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Underthrusting and exhumation of continent-derived units within orogenic wedge: an example from the Northern Apennines (Italy)

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ABSTRACT

The Punta Bianca Unit (NW Italy) is a continent-derived metamorphic unit that experienced underthrusting and later exhumation in the hinterland sector of the Northern Apennines fold-and-thrust belt. We present a novel 1:5000 scale geological map that aims to illustrate the polyphase tectonic evolution of the Punta Bianca Unit and its relationships with non-metamorphic units. The geologic data presented in the map are coupled with the structural analysis of the main tectonic elements, lithostratigraphic, finite strain and microstructural data that allow to highlight the tectonic history of the study area. In particular, we recognized that the Punta Bianca Unit underwent an early phase of underplating (D1), followed by syn-orogenic exhumation to shallow crustal levels and coupling with the overlying Tuscan Nappe (D2), and nappe stacking/refolding (D3). Low-angle semibrittle (D4) and high-angle brittle (D5) faulting affected both the Punta Bianca Unit and the Tuscan Nappe during the latest stages of deformation.

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1. Introduction

Orogenic wedges are the result of active convergence between two colliding continental plates. They consist of stacked tectonic nappes, accreted from the underthrust plate at shallow to deep crustal levels. While thrusting controls the growth of orogenic wedges, extensional and gravitational instabilities may shape their long-term evolution, and are responsible for the exhumation from deep structural levels (Kearey et al., 2009; Konstantinovskaya & Malavieille, 2011; Platt, 1986; Saffer & Bekins, 2002; Stern, 2002). Extension within orogenic wedges is not necessarily the result of a change in tectonic regime from contractional to extensional (e.g. Ring & Glodny, 2010), but may be determined by local and transient instabilities related to the internal dynamics of the wedge. For example, Dahlen (1990) and Davis et al. (1983) showed that continuous underthrusting may trigger gravitational collapse of the orogenic wedge, if the critical taper slope stability angle is exceeded (see also Platt, 1986). Many authors have also demonstrated that the coeval activity of oppositely verging thrusts and low-angle normal faults may drive the exhumation of deep-seated metamorphic rocks (e.g. Grujic et al., 1996; Law et al., 2004; Ring & Glodny, 2010). Studying exhumed metamorphic units represents, hence, the key to understand the tectonic and metamorphic processes that control the internal dynamics of orogenic wedges.

In this work, we investigate the tectonic structures exposed in the Punta Bianca Unit (PBU). The PBU represents the innermost exposure among the exhumed continental units that occupy the lower structural levels in the Northern Apennines. We present a new, 1:5000 scale geological map of the PBU (Main Map), supported by novel structural data that show, at greater resolution than previous studies, the tectonic structures of this key sector of the belt. We provide the first detailed microstructural description of the lithologies of the PBU and finite-strain analysis data. This contribution highlights an example of a polyphase tectonic history that occurred during underthrusting, syn-orogenic exhumation and stacking of an underplated metamorphic unit within an orogenic wedge.

2. Geologic setting

The Punta Bianca Unit (PBU) belongs to the Tuscan Metamorphic Units (TMUs), a group of exhumed nappes exposed in the Northern Apennines hinterland (Figure 1a, b). The TMUs consist of a Variscan basement covered by Triassic to Oligocene–Miocene meta-sedimentary sequences (Boccaletti et al., 1971; Carmignani et al., 2001; Elter, 1960). Alpine deformation transposed the structures related to the Variscan event that are only locally preserved at a few sites (e.g. Franceschelli et al., 2004 and references therein;

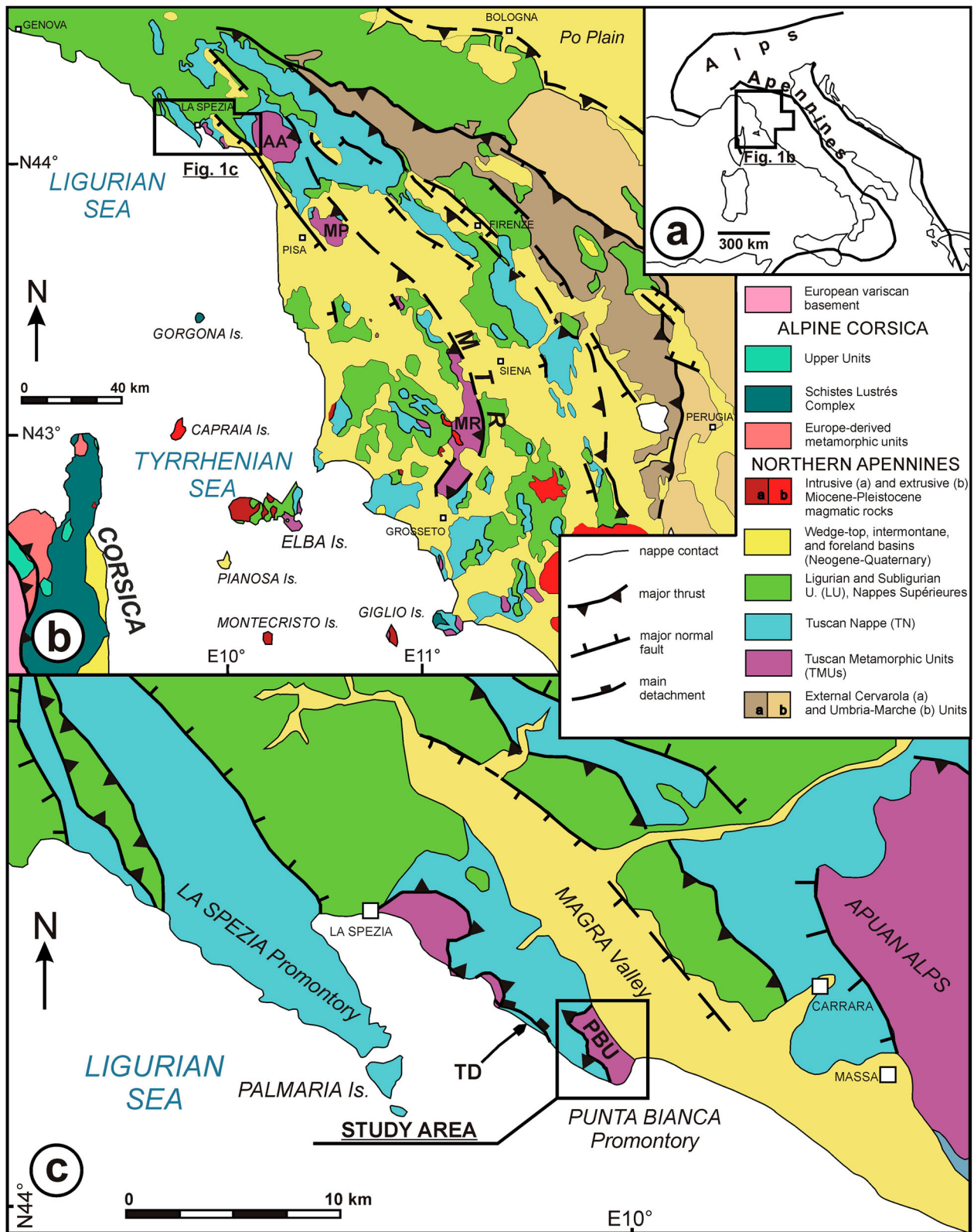


Figure 1. Geological setting: (a) Tectonic sketch map of Italy and neighboring regions. Black lines are thrust fronts of Alpine belts; (b) simplified geological map of the Northern Apennines and Corsica (modified after Papeschi et al., 2017). AA: Alpi Apuane; MP: Monti Pisani; MR: Monticiano-Roccastrada; MTR: Mid-Tuscan Ridge; (c) Tectonic sketch map of the La Spezia area highlighting the location of the study area (modified after Clemenzi et al., 2015). PBU: Punta Bianca Unit; TD: Tellerio Detachment.

Molli, 2008). Alpine metamorphism of the TMUs peaked at conditions ranging from blueschist to subgreenschist-facies conditions (Di Pisa et al., 1985; Franceschelli et al., 1986; Giorgetti et al., 1998; Lo Pò & Braga, 2014; Molli et al., 2000; Papeschi et al., 2020;

Theye et al., 1997). The TMUs are regionally overlain by (1) the Tuscan Nappe (Figure 1b), consisting of Triassic–Oligocene–Miocene passive margin sequences with anchizone-facies metamorphism (Baldacci et al., 1967; Carmignani et al., 1978; Carosi et al., 2003) and

(2) the Ligurian and Subligurian Units, comprising oceanic and ocean-continent transition sequences that experienced anchizone to lower-blueschist facies metamorphism during the Alpine Cycle (Elter, 1975; Marroni et al., 2001).

The PBU crops out at the southern tip of the Punta Bianca Promontory in the Gulf of La Spezia (Figure 1), underneath the Tuscan Nappe (TN) and the Ligurian Units (LU) exposed to the NW (Figure 1c; Carosi et al., 2003; Federici & Raggi, 1975; Montomoli et al., 2001; Storti, 1995). The TN experienced a polyphase tectonic history that involved the early development of a regional W-verging fold (La Spezia fold; Carosi et al., 2003; Carter, 1992; Gianmarino & Giglia, 1990; Montomoli, 2002) and late faulting, mainly along the east-verging Tellaro Detachment (Figure 1c; Clemenzi et al., 2015; Molli et al., 2018a; Storti, 1995). The TN was affected by very low-grade metamorphism, with peak temperatures around $\sim 200^{\circ}\text{C}$ (Molli et al., 2011; Montomoli et al., 2001).

The PBU consists of a Paleozoic–Triassic metasedimentary sequence (Figure 2; Ciarapica & Passeri, 2005; Martini et al., 1986; Rau et al., 1985) that experienced lower greenschist-facies metamorphism constrained at temperatures of $\sim 300\text{--}400^{\circ}\text{C}$ and pressures between ~ 0.4 GPa (Franceschelli et al., 1986) and 0.7 GPa (Lo Pò et al., 2016). The Alpine tectonic evolution of the PBU was previously described by Carosi et al. (1991) and Storti (1995), who recognized an earlier E-verging nappe stacking event (D1), followed by D2 and D3 symmetric W- and E-verging syn-orogenic extension of the overthickened thrust wedge.

3. Methods

The map at 1:5000 scale covers an area of about 10 km^2 , comprised between $44^{\circ}2'10''\text{N}$ – $44^{\circ}4'10''\text{N}$ of latitude and $9^{\circ}56'20''\text{E}$ – $9^{\circ}59'20''\text{E}$ of longitude and corresponding to the southeastern edge of the Punta Bianca Promontory (Liguria, Italy). The mapped area is outlined by the Costa Celle ridge to the north, the Pian della Chiesa and Costa di Murlo ridges to the west, the Magra River to the east and the Ligurian Sea to the south.

The topographic base map of the geological map (converted in vector-format from a raster, Carta Tecnica Regionale – Regione Liguria sc. 1:5000 1990/2006) using the Gauss-Boaga projection and the Hayford-Roma40/West datum. Abbate et al. (2005) realized the previous geological map of the area at 1:50,000 scale as part of the CARG project of the *Istituto Superiore per la Protezione e la Ricerca Ambientale* (ISPRA). The map we present expands the above-mentioned work and includes new lithological, structural (measures of foliations, lineations and fold axes) and petrographic data, aiming to characterize the deformation style of the PBU. Lineations and foliations

were classified according to Passchier and Trouw (2005) and fold following Ramsay and Huber (1987). We realized standard, oriented thin sections for microstructural analysis by cutting samples parallel to the object lineation and perpendicular to the main foliation. Microstructural observations were carried out using standard polarized optical microscopy at the microtectonics lab and the Philips XL30 Scanning Electron Microscope (SEM) at the University of Pisa equipped with an energy-dispersive X-ray spectroscopic system (EDAX). Chemical analysis of mineral grains were performed using an accelerating voltage of 20 keV and a beam current of 5 nA. We selected five samples, two of polymictic metabreccia, two of monomictic metabreccia and one of metavolcanite for finite strain analyses, following the R_f/ϕ method described by Dunnet (1969). Considered strain markers were deformed clasts in the metabreccia and vesicles in the metavolcanite (Main Map).

4. Lithostratigraphy

4.1 The Punta Bianca Unit

The PBU shows a $\sim 150\text{-m}$ -thick Triassic succession overlying a Paleozoic, polymetamorphic basement (Figure 2). The basement is mapped as a single formation (*Filladi e Quarziti di Buti* Fm.; BUT), consisting of phyllite and metasandstone with thin quartzite layers. The protolith age was referred to the Upper Ordovician by Abbate et al. (2005) based on a correlation with the nearby Apuan Alps (Figure 1). Rau et al. (1985) recognized within the Triassic metasedimentary sequence two distinct sedimentary cycles: (1) the first cycle of Anisian–Ladinian age and (2) the second cycle of Upper Ladinian–Carnian age, separated by a disconformity. Rau et al. (1985) distinguished 16 lithofacies (coded in letters from A to R; Figure 2). Abbate et al. (2005) grouped the lithofacies into 10 formations, because most lithofacies describe subtle lithological variations identifiable only in a well-exposed section along the coast from Punta Bianca to Cala Marola (Main Map) that are not discernible at map scale (e.g. lithofacies G–H–I in Figure 2).

The Anisian–Ladinian cycle (Figure 2) has been interpreted as the sedimentary fill of a failed rift system (Martini et al., 1986; Rau et al., 1985). The cycle starts with massive, coarse-grained green metaconglomerate that contains lenses of phyllite and metasandstone (*Metaconglomerati* Fm.; MCG), referred to the Anisian and interpreted as a continental deposit. MCG is transitional and fining upward to layers of metasandstone, phyllite, and fine-grained metaconglomerate (*Metarenarie e Metapeliti* Fm.; MAP) of Anisian age and continental environment. Metaconglomerate layers in both MCG and MAP range from clast- to matrix-supported and contain phyllite and quartzite clasts, eroded from

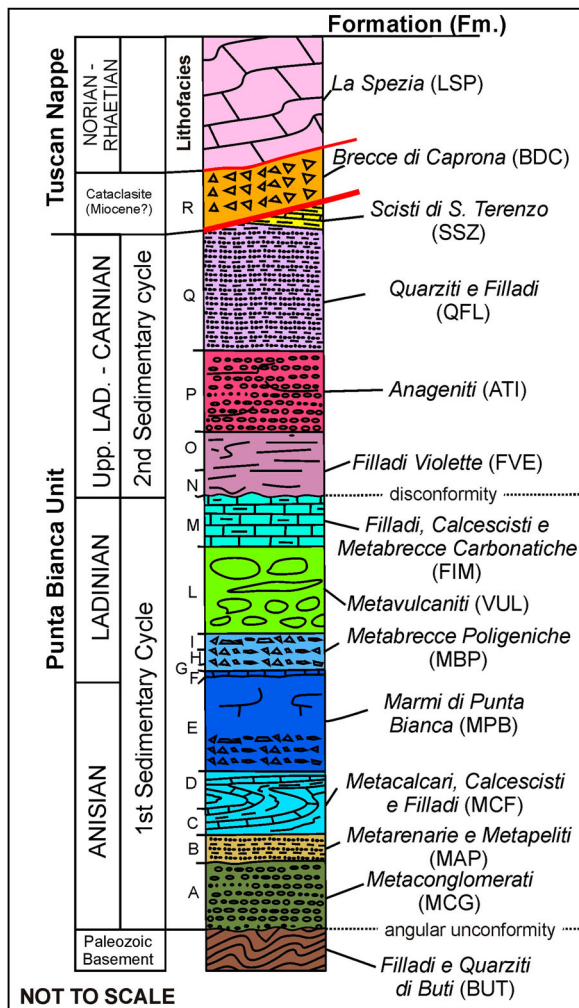


Figure 2. Schematic stratigraphic column of the PBU and the overlying TN in the study area. Letters from A to R mark the lithofacies by Rau et al. (1985). Corresponding formations after Abbate et al. (2005) are shown on the right.

the Variscan basement. MAP is transitional to diplopora-bearing metalimestone and black phyllite of Anisian age and open shelf environment (*Metacalcari, Calcescisti e Filladi* Fm.; MCF). MCF passes upward to massive marble with thin layers of calcschist and lenses of monomictic carbonate metabreccia containing clasts with fragments of diplopora, crinoids and ammonites (*Marmi di Punta Bianca* Fm.; MPB). MPB marks the transition from the Anisian to the Ladinian and is interpreted as a scarp breccia supplied by carbonate platforms. MPB is overlain by matrix-supported polymictic metabreccia lenses, containing clasts of marble, phyllite and quartzite, interlayered with metasandstone and phyllite (*Metabreccie Poligeniche* Fm.; MPB), interpreted as Ladinian scarp deposits. Upward, the sequence is characterized by metasandstone and phyllite that envelop lenses of metabasalt showing an alkaline affinity (*Metavulcaniti* Fm.; VUL) of Ladinian age (Ricci & Serri, 1975; Stoppa, 1985), emplaced in a relatively deep marine environment as suggested by the presence of pillow structures. Anisian – Ladinian cycle (Figure 2) ends with a

sequence of marble, calcschist, phyllite, and polymictic metabreccia deposited in a deep marine environment (*Filladi, Calcescisti e Metabreccie Carbonatiche* Fm.; FIM). According to Rau et al. (1985), FIM contains paleokarstic features that record Middle Triassic emersion above the sea level.

The Upper Ladinian–Carnian cycle (Figure 2; Martini et al., 1986; Rau et al., 1985) indicate, at regional scale, the base of the Alpine cycle and is marked by the deposits of the Verrucano Group (e.g. Cassinis et al., 2018), representative of continental and coastal deposits of arid environment. From bottom to top, the Verrucano Group comprises (1) violet phyllite and metasiltstone with lenses of metaconglomerate and quartzite of Upper Ladinian–Carnian age (*Filladi Violette* Fm.; FVE), (2) quartz-metaconglomerate, with thin layers of quartzite and phyllite of Upper Ladinian–Carnian age (*Anageniti* Fm.; ATI) and (3) inter-layered quartzite and violet phyllite (*Quarziti e Filladi* Fm.; QFL), referred to the Carnian. Along the tectonic contact with the Tuscan Nappe, lenses of phyllite and quartzite with layers of metalimestone (*Scisti di S. Terenzo* Fm.; SSZ) cap the Verrucano Group. This transitional siliciclastic–carbonatic formation is interpreted to mark the transition to the Upper Triassic carbonate platform deposits that characterize the Tuscan Sequence (e.g. Cassinis et al., 2018; Ciarapica & Passeri, 2005).

4.2 The Tuscan Nappe

The Tuscan Nappe (TN) in the study area is characterized only by two formations: a Miocene tectonic breccia (*Breccie di Caprona* Fm.; BDC; Carosi et al., 2018) overlain by the Norian–Rhaetian *La Spezia* Fm. (LSP) (Figure 2). The tectonic breccia consists of a carbonatic matrix containing clasts of limestone, dolomitic limestone and, minor quartzite and phyllite. They derive from original alternations of evaporite, dolomite and limestone, known as *Calcare Cavernoso* Fm. (age: Norian; Gandin et al., 2000; Vighi, 1958), that underwent strong tectonization and later karstic reworking during the Oligocene–Miocene (e.g. Burckhardt, 1946). The *La Spezia* Fm. consists of interlayered limestone, dolomitic limestone, marl and grey-blackish shale of carbonatic ramp environment. Oolitic and lumachella limestone are locally present.

5. Structural analysis

5.1 Map-scale structures

In the study area (Figure 1c), the TN and the PBU are arranged in an open, km-scale antiform (interpreted as a F3 fold, see Section 5.2) characterized by a (30–60°) W–SW-dipping western flank (Figure 3a, b), a gentler (0–15°) E–NE dipping eastern flank, and a periclinal

plunge of about $\sim 5^\circ$ to the N–NW (Figure 3). The western flank of the antiform culminates in a recumbent SW-verging hectometer-scale F2 fold (see par. 5.2) that affects the formations of the PBU (Figure 3a–d). An F2 structure with similar geometry but opposite vergence occurs in the northern part of the study area (Ameglia area) (Main Map).

The tectonic contact between the PBU and the TN, refolded by the antiformal stack, strikes about NW–SE and dips to the W between $40\text{--}50^\circ$ (Figure 3a, c; Montemarcello area) and $10\text{--}20^\circ$ (Ameglia area) (Main Map). At map scale, the contact is marked by lenses of cataclasites of the *Brecce di Caprona* Fm. in the TN and by tectonic slices of the upper formations of the Verrucano Group in the PBU. Due to the incompetent nature of the *Brecce di Caprona* Fm., no clear kinematic indicators can be observed. A second-order top-to-E–NE shear zone with ramp-and-flat geometry related to the D4 event (see Section 5.2) slices the *Verrucano* group over the lower formation of the

PBU and truncates the hinge zone of the F3 antiformal stack (Figure 3). In the Ameglia area, this thrust elides the Anisian–Ladinian formations and the *Verrucano* Group overlies directly the Paleozoic basement (Main Map). NW–SE striking high-angle normal faults, dipping to both the SW and the NE, segment the first-order folds and tectonic contacts (Figure 3e). High-angle normal and transcurrent faults, oriented nearly E–W and N–S, segment the first-order folds and tectonic contacts (Figure 3e, Main Map).

5.2 The Punta Bianca Unit: mesoscale structures

The PBU shows a polyphase deformation history, characterized by three ductile tectonic phases (D1–D2–D3), overprinted by a semibrittle (D4) and a brittle (D5) faulting events.

The first tectonic phase (D1) is marked by a relic slaty cleavage (S1) associated with locally preserved isoclinal F1 folds, strongly refolded by F2 folds. The S1

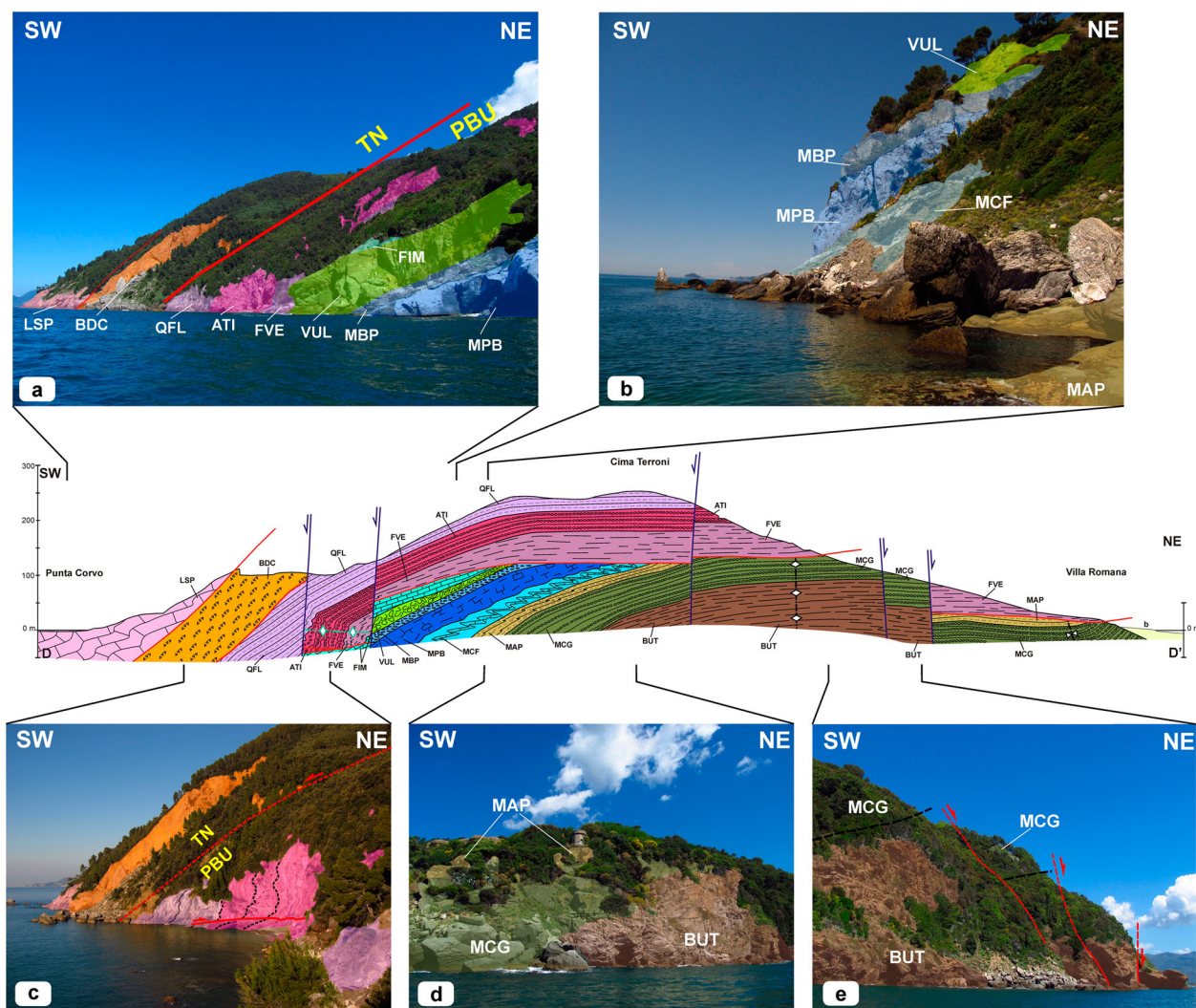


Figure 3. Structures exposed along the D–D' cross section (see Main Map). From West to East: (a) the TN overlies the W-dipping formations of the PBU. (b) W-dipping attitude of the formations of the PBU. (c) Overview of the contact between the PBU and the TN close to the main W-verging F2 fold (hinge zone in the *Verrucano* group), crosscut by a D4 shear zone (SZD4). (d) Contact between the Paleozoic basement and the Anisian–Ladinian formations. (e) D5 normal faults affecting the contact between BUT and MCG on the eastern side of the D3 antiform.

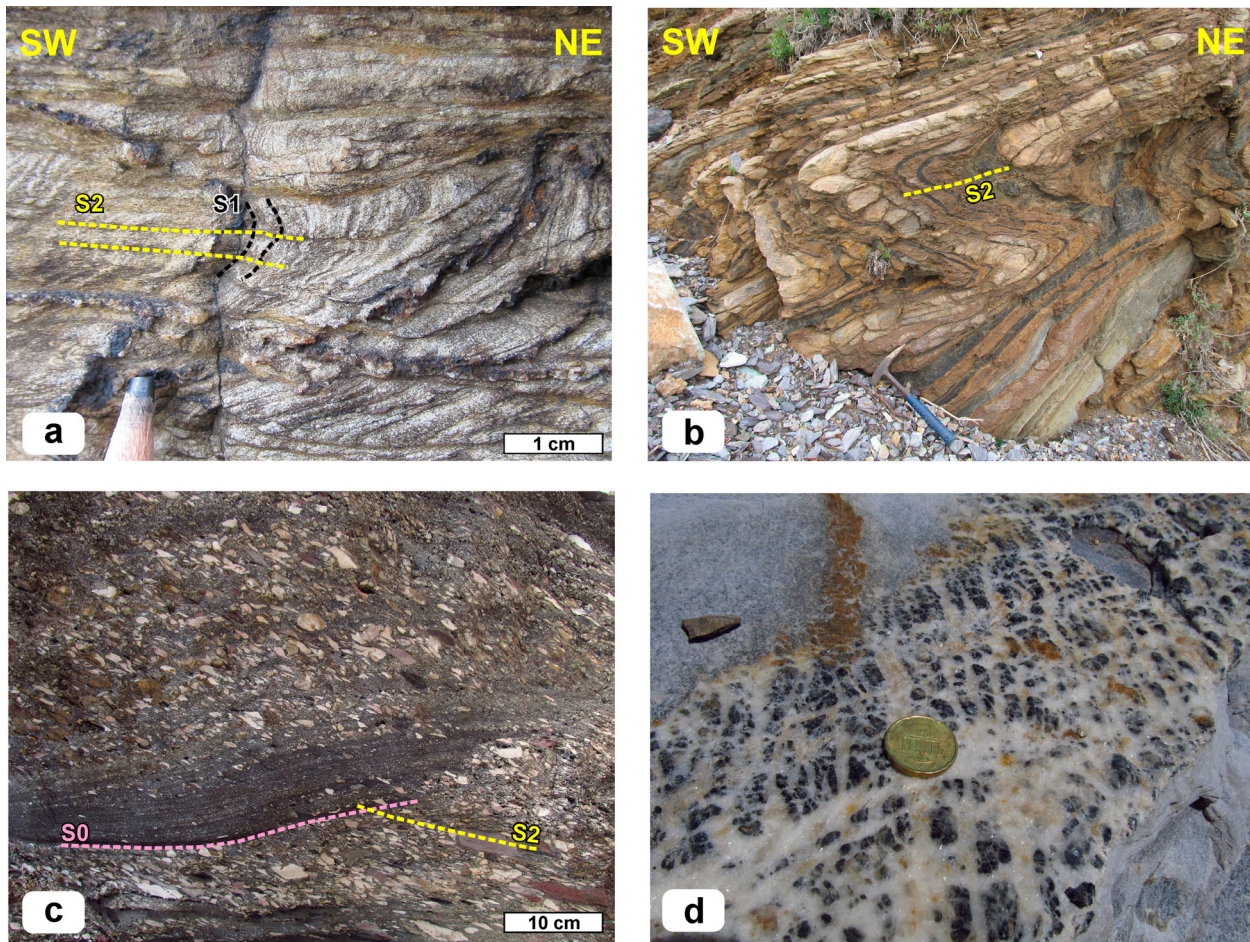


Figure 4. Mesoscale features of the PBU: (a) Quartz-rich metasandstone in the *Filladi e Quarziti di Buti* Fm. showing a continuous S1 foliation preserved between S2 cleavage domains. (b) SW-verging tight F2 folds developed in the *Metacalari, Calcescisti e Filladi* Fm. (c) Relationships between bedding (S0) and the main foliation (S2), defined by flattened marble and phyllite clasts in the *Metabreccia Poligeniche* Fm. (d) Chocolate tablet boudinage of a grey dolomite vein in the *Metacalari, Calcescisti e Filladi* Fm. Gaps are filled by calcite.

cleavage is commonly parallelized to the bedding (S0) (Figure 4a) and occurs mostly within microlithons of the S2 cleavage (see below). The S1 cleavage is commonly parallelized to the bedding (S0).

The second tectonic phase (D2) forms recumbent non-cylindrical F2 folds with tight to isoclinal geometry (Figure 3b) and subhorizontal N–S to NW–SE trending A2 axes. F2 folds constitute the major map-scale features, forming hectometer-sized structures characterized by SW- (cross section D–D'; Figure 4) and NE-vergence (cross section A–A'), respectively in the western and eastern part of the study area. Mesoscale F2 folds display S- and M-type geometries, forming parasitic structures around map-scale structures (Figures 3c and 4b). The hinge zones and reverse limbs of F2 folds are commonly sheared along top-to-W–SW shear zones (SZD2) with 1–10 mm thickness and displacements in the range of a few centimeters. Object lineations (L2), associated to SZD2 are defined by stretched aggregates of quartz and calcite and trend predominantly SW–NE. The S2 foliation represents the main mesoscale foliation. The S2 foliation is a crenulation cleavage defined by the preferred

orientation of mineral grains and aggregates and by flattened and re-oriented objects, such as vesicles (*Metavulcaniti* Fm.), clasts of carbonatic material (Figure 4c; *Marmi di Punta Bianca* Fm.), and clasts of quartzite, schist, and carbonates (*Metabreccia Poligeniche* Fm.). Finite strain analyses on these markers allowed to estimate deformation by dominant flattening, plotting within the flattening field of Flinn's diagram (1965) with K values ranging from 0.013 and 0.373 (Main Map).

An additional marker of deformation in the flattening field is represented by chocolate tablet boudinage structures that are commonly developed in dolomite veins parallel to the S2 foliation (Figure 4d). These veins are boudinated along roughly perpendicular NW–SE and NE–SW directions, defined by oriented calcite and quartz fibers that fill the gaps between the boudins. Boudinage of strong and competent layers (e.g. *Anageniti* Fm.) surrounded by incompetent phyllites, where the S2 foliation is necked, is also common (Figure 5a). Upright to gently NE-verging open F3 folds with weakly non-cylindrical geometry mark the third tectonic phase (D3). F3 folds refold at map-

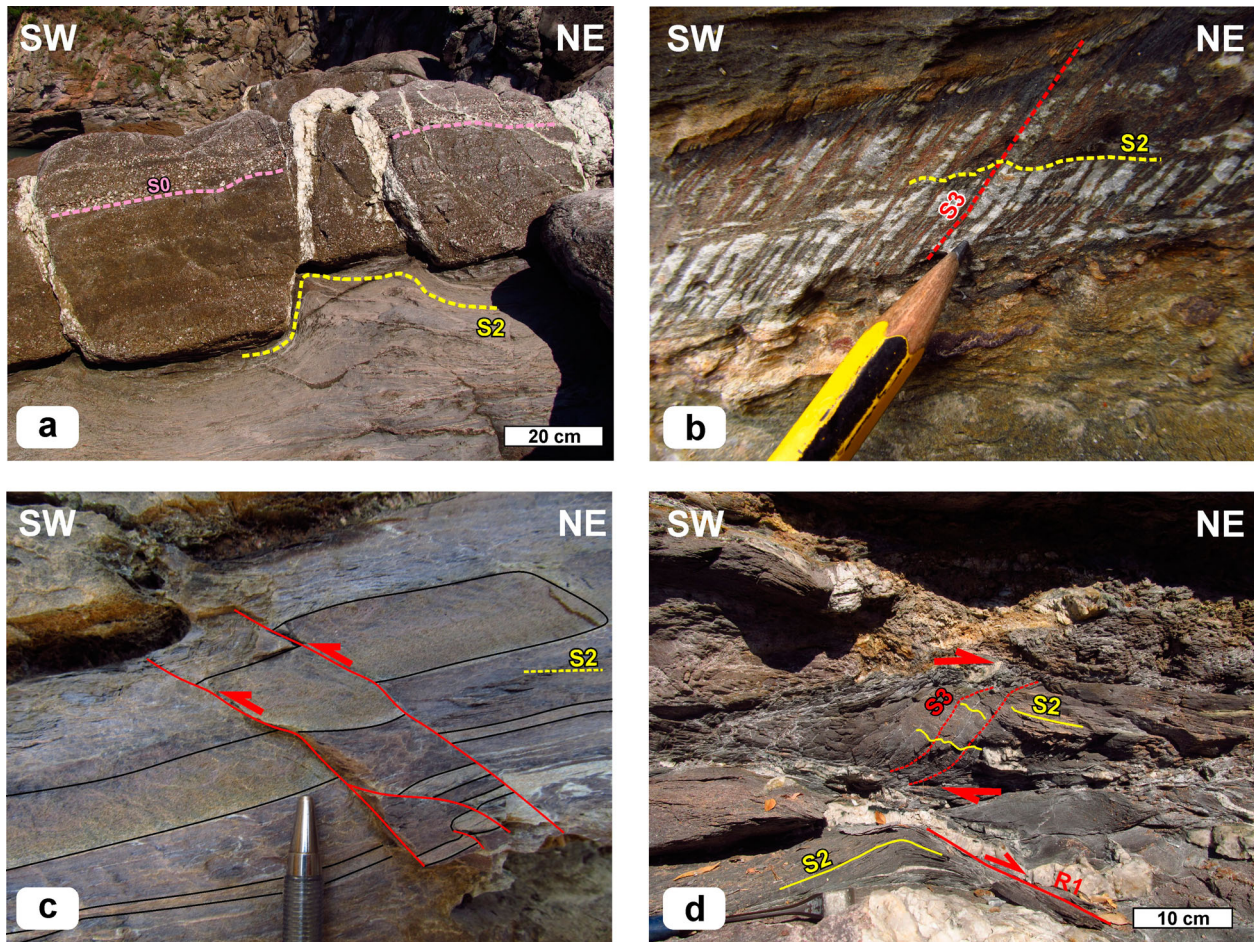


Figure 5. Mesoscale features of the PBU: (a) Symmetric boudinage in the *Anageniti* Fm. Quartz veins separate boudins of a metaconglomerate layer, whereas the S2 foliation is necked in the surrounding phyllite. (b) Detail of the S2 foliation, crenulated by steep W-dipping S3 foliation planes in a metapelitic interlayer of the *Metarenarie e Metapeliti* Fm. (c) Small scale D3 thrusts with centimetric westward displacements affecting pre-existing boudins of metasandstone layers at the base of the *Metabrecce Poligeniche* Fm. (d) D4 shear zones developed in phyllite and quartzite (*Quarziti e Filladi* Fm.). Top-to-NE sigmoidal structures, containing deformed S3 and S2 foliations, are dragged along top-to-NE low-angle Riedel shears.

scale both the S2 foliation, which dips up to 20° to the SW- and NE respectively in the western and eastern part of the study area (Figure 3), and the tectonic contact between the PBU and the TN (see Section 5.1). A3 axes trend NW–SE and are almost coaxial with A2 axes. The F2–F3 interference pattern is of type 3, according to the classification by Ramsay and Huber (1987). The S3 axial plane foliation is a crenulation cleavage that strikes NW–SE and dips towards the W ($30\text{--}60^\circ$) (Figure 5b). The S3 is characterized by millimetric to centimetric spacing and is well-developed only in fine-grained lithologies, such as phyllites. Locally, D2 boudins are inverted by the D3 phase, producing small-scale W-verging thrusts (Figure 5c).

The fourth tectonic phase (D4) is associated with gently SW-dipping to subhorizontal top-to-ENE shear zones (SZD4), with displacements, ranging from a few centimeters up to hundreds of meters. This phase is responsible for the eastward tectonic slicing of the *Verrucano* group over the Anisian-Ladinian sequence, affecting also the Tuscan Nappe (Figure 3). The architecture of D4 shear zones, well observed in

the southern part of the study area (Cala Marola, Main Map), displays: (1) a core zone with a foliated catclasite that contains sheared sigmoidal lenses of wall rocks with deformed S3 foliation; (2) a fractured damage zone in the host rocks (Figure 5d); (3) synthetic P and R1 and antithetic R2 Riedel shears (nomenclature after Logan et al., 1992), associated with drag folds and sigmoidal objects indicating top-to-E/NE kinematics (Figure 5d).

The latest structures in the area, marking the D5 tectonic phase, are represented by sets of N–S to NW–SE and E–W high-angle faults with normal to transcurrent kinematics. These structures are only locally exposed along the coast (e.g. Figure 3e) and their orientation is extrapolated from their attitude at map scale (Main Map).

6. Petrography and microstructures

The PBU sequence experienced greenschist-facies metamorphism and polyphase deformation, resulting in a wide range of microstructures. For descriptive

purposes, we grouped the investigated suite of selected thin sections into seven main lithotypes: (i) phyllite and metasandstone, (ii) calcschist, (iii) polymictic metabreccia, (iv) monomictic metacarbonate breccia, (v) marble, (vi) metabasalt and (vii) quartz-rich metaconglomerate.

A foliated microfabric characterizes phyllite and metasandstone (i) with fine-grained Wmca + Chl + Qtz + Ab + Ep + Fe-Ti oxides (abbreviations after [Siivola & Schmid, 2007](#)) defining the S1 and S2 foliations ([Figure 6a](#)). The S1 cleavage is preserved in quartz-rich microlithons between S2 cleavage domains. Spaced, opaque-rich surfaces ([Figure 6a](#)) define a younger crenulation cleavage (S3). Epidote, albite, and tourmaline form fine-grained porphyroblasts in mica-rich domains. Quartz shows granoblastic microstructure with serrated boundaries and small bulges.

Subparallel quartz-rich, calcite-rich and white mica + chlorite + Fe-Ti oxide rich layers with a preferred orientation parallel to the S2 foliation define the foliated structure of calcschist (ii). The S1 cleavage, defined by Wmca + Chl + Qtz + Cal + Fe-Ti oxide grains, occurs locally preserved in microlithons. Epidote is present as intertectonic porphyroblasts ([Figure 6b](#)). Quartz and calcite grains show serrated grain boundaries and a moderate shape preferred orientation parallel to the S2 foliation ([Figure 6c](#)). Undulose extinction and small bulges, indicative of bulging recrystallization ([Stipp et al., 2002](#)), are common in quartz. Calcite displays undulose extinction and mechanical e-twinning. Common mineral accessories in phyllite, metasandstone and calcschist (i-ii) consist of Tur, Py, Ap, Zrn, and Rt/Ttn. Barite and LREE (light rare earth elements)-phosphate are observed within phyllite and metasandstone. Pyrite grains commonly display euhedral habit and occur surrounded by displacement-controlled and face-controlled quartz fringes, elongated parallel to the S2 foliation ([Figure 6d](#)).

Polymictic metabreccia (iii) consists of heterometric clasts of phyllite, quartzite and marble, flattened along the S2 foliation, embedded in a Qtz + Ab + Wmca + Chl + opaque + piemontite metapsammitic matrix. Clasts preserve internal structures, such as bedding planes, inherited from their sedimentary protolith. Competency contrast between strongly flattened calcite-rich clasts and quartz-rich clasts is common.

Monomictic metacarbonate breccia (iv) consists of strongly flattened and recrystallized carbonate clasts, oriented parallel to the S2 foliation, that are made up of fine-grained calcite-rich aggregates that are wrapped by a greenish Wmca + Chl + Cal + Fe-Ti oxide-bearing matrix.

Marble (v) shows fine-grained calcite grains with granoblastic to locally polygonal microstructure with a weak shape preferred orientation parallel to the S2 foliation and serrated grain boundaries. Mechanical

e-twins occur within some grains. The S3 crenulation cleavage is well-developed only in rare white mica + chlorite-bearing lepidoblastic layers.

Metabasalt (vi) is characterized by a fine-grained Chl + Ca-Am + Wmca + Qtz + Ttn + Ep + Ilm + Mag assemblage. The earlier S1 cleavage is, seldom, preserved in some layers, marked by oriented Chl, Ca-Am and Wmca. The main foliation (S2) is defined by flattened quartz + calcite aggregates, interpreted as former magmatic vesicles, whereas the rock matrix display limited preferred orientation along the S2 foliation ([Figure 6e](#)). Plagioclase phenocrysts, replaced by Ep + Chl + Wmca, and magmatic ophitic textures are still recognizable ([Figure 6f](#)). Quartz grains show deformation bands, patchy undulose extinction and serrated grain boundaries with small bulges ([Figure 6g](#)), indicative of bulging recrystallization (e.g. [Stipp et al., 2002](#)).

Quartz-rich metaconglomerate (vii) mainly consists of quartz polycrystalline clasts and minor tourmaline grains surrounded by a very fine-grained Qtz + Ser + Chl matrix. The S2 foliation is barely defined by oriented phyllosilicates. Quartz clasts show highly variable internal microstructures, ranging from polygonal to strongly lobate grain boundaries and grains with patchy to undulose extinction patterns and trails of quartz grains ([Figure 6h](#)). Some clasts contain also cracks and healed fractures, as well as small bulges, indicative of bulging recrystallization (e.g. [Stipp et al., 2002](#)). We interpret the heterogeneous microstructures preserved within clasts as inherited from the protolith, only partially related to the Alpine deformation of the PBU.

7. Discussion and conclusion

Detailed structural geological mapping, coupled with microstructural observations, allowed defining the geometry and deformation pattern of the Punta Bianca Unit. The PBU represents an example of polyphase deformation that occurred during the evolution of an orogenic wedge, recording underplating and subsequent exhumation. In summary, the main structural features of the PBU are:

- Presence of a relic earlier foliation (S1) defined by greenschist-facies paragenesis (e.g. Wmca + Chl + Ab + Ep)
- Recumbent SW- and NE-verging F2 folds associated with a S2 foliation, marked by greenschist-facies paragenesis and flattened strain markers
- Upright F3 folds that refold the S2 foliation and the tectonic contact with the Tuscan Nappe, associated with a steeply W-dipping S3 crenulation cleavage defined by opaque-rich surfaces. This phase is also associated with small scale thrusts and inversion of D2 boudins

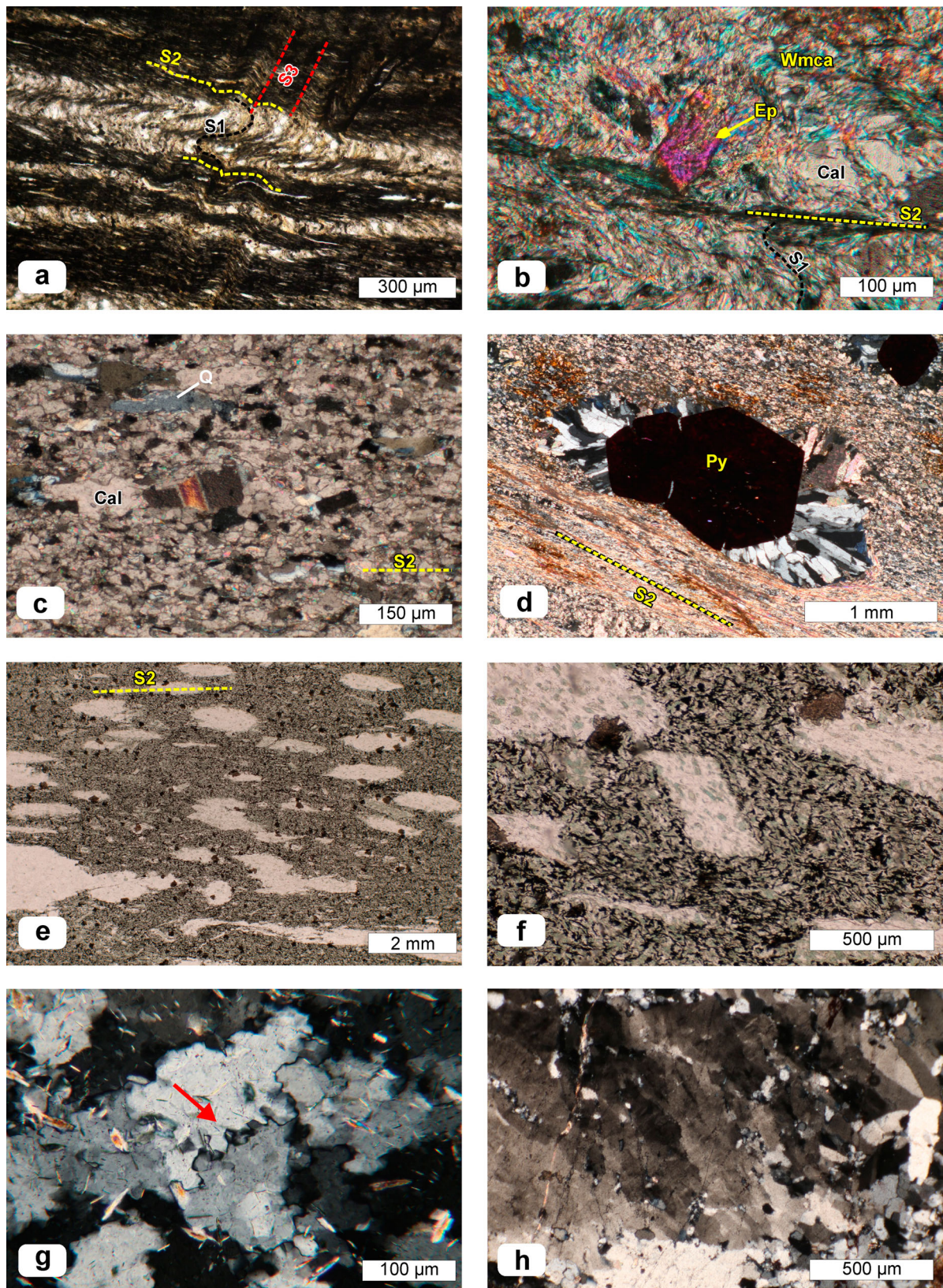


Figure 6. Micrographs collected at (a–b–c–d–g–h) crossed and (e–f) plane polarized light. Mineral abbreviations after [Siivola and Schmid \(2007\)](#). (a) Relationships between the S1 slaty cleavage and the S2–S3 crenulation cleavages in a metasandstone (*Metarenarie e Metapeliti* Fm.). (b) Intertectonic epidote grain that overgrows the S1 foliation, crenulated by the S2 in the surrounding matrix, observed in a calcschist (*Metacalcarì, Calcescisti e Filladi* Fm.). (c) Deformed quartz and calcite grains in a calcschist (*Marmi di Punta Bianca* Fm.) showing a shape preferred orientation parallel to the S2 foliation. (d) Face-controlled quartz strain fringes developed around euhedral pyrite grains, parallel to the S2 foliation (*Metabreccia Poligeniche* Fm.). (e) Flattened calcite-quartz vesicles surrounded by a greenish opaque-Ca-amphibole-chlorite matrix in a metabasalt (*Metavulcaniti* Fm.). (f) Relic euhedral magmatic plagioclase grain pseudomorphosed to a mix of sericite and chlorite, surrounded by a chlorite + opaque + Ca-amphibole matrix (*Metavulcaniti* Fm.). (g) Bulging (red arrow) of quartz in a vesicle within metabasalts (*Metavulcaniti* Fm.). (h) Example of the heterogeneous microstructures shown by quartzite clasts in the *Anageniti* Fm. Polygonal grain boundaries coexist with cracks, subgrains, trails of recrystallized quartz grains, and deformation bands.

- Top-to-E/NE semibrittle shear zones (D4) that slice the *Verrucano* group over the older formations of the PBU
- Late high-angle normal and transcurrent faults (D5), affecting the whole structural architecture

The D1 and D2 tectonic phases are linked to deformation in the middle crust, as testified by the associated greenschist-facies parageneses indicative of ~300–400°C and $P \sim 0.4\text{--}0.7$ GPa (Franceschelli et al., 1986; Lo Pò et al., 2016; Molli et al., 2018a, b). D1 structures were strongly obliterated during the D2 phase and, therefore, it is not possible to constrain with precision their kinematics and geometry. According to Carosi et al. (1991) and Storti (1995), the D1 phase can be related to NE-verging underthrusting, based on a comparison with the nearby Alpi Apuane Unit and Massa Unit (Carmignani & Kligfield, 1990; Molli, 2008; Molli et al., 2000, 2018a).

The overall geometry of D2 structures and the flattened finite strain ellipsoid are consistent with vertical shortening (e.g. Platt, 1986). Vertical shortening fits well with syn-orogenic extension, as also suggested by Storti (1995). Therefore, we suggest that the D2 phase marks the main exhumation event in the area, although it is possible that exhumation started as early as during the D1 phase, as in the Alpi Apuane (e.g. Molli et al., 2018a). W-verging structures, such as D2 folds and shear zones, might have formed during W-directed extension in the area, driving the exhumation to shallower levels within the orogenic wedge. Although no unambiguous kinematic indicators are preserved within the *Breccia di Caprona* Fm., these breccia likely marks a W-dipping and W-SW verging extensional structure probably reworking a former thrust fault, juxtaposing sub-greenschist-facies rocks of the TN ($T \sim 200^\circ\text{C}$; Montomoli et al., 2001) in its hanging wall, from the greenschist-facies PBU.

Post-D2 phase deformation of the PBU occurred after its exhumation and coupling with the TN at shallow crustal levels. Indeed, (1) the coaxial involvement of the base of the Tuscan Nappe and the S2 foliation in large-scale F3 folds and (2) the presence of D4 shear zones affecting both units, suggest that the TN and the PBU were already coupled before D3–D4 deformation phases took place. Opaque-rich surfaces, marking the S3 foliation, represent stress-induced pressure solution surfaces (e.g. Gray & Durney, 1979a, b; Engelder & Marshak, 1985; Schweitzer & Simpson, 1986) and are compatible with deformation at very-low metamorphic grade (e.g. Kanagawa, 1991; Kisch, 1991). Such conditions of deformation are comparable with the deformation mechanisms recognized in the Tuscan Nappe in the La Spezia area (Carosi et al., 2003). Coupling of the TN with the underlying metamorphic units, suggested by the presence of clasts of metamorphic rocks in the tectonic breccia at the

base of the TN (Carosi et al., 2002, 2004) has been timely constrained at regional scale to the late Miocene-early Pliocene (Balestrieri et al., 2011; Fellin et al., 2007). F3 folding is indicative of regional shortening and antiformal stacking (e.g. Molli et al., 2018b), likely in association with out-of-sequence thrusting, as reported in other sectors of the Northern Apennines (Bonini & Sani, 2002; Clemenzi et al., 2014; Massa et al., 2017; Musumeci et al., 2008; Papeschi et al., 2017). Out-of-sequence thrusting has also been proposed to explain the structures present in the offshore area of the La Spezia gulf (Abbate et al., 2005). Consequently, D4 faults and shear zones may be alternatively interpreted as thrust fault flats, shallow ramps or as extensional detachments (as in the nearby Tellaro detachment; Clemenzi et al., 2015; Molli et al., 2018a). In the former scenario, post-orogenic extension linked to the opening of the Northern Thyrrean Sea (e.g. Jolivet et al., 1998) would have been accommodated entirely by D5 high-angle normal faults in the area.

As a whole, the polyphase history recorded by the PBU, summarized in this study, highlights the complex tectonic history recorded during continental subduction and exhumation in the hinterland sector of the Northern Apennines. The new and revised structural geological map of the PBU constitute the basis for further studies in the area.

Software

The geological map and the tectonic sketch were produced using ESRI ArcGIS 10.0 and CorelDraw X4. The stereographic projections were realized using OpenStereo and Stereonet. Vector-based versions of the topographic maps were realized from the rasters of the Carta Tecnica Regionale – Regione Liguria (www.regione.liguria.it).

Supplementary material

Geographic coordinated and details of the samples selected for this study are available on SESAR (www.geosamples.org). The finite strain analysis dataset, including high-resolution scans of polished slabs, tables and finite strain data, is available for download at <https://doi.org/10.17632/hyxw2shy3z.1>.

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