basin succession in Western Monferrato and Northern Apennines. Modified after Marroni *et al.* (2010) and Codegone *et al.* (2012).

Figure 3 – (A) Highly disrupted block-in-matrix fabric of the *Argille varicolori* characterized by intense fragmentation of the originally coherent succession (NE of Moglietto); (B) Polished hand sample of the matrix of the *Argille varicolori* of Fig. 3A showing a layer-parallel extensional fabric characterized by pinch-and-swell structures and boudinage of the shaly layers; (C) Detail of the "Salti del Diavolo" conglomerates (SE of Novarese); (D) Alternating calcareous turbidite and grey marl and clay of the Monte Cassio Flysch (NNE of Torrione); (E) Calcareous marl alternating with (F) light brow-yellowish hybrid turbiditic calcarenite of the Monte Cassio Flysch (NE of Moglietto).

Figure 4 – (A) Typical aspect of the grey calcareous hemipelagic Monte Piano marls (South of C. Valentino); (B) Alternating coarse-grained yellowish sandstone and burrowed grey-greenish mudstone of the Cardona Formation (ENE of C. Micheli); (C) Alternating yellowish sandstone and silty marl of the Antognola Formation (West of Piazzo); (D) Alternating brown-reddish silicified marl and silty marl of the Lower Pteropodi marls (West of Valletta); (E) Highly disordered block-in-matrix fabric of the Polygenetic argillaceous breccias showing differently shaped blocks of limestone, sandstone, marl and siltstone that float with random distribution in a brecciated shaly matrix (NW of Gerbole). (F) Polished surface of a hand sample of the Polygenetic argillaceous breccias showing the isotropic texture of the matrix (about 1 km to the NE of Moglietto).

Figure 5 – (A) Alternating yellowish microconglomerate and grey marl of the Moransengo sandsones (SE of C. Micela); (B) Whitish calcareous marls of the Pietra da Cantoni (South of Scalaro); (C) Light gray to whitish hybrid arenite and sandstone of the Tonengo sandstones (East of Pareglio).

Figure 6 – (A) Polished hand sample of *Argille varicolori* showing asymmetric boudinage related to extensional shearing and *in situ* disruption of alternating layers of sandstone (white) and shale (red and grey) (East of Gerbole). White lines indicate R-shears; (B) Polished surface of hand sample showing R-shears (see dashed lines) transecting the varicolored shaly layers of the *Argille varicolori* (North of Piazzo); (C) Decimeters wide, intralayered flattened fold in the *Argille varicolori* (ENE of Gerbole); (D) Mesoscale left-lateral transtensive fault showing a "tulip type" flower structure in the Monte Piano marls (South of Piazzo); (E) Plan view of a mesoscale left-lateral transtensive fault in the Monte Piano marls (South of Piazzo). The photograph on the left is schematically redrawn on the right of the figure. Mesoscale data of the fault are also shown in the structural diagram (Schmidt net, lower hemisphere); (F) "Structurally ordered" block-in-matrix fabric within the *Argille varicolori* tectonic mélange close to the main thrust (SW of la Pietra). The fabric is related to NE-verging reverse shear (red lines) and it is characterized by elongated extra-formational blocks embedded in a matrix pervasively affected by scaly fabric and S-C features; (G) Polished surface of a hand sample of the *Argille varicolori* tectonic mélange showing the reverse shear surfaces and related R-shear, and a pervasive scaly fabric (about 1 km to the NE of Moglietto).

Figure 7 – Mesoscale data (Schmidt net, lower hemisphere) of the extensional scaly fabric (A) and fold axes (B) of the *Argille varicolori* broken formation, and the scaly fabric (C) of the *Argille varicolori* tectonic mélange.

Figure 8 – Simplified geological-structural map of the investigated area showing the crosscutting relationships between different faulting stages (indicated with different colors) and stratigraphic unconformities (see text for a complete explanation). These relationships allow to define four tectonic stages as summarized in the time column in the right part of the figure.

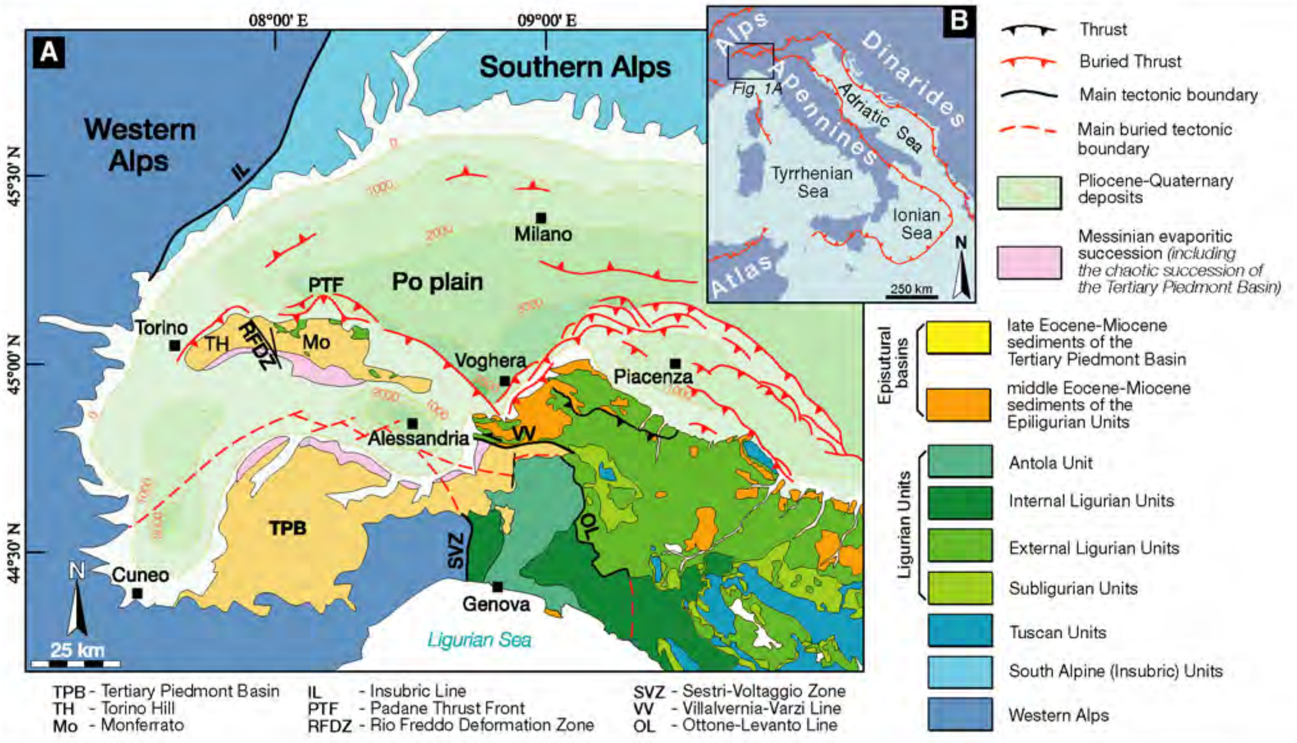
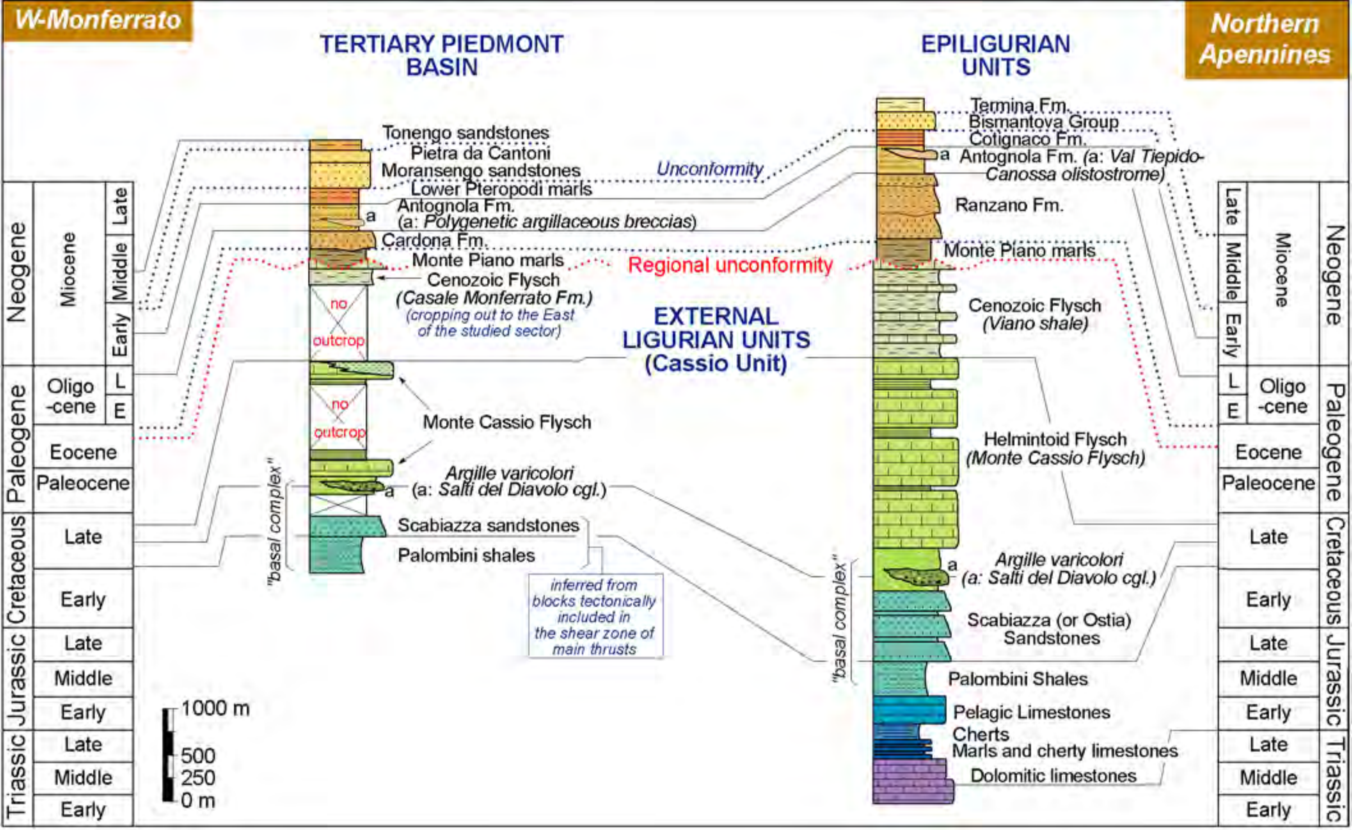


Figure 1 - Festa and Codegone



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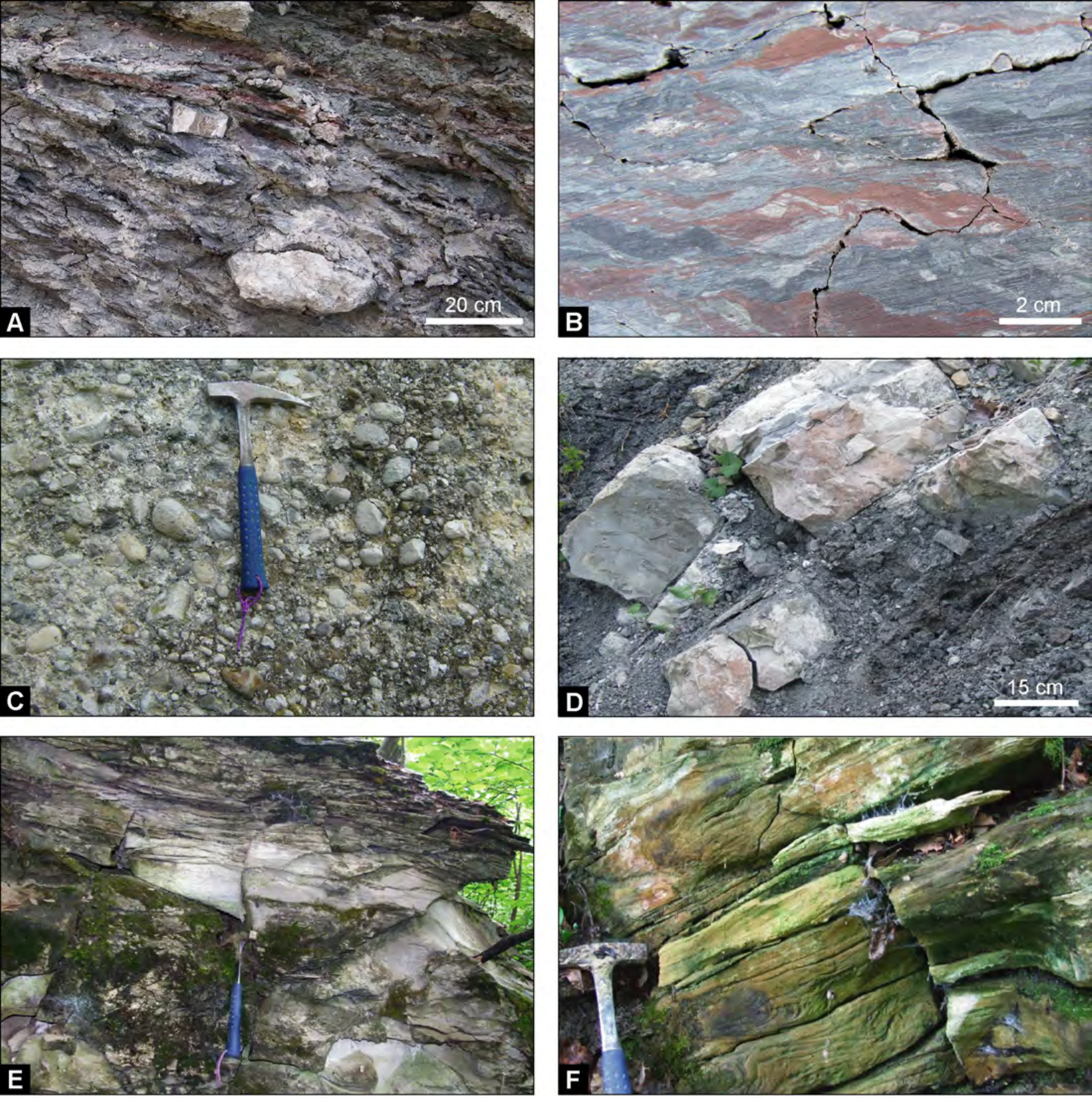

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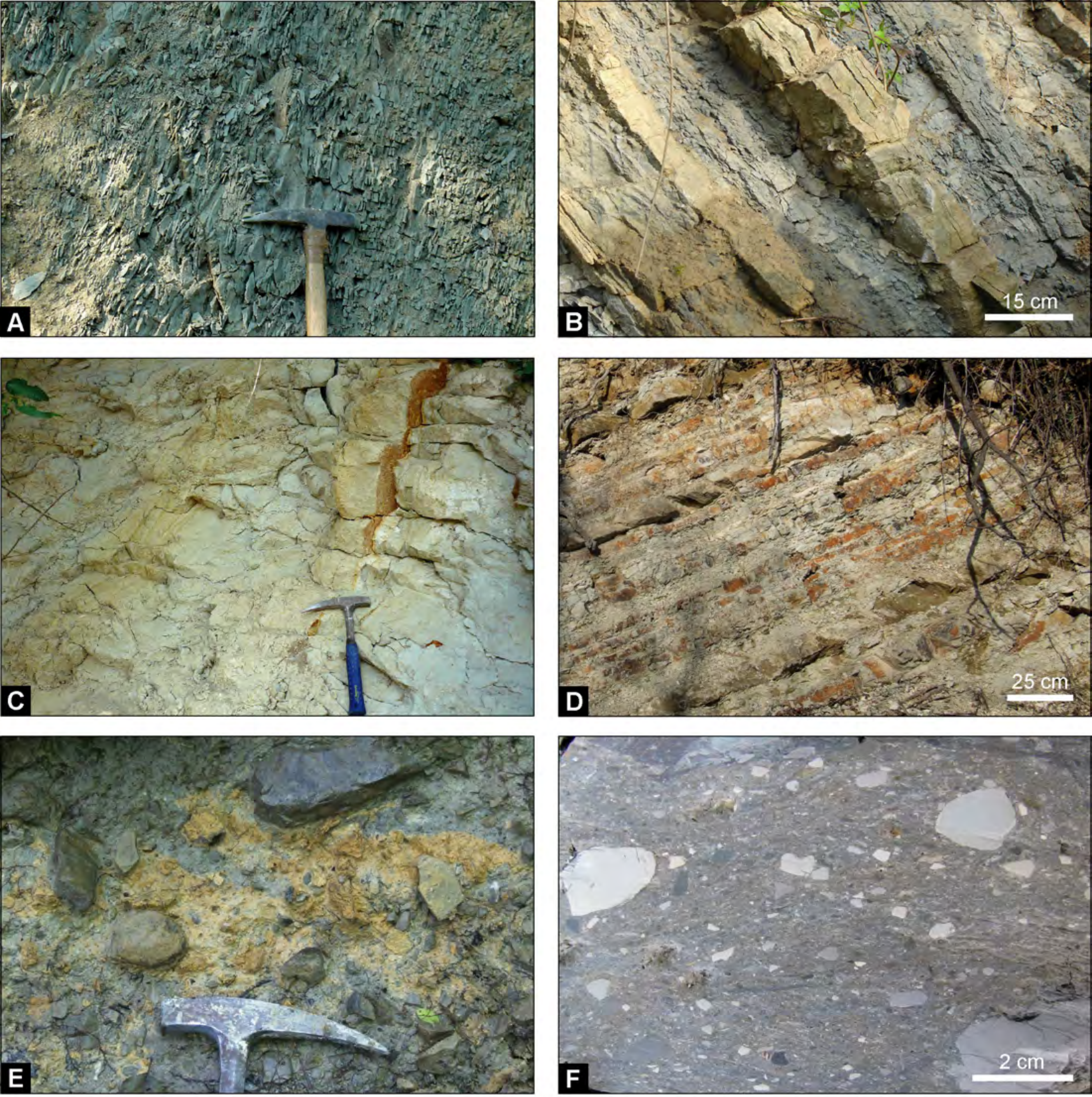

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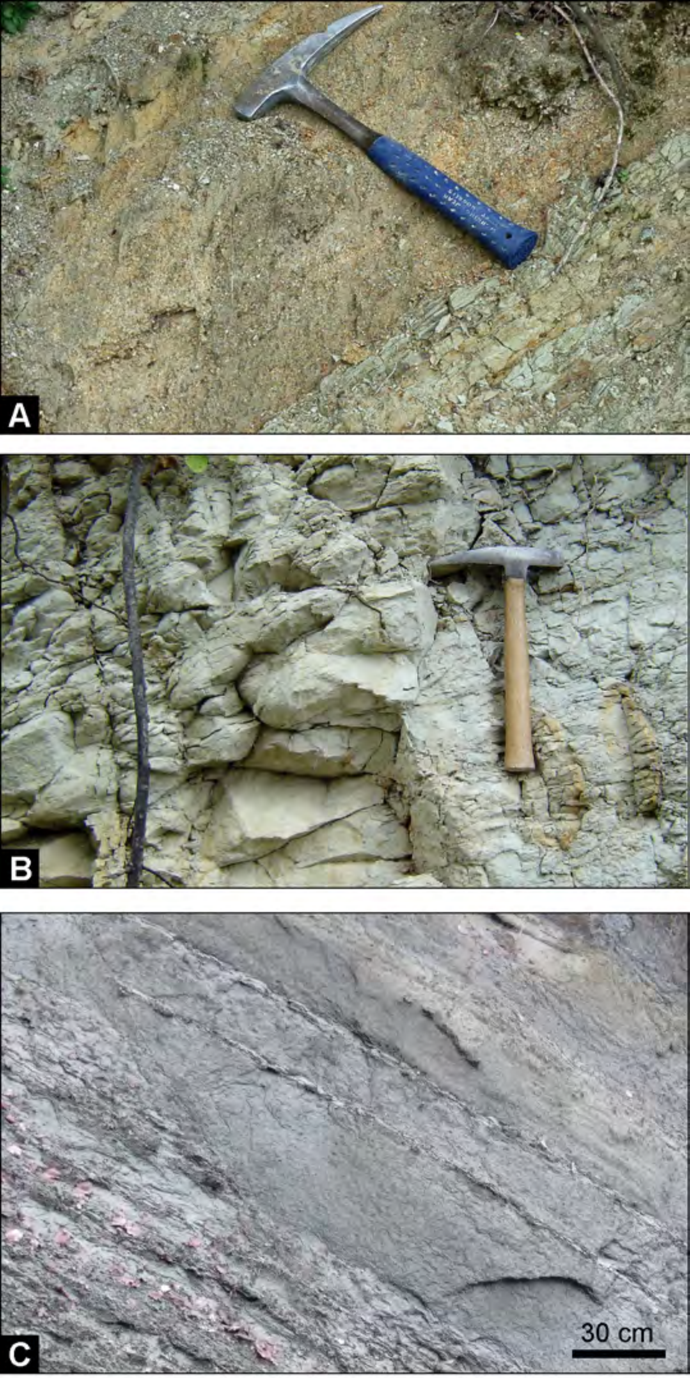

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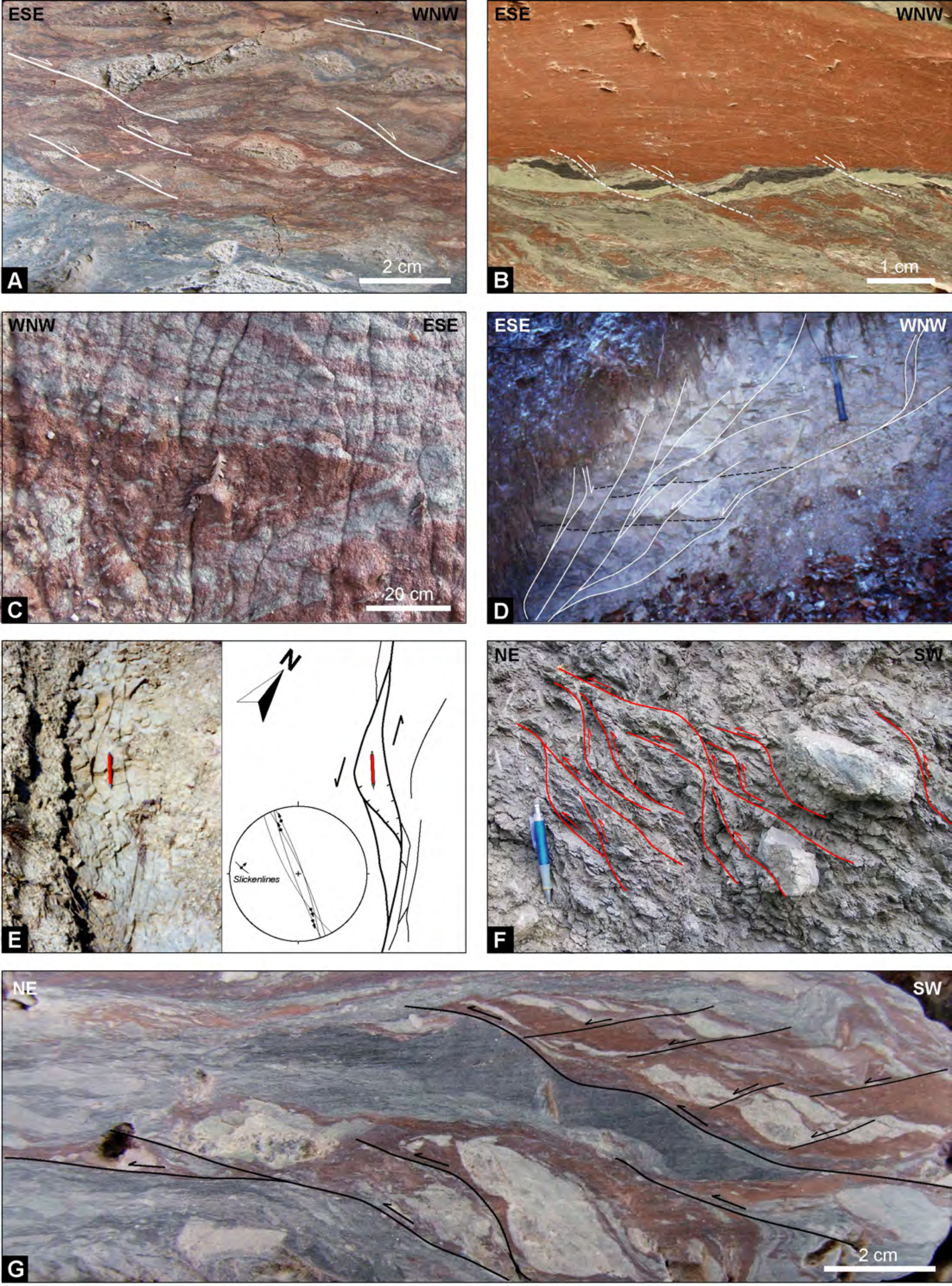

Figure 6 - Festa and Codegone

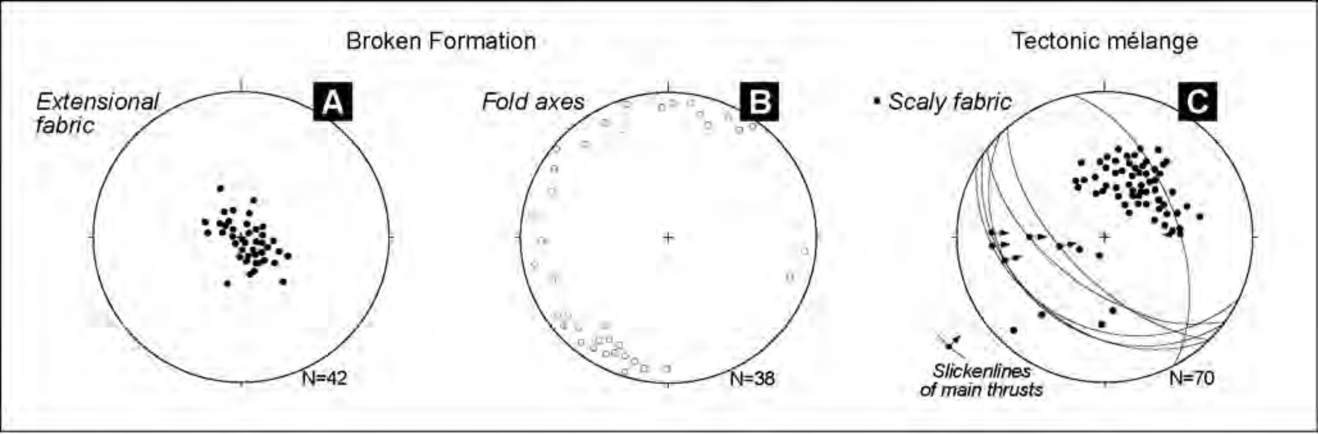

Figure 7 - Festa and Codegone

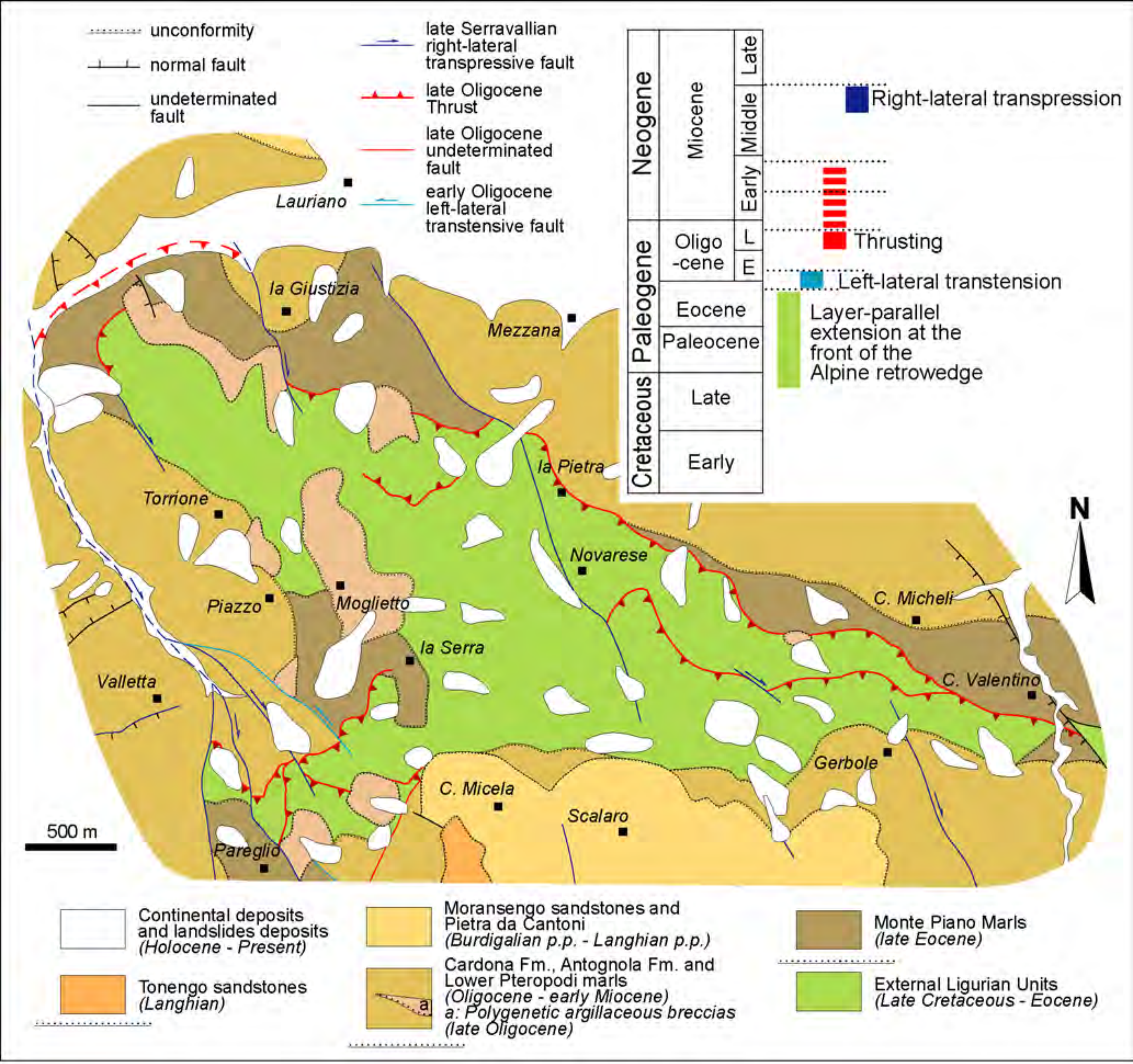

Figure 8 - Festa and Codegone