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Structural and Stratigraphic Setting of Campagna and Giffoni Tectonic Windows: New Insights on the Orogenic Evolution of the Southern Apennines (Italy)

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Abstract: We present a structural study on the tectonic windows of Giffoni and Campagna, located in the western sector of the southern Apennines (Italy). We analyzed thrusts, folds, and related minor deformation structures. Here, a major in-sequence E-verging thrust fault juxtaposes Meso-Cenozoic successions of the Apennine Platform (Picentini Mts unit) and the Lagonegro-Molise Basin (Frigento unit). However, out-of-sequence thrusts duplicated the tectonic pile with the interposition of the upper Miocene wedge-top basin deposits of the Castelvetere Group. We reconstructed the orogenic evolution of these two tectonic windows, including five deformation phases. The first (D1) was related to the in-sequence thrusting with minor thrusts and folds, widespread both in the footwall and the hanging wall. A subsequent extension (D2) has formed normal faults crosscutting the D1 thrusts and folds. All structures were subsequently affected by two shortening stages (D3 and D4), which also deformed the upper Miocene wedge top basin deposits of the Castelvetere Group. We interpreted the D3–D4 structures as related to an out-of-sequence thrust system defined by a main frontal E-verging thrust and lateral ramps characterized by N and S vergences. Low-angle normal faults were formed in the hanging wall of the major thrusts. Out-of-sequence thrusts are observed in the whole southern Apennines, recording a crustal shortening event that occurred in the late Messinian–early Pliocene. Finally, we suggest that the two tectonic windows are the result of the formation of an E–W trending regional antiform, associated with a late S-verging back-thrust, that has been eroded and crosscut by normal faults (D5) in the Early Pleistocene.

Keywords: southern Apennines; out-of-sequence thrust; wedge-top basin; tectonic window

1. Introduction

The fold-and-thrust belt of the southern Apennines (Figure 1) is defined by low- and high-angle thrusts [1–9]. Thin-skinned tectonics, characterized by dominant low-angle thrusts, has been active mainly in the first part of the orogenic evolution, from the early Miocene to the early Pliocene, recording most of the orogenic shortening (e.g., [2,10]). On the other hand, thick-skinned tectonics, defined by high-angle thrusts, played a significative role in the crustal shortening during the Pliocene–Middle Pleistocene; they were nucleated at deeper structural levels showing smaller displacements (e.g., [1,4,7,8]). Thick-skinned tectonics has probably acted through the positive inversion of pre-existing normal faults located in the Permo-Triassic rocks of the downgoing Adria plate [3], likely triggered by the buttressing of the thick Apulian Mesozoic carbonates against the allochthonous wedge in the early Pliocene [6,11]. The fault inversion generated deep-seated envelopment thrusts [12,13] that crosscut upward the already formed orogenic wedge and presently appear as out-of-sequence structures (Figure 1b; [11,14,15]). In the axial sector of the southern Apennine chain, these ramp-dominated thrusts have formed several anticlines within the buried Apulian carbonates that originated hydrocarbon traps presently drilled and exploited (e.g., [16]). These envelopment thrusts are widespread in the southern Apennines (e.g., [11,14,15,17]), frequently deforming the upper Miocene–Middle Pleistocene wedge-top basin deposits both in the western and eastern sectors of the chain. However, few studies have provided information about the orientation, structural style, kinematics, and age of these out-of-sequence structures (e.g., [11,14,15]). In this work, we analyzed the tectonic windows of Giffoni and Campagna in the southern Apennines (Figure 1a), where in- and out-of-sequence thrusts and related structures are remarkably exposed. These two regional structures have been previously studied by different authors [18–22] and were mapped in the new official geological cartography [23,24]. We present a detailed study of the mesoscale deformation structures, with the aim to reconstruct the orogenic evolution of this key sector of the chain, where a crustal section of the allochthonous wedge is naturally exposed.

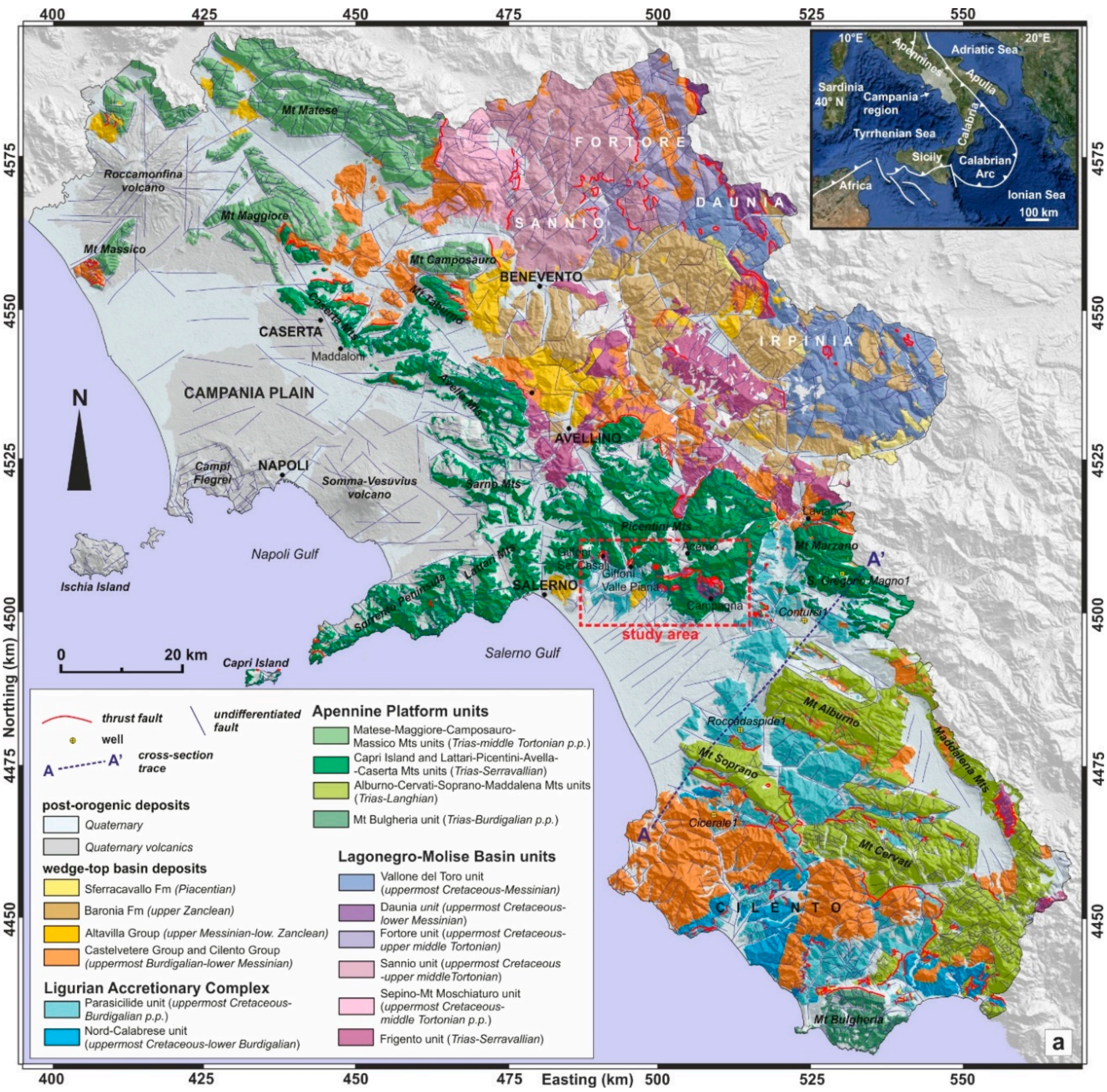

Figure 1. *Cont.*

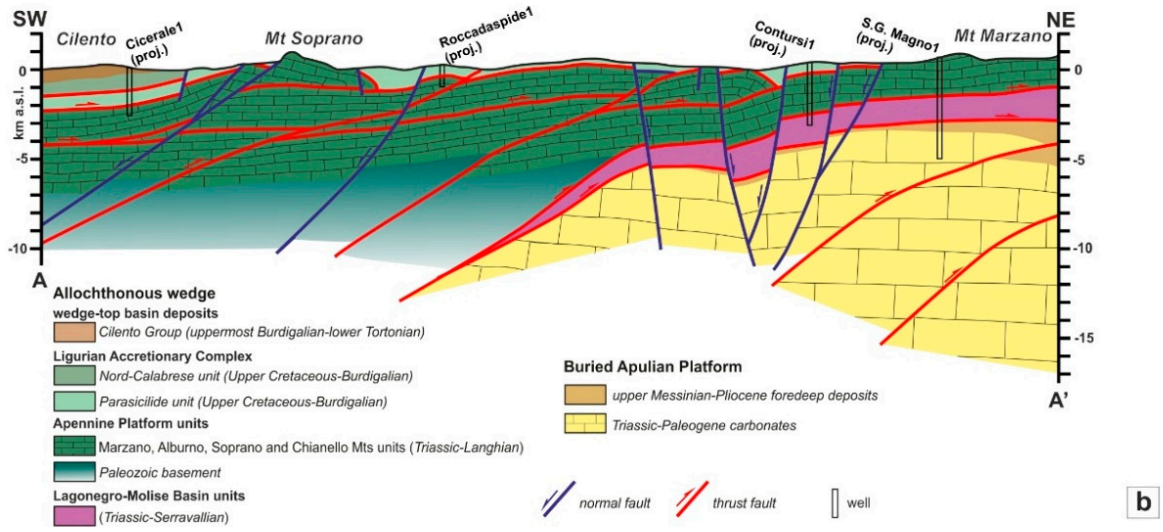

Figure 1. (**a**) Schematic geological map of the southern Apennines. (**b**) Geological cross-section. (**a**,**b**) modified after [8].

2. Geological Setting

The superposition of different thrust-sheets characterizes the study area (Figure 1a,b). The main tectonic units refer to three paleogeographic domains: (i) Ligurian Accretionary Complex (Parasicilide unit; [25–31]); (ii) Apennine Platform (Picentini Mts and Mt Croce units; [7,8,19–24,32–39]); (iii) Lagonegro-Molise Basin (Frigento unit; [7,8,10,40–44]).

The Parasicilide unit is widely exposed in the Sele River valley and the Salerno area (Figure 1a). It is made up of deep-basin deposits (Figure 2), including at the base of the uppermost Cretaceous–middle Eocene pelitic Argille Scagliose Fm, upward passing to upper Eocene–Aquitanian marly-calcareous M. S. Arcangelo Fm and varicolored clays of the Argille Varicolori Fm. Burdigalian foredeep sandstones of the Albanella Fm seal the Parasicilide succession.

The Picentini Mts unit mainly consists of a thick shallow-water succession (Figure 2) with at base Carnian–Norian dolostones and limestones, upward passing to Jurassic–Upper Cretaceous dolomitic limestones and limestones. Pelagic dolostones and limestones with cherts locally replace the shallow-water Norian–Lower Jurassic succession. At places, the Maastrichtian–Paleocene margin recrystallized calcareous breccias (Calcari Cristallini Fm) cover the Mesozoic succession.

The Monte Croce unit, exposed only in the Campagna tectonic window, is composed, from bottom to top (Figure 2), of Upper Cretaceous–lower Aquitanian margin recrystallized breccias, calcarenites, and scaglia-like reddish argillites (Fontana Frasci Fm) upward passing to Aquitanian–Serravallian deep basin, scaglia-like, pelitic, marly, and calciclastic turbidites and, finally, Serravallian foredeep sandstones (Fontana Porcellara Fm and Vallimala Flysch). The lower part of the succession is partially replaced by diagenetic dolomite.

The Frigento unit (Figure 2) consists of Ladinian–Carnian, slope to basin, calcilutites, and sandstones embedding boundstone bodies (Monte Facito Fm) at the base, covered by Carnian–Norian cherty calcarenites and calcilutites (Calcari con Selce Fm). The succession passes upward to Rhaetian–Jurassic radiolarites and reddish and greenish silicized argillites (Scisti Silicei Fm), and Lower Cretaceous dark siliceous shales with intercalations of calcilutites (Flysch Galestrino Fm). Finally, Upper Cretaceous–lower Miocene calcarenites, calcilutites, and varicolored clays (Flysch Rosso Fm), Langhian Numidian sandstones, and Serravallian foredeep sandstones of Serra Palazzo Fm cover the whole succession.

All tectonic units are sealed by the wedge-top basin deposit of the Castelvetere Group (CVTG), which in the Campagna tectonic windows is represented by the Fontana Frigine Fm. Other uppermost Messinian–Pliocene wedge-top basin deposits, with minor extension, unconformably cover the older successions. Finally, Lower–Middle Pleistocene alluvial and lacustrine clastic deposits, including the Eboli conglomerates, extensively cover the analyzed area.

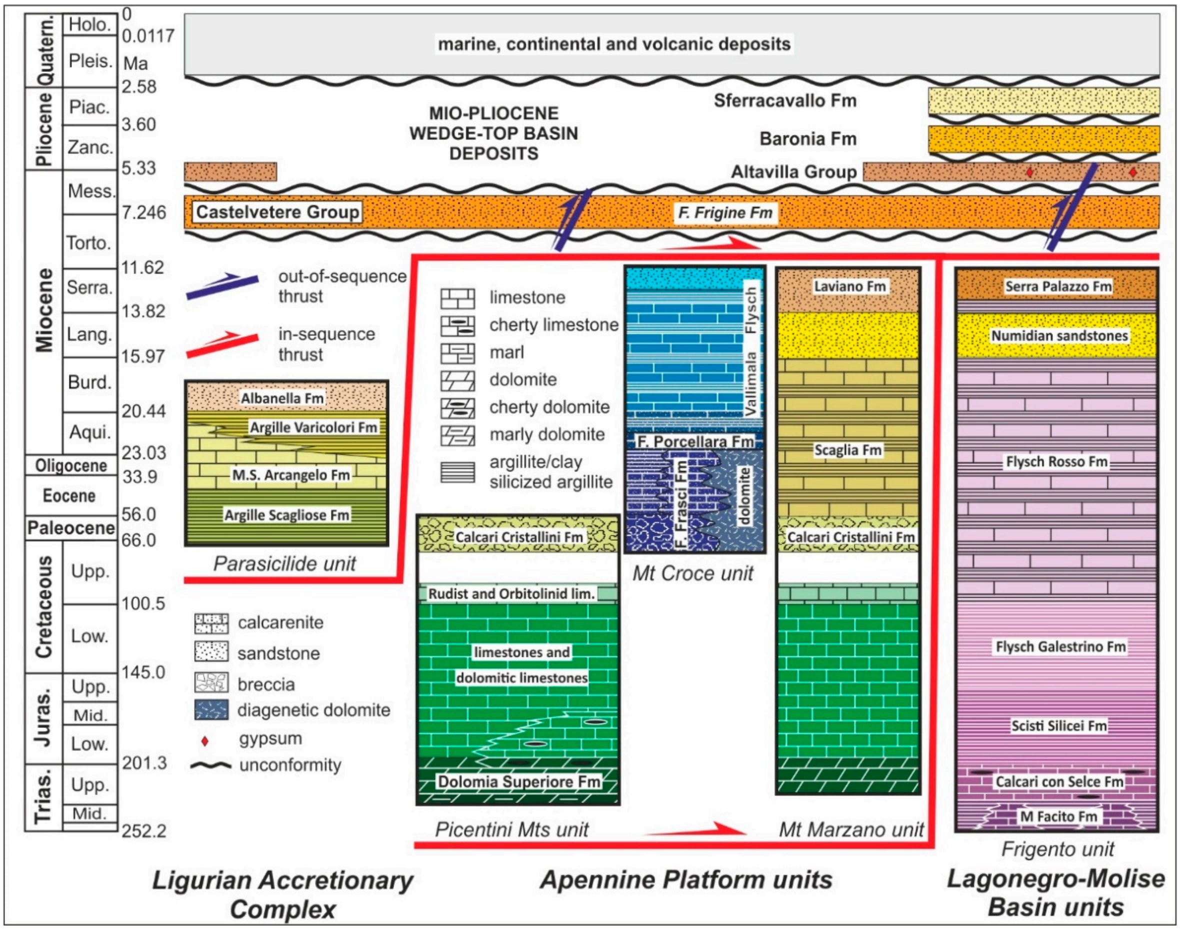

Figure 2. Schematic stratigraphic logs of the successions exposed in the Giffoni and Campagna tectonic windows (modified after [11]).

The Campagna tectonic window is a 12 km long E–W trending structure (Figure 3). Here, a complex thrust-sheet pile is tectonically exposed below the Apennine Platform succession (Picentini Mts unit). From top to bottom, the footwall consists of the Mt Croce unit (Apennine Platform margin), covered by the upper Miocene wedge-top basin of the Castelvetere Group (CVTG), sandwiched between the Frigento unit (Lagonegro-Molise Basin) thrust-sheets.

The Giffoni tectonic window (Figure 4) includes a larger structure (Giffoni Sei Casali) and two minor windows (Giffoni Valle Piana). Here, the Frigento unit is exposed, tectonically covered by the Picentini Mts unit. Both the Giffoni and Campagna areas host low-angle normal faults (LANFs; [22,23]) and high-angle normal faults. The latter structures frequently hide the exposition of the thrust faults. In particular, Lower Pleistocene SW-dipping normal faults, with hundreds of meters of displacement, lowered the SW sector (Salerno Plain), bringing near the highest thrust-sheet (Parasicilide unit) and the lowest succession (Triassic rocks) of the Picentini Mts unit. The volumetrically massive deposits of Eboli Conglomerates are associated with the activity of these normal faults [45].

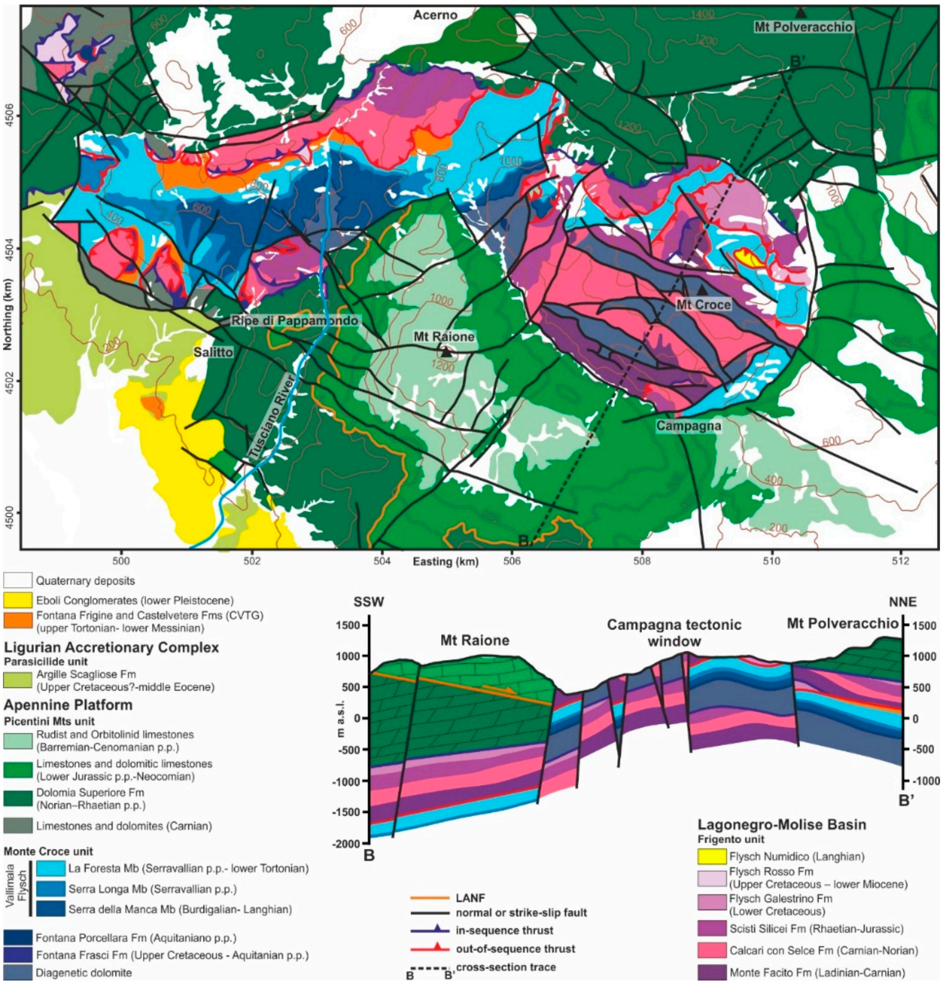

Figure 3. Geological map of the Campagna tectonic window (modified after [23,24]). WGS84-F33N Projection.

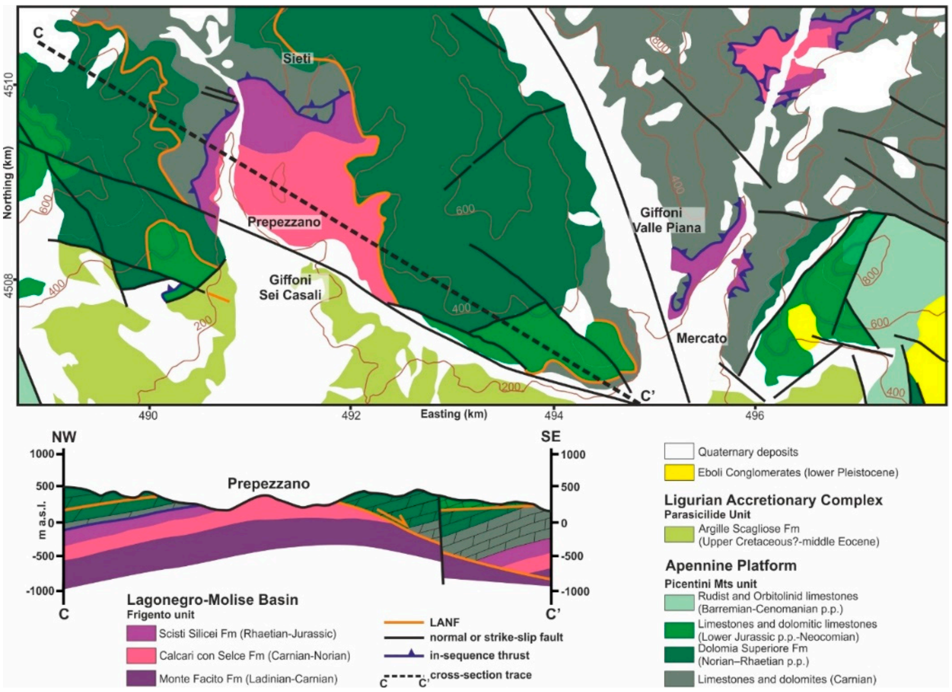

Figure 4. Geological map of the Giffoni tectonic window (modified after [23]). WGS84-F33N Projection.

3. Structures

In the following paragraphs, we illustrate the mesoscale structures observed in the tectonic windows of Campagna and Giffoni. To discriminate between out- and in-sequence thrusts, we used, as a criterion to identify the out-of-sequence structures, involvement in the thrusting of the wedge-top basin deposit of CVTG, whose sedimentation occurred within basins located on top of the already structured thrust-sheet prism. To reconstruct the chronology of the deformation structures, we analyzed the superposition relations between them. In not all areas, structures with different ages are sufficiently exposed. For this reason, we first illustrate the Salitto area because of the exposure completeness of the deformation structures that allowed us to reconstruct the temporal succession of the different deformation stages.

3.1. Campagna Tectonic Window

In the Salitto area (Figure 3), well-exposed structures occur in the footwall of the out-of-sequence thrust that places the Frigento unit above the Monte Croce unit with the interposition of the CVTG deposits. The oldest deformation structures are well-recorded in the Mt Croce unit. They are overturned tight folds (F1) associated with thrust faults (TF1; Figure 5a–c). These structures are cut by normal faults (NF2) frequently appearing as oblique faults (Figure 5a,c). Usually, drag folds are associated with these extensional faults (Figure 5c,d). F1, TF1, and NF2 structures are, in turn, deformed by late thrust faults and associated folds (Figure 5a,c–e, and Figure 6a,e,g). TF3 thrust faults are more developed in the Salitto area, frequently parallel to the NF2 faults (Figure 5d), at places forming conjugate sets (Figure 5e). In many instances, the calcareous beds of the Mt Croce unit host tectonic stylolites orthogonal to the bedding. Commonly, they form two orthogonal sets, suggesting E–W and N–S shortening directions, with the last one the youngest (Figure 5f).

TF3 thrust faults are locally tilted by folding associated with the late TF4 thrusts and presently appearing as strike-slip faults with a ramp-flat geometry and associated vertical folds (Figure 6a). At mesoscale, the two late thrusting events (TF3 and TF4) and associated fold sets (F3 and F4) form interference patterns such as that illustrated in Figure 6b where a TF3 and related F3 fold, verging to NE, are folded by an F4 fold, indicating an almost perpendicular NW–SE shortening. The two folds form a dome structure (type 1 of Ramsay's classification; [46]).

In the marly layers of the Mt Croce succession, the more developed F3 folding forms an axial plane cleavage (Figure 6c,d) dipping to the west. These two sets of late thrusts also deform the sandstones and conglomerates of the CVTG (Figure 6e–g). Minor thrusts (Figure 6e) and folds (Figure 6f) occur within the CVTG conglomerates with the development, in the marly layers, of an axial plane cleavage (Figure 6f). Finally, it is common to observe on the slickenside plane of thrust faults, hosted in the CVTG sandstones, two orthogonal fiber sets, E- and N-verging, with the latter generally superposed to the former one (Figure 6g).

Poles to bedding form a rough NE–SW-directed girdle (Figure 7a), with the main cluster suggesting a mean moderately SW-dipping bedding for the Salitto area. The projection of the fold axes (A1) of the folding set (F1) indicates dominant subhorizontal NW–SE-directed structures with some steep axes (Figure 7b). Poles to axial planes (AP1) suggest a dominant NE vergence (Figure 7c), as well as the few measured TF1 thrust faults (Figure 7d). Because the subsequent folds tilted older structures, such as the TF1, we restored them, reporting to horizontal the bedding. Hence, we rotated each tilted TF1 thrust faults (Figure 7e). We used as the rotation-axis, the direction line of the measured bedding crosscut by the thrust fault, and the bedding dip as the rotation angle. After the rotation, the data inversion indicates a NE–SW shortening (Figure 7f).

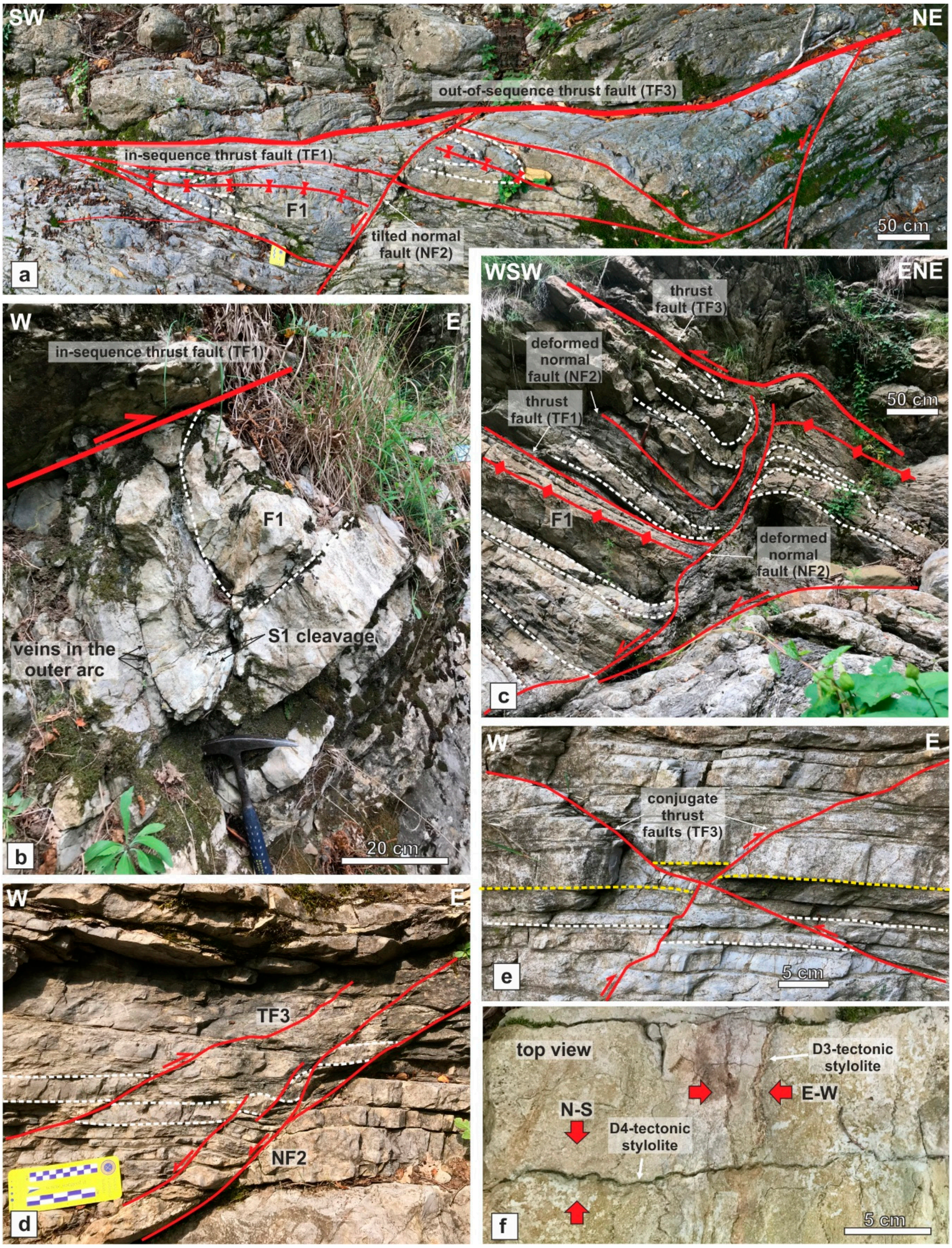

Figure 5. Campagna tectonic window (Salitto). Mt Croce unit: (**a**) early fold and thrusts (TF1) crosscut by normal faults (NF2) subsequently cut by a late thrust (TF3); (**b**) early thrust fault (TF1) verging to the east with an associated overturned syncline in the footwall, the fold host veins in the outer arc, and cleavage in the inner arc; (**c**) early normal faults (NF2) subsequently deformed by a late thrust fault (TF3); (**d**) normal (NF2) and thrust (TF3) faults; (**e**) conjugate thrust faults; (**f**) two orthogonal sets of stylolites.

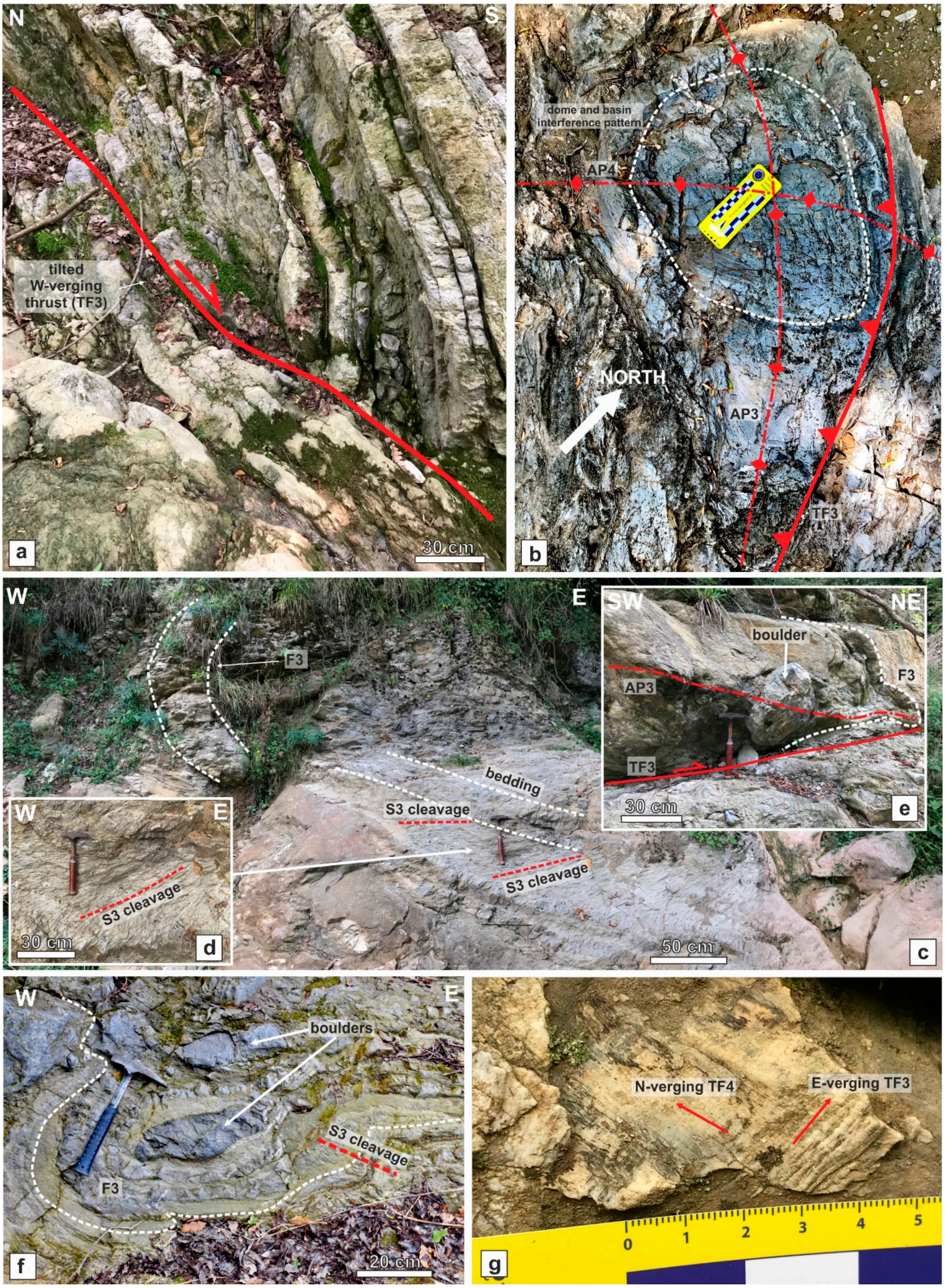

Figure 6. Campagna tectonic window (Salitto). Mt Croce unit: (**a**) W-verging thrust (TF3) subsequently tilted by an N–S shortening (D4 stage). (**b**) Dome-and-basin interference pattern between the two orthogonal folding events related to the D3 and D4 stages; (**c**) macro-scale overturned fold in the marls and sandstones; (**d**) fold axial plane cleavage associated with the macro-scale fold. CVTG: (**e**) minor thrust fault and hanging wall anticline in the CVTG. (**f**) Minor fold in the CVTG conglomerate; (**g**) two orthogonal sets of slickenside fibers along the same thrust plane.

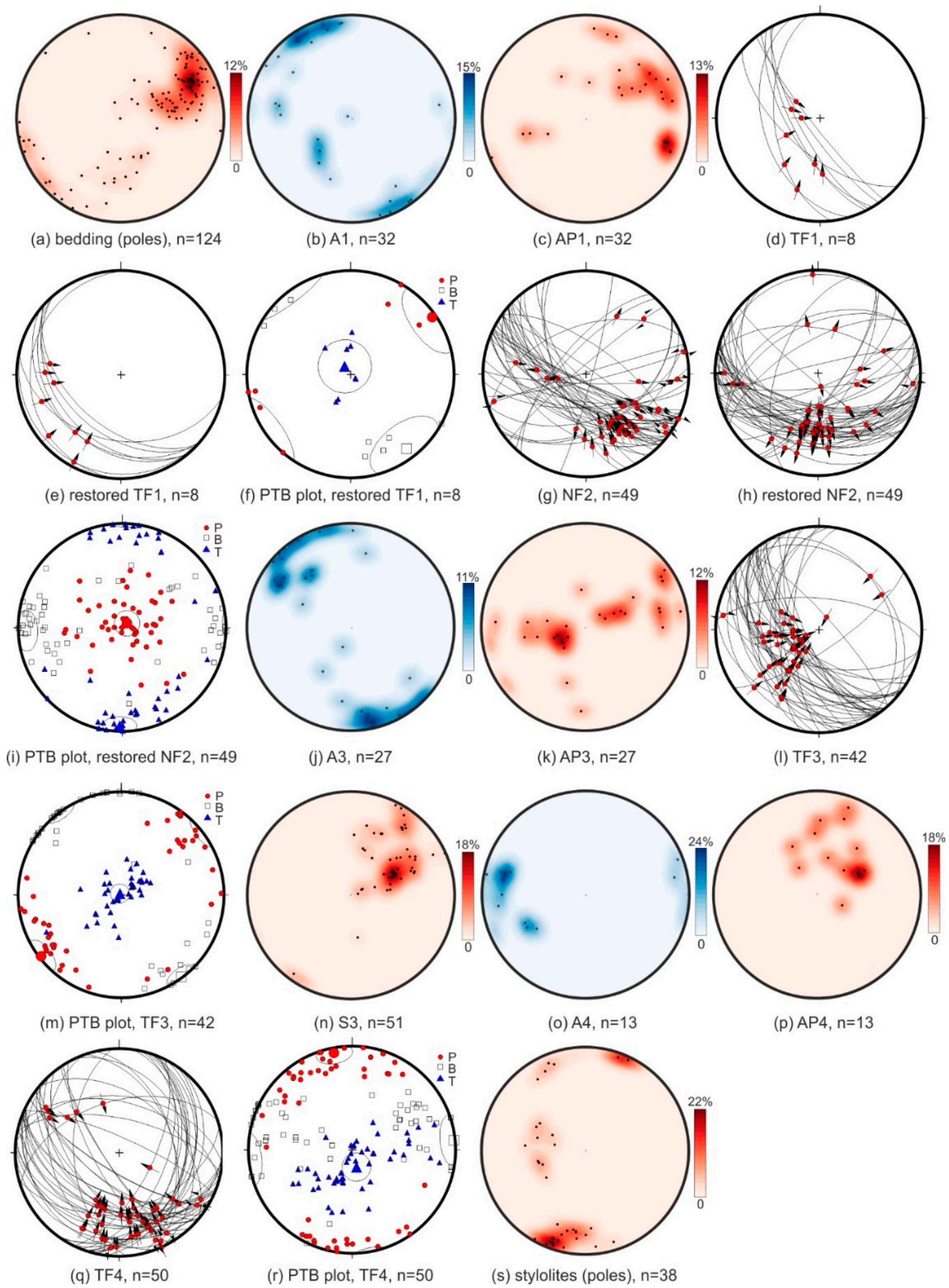

Figure 7. Salitto (Campagna tectonic window). (**a**–**s**) Stereographic projections (lower hemisphere, equiareal net) and PBT plots of the analyzed structures described in the text. A—fold axis; AP—axial plane; NF—normal fault; TF—thrust fault. S—tectonic foliation. Color bar indicates the density percentile of the contour plot. (**f**) θ = 30°; mean vectors; P: 055/04 (R = 85%); T: 143/11 (R = 83%); B: 324/82 (R = 87%). (**i**) θ = 44°; mean vectors; P: 076/86 (R = 74%); T: 268/09 (R = 65%); B: 181/03 (R = 75%). (**m**) θ = 54°; mean vectors; P: 232/03 (R = 75%); T: 144/02 (R = 80%); B: 316/88 (R = 87%). (**r**) θ = 40°; mean vectors; P: 349/06 (R = 70%); T: 085/01 (R = 50%); B: 166/76 (R = 68%).

We inverted fault kinematic data by the PBT method [47] that provides for every fault, defined by plane attitude, slip orientation, and kinematics, the axis of maximum shortening (P), maximum stretching (T), and the intermediate axis (B), orthogonal to the P–T plane. We used the software TectonicsFP (version 1.79; [48]), which allows one to calculate the best-fit angle (θ), minimizing the sum of all misfit angles between the measured slip direction and the calculated maximum shear stress. Furthermore, the software also provides the confidence cones of every axis expressed as a percentile (%R). In the case of lacking conjugate faults, we used a fixed value of angle θ equal to 30° for all fault-slip data.

NF2 faults show dominant strike-slip kinematics (Figure 7g); however, when restored (Figure 7h), they indicate dominant normal kinematics. The inversion of the NF2 data suggests an N–S extension (Figure 7i). A3 fold axes are mainly subhorizontal with a dominant NNW–SSE direction (Figure 7j), and poles to AP3 axial planes (Figure 7k) form a girdle suggesting an ENE–WSW shortening. TF3 thrust faults generally are moderately dipping to SW (Figure 7l), marking a NE–SW shortening (Figure 7m). In addition, the poles to S3 cleavage (Figure 7n) provide a mean moderately SW-dipping plane. A4 fold axes are generally gently dipping or subhorizontal with an E–W direction (Figure 7o), and AP4 poles indicate a dominant N-vergence (Figure 7p), as well as the TF4 thrust faults (Figure 7q), which inversion furnishes an N–S shortening (Figure 7r). Finally, poles to stylolites (Figure 7s) indicate two main shortening directions: NNE-SSW (main) and E–W (secondary).

In the Acerno-Tusciano River area (Figure 3), D3 and D4 structures are better-developed with respect to the D1 and D2 structures. Several mesoscale D4 back-thrusts affect the Mt Croce unit frequently with associated anticline and syncline in the hanging wall and footwall, respectively (Figure 8a). A decametric-sized shear zone is located in the footwall of a main FT4 thrust (Figure 8b). Here, shales and marly levels are characterized by widespread S-C structures, with shear planes (C) forming low-angles to the bedding (Figure 8b) and indicating a mean SSW vergence. F3 and F4 folds are from open to tight (Figure 8c–e). The F3 folds form an interference pattern of type 3 of Ramsay's classification [46] with the F1 folds (Figure 8d) and of type 2 with the F4 folds (Figure 8e). In the Campagna area, the hanging wall carbonates host several LANFs. The largest is localized in Mt Raione (Figure 3). Here, the western slope of the mountain is defined by the superposition of Jurassic onto Triassic rocks through a LANF. This structure is highlighted by the increase in the Jurassic succession thickness toward the NE. A segment of the Mt Raione LANF is exposed in the Ripe di Pappamondo (Figure 3); here, a major low-angle normal fault separates the Jurassic limestones in the hanging wall and Triassic dolomites in the footwall with a well-developed cataclasite (Figure 8f). Here, the gently dipping fault plane shows small ramps where slickenside striations occur, indicating normal kinematics (Figure 8g).

A3 fold axes are generally subhorizontal and N–S directed (Figure 9a). Poles to AP3 axial planes form an E–W girdle (Figure 9b), indicating both vergences to E and W, as well as the TF3 thrust faults (Figure 9c). The inversion of fault data suggests an ESE–WNW shortening (Figure 9d). A4 fold axes (Figure 9e) are about subhorizontal with a main WSW–ENE direction. AP4 poles form a girdle with a main cluster indicating dominant SSE dipping planes (Figure 9f). Finally, TF4 thrust faults show both vergences to N and S (Figure 9g), and the PBT plot suggests an N–S shortening (Figure 9h). S and C planes of the S-C structures (Figure 9i) generally dip to N/NE, with the C-planes showing lower dip angles. We calculated the attitude of the reverse slip vectors as that of the line forming an angle of 90° from the intersection between S and C planes. The projection of the C-shear planes and corresponding slip vectors (Figure 9i) indicates a prevalence of sense of shear top to the south. LANFs measured in the Ripe di Pappamondo area are characterized by planes and slip vectors dipping both to the north and south (Figure 9j). The inversion of LANF kinematic data indicates an N–S extension (Figure 9k).

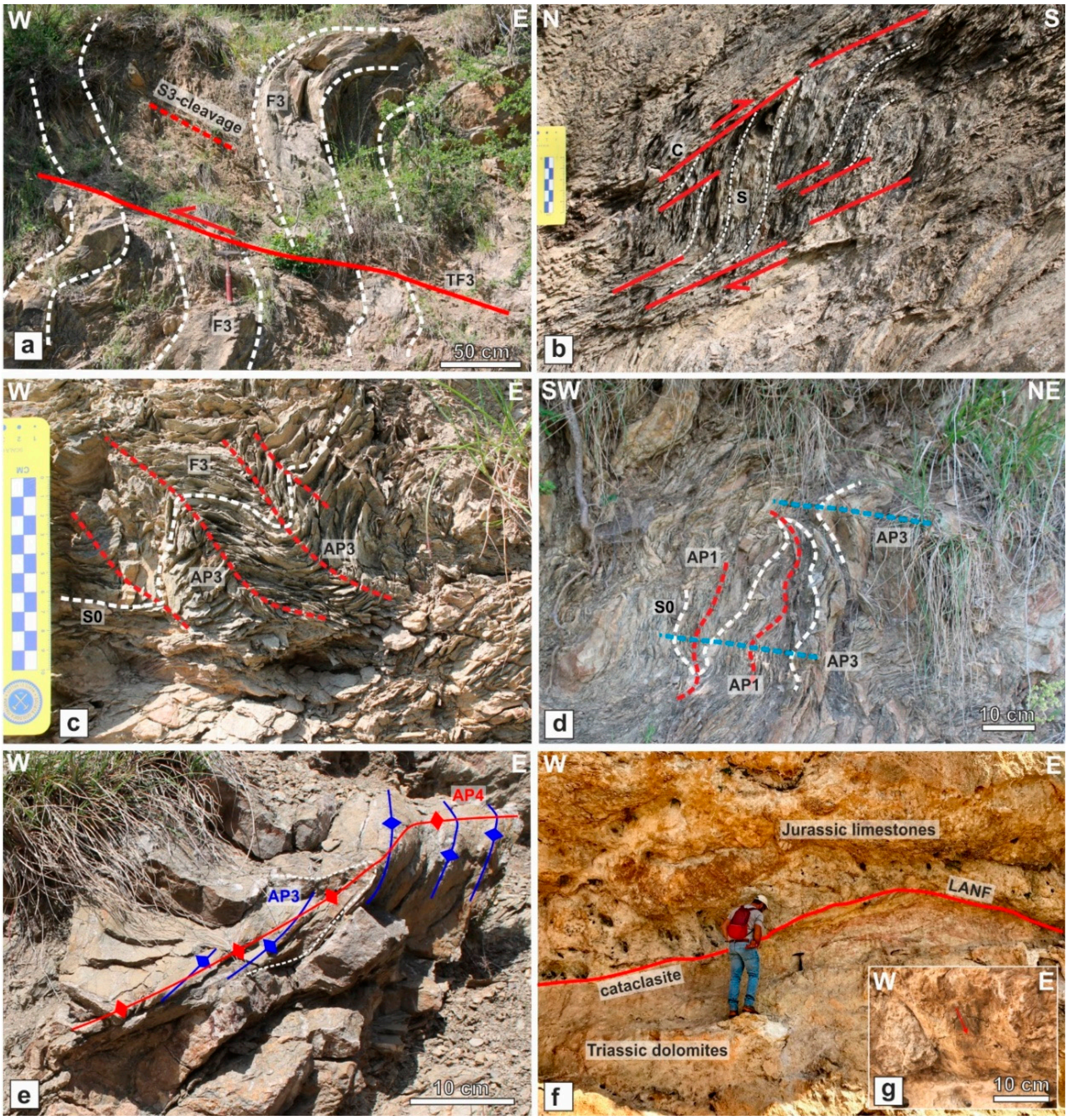

Figure 8. Campagna tectonic window (Acerno-Tusciano River). Mt Croce unit: (**a**) thrust fault (TF4) verging to SW with associated anticline and syncline in the hanging wall and footwall, respectively; (**b**) shear zone located in the footwall of a TF4 with S-C structures (S is the tectonic cleavage S1 associated to the D1 deformation); (**c**) F3 folds verging to W. Interference pattern between F3 and F4 folds: (**d**) type 3; (**e**) type 2. (**f**) Low-angle normal fault (LANF) located between Triassic dolomites (footwall) and Jurassic limestones (hanging wall) of the Apennine Platform (Ripe di Pappamondo). (**g**) Particulars of the LANF of the previous image, showing the gently dipping fault plane with slickenside striations.

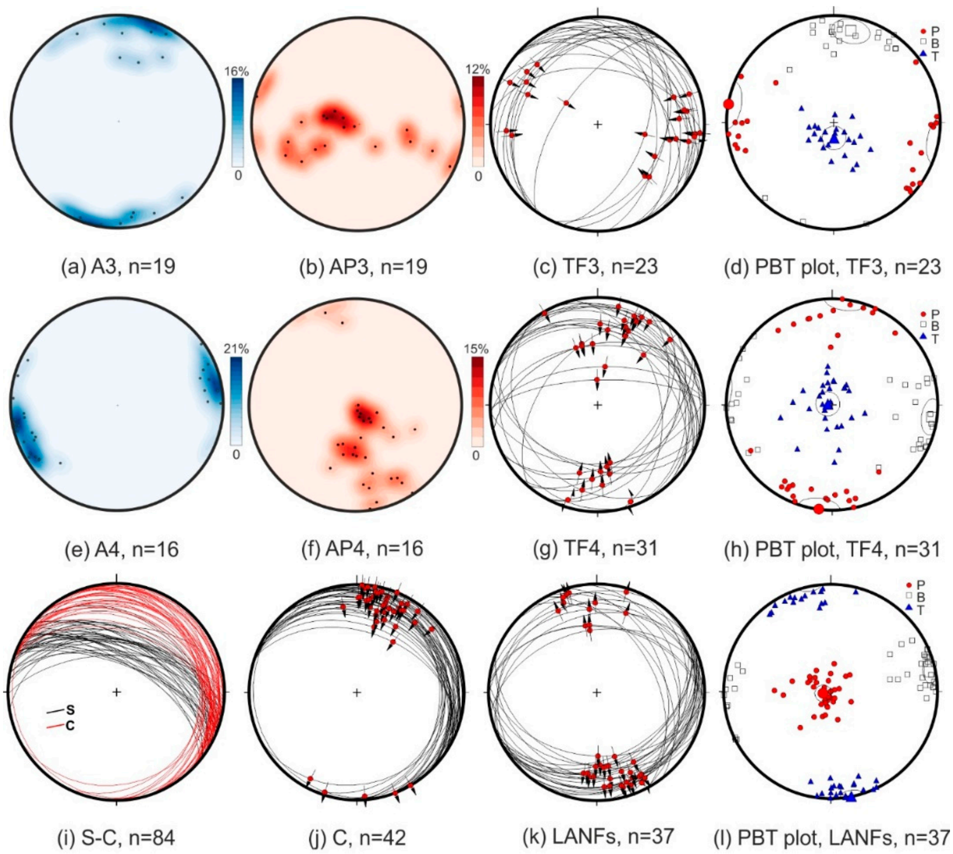

Figure 9. Acerno-Tusciano River (Campagna tectonic window). (**a**–**l**) Stereographic projections (lower hemisphere, equiareal net) and PBT plots of the analyzed structures described in the text. A—fold axis; AP—axial plane; TF—thrust fault. Color bar indicates the density percentile of the contour plot. (**d**) θ = 26°; mean vectors; P: 280/01 (R = 81%); T: 011/14 (R = 84%); B: 178/78 (R = 90%). (**h**) θ = 26°; mean vectors; P: 187/00 (R = 79%); T: 097/06 (R = 82%); B: 283/86 (R = 85%). (**l**) θ = 70°; mean vectors; P: 258/84 (R = 92%); T: 079/07 (R = 91%); B: 169/01 (R = 92%).

3.2. Giffoni Tectonic Window

The structural survey of the Giffoni Valle Piana and Giffoni Sei Casali areas was carried out in the localities of Sieti, Prepezzano, and Mercato villages (Figure 4). In-sequence thrust faults (TF1) are excellently exposed in these areas. Generally, Carnian dolomites of the Picentini Mts unit tectonically superpose on the Lower Jurassic silicized argillites of the Frigento unit (Figure 10a,b). In the Prepezzano locality, dolomites in the hanging wall are characterized by an intense fracturing, and frequently, a cataclasite made exclusively of dolomitic clasts occurs associated with the TF1 thrust (Figure 10b). Several Riedle shears crosscut the F1 thrust plane (Figure 10c), indicating a SE vergence. Rocks located in the footwall (Scisti Silicei Fm) host several deformation structures. The oldest ones are minor thrust faults (Figure 10d,e), probably associated with the in-sequence thrusts. These early structures are dislocated by normal faults subsequently tilted and now commonly appearing with reverse kinematics (Figure 10d–f). Similar early thrust faults are also hosted in the Calcari con Selce Fm (Figure 10g). All described structures are deformed by subsequent thrusting and folding stages. Similarly to the previous analyzed areas, we observed two sets of late thrusts (TF3-4). TF3 thrusts are defined by vergences both to E and W, whereas TF4 thrusts show dominant N-vergences. Riedel shears occur associated with both structures.

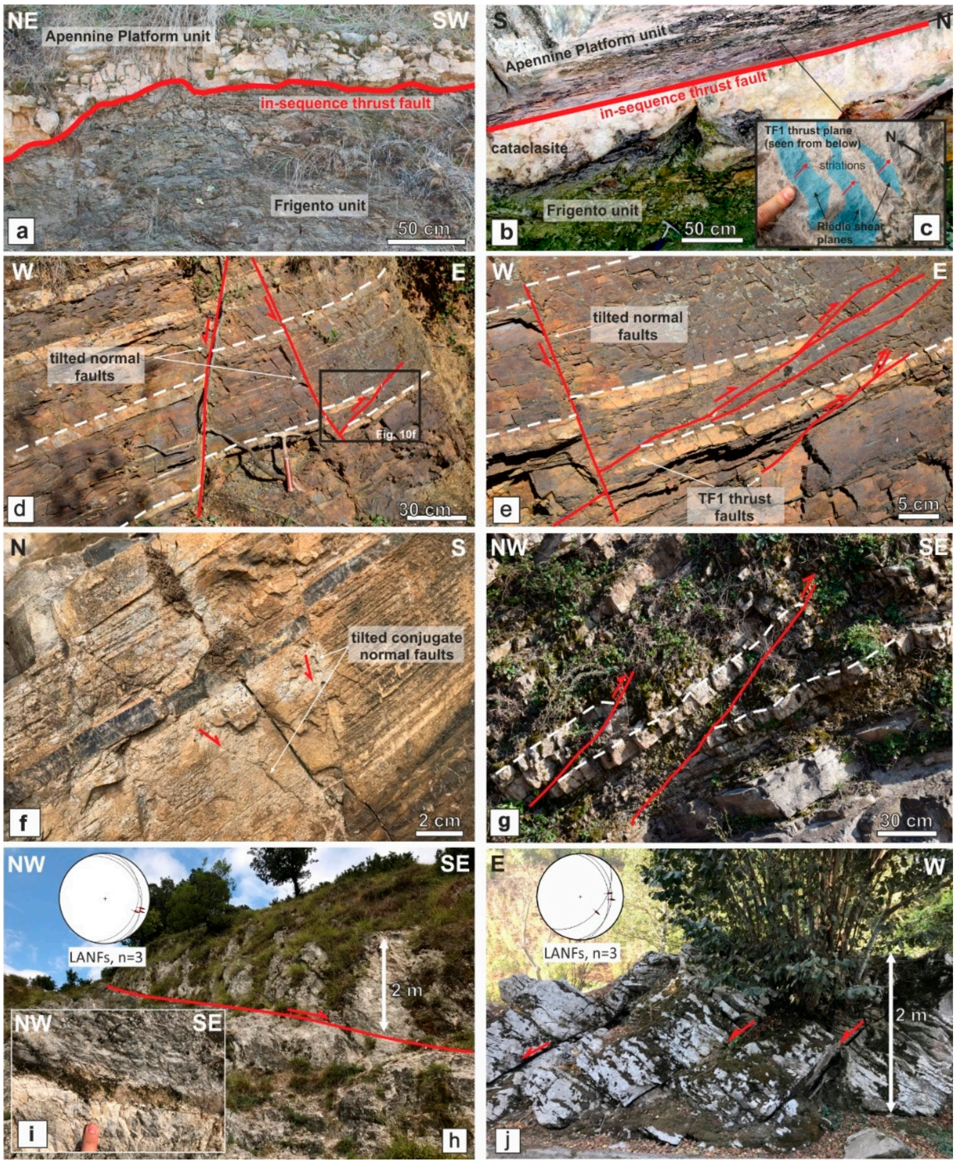

Figure 10. Giffoni tectonic window. (**a**,**b**) in-sequence thrust (TF1) between the Apennine Platform unit (Triassic dolomites) in the hanging wall and the Frigento unit (Scisti Silicei Fm) in the footwall (Prepezzano). (**c**) Riedle shears crosscutting the TF1 thrust fault plane. Frigento unit (Scisti Silicei Fm): (**d**,**e**) tilted conjugate normal faults (NF2) crosscutting thrust faults (TF1) (Prepezzano). (**f**) Tilted conjugate normal faults (Sieti). (**g**) Minor thrust faults (TF1) in Calcari con Selce Fm (Giffoni Valle Piana). (**h**) LANF in Rhaetian–Jurassic dolostones (Giffoni Valle Piana). (**i**) Fault gauge associated with the LANF of the previous picture. (**j**) minor LANFs in Carnian well-bedded limestones (Prepezzano).

As reported in Figure 4, the tectonic window is characterized by the occurrence of LANFs, such as the Campagna area. A well-exposed LANF occurs in the Rhaetian–Jurassic dolostones in the hanging wall of the Giffoni Valle Piana tectonic window (Figure 10h). A gauge is present along the fault plane (Figure 10i). This LANF dips to ESE with an angle of 30° (stereographic projection of Figure 10h). LANFs with minor displacements are widespread in the area, such as illustrated in Figure 10j, always showing a down to E/SE sense of shear.

Poles to bedding (Figure 11a) form a main cluster indicating a mean moderately W-dipping plane (mean value 283/29). A1 fold axes are subhorizontal with a NE–SW direction (Figure 11b). Poles to AP1 axial planes form an NW–SE girdle distribution (Figure 11c). The Riedel shears associated with the TF1 thrust faults (Figure 11d), when restored, indicate a mean ESE vergence (Figure 11e). Tilted NF2 normal faults (Figure 11f) when restored (Figure 11g) suggest an E–W extension (Figure 11h). TF3 thrust faults form conjugate sets, both verging to W and E (Figure 11i) with the PBT plot, marking an E–W shortening (Figure 11j). Riedel shears associated with TF3 thrusts indicate both W and E vergences (Figure 11k). Finally, TF4 thrust faults are mainly dipping to NNW, indicating an SSE vergence (Figure 11l). The PBT plot (Figure 11m) shows an NNW–SSE shortening. The few Riedel shears furnish an NNW vergence (Figure 11n).

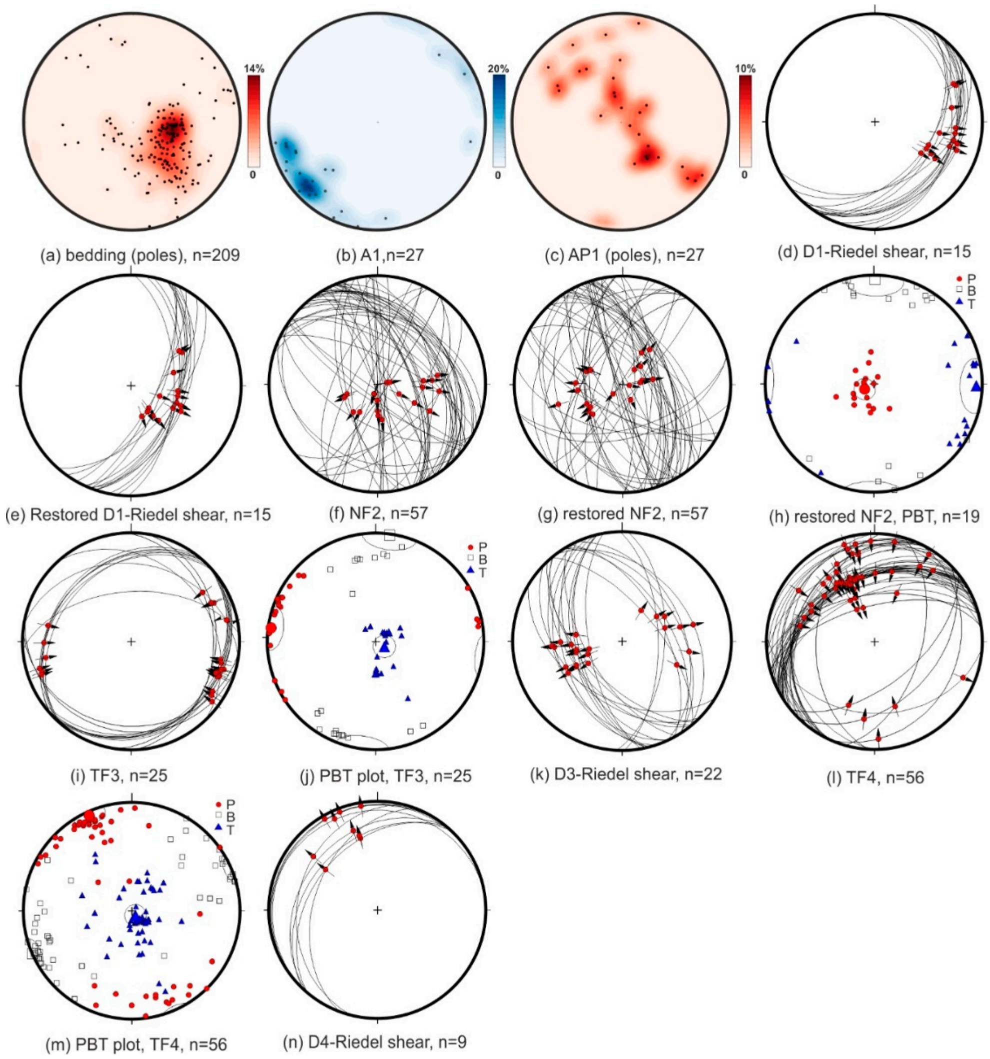

Figure 11. Giffoni tectonic window. (**a**–**n**) Stereographic projections (lower hemisphere, equiareal net) and PBT plots of the analyzed structures described in the text. A—fold axis; AP—axial plane; NF—normal fault; TF—thrust fault. (**h**) θ = 22°; mean vectors; P: 141/80 (R = 88%); T: 004/10 (R = 78%); B: 273/03 (R = 74%).(**j**) θ = 20°; mean vectors; P: 277/03 (R = 82%); T: 007/01 (R = 74%); B: 119/83 (R = 90%). (**m**) θ = 38°; mean vectors; P: 155/03 (R = 81%); T: 247/01 (R = 78%); B: 005/87 (R = 84%).

4. Discussion

The tectonic windows of Giffoni and Campagna provide the opportunity to study naturally exposed sections of the allochthonous wedge both in terms of stratigraphy and tectonics. The successions of the Picentini Mts unit (Apennine Platform) and the Frigento unit (Lagonegro-Molise Basin) are well-studied and are widespread in the whole southern Apennines [7,8,10,21,22,32–35,38–43]. On the contrary, the Mt Croce unit crops out only in the Campagna tectonic window, and it has been poorly studied [19,20,35–37]. This succession shows analogies with that exposed in the Laviano area, on the northern side of the Mt Marzano (Figures 1a and 2). The Laviano succession was recently studied by [49]. It is an excellent example of shallow-water Triassic–Upper Cretaceous carbonates covered by a margin to deep basin succession from Maastrichtian to Serravallian in age. The authors relate this deepening of the depositional environment with the Late Cretaceous–Paleogene abortive rifting that occurred in Adria, in analogy with that observed from Libya to southern Sicily [49]. A similar margin to slope succession characterizes the Mt Croce unit. It starts with Upper Cretaceous–Paleocene calcareous breccias, corresponding to the Calcari Cristallini Fm, a widespread recrystallized calcareous clastic deposit, marking the start of the platform sinking in several places of the southern Apennines [7,8,49]. The succession passes upward to a thick, scaglia-type slope calciclastics deposit and basin calcilutites, marls, and argillites. The succession ends with Serravallian foredeep sandstones corresponding to the similar sediments in the Laviano area. Finally, unconformable deposits of the upper Tortonian–lower Messinian CVTG cover both successions. This close analogy suggests a similar paleogeographic position in the uppermost Cretaceous, where they formed the eastern margin of the Apennine Platform. Furthermore, both margin successions were involved in the same out-of-sequence thrusting event [11].

The structural analysis presented in the previous paragraphs gives us some inputs to propose a possible reconstruction of the tectonic events of this key sector of the southern Apennines. The best place to observe the superposition between the different orogenic stages is the Salitto outcrop (Campagna tectonic window). Here, we have recognized the superposition of five deformation stages in the footwall of the out-of-sequence thrust, which juxtaposes the Frigento unit onto the Mt Croce unit, with the interposition of the CVTG rocks. The first (D1) includes regional thrusts and minor mesoscale thrusts with related folds, all defined by a vergence to the E/SE. This in-sequence thrusting event allowed the tectonic covering of the Apennine Platform rocks (Picentini Mts unit) onto the Lagonegro-Molise Basin deposits (Frigento unit). The second stage (D2) was recorded by normal faults, deformed by the subsequent shortening deformations. As suggested by [11,31], we associate this extensional event with the formation of several structural depressions where the CVTG sediments were deposited. A synorogenic extensional environment was also envisaged for the older Langhian–lower Tortonian wedge-top basin deposits of the Cilento Group [27,28,31]. A recent study [50] in the Cilento area (Figure 1a) about temperature-dependent clay minerals and vitrinite reflectance in the Cilento Group and Mt Sacro Fm (CVTG) indicates a basin evolution marked by two phases of severe subsidence, interpreted as the result of syn-orogenic extension at shallow crustal levels. Hence, this extensional event occurred in the southern Apennines with the deposition of CVTG sediments within structurally controlled depocenters. Furthermore, in several outcrops of the southern Apennines, including those localized in the Campagna tectonic window, the base of CVTG deposits is marked by carbonate conglomerates with an arenaceous matrix [14,15,40,51–53]. This feature could mark the erosion of carbonates placed in the footwall of the D2 normal faults.

The latter two stages (D3 and D4), defined by thrusts, folds, S-C structures, and tectonic stylolites, also affected the wedge-top basin deposits of CVTG, highlighting the out-of-sequence nature of these deformation events. The first two events (D1 and D2) are also well-recorded in the Giffoni area. Here, the Frigento unit (footwall) hosts early thrusts (D1) crosscut by normal faults (D2) and subsequently tilted. Furthermore, the younger deformations have been recorded only as minor thrusts. In the Acerno-Tusciano River area (Campagna tectonic window), the last two shortening stages (D3 and D4) were mainly recorded.

According to the orientation analysis, the D1 stage was characterized by dominant NE (Salitto) and E/SE (Giffoni) vergences. Hence, a mean tectonic transport to the east is inferred for the in-sequence thrusting (D1) in the study area. The D2 event was defined by N–S (Salitto) and E–W (Giffoni) extensions. These two orthogonal directions suggest a radial extensional strain field that characterized the D2-extension in the study area. The D3 stage was characterized by NE–SW (Salitto) and E–W (Acerno-Tusciano River and Giffoni) shortening directions with a prevalence of the NE vergence for the Salitto area and both vergences (NE and SW) for the Acerno-Tusciano River and Giffoni sectors. Finally, the D4 event with N–S (Salitto and Acerno-Tusciano River) and NNW–SSE (Giffoni) shortening directions had dominant vergences toward N (Salitto), S (Giffoni), or both N and S (Giffoni).

In order to carry out the mean shortening directions for the out-of-sequence thrusting events (D3-4), we joined all measurements of the two tectonic windows (Figure 12a,c) and performed the PBT plots (Figure 12b,d). The data inversion indicates the dispersion of the P-axes in both cases with mean shortening directions about WSW–ENE- and NNW–SSE-oriented for the D3 (Figure 12b) and D4 (Figure 12d) stages, respectively. It is worth noting as in both D3 and D4 events, thrusts and back-thrusts are equally present.

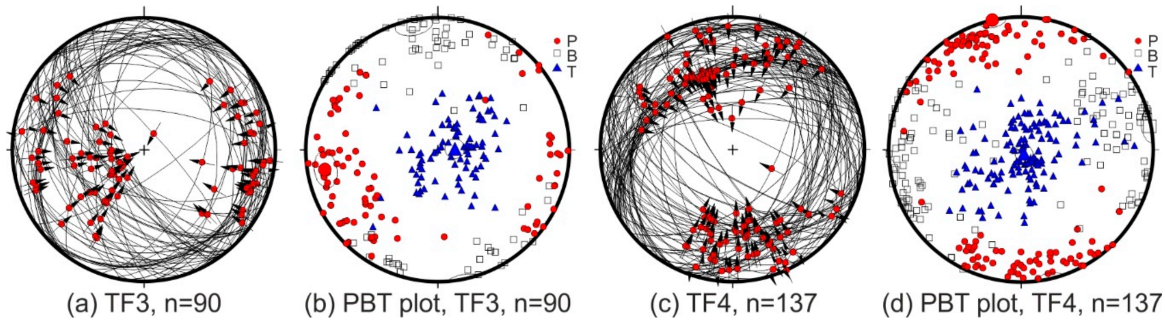

Figure 12. (**a**–**d**) Stereographic projections (lower hemisphere, equiareal net) and PBT plots of the total out-of-sequence thrust faults of D3 and D4 deformation stages measured in both tectonic windows. (**b**) θ = 32°; mean vectors; P: 260/15 (R = 63%); T: 349/04 (R = 66%); B: 086/80 (R = 81%). (**d**) θ = 30°; mean vectors; P: 348/00 (R = 74%); T: 080/02 (R = 64%); B: 1466/87 (R = 77%).

As concerns the two out-of-sequence thrusting stages (D3 and D4), as shown in previous papers [11,14,15], they form the most common shortening structures in the southern Apennines. The age of these events is late Messinian–early Pliocene as suggested by different features, including (i) these thrusts deform the upper Tortonian–lower Messinian deposits of CVTG; (ii) the analogy with similar structures described in the Central Apennines dated late Messinian–early Pliocene [54–57]; (iii) recent dating of the out-of-sequence thrust of the Mt Massico [17] to 5.1 ± 3.7 Ma (early Pliocene) through the U-Pb geochronology on synkinematic calcite fibers; and finally, (iv) the fission tracks analysis on Apatites, collected within sandstones of the Mt Croce unit [6], furnishes an age of 5.2 ± 0.9 Ma (early Pliocene) for the oldest tectonic exhumation event of this thrust-sheet.

In the Campagna tectonic window, the D3 and D4 thrusts indicate E–W and N–S shortening directions, such as previously described by [22] and observed in other areas of the southern Apennines [11]. According to [11,14,15], these out-of-sequence thrusts were formed by the positive inversion of normal faults located in the buried Apulian Platform. Some of them propagated upward, crosscutting the overlying allochthonous wedge, and, although they form as in-sequence thrusts at deeper structural levels with respect to the orogenic belt, they appear as out-of-sequence structures at surface. Such tectonic features are called envelopment thrusts [12–14].

All these geological features allowed us to reconstruct three geological sections, at a regional scale, crossing the two tectonic windows and the Mt Marzano-Laviano sector (Figure 13). To constraint the cross-sections, we used information from Acerno01, San Gregorio Magno01, Contursi01, and Nusco02 boreholes [58,59] and the seismic profile of CROP04 interpreted by [60].

The B″-B‴ cross-section (Figure 13b) starts from the Campagna sector up to the thrust front located on the north side of the Picentini Mts. Hence, in our reconstruction, the out-of-sequence thrust, which allowed the superposition of the Mt Croce unit onto the Frigento unit, joins to that exposed at the front of the Picentini Mts, such as suggested in [11]. This interpretation also suggests that the Campagna tectonic window is related to the formation of an E–W trending antiform associated with a blind late back-thrust rooted in the Apulian carbonates. Furthermore, we suggest that the margin succession of Mt Croce laterally passes northward to the pelagic succession of the Frigento unit.

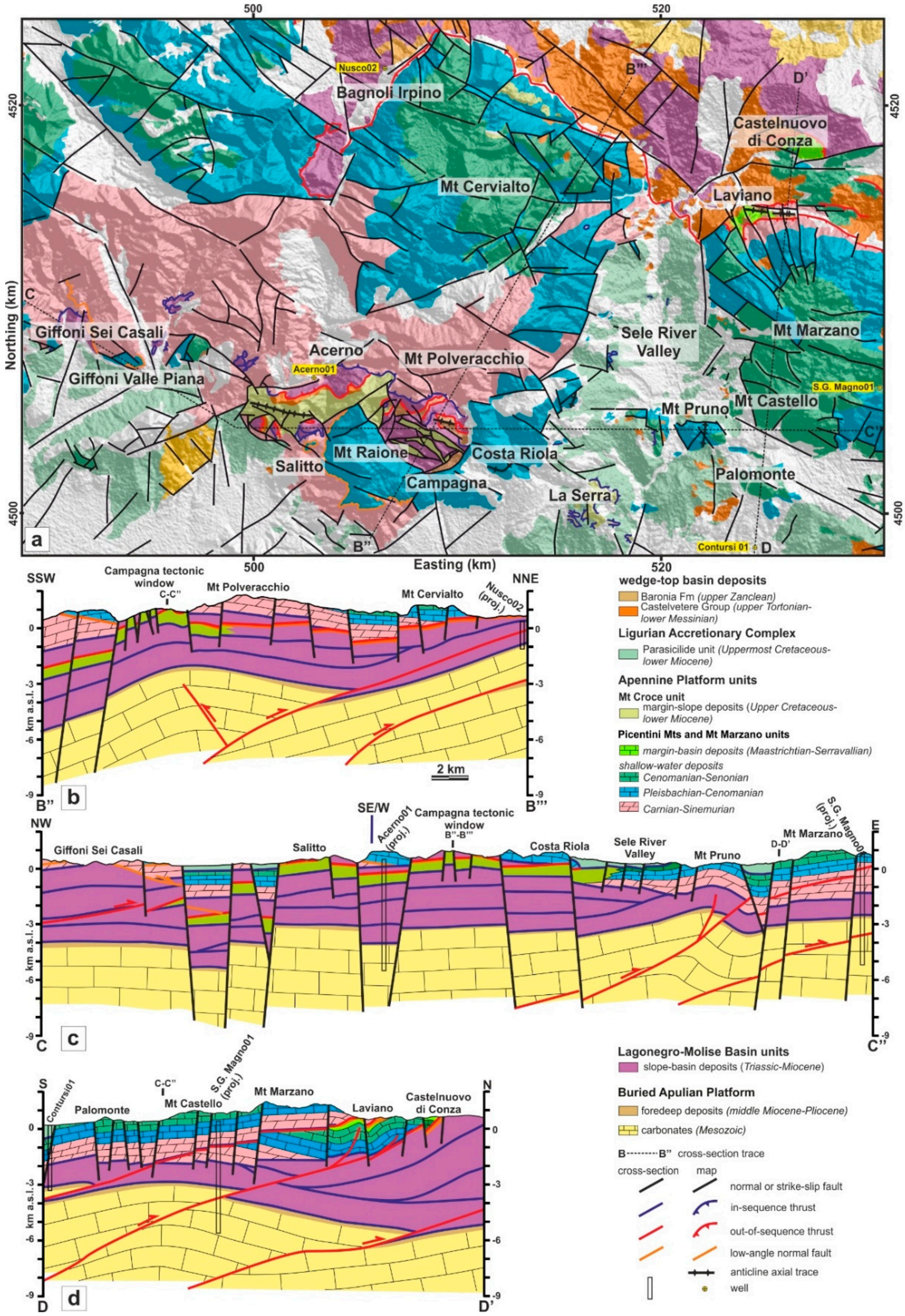

Figure 13. (**a**) Geological map of the Giffoni and Campagna tectonic windows, Picentini Mts, Sele River Valley, and Mt Marzano (modified after [8]). (**b**–**d**) Geological cross-sections.

The C-C" cross-section (Figure 13c) runs through the two tectonic windows up to the Sele River Valley. In our interpretation, the out-of-sequence thrust exposed in the Campagna tectonic window is dipping to the west, forming a frontal anticline in the hanging wall (Costa Riola fold, Figure 13a) bounding the western side of the Sele River Valley. Furthermore, another thrust fault in the buried

Apulian carbonates propagates upward, breaching, and forming the antiform within the Apennine Platform carbonates (Mt Pruno fold, Figure 13a). As concerns the stratigraphy, we suggest a westward lateral variation of the Apennine Platform carbonates (Mt Marzano unit) to the margin succession of the Mt Croce unit. Such a hypothesis is supported by the exposition in the Sele River Valley of Calcari Cristallini Fm below the Parasicilide unit (La Serra, Figure 13a)

Finally, section D-D′ (Figure 13d) crosscuts the Mt Marzano up to the Laviano area. Here, differently from the Mt Croce unit, the Maastrichtian–Serravallian margin to the basin Laviano succession is covered by the shallow-water Mesozoic carbonates of the Apennine Platform (Mt Marzano unit). The cross-section shows as the Mt Marzano unit, rocks cover the Laviano succession with the interposition of the CVTG through an out-of-sequence thrust propagated by the buried Apulian carbonates. In turn, the Laviano succession overthrusts the Frigento unit again with the CVTG in the footwall. The latter thrust has two blind splays forming two large folds in the Laviano area, and the frontal ramp forms the anticline of Castelnuovo di Conza.

In the hanging wall of these thrusts, LANFs are present. The structural survey carried out in this study indicates structures with slip-vectors down to SE for the Giffoni tectonic window and both to north and south for the Campagna area. Different works studied these extensional structures in the Giffoni area. The authors in [22,61] related these faults with the synorogenic NW–SE trending extension parallel to the chain axis, whereas in [62], with the opening of the back-arc Marsili oceanic basin during the late Pliocene–Pleistocene. However, in the Campagna area, these structures indicate an N–S extension, not related to the previous directions indicated by [22,61]. Hence, we suggest relating the formation of the LANFs to the out-of-sequence thrusting events, which over-thickened the orogenic wedge, causing extension in the shallow level. This genetic relation is also observed elsewhere in the southern Apennines, such as in Mt Alpi, where deep-seated thrusts allowed the buried Apulian Platform to uplift, triggering LANFs in the overlying allochthonous wedge [63].

From a macro-scale point of view, the area around the two tectonic windows, from the Lattari to Picentini Mts, exposes the oldest (Carnian–Norian in age) rocks of the Apennine Platform. According to [22], we suggest that this feature is related to the formation of a very large E–W trending antiform (about 40 km in length) and its subsequent erosion in the crest. As illustrated in the cross-section B″-B‴ we related this antiform to an out-of-sequence blind thrust.

With this in mind, we reconstructed the succession of the tectono-stratigraphic events for the Campagna and Giffoni tectonic windows between Serravallian and Early Pleistocene shown in the scheme of Figure 14. After the Serravallian–middle Tortonian in-sequence E-verging thrusting (Figure 14a) that juxtaposed the Apennine Platform (Picentini Mts and Mt Croce units) onto the Lagonegro-Molise Basin (Frigento unit), the whole tectonic pile was affected by a radial extensional deformation field characterized by E–W and N–S main directions (Figure 14b). This extension caused a general dismembering of the tectonic prism. This feature triggered erosion within the Apennine Platform carbonates, which fed, together with the siliciclastic supply coming from the overriding plate and the tectonic wedge itself [64,65], the depocenters with the sedimentation of the upper Tortonian–lower Messinian CVTG (Figure 14b). Subsequently, in the late Messinian– early Pliocene, the out-of-sequence E-verging thrusting duplicated the tectonic pile with the interposition of CVTG deposits (Figure 14c). The thrust fault system was characterized by several lateral ramps, verging both to N and S. Synchronous with the out-of-sequence event LANFs developed (Figure 14c,d). In the Giffoni tectonic window, the WNW–ESE extension prevailed, whereas, in the Campagna sector, the N–S extension was dominant. A late out-of-sequence event produced blind-thrust faults that deformed the previously formed structures producing a regional E–W trending antiform (Figure 14d). Finally, with the starting of the Early Pleistocene, this antiform was eroded (Figure 14f) with the formation of a large amount of calcareous detritus, presently forming the Eboli conglomerates [66] widespread to SW of the tectonic windows (Figure 3). This event was associated with an extensional stage [45,66] that lowered the Salerno area with the formation of a significant tectonic depression bounded by normal faults with hundreds of meters of displacement. This severe erosion of the regional antiform allowed the lowermost part of the hanging wall (Triassic rocks) to be exposed, now surrounding the two tectonic windows.

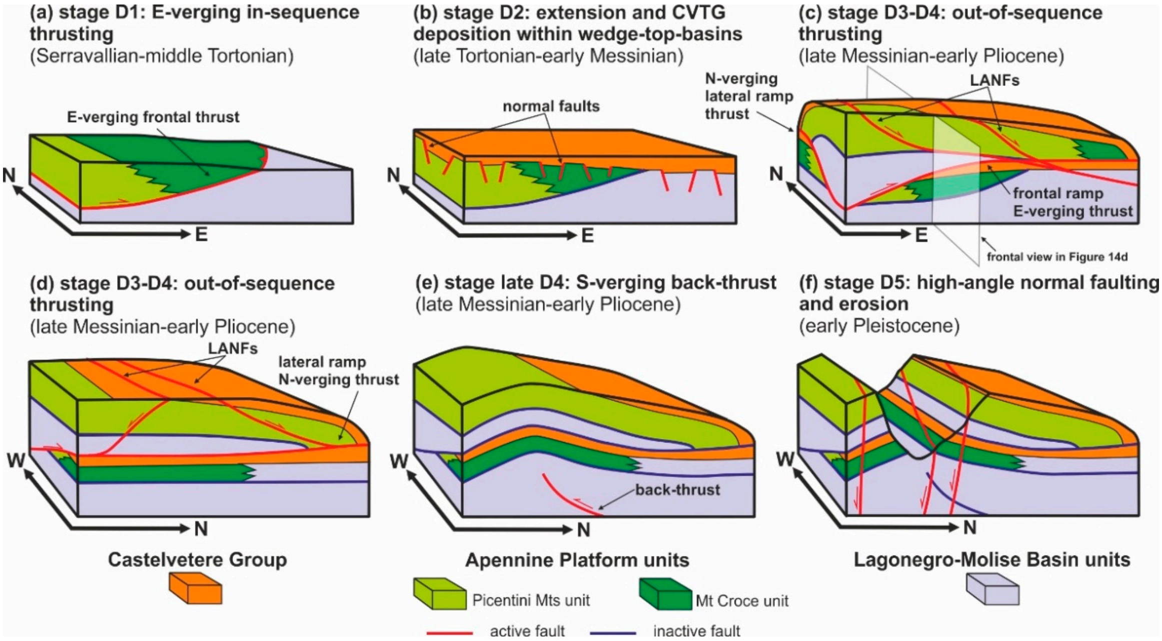

Figure 14. (**a**–**f**) Image showing the tectono-stratigraphic evolution from Serravallian to Early Pleistocene of the Campagna and Giffoni tectonic windows.

5. Conclusions

The detailed structural survey of the tectonic windows of Campagna and Giffoni allowed us to provide, for the first time, the reconstruction of the main orogenic stages that characterized this sector of the southern Apennines chain from the Serravallian to the Early Pleistocene. Furthermore, we clearly identified in- and out-of-sequence thrusting events and an extensional phase, interspersed between the crustal shortening pulses. Finally, we provided a comparison between the succession of Mt Croce, involved in the out-of-sequence thrusting, with that exposed in front of the chain (Laviano area).

The Campagna and Giffoni tectonic windows provide naturally exposed sections showing the superposition of several thrust-sheets. We reconstructed five main events that define the tectonic evolution of this area. The first orogenic pulse (D1) was recorded by an in-sequence thrusting that superposed the Apennine Platform (Picentini Mts and Mt Croce units) onto the Lagonegro-Molise Basin (Frigento unit), which occurred in the Serravallian. D1 structures are well-exposed in the footwall of the main regional compressive faults as mesoscale thrust and folds. A second stage (D2) was characterized by extension recorded as normal faults, tilted by the subsequent deformations. The deposition of the upper Tortonian–lower Messinian wedge-top basin CVTG sediments was related to this extensional event. The stages D3 and D4 were characterized by out-of-sequence thrusting involving the whole tectonic pile, included CVTG deposits that well-recorded these shortening deformations as mesoscale thrusts, folds, S-C, and pressure–solution structures. This thrusting doubled the allochthonous wedge, allowing the superposition of the Frigento unit onto the Mt Croce unit. The latter succession shows several tectono-stratigraphic analogies with that exposed in the Laviano area (located to NE of the two tectonic windows), both representing the eastern margin of the Apennine Platform. We suggest that the D3–D4 structures were associated with frontal E-verging thrusts and N/S lateral ramp thrusts, respectively, which occurred in the early Pliocene. As suggested by [11,14,15], these out-of-sequence thrusts have to be considered as envelopment thrusts, formed by the positive inversion of normal faults located at depth in the buried Apulian Platform and propagated upward within the overlying allochthonous wedge. Related to the out-of-sequence activity, LANFs developed in the hanging wall of both tectonic windows. The main thrusts, exposed in the two tectonic windows, are folded by a late event of out-of-sequence thrusting, forming a regional E–W trending antiform that was subsequently eroded, allowing the exposition of the oldest rocks of the Apennine Platform succession and the thrust-sheet pile in its footwall. The regional folding and erosion, with added severe normal faulting (stage D5) that occurred in the Early Pleistocene, produced a large amount of carbonate detritus, now forming the Eboli conglomerates widely exposed around the two tectonic windows.

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