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Geology and tectonic setting of the Fornovolasco area, Alpi Apuane (Tuscany, Italy)

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ABSTRACT
The study area is located in the Alpi Apuane (Tuscany, Italy), and extends between N 44° 0′49.883″–E 10°20′23.467″ (SW corner) and N 44°2′53.403″–E 10°23′19.175″ (NE corner). The area shows a pile of tectonic units belonging either to the Apuane metamorphic complex, and Tuscan Nappe, stacked during the Alpine orogeny. The latter is represented by a sedimentary Triassic-Miocene succession, and it is characterized by a large-scale east-dipping monocline, with local excision of stratigraphic terms due to the occurrence of intra-unit low-angle normal faults. The Apuane metamorphic complex is formed by Paleozoic phyllites, post-Variscan magmatic rocks (Fornovolasco Metarhyolite Fm.), and Mesozoic-Tertiary metasedimentary formations. The 1:5000 scale geological map and the cross-sections illustrate the tectonic setting of the Fornovolasco area, resulting from the Tertiary tectono-metamorphic events. In the Fornovolasco area, small Tl-rich pyrite + magnetite ore bodies occur close to the contacts between the Paleozoic basement and the cover metasedimentary formations.

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1. Introduction

The Fornovolasco area is located in the Alpi Apuane (NW Tuscany, Italy), where formations belonging to the Tuscan Nappe and the Apuane metamorphic complex outcrop. The latter consists of a Paleozoic basement and its Meso-Cenozoic metasedimentary cover (Figure 1), metamorphosed up to greenschist facies conditions (Molli, Giorgetti, & Meccheri, 2002 and references therein). Traditionally, the study area has been attributed to the so-called Stazzemese Slices, Stazzemese Parauthocton or Fornovolasco-Panie Unit (e.g. Massa, 2007 and references therein). The attention of several generations of geologists was focused on this sector of the Alpi Apuane, owing to the occurrence of several intriguing geological structures as well as ore deposits, mainly represented by pyrite ± baryte ± iron oxide ore bodies. This type of mineralization is preferentially hosted within the Paleozoic basement or close to the contact between the schists of the basement and the Triassic metadolostone of the Grezzoni Fm. (e.g. Carmignani, Dessau, & Duchi, 1976; Lattanzi, Benvenuti, Costagliola, & Tanelli, 1994).

The first geological mapping of the Fornovolasco area dates back to Zaccagna (1894, 1926). Nardi (1961) compiled the first modern geological map of the area, whereas further maps at 1:50,000 scale were later published by Carmignani et al. (2000) and Puccinelli, D'Amato Avanzi, and Perilli (2016a). Carmignani et al. (1976) reported a detailed mapping of the area around the small pyrite + magnetite ore deposit of 'Cava del Ferro' (Le Buge locality), whereas Pandeli, Bagnoli, and Negri (2004) focused their attention on the pre-Norian succession.

In the present paper, the geological map of the Fornovolasco area, resulting from a new geological survey at the 1:5000 scale, is presented. The aim of this new mapping is manifold. In particular, it aims to improve the knowledge about this sector of the Alpi Apuane metamorphic complex, giving a reference framework for both the pyrite + magnetite ore deposits and the meter to decameter-sized metarhyolite lenses cropping out in the Fornovolasco area.

2. Geological background

The tectonic setting of the Alpi Apuane (Figure 1) is the result of two main tectono-metamorphic events (D1 and D2 phases; Carmignani & Kligfield, 1990), related to the deformation of the Adria continental margin during the continental subduction and the syn- to post-collisional exhumation (Molli, 2008; Molli et al., 2002; Molli, Giorgetti, & Meccheri, 2000).

The D1 event, associated with underplating and stacking of the tectonic units, developed a progressive deformation in two stages (D1a and D1b in Molli & Meccheri, 2000; Molli & Vaselli, 2006) which

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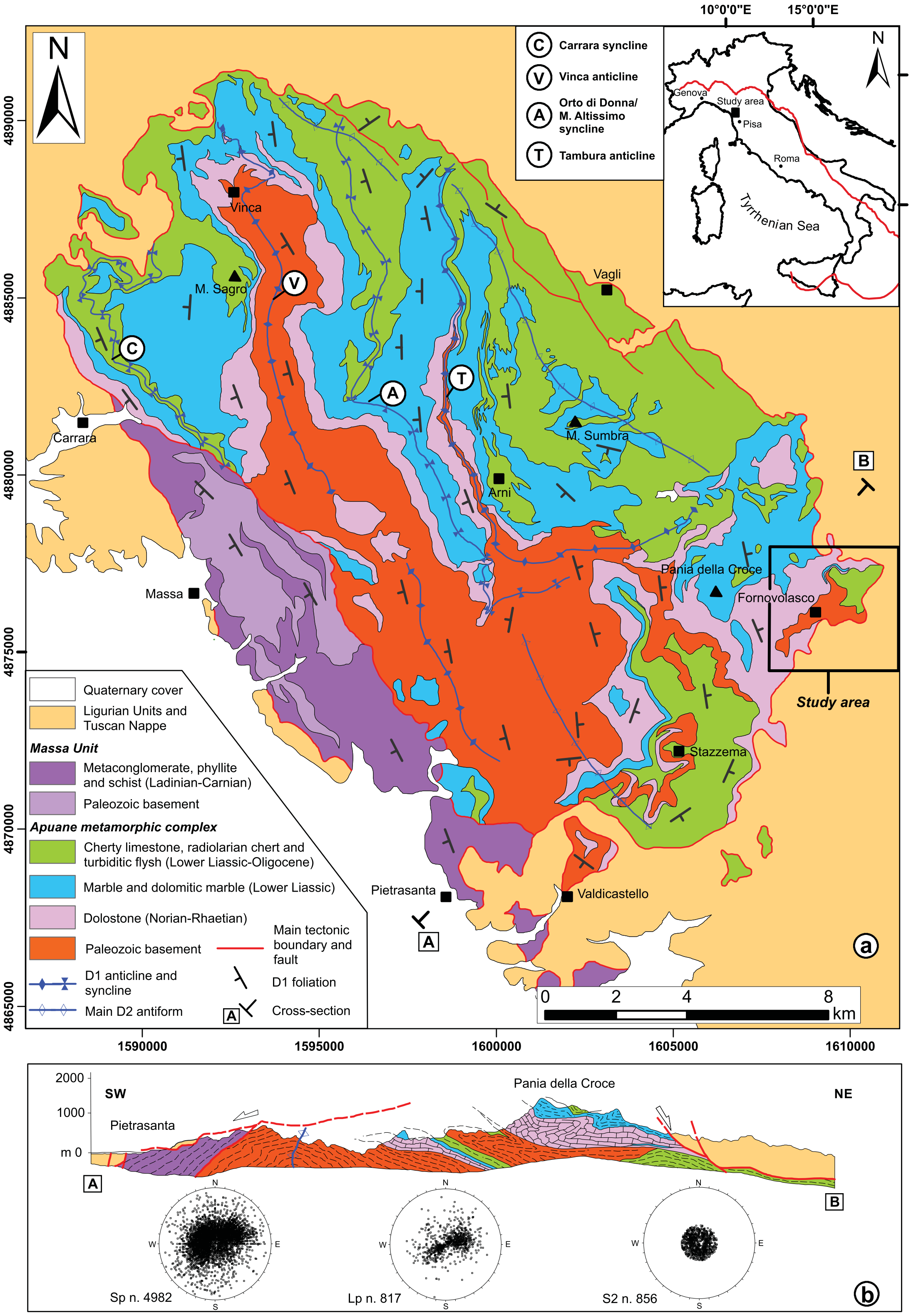

Figure 1. (a) Geological sketch map (modified from Carmignani & Kligfield, 1990) and (b) cross-section across the Alpi Apuane massif. Equal area lower hemisphere stereograms show the poles of the main foliation (Sp), the stretching lineation (Lp), and the late crenulation cleavage (S2). Projected Coordinate System: Monte_Mario_Italy_zone_1.

produced pervasive foliations (S1a and S1b) representing the axial planes of isoclinal micro- to kilometric-scale NE-vergent folds. This foliation is associated with a stretching lineation trending SW-NE and interpreted as the main transport direction of the tectonic units (Carmignani, Giglia, & Kligfield, 1978; Molli, 2008). According to several authors (e.g. Fellin et al., 2007 and references therein), the peak metamorphism was reached during the early D1 phase, dated at ca. 27 Ma using K-Ar and ^{40}Ar-^{39}Ar techniques on white mica (Kligfield, Hunziker, Dallmeyer, & Schamel, 1986); *P-T* conditions were estimated at 350–450°C and 0.6 GPa (Molli et al., 2002 and references therein).

The D2 event is associated with the exhumation of the metamorphic units (e.g. Molli, 2012) and is related to the development of different generations of folds and high-strain shear zones. As a result, a complex mega-antiform with Apenninic trending axis (NW-SE) was produced (Carmignani & Kligfield, 1990). Non-cylindrical parasitic folds with sub-horizontal axial planar crenulations (S2) are related to this phase and involved the transportation to the east on the eastern limb of the antiform and to the west on the western side (Carmignani & Kligfield, 1990; Carmignani, Disperati, Fantozzi, Giglia, & Meccheri, 1993; Carmignani, Fantozzi, Giglia, & Meccheri, 1993). The early stages of the D2 phase were characterized by *T* higher than 250°C and, according to zircon fission track ages, dated back earlier than 11 Ma (Fellin et al., 2007).

The latest stages of deformation, related to the final exhumation and uplift of the metamorphic units, were characterized by the transition from a ductile to a brittle regime, with the formation of kink folds, low- and high-angle faults, and joint systems (Corti, Serena, Bonini, Sani, & Mazzarini, 2006; Molli et al., 2010; Ottria & Molli, 2000 and references therein). The uplift and the final exhumation are testified by the apatite fission tracks dated at 2–6 Ma (Abbate, Balestrieri, Bigazzi, Norelli, & Quercioli, 1994; Bigazzi, Di Pisa, Gattiglio, Meccheri, & Norelli, 1988), and by the occurrence of metamorphic clasts in Plio-Quaternary basins (e.g. Coltorti, Pieruccini, & Rustioni, 2008).

The most recent study of the Fornovolasco area was performed by Pandeli et al. (2004) who examined the nature of the so-called Fornovolasco schists, a debated pre-Norian formation of uncertain stratigraphic setting. These authors proposed a new interpretation for this succession, distinguishing three units, partly correlated with the Variscan basement and partly with the Triassic cover. The middle-lower portion (the so-called Fornovolasco schists *s.s.*), formed by feldspathic-chloritic metagraywackes with levels of graphitic metapelites and embedding lenses of porphyritic tourmaline-rich rocks, has been correlated to the Lower Paleozoic rocks of the Apuane metamorphic complex, owing to their compositional features; the associated porphyritic rocks have been related to the Middle Ordovician Porphyroids Fm. (Pandeli et al., 2004). Moreover, the 'Fornovolasco schists' are affected by a widespread tourmalinization. The upper part of this sequence is represented by the locally mineralized metadolostone of the Grezzone Metallifero Fm. and the metasiliciclastic rocks of the Verrucano group. Whereas the latter contains intercalations of dolomitic metalimestone (Tinello Metacarbonates; Pandeli et al., 2004) dated to Late Ladinian-Carnian (Ciarapica & Zaninetti, 1983), the former formation is of difficult stratigraphic attribution. According to Pandeli et al. (2004), it could be associated with the Middle Triassic marine furrow of the Punta Bianca I Cycle (Martini, Rau, & Tongiorgi, 1986).

Due to the intense deformations, developed during the Alpine orogenesis, which characterize the studied area, the 'Fornovolasco schists' are interpreted as a set of tectonic slices belonging to different litho-stratigraphic units (e.g. Carmignani et al., 1976; Carmignani et al., 2000; Puccinelli et al., 2016a, 2016b) where the original stratigraphic relationships were completely obliterated. In the present work, the 'Fornovolasco schists' will be described following the stratigraphy proposed in the modern geological maps of the Alpi Apuane (e.g. Carmignani et al., 2000; Puccinelli et al., 2016a).

3. Methods

The geological map of the Fornovolasco area (Main Map – about 10 km^2) was produced by means of a geological survey at 1:5000 scale, relying on the classical tools of structural geology which joined together field and laboratory work with meso- and micro-structural studies. The topographic base used for the Main Map was modified from the Carta Tecnica Regionale of the Tuscany Region at 1:10,000 scale. The geological database was implemented using ESRI ArcGis 10.3 and following the guidelines for the Geological Map of Italy (1:50,000 scale; Artioli et al., 1997). The geological map includes the tectonic sketch map of the Alpi Apuane and surroundings, the structural scheme of the mapped area, the geological cross-sections, and images showing the main results achieved during the geological mapping, i.e. the identification of the Fornovolasco Metarhyolite Fm. and the occurrence of Vinca Fm. The Quaternary deposits (landslides, slope, alluvial, and anthropic deposits) were mapped at 1:5000 scale by means of the analysis of aerial photographs and Google Earth images and geomorphological survey. The aerial photos, provided by the Tuscany Regional Administration, cover the whole study area and were acquired on 23 June 1996. The geomorphological and geological surveys were performed simultaneously.

4. New data on the Fornovolasco area

4.1. Stratigraphic and structural setting

The studied area is characterized by the overlapping of two main tectonic units represented, from the top to the bottom, by (i) the non-metamorphic to anchimetamorphic Upper Triassic-Lower Miocene sedimentary succession of the Tuscan Nappe (e.g. Cerrina Feroni, Plesi, Fanelli, Leoni, & Martinelli, 1983) and (ii) the Apuane metamorphic complex, represented by a mainly metasedimentary sequence of Paleozoic to

Miocene age. Since the latter complex outcrops extensively in the studied area, its succession will be described below. A full description of the Tuscan Nappe can be found in Puccinelli, D'Amato Avanzi, and Perilli (2016b).

In the studied area, the Apuane metamorphic complex is formed by a Variscan basement and a Triassic-Miocene metasedimentary cover. This sequence is affected by intense deformations, often showing tectonized contacts and making difficult to document a continuous stratigraphic succession. For this reason, in the following, the formations occurring in the studied area will be presented from top to bottom in a geometrical sequence:

- *Pseudomacigno Fm.* – Upper Oligocene–Lower Miocene: the main outcrops are located NE of Fornovolasco, along the Turrite di Gallicano River. This formation is formed by dark gray quartz-feldspathic metasandstone. In its lower part, layers up to some meters in thickness occur, whereas in the upper part, metapelitic and metasiltitic intercalations become more frequent (Figure 2(a)). Gradation and sedimentary structures (e.g. ripples, crossed-laminations) are usually preserved in the arenitic layers.
- *Scisti Sericitici Fm.* – Lower Cretaceous – Upper Oligocene (Aptian – Chattian): this formation crops out in small tectonic slices at the base of Tuscan Nappe, and in particular, along the road from Fornovolasco to San Pellegrinetto and at NW of Col di Luco (for location, see the Main Map). It is formed by green and red/violet metapelite with intercalations of ivory and green metalimestone and calcschist.
- *Metacalcari selciferi Fm.* – Lower Jurassic (Upper Pliensbachian): this formation crops out in a small tectonic slice located at the base of the Panie massif, near Casa Castellaccio, along the road from Fornovolasco to Vergemoli. It is formed by metalimestone with chert nodules, with color ranging from dark gray to bluish-gray; a frequent ochre/light-gray color occurs on altered surfaces. The sequence of metalimestone layers (cm- to dm-sized in thickness) shows interlayered dark-gray phyllite/calcschist.
- *Marmi Fm.* – Lower Jurassic (Hettangian – Upper Sinemurian): it is formed by white, ivory, and light to dark-gray metalimestone, sprinkled with gray/gray-green to yellowish/ochre veins, related to the occurrence of accessory phyllosilicates (mainly represented by muscovite and chlorite), sulfides, and iron oxides. Anastomosed layers of dolostone can be found interbedded within the Marmi Fm.
- *Grezzoni Fm.* – Upper Triassic (Norian): this formation is made up of three different lithofacies, which are from bottom to top: (i) gray vacuolar dolomitic metalimestone (lithofacies GREa), with associated cataclasite and polygenic sedimentary breccias, probably of karst origin, containing numerous clasts of Apuane metamorphic rocks with matrix of ochre color and carbonatic composition; (ii) inter-sopratidal metadolostone with stromatolitic layers and *fenestrae* structures, sporadically associated with the tidal channel metabreccias and more frequently desiccation metabreccias (Figure 2(b)); (iii) black dolomitic metalimestone, with yellowish/grayish alteration patina. Locally, between Le Buge and Casa Castellaccio, along the road from Fornovolasco to Vergemoli, this formation includes small tectonic slices of Marmi Dolomitici Fm. (Hettangian). The Marmi Dolomitici Fm. is formed by light gray and rarely whitish dolomitic metalimestone interlayered with light-gray massive dolomitic levels. Frequently, well-preserved oncoids and bioclasts occur.
- *Vinca Fm.* – Upper Triassic (Upper Carnian – Lower Norian): it consists of polymictic meta-para-conglomerate with dark-gray/greenish phyllitic to the metapsammitic matrix, greenish quarzitic metasandstone, from medium to coarse grained, texturally immature, containing scattered white and subordinated pale pink heterometric quartz pebbles from angular to rounded in shape ('Anageniti'). Clasts of low-grade metamorphic rocks are frequent and they are represented by greenish quartzitic phyllite, quartzite, and tourmalinite (Figure 2(c)); in addition, clasts of quartz veins, locally showing scattered pyrite crystals, have been observed. These clasts are angular to sub-angular in shape. Locally, layers of massive metadolostone, with cm to m thickness and light-brown/yellowish to dark gray in color, are present. They are interlayered with black or gray/green metapelite and metasandstone (Figure 2(d)). Pandeli et al. (2004) correlate the Vinca Fm. with the 'Tinello Metacarbonates', cropping out at the Buca del Tinello (W of Fornovolasco) and underlying the Grezzoni Fm. The 'Tinello Metacarbonates' contain benthic microforaminifera dated to Ladinian-Carnian by Ciarapica and Zaninetti (1983). Taking into account such a fossil content and the regional scale stratigraphic correlations (e.g. Coli, Frosini, & Pandeli, 2003; Pellegrini, 1985), an Upper Carnian-Lower Norian age for the Vinca Fm. can be assumed.
- *Grezzone Metallifero Fm.* – Middle Triassic (?): a recent description of this formation is given by Pandeli et al. (2004). It is made up of massive dolomitic metalimestone, more or less recrystallized, gray to black in color (Figure 2(e)). Locally, centimetric alternation of yellowish calcschist and black metapelite occur. It crops out in the Trimpello-Le Buge area, Fontanaccia, Fornaccia, and Buca del Tinello, and it is associated with the ore deposits of Fornovolasco. The age and stratigraphic position of the

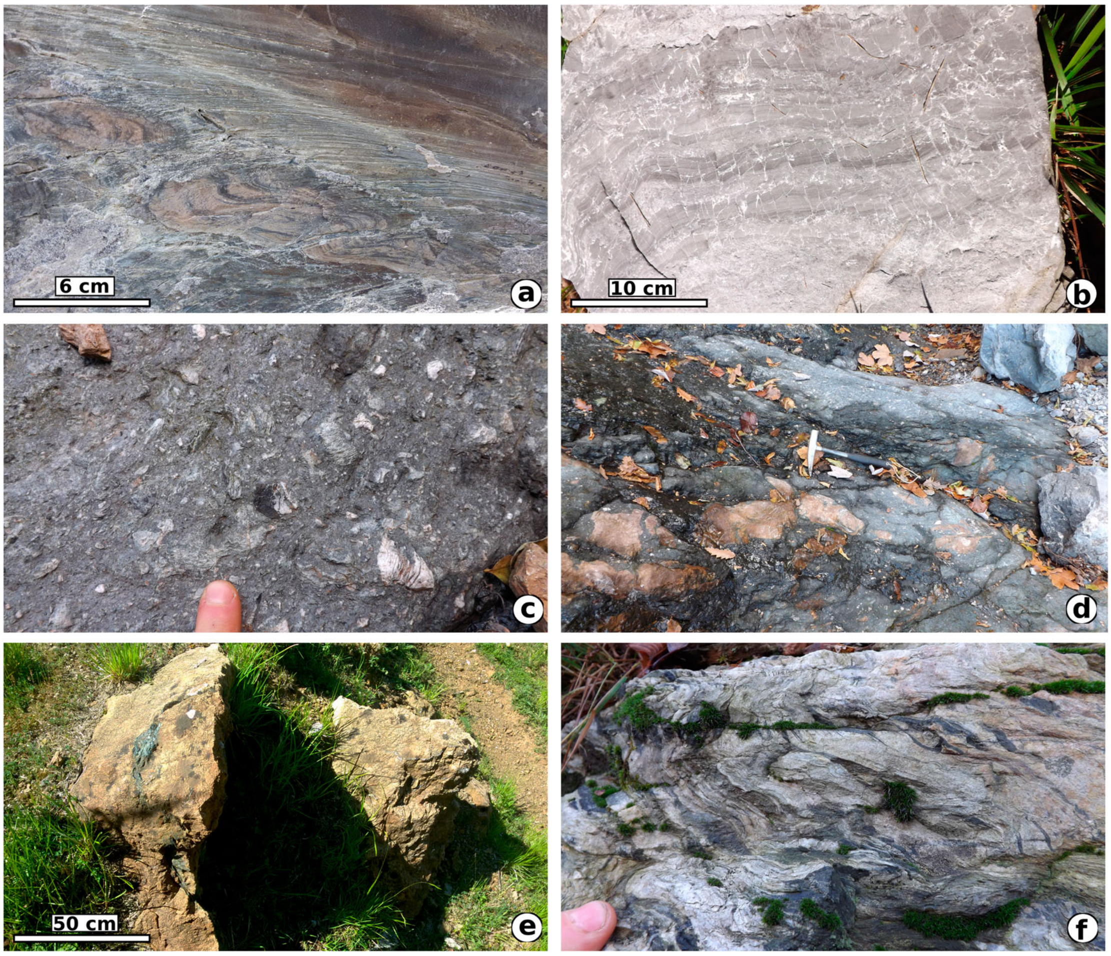

Figure 2. Some lithologies cropping out in the Fornovolasco area. (a) Centimetric alternation of metarenites and metapelites of the Pseudomacigno Fm. cropping out at SE of Casa Castellaccio. (b) Breccia at the base of the Grezzoni Fm., cropping out near Grotta del Vento.(c) Coarse metabreccia (Vinca Fm.) with clasts of phyllites, quartz veins, and tourmalinite. Outcrops below the Fornovolasco-Vergemoli road, close to the Fontanaccia area, at north of Le Buge. (d) Dolostone layer intercalated within black and gray/green metapelites, and metasandstones of the Vinca Fm. Same outcrop of (c). (e) Massive dolostone with iron oxides mineralization belonging to the Grezzone Metallifero Fm., along the road from Trimpello to Vergemoli. (f) Phyllites (Filladi Inferiori Fm.) with tourmalinite layers. Farneto, east of the Fornovolasco mining complex.

'Grezzone Metallifero' are uncertain, owing to the absence of any paleontological content.

- *Filladi Inferiori Fm.* – ?Lower Cambrian – Middle Ordovician: as reported above, Pandeli et al. (2004) related the 'Fornovolasco schists *s.s.*' Fm. to the Filladi Inferiori Fm. This is the only Paleozoic formation so far described in the Fornovolasco area and it has been related to the metasedimentary sequences of southeast Sardinia on the basis of lithological similarities (e.g. Bagnoli et al., 1979; Carmignani, Rau, Squarci, Tongiorgi, & Vai, 1977; Gattiglio, Meccheri, & Tongiorgi, 1989). Recently, Paoli et al. (2017) dated this formation to the Early Cambrian – Middle Ordovician, on the basis of detrital zircon ages (maximum depositional age ca. 560 Ma). This formation consists of muscovitic-quartzitic phyllite, from dark gray to gray-green in color, alternating with layers of a variable thickness of light-gray or light-green quartzite (Figure 2(e)). A peculiar feature of the Filladi Inferiori Fm. outcropping in the Fornovolasco area is its extensive tourmalinization. As reported by Pandeli et al. (2004), lenses of tourmaline-bearing porphyritic rocks are embedded in this phylladic complex. On the basis of new field and laboratory data, these porphyritic rocks have been distinguished from the Filladi Inferiori Fm. and are described in Section 4.2.

The entire succession of the litho-stratigraphic units described above is affected by a polyphasic deformation related to the D1 and D2 tectonic events (e.g. Carmignani & Kligfield, 1990). The area of Fornovolasco is characterized by the occurrence of strongly non-cylindrical isoclinal folds related to the D1 phase, with a penetrative composite foliation (S1a and S1b) as an axial plane, well developed in metapelite belonging to the Pseudomacigno Fm. Moreover, the syn-metamorphic tectonic contacts (i.e. those observed in the Trimpello, Le Buge, and Casa Castellaccio localities and that occurring along the Turrite di Gallicano River, giving rise to the overthrusting of the Paleozoic basement on the Tertiary Pseudomacigno Fm.) may be attributed to an early deformation phase (D1a) (see cross-sections C–C'' and A–A′); then, these tectonic contacts were isoclinally folded during a later deformation event (D1b).

The tectonic structures formed during these first stages were later overprinted by centimetric to pluridecametric folds (D2), with open to closed geometry, having a sub-horizontal crenulation cleavage as an axial plane (S2). Large-scale interference structures between D2 and D1 folds and foliations may be recognized at the meter- to hectometer-scale between Le Buge, Fontanaccia, and Casa Castellaccio (see the Main Map and the cross-section C–C′). During the D2 event, some tectonic boundaries formed during the D1 event were reactivated as low-angle normal faults. The most important reactivation involved the tectonic contact occurring from Col di Luco to Petrosciana di Sotto and from this latter locality to Casa Castellaccio. This structure has a listric geometry and a top-to-the-NE sense of shear, as suggested by synthetic faults (see, for instance, the southwestern part of the cross-section A–A′).

The main structure of the Tuscan Nappe observed in the study area is represented by its former basal thrust reworked as a low-angle normal fault during the exhumation of the metamorphic units. This contact locally trends approximately W-E/ENE and it is characterized by the widespread occurrence of carbonate cataclasite and tectonic breccias, mapped as Calcare Cavernoso. A subsidiary intra-unit low-angle normal fault caused the local excision of the stratigraphic succession; for instance, close to Casa Maggiolini, it juxtaposed the Maiolica Fm. with the Calcare Cavernoso. This kilometer-scale structure is extended from Le Merze-Matteaccio to Vispereglia (see the Main Map), striking SW–NE and gently dipping towards SE, and can be related to the 'Pescaglia LANF', a kilometric structure having a listric geometry (Carmignani, Disperati, et al., 1993) with a top-down-to-the-NE sense of shear (Carosi, Frassi, Montomoli, & Pertusati, 2005).

High-angle normal faults dissect all previous structures and show an NW–SE trend, dipping towards NE (see, for instance, the northeastern part of the cross-section A–A′). They may be related to the latest stages of the D2 deformation event. The presence of this kind of faults can explain the sharp closure of the Apuane metamorphic complex below the Tuscan Nappe along the Turrite di Gallicano River, close to Trombacco (see Main Map).

4.2. The 'Fornovolasco Metarhyolite'

The occurrence of lenticular bodies of tourmaline-rich porphyritic rocks embedded within the phylladic complex belonging to the Filladi Inferiori Fm. has been known since Lotti (1882). Zaccagna (1932) reported the results obtained by Franchi who classified this rock as a tourmaline-bearing eurite. Bonatti (1933) gave a first petrographic description of these rocks, describing the small outcrop close to Le Casette locality, SW of Fornovolasco. In addition, he reported the occurrence of this rock also in two other small outcrops close to the Fornovolasco village. A peculiar feature of this rock is its massive nature, strongly contrasting with the schistosity shown by the surrounding rocks; from a petrographic point of view, this lithology is mainly formed by quartz (sometimes with magmatic embayments), tourmaline, feldspar, biotite, and white mica. Apatite, zircon, and rutile are accessory minerals. Bonatti (1933) concluded that this porphyritic rock could be a 'meta-tufite', although he pointed out that the finding of new evidences in similar outcrops could help in unveiling the actual nature of these rocks.

Pandeli et al. (2004) related these lenses of tourmaline-bearing porphyritic rocks to the Middle Ordovician Porphyroids Fm., without their formal distinction from the surrounding schists.

During this survey, previously unknown decameter-sized lenses of these porphyritic rocks were mapped. The larger body extensively outcrops close to the Boscaccio locality, where it forms the slope between Col di Luco and the Turrite di Gallicano River (Figure 3(a)). These bodies are usually formed by fine-grained massive rocks (Figure 3(b)), locally showing the widespread occurrence of cm-sized tourmaline orbicules (Figure 3 (c)). This is a textural feature that could indicate a subvolcanic or intrusive nature of this particular lithotype (e.g. Hong, Cooke, Zhang, Fox, & Thompson, 2017 and references therein). The finding of such a peculiar textural feature promoted a new investigation of these rocks, allowing their full petrographic and geochemical characterization. In addition, its dating, on the basis of U-Pb zircon ages, points to a Permian magmatic event (Vezzoni, Biagioni, D'Orazio, Pieruccioni, & Petrelli, 2017). Owing to its peculiar nature and to its geological significance, the porphyritic rocks occurring as lenses within the Filladi Inferiori Fm. have been distinguished and mapped as a different geological formation, hereafter called Fornovolasco Metarhyolite Fm., in agreement with their chemical composition. Other small outcrops of this formation (in some cases previously reported also by Pandeli et al., 2004) have been mapped along the road Fornovolasco-Vergemoli, close to Le Buge; along the Battiferro stream, close to the Fornovolasco village and finally near the Farneto locality.

4.3. The pyrite+magnetite ore deposits

The small pyrite+magnetite ore deposits of Fornovolasco belong to the series of pyrite±baryte±iron oxide ore deposits occurring in the southern Alpi Apuane, along a narrow belt from Valdicastello to Fornovolasco (Figure 1). Recently, it was shown that these deposits are characterized by a marked Tl anomaly (up to

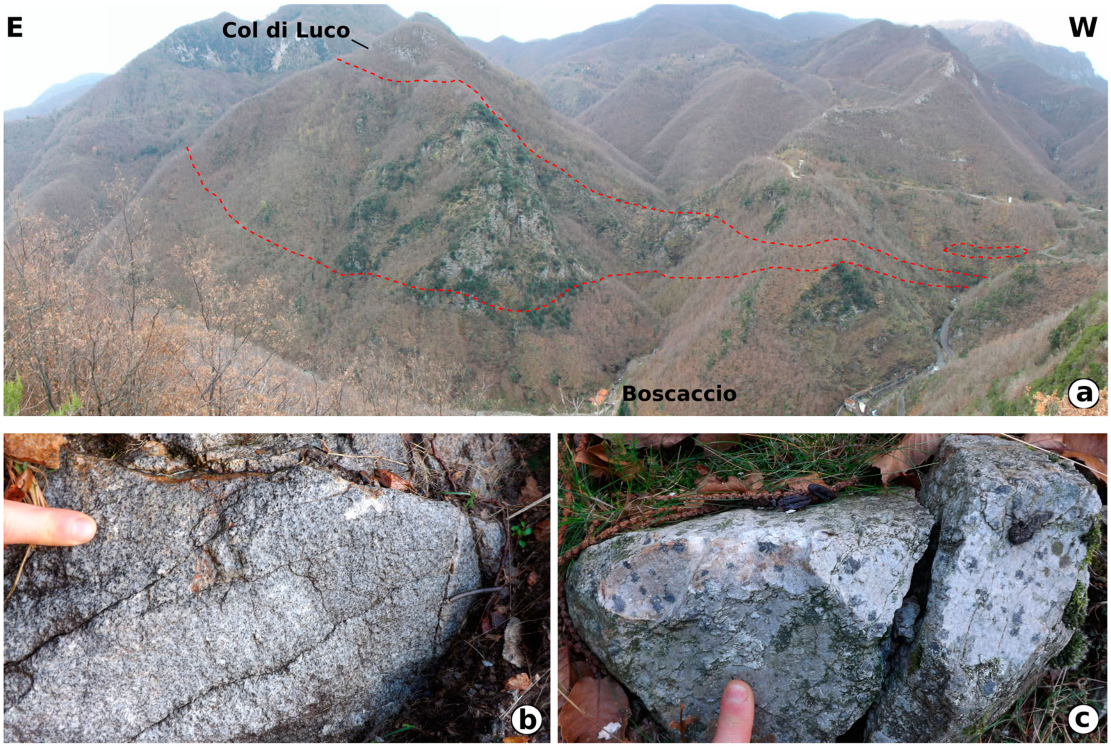

Figure 3. (a) Panoramic view of the Boscaccio area, located at north of Col di Luco as seen from Le Buge. The red dotted lines border the main outcrop of the Fornovolasco Metarhyolite. (b) Fine-grained metavolcanite cropping out near Le Casette. (c) Cm-sized tourmaline orbicules in the Fornovolasco Metarhyolite cropping out in the Boscaccio locality.

1110 µg g^{-1} Tl in pyrite ore from Fornovolasco; D'Orazio, Biagioni, Dini, & Vezzoni, 2017), representing potential environmental hazards.

Known since a long time (mid-thirteenth Century; e.g. Biagioni, Orlandi, & Bonini, 2008), the Fornovolasco ore deposits have been scarcely studied. The most important mining works (hereafter 'Fornovolasco mining complex') were done near the small village of Trimpello, in the locality known as 'Cava del Ferro' (Figure 4(a)) or Le Buge; other minor works were performed in the Fontanaccia, at north of Le Buge, and Fornaccia, near Boscaccio (see the Main Map). Carmignani et al. (1976) described the geological setting of these ore deposits, reporting a simplified geological sketch of the Fornovolasco mining complex. The ore bodies are located at the contact between the phylladic complex of the Filladi Inferiori Fm. and the metadolostone belonging to the Grezzone Metallifero Fm. (Figure 4(b)). The contact between these two formations is tectonic, as proved by the occurrence of slices of metarenites and metapelites belonging to the Pseudomacigno Fm. According to Carmignani et al. (1976), the mineralization had a metasomatic origin and involved the substitution of carbonatic rocks by pyrite and magnetite, as proved by substitution relics within the ore bodies, represented not only by carbonate rocks but also by clasts of quartz and phyllites. Cioffi (1991) proposed an alternative genetic model, i.e. the present textural and mineralogical features of the Fornovolasco ore deposit would be the result of the Alpine metamorphism overprinting a Middle Triassic sedimentary pyrite+iron oxide proto-ore.

During the mapping of the Fornovolasco area, the Fornovolasco mining complex was re-examined. The main ore bodies are located in a strongly deformed area, characterized by several tectonic contacts involving the Variscan basement, the Triassic metadolostone, and the Tertiary Pseudomacigno Fm. Several generations of tectonic boundary and folds can be identified.

The ore bodies are usually located at the contact between the pre-Alpine basement and the Triassic carbonates, concordant with the main field schistosity (S1b) characterizing the Fornovolasco area. Ore bodies occur as lenses having a thickness of 50–70 cm and lengths ranging between 1–2 m and ca. 10 m. Their mineralogy is represented by pyrite ± arsenopyrite ± pyrrhotite, with traces of baryte (close to the contact with phyllites; Figure 4(c)) or magnetite ± hematite (usually at the contact with metadolostone; Figure 4 (d)). The latter shows some textural features similar to those shown by the metasiliciclastic 'Verrucano-like' deposits of the Vinca Fm., with clasts of phyllite, quartz vein, porphyritic rock, and rare carbonate embedded in a matrix formed by iron oxides, without any feature suggesting a genesis through metasomatic replacement. The pyrite and iron oxide ore assemblages are usually separated, in agreement with the zoning at the ore deposit scale observed by previous authors (e.g. Carmignani et al., 1976). The transition

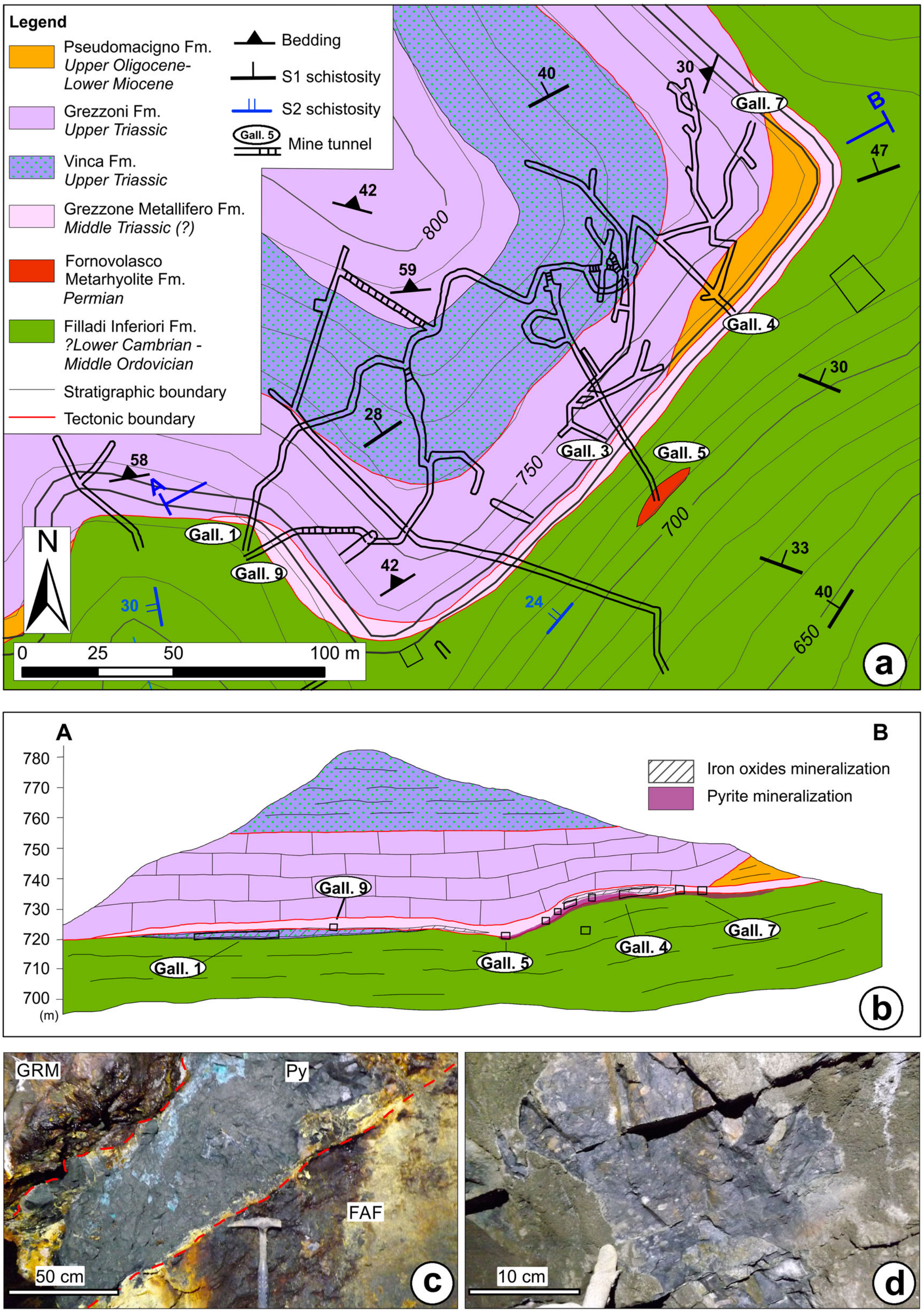

Figure 4. (a) Geological map and (b) cross-section across the Fornovolasco mining complex, where the main ore bodies occur. (c) A pyrite ore body (Py) intercalated between phyllites (possibly related to the Filladi Inferiori Fm., FAF) and Grezzone Metallifero Fm. (GRM). Pale blue patches are represented by melanterite, $FeSO_4{\cdot}7H_2O$, the first oxidation product of pyrite. (d) 'Verrucano-like' deposit with an iron oxides matrix, mainly represented by magnetite.

between these two ore types seems to involve a meter-sized zone with mixed magnetite and pyrite embedded in metacarbonates.

The Alpine tectonic events favored the formation of dolomite ± quartz vein systems within the metadolostone or quartz ± feldspar ± carbonate veins in the phylladic rocks. In both vein systems, well-crystallized sulfides and sulfosalts (e.g. sphalerite, jamesonite; Orlandi, Moëlo, & Biagioni, 2008), titanium oxides (e.g. Biagioni et al., 2008), and secondary phases (e.g. the bismuth phosphate ximengite; Biagioni, Orlandi, Perchiazzi, & Merlini, 2010) have been reported.

5. Conclusions

The new detailed geological map (Main Map) at the scale of 1:5000 is the most detailed representation of the geological and structural setting of the Fornovolasco area presently available. The work was carried out by integrating classical field-mapping with GIS and photo-interpretation of aerial and satellite images, used to check map consistency and significantly improve the quality, particularly in areas characterized by steep topography.

During the geological survey, it was possible to identify and map a new geological formation indicated as Fornovolasco Metarhyolite, which is represented by Permian acid metavolcanic rocks, characterized by the local occurrence of tourmaline orbicules. This formation is thus the first evidence of post-Variscan magmatism recorded in the Paleozoic basement of the Alpi Apuane. In addition, a detailed mapping of the siliciclastic and siliciclastic–carbonate deposits of Ladinian-Carnian age (Vinca Fm. and Grezzone Metallifero Fm.), previously not mapped in detail in this sector of Alpi Apuane, is reported.

Software

Georeferencing and digitization, preliminary cartographic design, geological database, and geological map were entirely developed using ESRI ArcGis 10.3. Map layout and final editing were performed using CorelDraw X6. The stereographic projections were realized with Dips 5.1. The cross-sections and the pictures were created using CorelDraw X6.

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No potential conflict of interest was reported by the authors.

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