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Science

# Fault tectonics of the Tuscan Nappe in the eastern sector of the Apuan Alps (Italy)

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**ABSTRACT**

We present the geological-structural map of the Tuscan Nappe exposed on the eastern border of the Apuan Alps metamorphic dome (Tuscany, Italy). The 1:6,500 scaled Main Map covers an area of about 10 km$^2$. It contains the first detailed overview of the fault tectonics affecting the Tuscan Nappe during the exhumation and uplift of the Tuscan Metamorphic Units. We documented a polyphase fault tectonics that initially produced low-angle extensional faults and later high-angle faults. The latter started within a transtensional tectonic regime that produced left-lateral strike-slip faults. Lately a pure extensional tensor, indicating a switch of the maximum compression $\sigma1$ axis from sub-horizontal to sub-vertical, produced faults with a dominant dip-slip component. In our reconstruction the lateral thickness variations documented in several formations of the Tuscan Nappe is mainly controlled by tectonics and not by stratigraphy, as previously suggested.

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Tuscan Nappe; Apuan Alps; polyphase brittle tectonics; transtensive faults

## 1. Introduction

The Apuan Alps are a tectonic window that exposes the deepest roots of the Northern Apennines orogenic belt, Italy. For this reason, they play a key role in the understanding of the tectonic processes leading to both the development of this orogenic belt and its present-day architecture. The boundary of the tectonic window (the window fault of Hodgkins & Stewart, 1994; see also Molli, 2012) consists of a cataclastic fault zone separating the Tuscan Metamorphic Units (i.e. the core of the tectonic window) from the overlying non-metamorphosed Tuscan unit (i.e. the Tuscan Nappe) (Figure 1). This main fault zone has a long and complex evolution. During the early Miocene it was a thrust responsible for the doubling of the Tuscan units whereas since the middle-late Miocene, it acted, as an extensional shear zone accommodating the exhumation of the Tuscan Metamorphic Units (i.e. Carmignani & Kligfield, 1990). In recognition of its acknowledgment at a global level (e.g. Wimbledon et al., 1996), the tectonic window was inventoried as the geosite #1 in the geosite inventory of the Apuan Alps Unesco Global Geopark (Amorfini & Isola, 2010).

Most of the studies performed in the Apuan Alps investigated the ductile deformation affecting the Tuscan Metamorphic Units whereas little information are available on the later brittle-ductile and brittle tectonics affecting this sector of the belt (Carmignani et al., 1994; Carosi et al., 2005; Corti et al., 2006; Cortopassi et al., 2006; Molli et al., 2010; Ottria & Molli, 2000; Vaselli et al., 2012). Detailed studies investigating the geometry and kinematics of brittle high-angle structures in the Tuscan Metamorphic Units documented a polyphase evolution with a first stage characterized by the interference between NE-SW trending left-lateral strike-slip faults and NNW-SSE trending right-lateral strike-slip faults with NNE-SSW trending normal and oblique-normal faults, followed by a second stage dominated by roughly NW-SE trending normal faults (Cortopassi et al., 2006; Ottria & Molli, 2000). However, excluding these studies and the small-scale maps representing the high-angle fault systems that delimit the tectonic depressions bordering the Apuan Alps main ridge (i.e. Versilia, Garfagnana and Lunigiana basins; Figure 1), the mapping of the brittle structures inside the Apuan Alps region has generally been neglected.

For the first time, we mapped low- and high-angle faults in the Tuscan Nappe exposed in the eastern sector of the Apuan Alps, i.e. in the Maestà della Formica area (Figure 1). Our findings, corroborating the fault tectonics documented in the Tuscan Metamorphic Units, are represented in a new c. 10 km$^2$ wide geological-structural map (Main Map). In the study area, the original architecture of the Tuscan Nappe is severely dissected by a polyphase faulting active under brittle-ductile to brittle deformation regimes.

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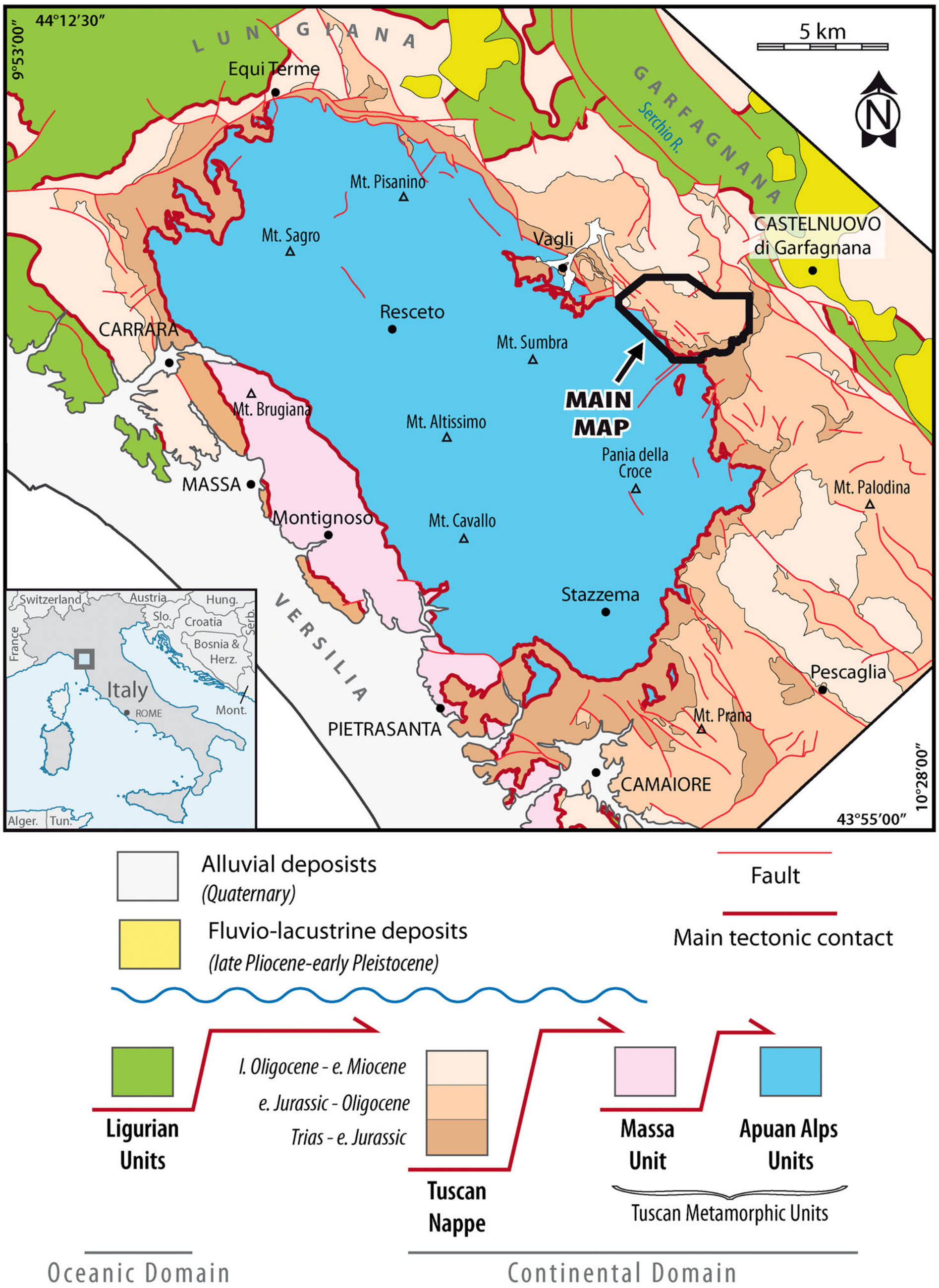

**Figure 1.** Geological sketch map of the Apuan Alps area and location of the study area (Main Map). The main tectonic contact separating the Tuscan Metamorphic Units (i.e. the core of the tectonic window) from the overlying non-metamorphosed Tuscan Nappe represents the window fault (modified after Carmignani et al., 2000).

Crosscutting relationships between different fault sets provided a detailed documentation of the late- to post-orogenic evolution of the area and, in a more general view, of the Apuan Alps mountain belt.

## 2. Geological background

The present-day architecture of the Apuan Alps region and, overall, of the Northern Apennines, derived from the convergence-related processes that started with the Upper Cretaceous intraoceanic subduction in the Ligure-Piemontese oceanic basin and continued up the middle Eocene continental collision between the two continental margins: the Europa plate and the Adria microplate. The units derived from the oceanic and Adria continental domain (e.g. Ligurian Units and Tuscan units, respectively) are stacked toward NE. The oceanic-derived units occupied the uppermost portion of the nappe stack above the non-metamorphic Tuscan unit (Tuscan Nappe). The deepest portions, now exposed in the Apuan Alps tectonic window, are represented by the Tuscan Metamorphic Units (Apuan Alps Unit and Massa Unit) (Figure 1).

The classical tectonic evolution model, elaborated for the Tuscan Metamorphic Units, is articulated in two main progressive deformation phases (Carmignani & Kligfield, 1990). The first phase D1 produced the tectonic nappe stack and it was associated with the development of a pervasive foliation which corresponds to the axial plane of isoclinal folds. During this phase, dated late Oligocene-early Miocene (derived from K-Ar and $^{40}$Ar-$^{39}$Ar datings on white mica: Kligfield et al., 1986 and biostratigraphic datings on the Tuscan Nappe: Catanzariti et al., 2002), the metamorphic units recorded the metamorphic peak at $T \approx 350$–$450$°C and $P \approx 0.6$ GPa (Molli et al., 2002 and references therein). The second phase D2 produced the progressive exhumation of the antiformal stack under extensional regime. It started at $T > 250$°C through the activation of low-angle shear zone(s) (early D2 stage) at earlier than 11 Ma (Fellin et al., 2007) and continued with the activation of high-angle normal faults (late D2 stage) responsible for the last uplift of the Apuan Alps region (Apatite Fission Track, 2–6 Ma; Fellin et al., 2007 and references therein). Alternatively, Carosi et al. (2005) suggested that the exhumation of the Tuscan Nappe occurred in a compressive tectonic setting, triggered by the interference between two main directions of horizontal shortening of subsequent folding phases, at a high angle between them, that induced buckling and vertical growth of the metamorphic dome.

The Tuscan units consist of a typical succession of a passive continental margin that was progressively involved in a collisional setting. In particular, the sedimentation of the Tuscan Nappe started with lagoon and carbonate platform deposits (Calcari a *Rhaetavicula contorta* fm., Rhaetian; Calcare massiccio fm., Hettangian – early Sinemurian) recording a progressive drowning (Calcari ad Angulati fm., late Hettangian/early Sinemurian – early Pliensbachian, Rosso ammonitico fm., Sinemurian – Pliensbachian) produced during the extensional tectonics related to the rifting leading the opening of the Ligure-Piemontese Ocean. The drowned platform was covered by turbiditic deposits (Calcare selcifero di Limano fm., late Pliensbachian; Calcare selcifero della Val di Lima fm., Bajocian-Bathonian) and pelagic deposits (Calcari e marne a Posidonia fm., Toarcian-Bathonian). These Upper Triassic – Middle Jurassic deposits are covered by cherts (Diaspri fm.) coeval to the radiolarian cherts documented in the oceanic-derived units (Ligurian Units) and so representing the first post-rift deposits. The Diaspri fm. is covered by lower Cretaceous turbidites (Maiolica fm.), sourced by fragmentation and erosion of the carbonate platform, and by the complex and puzzling formation of the Scaglia toscana (Late Cretaceous – early Oligocene). The Chattian-Aquitanian siliciclastic turbidites of the Macigno fm. represent the foredeep deposits associated with the west-dipping subduction of the Adria plate beneath the European margin.

The base of the Tuscan Nappe consists of a variable thick cataclasite (few metres to hundred metres) interpreted as derived from a Triassic evaporite formation representing the detachment sole of the Tuscan Nappe during its coupling onto the Tuscan Metamorphic Units under brittle-ductile conditions (i.e. D1 phase). These cataclasites were lately reworked by the low-angle normal faults responsible of the exhumation of the metamorphic dome (i.e. early D2 phase in the model of Carmignani & Kligfield, 1990). Since these two events occurred under similar brittle-ductile deformation conditions, the identification of the cataclasites originated during the nappe stacking and those produced during the subsequent extensional events is very difficult. Since the thickness and extension of these cataclasites marking the boundary between metamorphic and non-metamorphic units is mappable, they were historically considered and described as a formation named the Calcare Cavernoso.

In the Northern Tuscany, the thickness of each formation belonging to the Tuscan Nappe is strongly variable (e.g. Fazzuoli et al., 1985). These discrepancies have been generally explained assuming the articulate paleogeography characterizing the Adria passive margin during the Jurassic rifting episode (i.e. high sedimentation rate in subsiding basins and low sedimentation rate in structural highs). Also within the Maestà della Formica area, the thickness of several formations (e.g. Calcari ad Angulati, Calcare selcifero di Limano, Calcari e marne a Posidonia, Maiolica, Scaglia Toscana fms.) is strongly variable. Even if this thickness variation has been highlighted on previous geological maps (e.g. Carmignani, 1985; Carmignani, 2019; Carmignani et al., 2000; Puccinelli, 2016), no detailed stratigraphic/structural studies were performed in the Maestà della Formica area. The results of our stratigraphic/structural investigations presented in the Main Map, provide a reading key to correctly interpret the lateral thickness variation as produced by low-angle normal faults.

## 3. Methods

The Main Map resulted from a field mapping at 1:5,000 scale carried out during the years 2016–2019. A specific added value of our contribution is that each recognized outcrop is shown in the Main Map. In this way, the field data are clearly distinguished from the map interpretation. We used the topographic maps at 1:5,000 scale released by Regione Toscana (elementi Carta Tecnica Regionale 249082, 249121, 250053, 250094). The same topographic maps have been reduced at 1:6,500 scale and used to draw the Main Map, which covers an area of nearly 10 km$^2$.

Structural elements documented in the field (e.g. bedding, foliations, fold axes, faults) are represented in the Main Map using a synoptic representation that allows differentiating their tectonic superposition order. Each family of structural elements is also represented by means of stereographic projections to highlight their spatial orientation. In the Tuscan Metamorphic Units, we represented only the main foliation documented in the field. Abbreviations and legend followed the guidelines of the Italian geological mapping project at 1:50,000 scale (CARG project: http://www.isprambiente.gov.it/Media/carg/index.html). Landslides and slope deposits were mapped in the field and compared with the existing literature on the specific topic (e.g. Nardi et al., 2000; Puccinelli, 2016). In the Main Map, we represented only the wider landslide and slope deposits. The Man Map is accompanied by a tectonic sketch map of the Northern Apennines, by a tectonic sketch map of the Apuan Alps tectonic window, by four geological cross-sections and by stereographic projections of the main structural elements documented in the field.

## 4. Lithostratigraphy of the Tuscan Nappe in the Maestà della Formica area

In section 2. Geological Background, we briefly described the lithostratigraphy of the formations belonging to the Tuscan Nappe. Here we describe exclusively the distinguishing stratigraphic features of this unit exposed in the study area, which concern: (1) the stratigraphy of the Scaglia toscana fm., (2) the lacking of the carbonate platform deposits of the Calcare Massiccio fm. and (3) the rank of the Calcare cavernoso. For the description of the other formations see the Main Map and Figure 2.

The Scaglia toscana fm. shows a complex stratigraphy not yet adequately established in the Northern Apennines also for the difficulty of obtaining detailed age constraints. In the study area, it is widely exposed in the Pierdiscini – Maestà di Foce ridge and in the Pruneta and Metello areas (see the Main Map) for a maximum thickness of 200–230 m. During the field work, we documented four lithofacies that are briefly described below (see also Figure 2). They are represented in the geological cross-sections but not in the Main Map. The complete succession includes at the base 20–25 m of dark red shales (Shale lithofacies) covered by 50–60 m of 5–7 cm-thick layers of white calcilutites and fine-grained calcarenites (Calcilutite lithofacies). The formation evolves upward with reddish to light green shales intercalated with 2–5 cm thick layers of light green to whitish calcilutites and/or 10–50 cm thick layers of fine-grained calcarenites that can show lateral continuity or form lensed-shape bodies (Calcilutite and calcarenite lithofacies). These deposits pass upward to 40–50 m of medium calcarenites organized in layers showing variable thickness (from 70 cm to 2 m) (Calcarenite lithofacies). In the uppermost portion of the calcarenites, we occasionally documented nummulites-bearing breccias (e.g. south of Metello and north-west of Rontano). Calcarenites locally produce 6–10 m high cliffs. The top of the Scaglia toscana is represented by *c.* 20 m thick of dark red-violet red shales and siliceous shales. The Scaglia toscana fm. has been dated to the Late Cretaceous (Aptian) – early Oligocene time interval (Catanzariti et al., 2002).

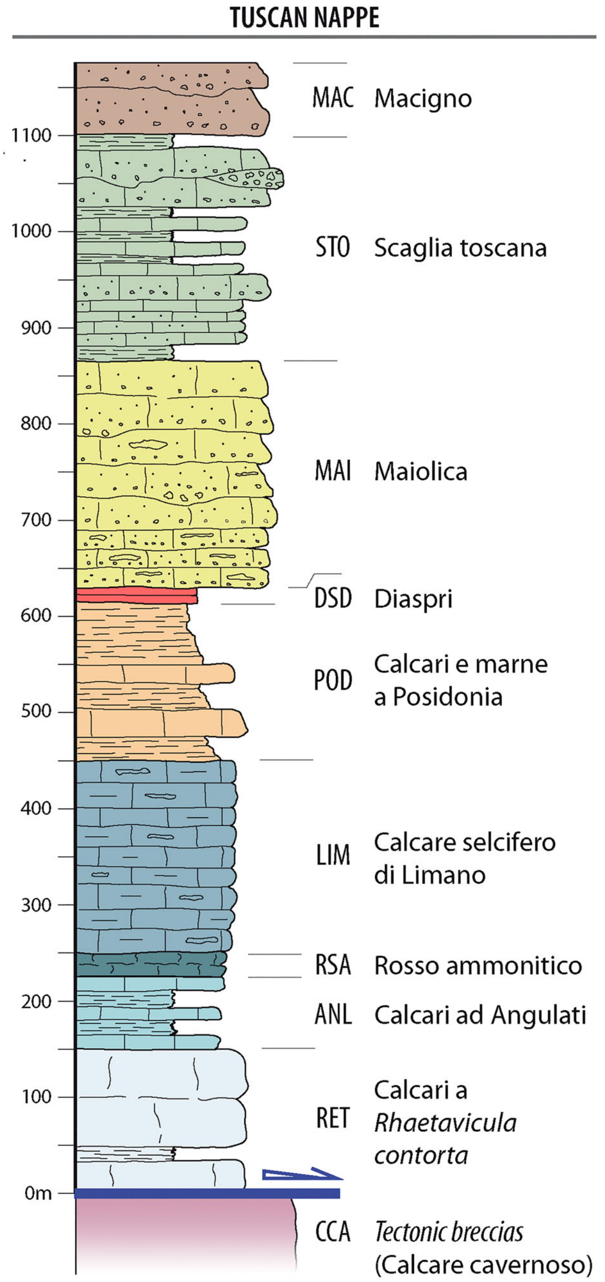

**Figure 2.** Stratigraphic column of the Tuscan Nappe exposed in the study area. According to our lithological observations, the Calcare massiccio fm. is missing in this area, and the Calcari ad Angulati fm. lies above the black and fetid stratified limestones of the Calcari a *Rhaetavicula contorta* fm. The thickness of each formation was obtained from the geological cross-section considering the maximum stratigraphic thickness

In contrast with previous geological maps (e.g. Carmignani, 1985; Carmignani et al., 2000; Nardi, 1961; Puccinelli, 2016), we mapped as Calcari a *Rhaetavicula contorta* fm. (and not as Calcare massiccio fm.) the black calcilutites that are fetid, when broken, exposed in the southern sectors of the study area. As briefly mentioned above, since the Calcare cavernoso consists of cataclasites produced during multiple events of faulting, we did not consider it as the formation that represents the stratigraphic base of the Tuscan Nappe (Figure 2).

## 5. Tectonics of the Tuscan Nappe in the Maestà della Formica area

The Tuscan Nappe recorded a polyphase deformation history similar to that documented in the underlying Metamorphic Tuscan Units. The main difference is due to the different structural levels in which the deformation took place: the Tuscan Nappe was deformed under anchimetamorphism conditions (illite crystallinity data: Cerrina Feroni et al., 1983) whereas the Metamorphic Tuscan Units were deformed under greenschist facies conditions (Molli et al., 2002 and references therein). The sequence of the deformation events is comparable to those described by Carmignani and Kligfield (1990) in the Metamorphic Tuscan Units and can be summarized as follows: a first stage featured by an axial plane foliation associated with isoclinal folds well developed in clay-dominant formations, followed by post-collisional collapse folds and low- to high-angle faults in the latest stages of deformation (e.g. Carosi et al., 2005; Pertusati et al., 1977).

### *5.1. Fold tectonics*

The oldest structures are represented by isoclinal F1 folds and a continuous axial plane foliation (S1), which were recognized mostly in pelite-bearing formations, such as the Scaglia toscana, Calcari e marne a Posidonia and Calcari ad Angulati fms. (Figure 3a, b). F1 folds are rare, always showing millimetre to decimetre size. F1 major folds deforming the entire Tuscan Nappe succession were never documented. F1 axes trend NW-SE and plunge mostly less than 20° toward SE. S1 foliation, generally at low-angle respect to the bedding, is oriented NW-SE and dips both toward NE and SW (see stereonet in the Main Map). At the microscopic scale, the S1 foliation is marked by white micas, thin films of clay minerals and oxides, resulting from pressure solution mechanisms, and by very small-elongated calcite crystals that may be interpreted both as result of rigid body rotation mechanism and selective dissolution processes (Figure 3c).

Two later folding events have been documented. They generated (1) close to tight F2 folds (opening angle 25–50°) with sub-horizontal axes dispersed around the NW-SE direction and less than 45° dipping axial planes (Figure 3d,e; see stereonet in the Main Map) and (2) open upright F3 folds characterized by axes displaying a considerable dispersion of their directions (Figure 3f; see stereonet in the Main Map).

The F2 folds are usually not associated with an axial plane foliation, although sometimes a fracture cleavage was documented at the outcrop scale. At the microscopic scale, it is marked by an occasionally and weak spaced cleavage, developed exclusively in the pelitic layers (Figure 3c). The F3 folds developed fracture cleavage exclusively in the pelitic layers.

### *5.2. Fault tectonics*

The geologic setting of the Maestà della Formica area is mainly controlled by fault systems. Two types of fault were documented during the geological-structural mapping: low-angle faults (dip angle less then 40°) and high-angle faults (dip angle ≥45°) (see the Main Map).

#### *5.2.1. Low-angle faults*

Several low-angle faults were documented at the contact between formations of the Tuscan Nappe. The fault zones are characterized by fractured and cataclastic rocks including foliated cataclasites displaying S–C fabric (Figure 4). The fault zones range in thickness from few to several 10 s of metres. The window fault (i.e. the boundary between the Tuscan Nappe and the Tuscan Metamorphic Units) is the thicker low-angle fault zone and it preserves the transition from cataclasites to fault breccia to fault gouge zones (Figure 4a, b).

The low-angle faults are directed NW-SE, dipping both toward NE and SW (see stereonet in the Main Map). Few fault planes show striations and slickensides pointing to a normal dip-slip sense of displacement (Figure 4c). The extensional nature of the low-angle fault zones is confirmed by the fact that, although portions of the stratigraphic succession are missing, the younger rocks still lie above the older ones (see the geological cross-sections in the Main Map).

Main low-angle fault zones have been documented between the tectonic breccia at the base of the Tuscan Nappe (i.e. Calcare cavernoso) and the Calcari ad Angulati fm. and between the Calcari ad Angulati and the Calcari e marne a Posidonia fms. (with the complete tectonic omission of the Rosso ammonitico and Calcari selciferi di Limano fms.). Analogously, the low-angle fault between the Calcari a *Rhaetavicula contorta* and the Calcare selcifero di Limano fms. produced the local omission of both the Calcari ad Angulati and the Rosso ammonitico fms. (see the Main Map and associated geological cross-sections). Other main low-angle fault zones were recognized at the direct superposition of the Maiolica fm. above the Calcari e marne a Posidonia fm. and inside the Calcare selcifero di Limano fm. (Figure 4d). The best example that

**Figure 3.** Folding tectonics in the Tuscan Nappe. (**a**) F1 fold in the Calcari ad Angulati fm. exposed to the east of Iapori. S0: bedding; A.P.1: F1 axial plane; S1: S1 foliation; (**b**) Isoclinal F1 folds in the Scaglia Toscana fm. exposed to the south of the Maestà della Formica locality. S0: bedding; S1: S1 foliation; the diameter of the coin used as scale is c. 24 mm; (**c**) photomicrograph of thin section collected in in the hinge zone of F2 fold in the Calcari e marne a Posidonia fm. (see **d** for location). S0: bedding; S1: S1 foliation; A.P.2: F2 axial plane; (**d**) F2 folds in the Calcari e marne a Posidonia fm. exposed close to le Coste locality. S0: bedding, S1: S1 foliation, A.P.2: F2 axial plane; (**e**) F2 fold in the Scaglia Toscana fm. exposed to the west of Case degli Orsi locality. S0: bedding, S1: S1 foliation; S2: S2 fracture cleavage; A.P.2: F2 axial plane; (**f**) F3 folds in the Diaspri fm. along the road to le Coste village. S0: bedding, A.P.3: F3 axial plane.

allowed to document the crosscutting relationships between low-angle and high-angle faults was mapped in the Mt. Ciutella area where the Maiolica fm. directly overlies the Calcari e marne a Posidonia fm. by the mean of a metre thick low-angle fault zone dissected by the high-angle faults (Figure 4e).

### *5.2.2. High-angle faults*

The previously described fault structures were subsequently crosscut by a high-angle faulting (Figure 5). It produced a pervasive main fault system with high-angle faults oriented N125–150 and a subordinate fault system oriented around the N-S direction (see stereonets in the Main Map). These high-angle faults are generally associated with incoherent and non-foliated cataclasites that evidenced the more brittle character than the previously described low-angle fault structures (Figure 5a, b). The plunge of the measured slickenlines on fault planes show strike-slip, oblique and, dip-slip kinematics (see stereonets in the Main Map).

The recognized cartographic displacements, the occurrence of strike-slip conjugate fault systems (Figure 5c) and the detected kinematic indicators point to right-lateral movement for the main NE-SW directed high-angle fault system, whereas the about N-S directed fault system acted as left-lateral strike-slip faults (see the Main Map and associated stereonets). The kinematic inversion of fault-slip data related to the strike-slip faults resulted in a strike-slip tensor with the sub-horizontal maximum compression σ1 axis directed NNW-SSE. The occurrence of negative flower structures such as those well developed in the Diaspri fm. (Figure 5c) could suggest

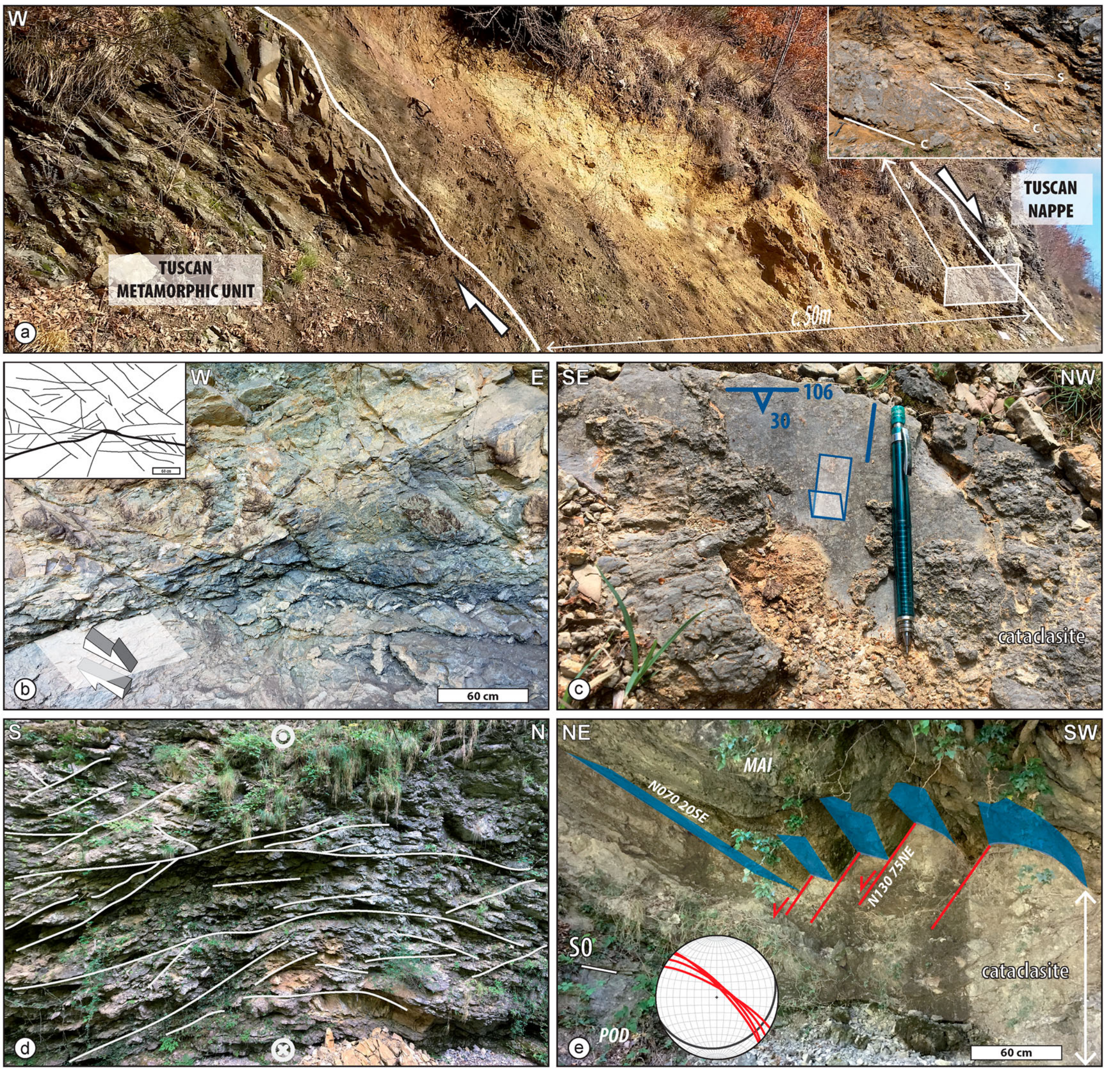

**Figure 4.** Low-angle faulting. (**a**) The window fault separating the core of the tectonic window (i.e. the Tuscan Metamorphic Units) from the overlying non-metamorphosed Tuscan Unit exposed to the south-west of Iapori. The window fault generally dips 10–20° towards the north-east. The fault zones are characterized by fractured and cataclastic rocks including foliated cataclasites displaying S-C fabric pointing to a top-to-the north-east sense of shear (see detail in the upper right portion of the picture; C: shear plane, S: foliation); (**b**) Detail of the window fault characterized by foliated cataclasite and by an array of synthetic and antithetic faults pointing to a top-to-the south-east sense of shear. The shaded white polygon represents the fault plane. A simplified sketch drawing the traces of faults is also shown. The black thick line represents the main fault plane; (**c**) Low-angle fault plane oriented N106E 30NE exposed to the south-east of the Mt. Uccelliera. It shows down-dip slikenlines (blue line) and it is associated with cataclasites. The white arrow indicates a top-to-the north-east sense of shear; (**d**) Low-angle fault zone affecting a vertical exposure of the Calcare Selcifero di Limano fm. in the Canale dell'Inferno, east of Castellina (see the Main Map). The bedding is completely transposed by several anastomosed shear planes (white lines) dipping both toward NE and SW and producing a lozenge-shape geometry. The picture is orthogonal to the top-to-the east sense of shear, which is indicated by the two white dots symbols in the upper and lower central portion of the picture; (**e**) Mt. Ciutella low-angle fault separating the Maiolica fm. (MAI) and the Calcari e marne a Posidonia fm. (POD). It produced a m-thick incoherent cataclasite deformed by high-angle down-dip fault (red lines). Blue polygons highlight the Mt. Ciutella low-angle fault plane. S0: bedding. Stereonet (Schmidt equal area, lower hemisphere) of the low-angle fault (blue) and high-angle faults (red) is also shown.

that the high-angle faulting was generated within a transtensional tectonic regime.

Some high-angle fault planes displayed multiple generations of slickenlines with normal dip-slip slickenlines overprinting the strike-slip ones (Figure 5d). This timing is supported also by the fact that the fault planes, where the dip-slip slickenlines were documented, are (sub-) vertical. If they originated as normal faults, in fact, the dip of the fault planes had to be *c.* 60° (Anderson, 1951). The normal faults (Figure 5b, e) provided a pure extensive tensor characterized by a minimum compression σ3 axis directed NE-SW (see the stereonet in the Main Map).

## 6. Discussion

The geological-structural analyses allowed the definition of a polyphase fault tectonics characterized by a stage of low-angle faulting followed by a high-angle faulting. This latter can in turn be subdivided

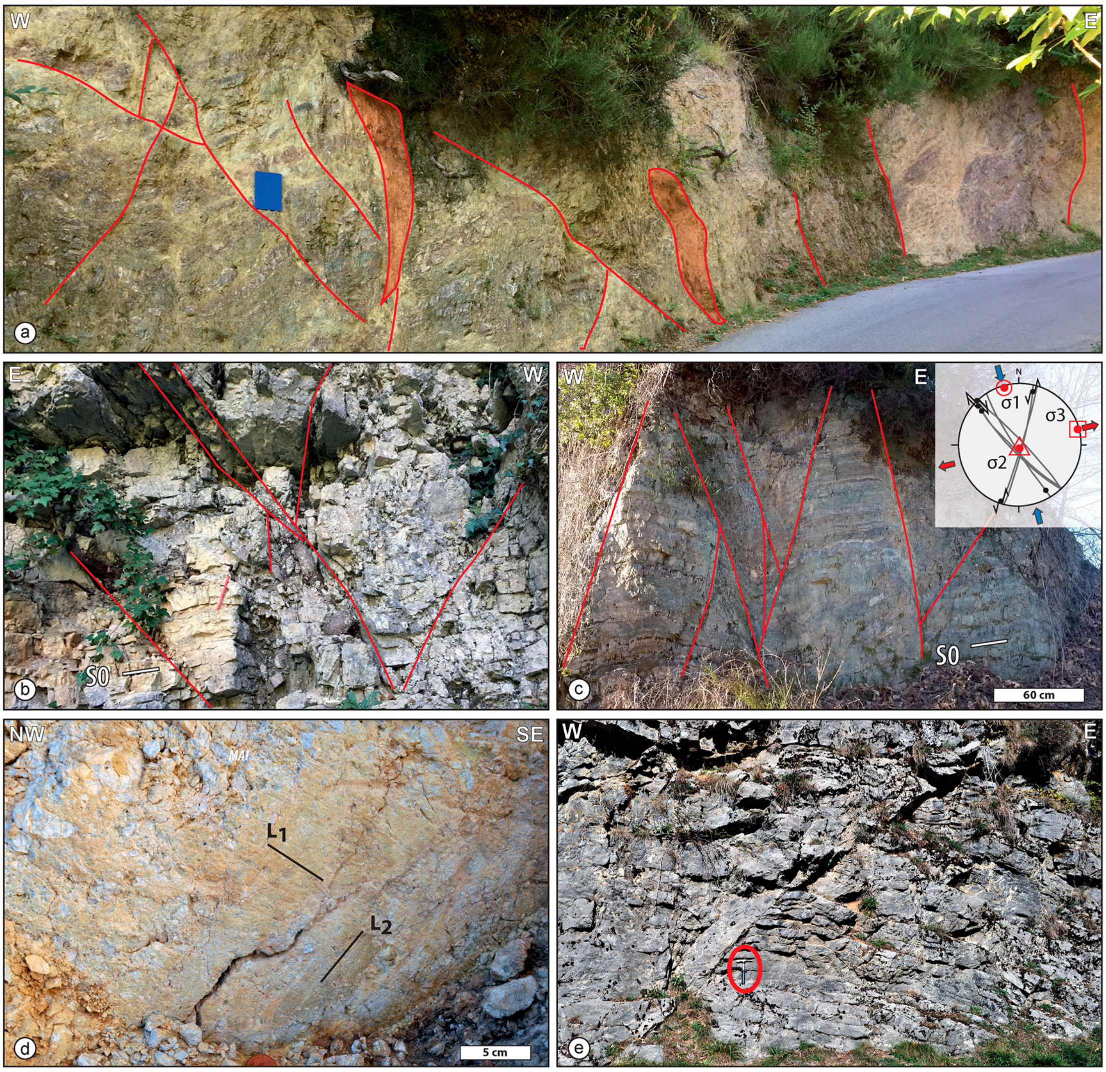

**Figure 5.** High-angle faulting. (**a**) c. 50 m-thick fault zone affecting the Diaspri fm. exposed south of the Mt. Uccelliera. Red lines represent the intersection between the main faults and the vertical road cut, the red shaded polygons represent the main fault planes. A4 folder for scale; (**b**) Normal faults affecting the Maiolica fm. exposed north of the Mt. Ciutella. These faults were activated during the latest event of faulting affecting the Tuscan Nappe. S0: bedding; (**c**) Flower structures developing in the Diaspri fm. exposed south of the Mt. Uccelliera. Stereonet (Schmidt equal area, lower hemisphere) shows the principal stress axes (σ1, σ2, σ3) obtained from the conjugated strike-slip faults. S0: bedding; (**d**) Fault plane in the Maiolica fm. displaying multiple generations of slickenlines with normal dip-slip slickenlines (L2) overprinting the strike-slip ones (L1); (**e**) Normal fault affecting the Calcari ad Angulati fm. exposed to the west of Iapori. Hammer as scale.

in a first phase generating strike-slip faults and a second phase that developed normal faults.

We interpreted the Mt. Ciutella low-angle fault and the overlying main low-angle faults dissecting the Tuscan Nappe succession as synthetic faults associated with the main low-angle extensional contact located at the base of the Tuscan Nappe (i.e. the window fault) and exposed SW of the Iapori village. Consequently, the low-angle normal faults would have accommodated part of the exhumation of the metamorphic dome during the D2 deformation phase of Carmignani and Kligfield (1990). The contribution of each fault to the overall exhumation process can be qualitatively inferred from the missing thickness of the formations of the Tuscan Nappe that was partly omitted by the fault itself. A main effect of the documented low-angle extensional faulting in the study area seems to be the complete tectonic omission of the massive limestones of the Calcare Massiccio fm., even if this conclusion should be corroborated with more data about the stratigraphic vs. tectonic relationships among the Calcari a *Rhaetavicula contorta*, Calcare massiccio and Calcari ad Angulati fms. in other Tuscan Nappe outcrop areas of the Apuan Alps tectonic window.

The above described F2 folds, which represent the main fold structures documented at the outcrop scale, can be inserted in the evolution of the low-angle faulting as detachment folds developed between low-angle fault zones. The age of the brittle-ductile low-angle extensional faulting documented in the Tuscan Nappe could be correlated with the age of the main removal of crustal thickness constrained in the Carrara marbles of the underlying

Tuscan Metamorphic Units as earlier of about 4 Ma (Balestrieri et al., 2003; Vaselli et al., 2012 and references).

Subsequently, the high-angle faulting cutting the low-angle fault system (together with erosion processes) enhanced the uplift of the Tuscan Units. The direction of the main fault systems and the kinematic reconstruction (i.e. native strike-slip faults then reactivated as normal faults) allowed the correlation with the brittle tectonic framework delineated for the Tuscan Metamorphic Units by Ottria and Molli (2000). The NNW-SSE directed maximum compression σ1 axis from the analyzed strike-slip faults of the Maestà della Formica area, as well as the NE-SW directed minimum compression σ3 axis from the analyzed normal faults match with that framework. Regarding the possible relationships between folding and faulting, we speculate that the F3 upright folds may be related to the high-angle strike-slip faulting in a transtensional context (i.e. transtension folds; Fossen et al., 2013).

Considering that the orientation of the high-angle faulting documented in the study area is analogous to those of the fault systems bounding the tectonic depression of the Serchio Valley, their age constraints can be obtained considering the ages of sediments deposited in the Serchio valley affected by faulting (late Pliocene – middle Pleistocene) (e.g. Moretti, 1992). The development of the high-angle fault structures can be therefore referred to a time interval between the late Pliocene and the middle Pleistocene. The present-day seismicity in the marginal zones of the Apuan Alps testifies that the area is still tectonically active.

## 7. Conclusions

The new detailed geological map presented here at the scale of 1:6,500 (i.e. the Main Map) allowed the better understanding of the structural evolution of the Tuscan Nappe exposed in the eastern sectors of the Apuan Alps, introducing new improvements in the geological mapping of the area. Geological mapping and structural analysis indicate that the late stages of the complex deformation history of the Tuscan Nappe evolved through two main different tectonic events: a first brittle-ductile extensional low-angle faulting and a late brittle high-angle faulting. The latter event produced initially strike-slip faults then reactivated by normal faults. The lateral thickness variations documented in several formations of the Tuscan Nappe exposed in the study area were mainly produced by the low-angle normal faults. As a consequence, the stratigraphic thickness variations often documented within the Tuscan Nappe should be revisited in this updated view.

## Software

The final map layout was made and assembled using Illustrator CC 2018. Topographic maps were acquired from 1:5,000 scaled topographic map from Carta Tecnica Regionale (Regione Toscana) elements n. 249082, 249121, 250053, 250094. Stereonet plots of bedding, foliation and fold axis were produced using OSXStereonet (v. 3.5) by Cardozo and Allmendinger (2013), whereas the plots of faults were produced using Win_-TENSOR software (Delvaux & Sperner, 2003). Planes are plotted as poles. All plots were redrawn using Illustrator CC 2018.

## Geolocation information

The Main Map is located in the Apuan Alps, Tuscany Region, Italy. It extends between latitude N 44° 06′21.1080″ and N 44°04′41.5056″ and longitude E 10°22′46.9020″ and E 10°23′19.175″.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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