INTRODUCTION

High-P–low-T (HP–LT) rocks are commonly found in suture zones of orogenic belts, recording early subduction of oceanic crust before initial continental collision (e.g. Honegger, Le Fort, Mascle, & Zimmermann, 1989; Liou, Wang, Coleman, Zhang, & Maruyama, 1989; Miyashiro, 1961). Exhumed blueschist- and eclogite facies rocks, found in orogens, not only represent markers of subduction processes and related metamorphism but also store information on the tectonometamorphic evolution of orogenic wedges and the recycling of crustal material at convergent margins (e.g. Angiboust, Agard, Rainbougu, Yamato, & Huet, 2011; Ernst, 1973, 1988, 2001; Maruyama, Liou, & Terabayashi, 1996; Platt, 1993; Stern, 2005; Tsujimori & Ernst, 2014). Petrological and geochronological investigations of HP–LT rocks can shed light on the pressure–temperature–time path experienced during oceanic subduction or early continental collision (e.g. Aoya, Endo, Mizukami, & Wallis, 2013; Davis & Whitney, 2006; Kryza, Willner, Massonne, Muszyński, & Schertl, 2011; López-Carmona, Abati, Pitra, & Lee, 2014;...
López-Carmona, Pitra, & Abati, 2013; Vitale Brovarone, Groppo, Hetényi, Compagnoni, & Malavieille, 2011; Warren & Waters, 2006), and are hence invaluable for understanding the exhumation and tectonic processes that are active in past and present orogenic belts (Maruyama et al., 1996; Platt, 1993; Ring, Brandon, Willett, & Lister, 1999; Ring & Glodny, 2010; Searle & Lamont, 2020).

In the Aegean area, for instance, detailed metamorphic petrology and geochronology of the Cycladic Blueschist Units, has demonstrated the importance of exhumation tectonics during exhumation of deep-seated HP–LT rocks (Jolivet & Brun, 2010; Ring & Glodny, 2010; Ring & Layer, 2003; Searle & Lamont, 2020). Syn-orogenic exhumation has been proposed also for the northern Tyrrhenian Sea (e.g. Jolivet et al., 1998), where the pioneering works of Theye, Reinhardt, Goffé, Jolivet, and Brunet (1997), Giorgetti, Goffe, Memmi, and Nieto (1998), and Rossetti et al. (1999) revealed the existence of exhumed continental and oceanic HP–LT rocks, related to early Apenninic continental collision (Rossetti, Glodny, Theye, & Maggi, 2015). In spite of this evidence, exhumation of HP–LT rocks in the Northern Apennines has been ascribed by many authors to be a result of post-orogenic extension (e.g. Brogi, 2008; Carmignani et al., 1994; Carmignani & Kligerfield, 1990), mostly because of the present-day setting of the northern Tyrrhenian Sea within an area of active crustal thinning (Cassinis, Scarascia, Lozej, & Finetti, 2005; Pondrelli et al., 2006).

In this contribution, we present a case study of blueschist facies metabasites and associated calcshists and metapelites from the Island of Elba (Italy) that record early continental collision and exhumation of continental crust in the Northern Apennines. A detailed petrographic and mineralogical description of the investigated rocks is presented and is integrated with the modelled mineral chemistry obtained by pressure–temperature ($P$–$T$) and $P$–$T$–$X$ pseudosection calculations, to constrain peak and retrograde metamorphism. The $P$–$T$ path, reconstructed from different rock types, allowed us to reconstruct the evolution of the investigated units in the geodynamic framework of the Northern Apennines–Alps orogenic system, and to shed new light on the exhumation of HP–LT units in the Northern Apennines, before crustal extension.

2 GEOLOGICAL OUTLINE

2.1 The Northern Apennines–Corsica orogenic system

The Alps and the Apennines are two oppositely verging orogenic systems, formed after 90 Ma of convergence between the Adria microplate and the European margin, leading to the complete subduction of the Alpine Tethys Ocean (Figure 1a; Boccaletti, Elter, & Guazzzone, 1971; Elter, Elter, Sturani, & Weidmann, 1966). The Alpine system, exposed on the Island of Corsica, is separated from the Northern Apennines by the Northern Tyrrhenian Sea, which has classically been interpreted as a late Miocene back-arc basin (Brunet, Monié, Jolivet, & Cadet, 2000; Jolivet et al., 1998). The European Variscan basement of Corsica is overlain on the northeastern sector of the island (Alpine Corsica) by W-verging (a) continental Europe-derived units, (b) ocean-derived units (Schistes Lustrés), accreted during the Late Cretaceous–Eocene period, and (c) the so-called Nappes Supérieures (upper units), consisting of non-metamorphic ophiolitic and continental units (Figure 1a; Durand-Delga, 1984; Malavieille, Chemenda, & Larroque, 1998). Eocene HP–LT parageneses are found in the entire Alpine Corsica nappe stack, except for the uppermost unit (Balagne-Nebbio Unit; Caron, 1994; Chopin, Beyssac, Bernard, & Malavieille, 2008; Daniel, Jolivet, Goffe, & Poinssot, 1996; Tribuzio & Giacomini, 2002; Vitale Brovarone & Herwartz, 2013; Vitale Brovarone et al., 2013). On the opposite side of the Northern Tyrrhenian Sea, the Northern Apennines are characterized by NE-verging nappes that were accreted during the subduction of the Adria microplate from the Oligocene to the present day (Figure 1a; Boccaletti et al., 1971; Elter, 1975). The Northern Apennine nappe stack comprises, from top to bottom: (a) the Ligurian and Subligurian Units, oceanic and ocean–continent transition nappes containing Jurassic ophiolite sequences and their Jurassic–Palaeocene cover with associated flysch deposits; (b) several Adria-derived nappes, notably the Tuscan Nappe in the hinterland sector and the Cervarola–Falterona Unit and Umbria–Marche Units in the external part of the belt, characterized by carbonate-dominated Triassic–Palaeogene passive margin sequences capped by Oligocene–Miocene foredeep deposits; (c) a group of metamorphic nappes, collectively referred to as the Tuscan Metamorphic Units (TMUs), that comprise a Palaeozoic Variscan basement overlain by fragments of a Carboniferous–Oligocene sedimentary cover, which is correlated with that of the Tuscan Nappe. The nappe stack is covered by Neogene–Quaternary wedge-top deposits and was affected by late Miocene–Quaternary intrusive and extrusive arc magmatism, dominated by anatectic melts of crustal signature (Serri, Innocenti, & Manetti, 1993).

Contrary to Alpine Corsica, the Northern Apennines nappe stack is dominated by non-metamorphic to subgreenschist facies units (e.g. Franceschelli, Leoni, Memmi, & Puxeddu, 1986). The Ligurian Units, representing the non-metamorphic analogue of the Schistes Lustrés, generally escaped HP–LT subduction-related metamorphism and remained at upper crustal levels. Sodic amphibole-bearing Ligurian Units are only found in the Monte Argentario area ($P$–$T$ ≥ 0.7 GPa at ~340°C; Theye, Reinhardt, Goffé, Jolivet, & Brunet, 1997) and in the Island of Giglio ($P$–$T$ = 0.7–0.8 GPa at 300–350°C; Biancone & Tucci, 1984; Rossetti et al., 1999). The Island of
FIGURE 1 Geological setting: (a) Tectonic sketch map of the Northern Apennines–Alpine Corsica orogenic system (modified after Bonini et al., 2014). MTR, Mid-Tuscan Ridge; AA, Alpi Apuane massif; MP, Monti Pisani massif; MR, Monticiano-Roccastrada massif. (b) Simplified structural-geological map of the Island of Elba (modified after Massa et al., 2017). The rectangle marks the study area, shown in Figure 2.
Gorgona, in the middle of the Northern Tyrrhenian Sea, is characterized by blueschist facies metaophiolites, which were interpreted to belong to the Schistes Lustrés. $P$–$T$ conditions of 1.3–1.6 GPa at 300–350°C were estimated for these rocks (Jolivet et al., 1998), which were dated at 25.6 ± 0.3 Ma using the 40Ar/39Ar system on phengite (Brunet et al., 2000). As for Adria-derived units, greenschist- to blueschist facies parageneses occur only in the TMUs. Typical chloritoid-bearing assemblages have been reported in the Apuan Alps ($P$–$T$ ranging from 0.4–0.6 GPa at 360–420°C to 0.6–0.8 GPa at 420–500°C; Jolivet et al., 1998; Molli, Giorgetti, & Meccheri, 2000; Molli, Vitale Brovarone, Beyssac, & Cinquini, 2018) and the Monti Pisani ($P$–$T$ = 0.8–0.9 GPa at ~475°C; Lo Pò & Braga, 2014). Similar or higher pressures were estimated for the carpholite-bearing Monticiano-Roccastrada Unit ($P$–$T$ = 0.6–0.8 to ~1.1 GPa at 340–370 to 370–420°C; Brogi &
2.2 Geology of the Island of Elba

The structure of the Island of Elba is characterized by N–S trending, E-verging nappes stacked by W-dipping thrusts that developed largely between the early Miocene and the Pliocene (Figure 1b; Keller & Coward, 1996; Massa, Musumeci, Mazzarini, & Pieruccioni, 2017; Pertusati, Raggi, Ricci, Duranti, & Palmeri, 1993; Viola et al., 2018). Early Miocene thrusting was followed by middle Miocene syn-orogenic extension and exhumation of metamorphic units and then by a renewed top-to-the-ENE late Miocene–Early Pliocene contractional phase, coeval with the emplacement of magmatic rocks (Massa et al., 2017; Musumeci et al., 2015; Papeschl, Musumeci, & Mazzarini, 2017; Viola et al., 2018). In this framework, the Zuccale Fault, previously interpreted as an extensional detachment (e.g. Collettini & Holdsworth, 2004), has been reinterpreted as an Early Pliocene out-of-sequence thrust (Musumeci et al., 2015; Viola et al., 2018).

The late Miocene Capo Norsī–Monte Arco thrust divides the nappe stack into an Upper Complex and a Lower Complex (Figure 1b). From top to bottom, the Upper Complex consists of three Ligurian-derived units (the Cretaceous Flysch Unit, the Palaeogene Flysch Unit and the ophiolite-bearing Ligurian Unit) that overlie the Adria-derived Tuscan Nappe and the greenschist facies Rio Marina Unit, containing Carboniferous–Triassic basement rocks. The Lower Complex comprises two basement-and-cover metamorphic units that are part of the TMUs: the greenschist- to blueschist facies Ortona Unit and the amphibolite facies Calamita Unit at the base of the nappe stack. A slice of strongly tectonized serpentinite, originally part of the Ligurian Unit, is sandwiched between the Rio Marina Unit and the Lower Complex, and smeared along the Capo Norsī–Monte Arco thrust (Massa et al., 2017; Serpentine Unit in Figure 1b). The nappe stack is intruded by several late Miocene intrusives. The Monte Capanne pluton (between 7.007 ± 0.007 and 7.323 ± 0.019 Ma; ID-TIMS U/Pb youngest zircon ages; Barboni, Annen, & Shoene, 2015) intruded the Ligurian Unit on Western Elba (Figure 1b); the Central Elba laccolith complex (between 7.437 ± 0.011 and 7.942 ± 0.008 Ma; ID-TIMS U/Pb youngest zircon ages; Barboni, Annen, & Shoene, 2015) consists of sheets of different magmas that were emplaced in the Cretaceous Flysch Unit and the Ligurian Unit (Figure 1b; Dini, Innocenti, Rocchi, Tonarini, & Westerman, 2002). The Porto Azzurro pluton intruded the Calamita Unit (Lower Complex) in Eastern Elba (Figure 1b; Barberi, Innocenti, & Ricci, 1967; Musumeci & Vaselli, 2012). Since most of the Porto Azzurro pluton is buried below the sea level, age constraints were obtained only from outcropping tourmaline-rich apophyses (5.9 ± 0.2 Ma; 40Ar/39Ar biotite age; Maineri et al., 2003), and leucogranitic dykes (6.33 ± 0.07 Ma; 40Ar/39Ar biotite age; Musumeci et al., 2015), both likely representing late magmatic manifestations. The intrusion of the Porto Azzurro pluton resulted in large-scale low-P–high-T (LP–HT) metamorphism in the Lower Complex, completely obliterating the regional metamorphic assemblage in the Calamita Unit and, partially, also in the southern part of the Ortona Unit.

LP–HT metamorphism occurred at P < 0.2 GPa reaching peak temperatures of 600–700°C in the Calamita Unit and 450–600°C in the Ortona Unit (Duranti, Palmeri, Pertusati, & Ricci, 1992; Musumeci & Vaselli, 2012; Papeschl, Musumeci, Massonne, Bartoli, & Cesare, 2019). Available radiometric ages on the LP–HT assemblage constrain contact metamorphism between 6.76 ± 0.08 Ma (40Ar/39Ar phlogopite age) and 6.23 ± 0.06 Ma (40Ar/39Ar muscovite age), corroborated by a 6.40 ± 0.15 Ma U/Pb zircon age (Musumeci et al., 2015; Musumeci, Mazzarini, Tiepolo, & Di Vincenzo, 2011).

Blueschist- to greenschist facies parageneses (Bianco et al., 2015) are preserved in the Ortona Unit (Acquadolce Subunit; Massa et al., 2017), north of Mt. Fico, where the effect of LP–HT metamorphism already dissipated along strike towards the North (Figures 1b and 2). Bianco et al. (2015) reported the occurrence of glaucophane-bearing lenses of...
metabasite, with a chemical composition transitional between tholeiitic basalt and alkali basalt, enveloped within foliated marble and phyllite. Lawsonite pseudomorphs, enclosed in epidote and albite, were later documented by Bianco et al. (2019). Based on the content of the glaucophane end-member in amphibole and the jadeite end-member in pyroxene, Bianco et al. (2015) estimated peak $P–T$ conditions ~0.9–1.0 GPa and 330–350°C. Later on, Bianco et al. (2019) suggested peak pressures likely above 1.5 GPa. However, detailed $P–T$ estimates were hindered by inhomogeneous metamorphism of the investigated rocks. $^{40}\text{Ar}/^{39}\text{Ar}$ dating on phengite from the schistose rocks associated with the metabasite yielded a 19.68 ± 0.15 Ma plateau age (Deino, Keller, Minelli, & Pialli, 1992), coeval with the 19.8 ± 1.4 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ glaucophane age obtained by Bianco et al. (2019) (location in Figure 2).

### 2.3 Acquadolce Subunit: geological outline

The Ortano Unit (Figure 2) is characterized by a Middle Ordovician basement (Ortano Porphyroid; Musumeci et al., 2011), overlain by Jurassic marble (Ortano Marble) and a complex of schist and metapsammite, containing lenses of marble, cherty marble and calc-schist, known as the Acquadolce Subunit (Massa et al., 2017). Metabasite bodies occur disseminated in the lower part of the Acquadolce Subunit, included within metacarbonates (Figure 2). Throughout the Ortano Unit, the metamorphic foliation strikes approximately N–S and dips gently to moderately (10–50°) to the W (Figure 2).

The Acquadolce Subunit is separated from the rest of the Ortano Unit by the late Miocene Felciaio Shear Zone (Figure 2), which was active during peak LP–HT metamorphism associated with the emplacement of the Porto Azzurro pluton in eastern Elba (Musumeci & Vaselli, 2012). For this reason, while the Ortano Marble and the Ortano Porphyroid experienced amphibolite facies metamorphism at $P < 0.2$ GPa (Duranti et al., 1992), the effect of the LP–HT imprint on the Acquadolce Subunit caused only the development of cordierite- and andalusite-bearing spotted schists, mainly in the southern part of the area (south of M. Fico–Punta dell’Acquadolce; Figure 2). The northern part of the Acquadolce Subunit largely escaped late Miocene LP–HT metamorphism and preserves blueschist facies parageneses, mostly in metabasite lenses (Bianco et al., 2015) with T/E MORB geochemical affinity (Bianco et al., 2019). Contact metamorphic parageneses in metapelites, calc-schists and metabasites are only represented by the incipient growth of biotite (Rio Marina–S. Filomena area), and of plagioclase, which forms a rim around pure albite cores (from Punta dell’Acquadolce to the South; Figure 2; Table S1).

The age and palaeogeographic attribution of the Acquadolce Subunit are in part unclear. Detrital zircon dating indicates an early Oligocene minimum deposition age at least for the schistose rocks of the Acquadolce Subunit occurring at the top of the sequence in the Ortano Subunit (Jacobs et al., 2018; sample location in Figure 2), whereas the marble, calc-schist and metabasite lenses were ascribed to the Cretaceous by Duranti et al. (1992). Recently, Massa et al. (2017) correlated the Acquadolce Subunit with the younger formations of the Tuscan Nappe (i.e. Cretaceous–Oligocene Scaglia Toscana Fm.).

### 3 | BLUESCHIST FACIES METABASITE AND ASSOCIATED LITHOLOGIES

The metabasite bodies of the Acquadolce Subunit occur in scattered outcrops, exposed along the coastline between Rio Marina and Punta dell’Acquadolce (Figure 2). The relationship with the host rocks is well exposed at Rio Marina (Torretta di Rio Marina outcrop) and has been summarized in the lithostratigraphic column in Figure 3a. At this location, metabasite occurs as lens-shaped bodies, hosted in metacarbonates, with thickness between some decimetres and 1–2 m (Figure 3a). The dominant mafic rock type is dark to light green (Figure 3b) and contains a very fine-grained amphibole+chlorite+epidote matrix which surrounds millimetric porphyroclasts of clinopyroxene and whitish albite aggregates. The structure of the metabasite varies from poorly foliated or granofelsic (e.g. Figure 3b) to well-foliated, showing continuous variation even through single layers (e.g. Figure 3c). The foliation in the metabasite is defined mostly by the preferred orientation of chlorite and amphibole. Close to the contact with the surrounding carbonates, the foliation is finely layered (few centimetres in thickness); however, in general, the metabasite shows a spaced foliation, surrounding rock portions lacking a discernable orientation. Metabasite layers commonly exhibit symmetric boudinage structures with carbonate+epidote-rich veins in necks between boudins, nearly perpendicular to the foliation.

The host of the metabasite is made up of relatively pure mylonitic marble (grey to white in colour) and impure light-green mylonitic calc-schist (Figure 3a). As shown in Figure 3a,b, at the Torretta di Rio Marina outcrop, the mylonitic calc-schist layers are commonly found within a few decimetres from the contact with the metabasite, generally interleaved with millimetric to centimetric lenses of amphibole+chlorite-rich metabasic material (Figure 3d). The green colour of the mylonitic calc-schist is largely related to the presence of chlorite, epidote, amphibole and white mica. These minerals occur either as grains dispersed throughout the carbonatic matrix or enriched in fine-grained lenses/layers of green-coloured schists (Figure 4a). Millimetre-sized white albite grains are visible at the mesoscale within the mylonitic calc-schists (Figure 4a). The mylonitic marble, away from the...
FIGURE 3  Mesoscale features of the succession hosting the metabasites at the Rio Marina outcrop: (a) Lithological column, showing the relationships between the metabasite bodies and the host mylonitic calcschist and marble. Yellow stars mark the location of samples. (b) Contact between marble, calcschist and metabasite. Note the presence of foliated metabasite (top) passing to granofelsic metabasite (bottom). (c) Fabric transitions in the metabasite. From top to bottom the foliation intensity increases along the yellow arrow on the left. The small, yellow marker highlights thin, interlayer calcschist. (d) Detail of calcschist interlayered with the metabasite, characterized by the presence of discontinuous metabasic layers with variable thickness (green arrows).

FIGURE 4  Mesoscale features of the succession hosting the metabasites at the Rio Marina outcrop. The Sp label and a yellow dashed line mark the main, mylonitic foliation. (a) Detail of greenish phyllite fragments and layers, containing amphibole (Am), epidote (Ep), chlorite (Chl), albite (Ab) and white mica (Wmca) in the mylonitic calcschist. Mineral abbreviations after Siivola and Schmid (2007). (b) Sharp contact between poorly foliated metabasite and the underlying strongly foliated calcschist. (c) Sheath folds, revealing closed, ellipse-like, surfaces, when looking at strike (i.e. N–S) sections. (d) Detail of a sheath fold, showing the E–W trending lineation, constantly plunging towards the observer (red dashed line).
metabasite lenses, contains millimetre-thick metapelitic layers mainly consisting of white mica, chlorite and albite.

The transition from the metabasite lenses to the host carbonate is marked by a sharp increase in foliation intensity (Figure 4b). There is a single, continuous (mylonitic) schistosity in the carbonates, defined by the preferred orientation of mineral grains and by intercalations of thin layers of phyllosilicate-rich material, stretched along the foliation (Figure 4b). Both blueschist- (i.e. amphibole) and greenschist facies minerals appear strongly oriented along this foliation, indicating a strong reorganization of the peak fabric during retrograde deformation.

The foliation is also folded around tight to isoclinal shear folds (Figure 4c), associated with constantly E–W to NE–SW trending stretching lineation (Figure 4d), defined by oriented aggregates of carbonates, trails of chlorite-white mica and oriented amphibole grains.

4  |  PETROGRAPHY

Microstructures and metamorphic parageneses of the Acquadolce Subunit have been investigated in a suite of samples (see Table S1), the location and names of which are reported in Figure 2. The samples are registered on SESAR and additional details (lithological description, GPS coordinates and microphotographs) are available at https://app.geosamples.org/. Oriented thin sections were prepared and cut parallel to the lineation and perpendicular to the foliation. Petrographic investigations with the optical microscope were coupled with preliminary analysis of the mineral chemistry using a ZEISS-EVO SEM equipped with an Oxford Instruments EDS detector at the National Institute for Geophysics and Volcanology (Pisa, Italy) and a Hitachi TM3030 Plus Tabletop Microscope SEM at the Department of Earth Sciences (University of Pisa).

We selected a sample of metabasite (IESP3SP56; foliation oriented dip/dip-direction: 28°/308°) and a sample of calcschist (IESP3SP53; 26°/320°) for detailed petrographic and mineral chemistry studies. The selected samples, collected 50 cm apart, are from metabasite and calcschist layers in contact at the Torretta di Rio Marina outcrop (Figure 3a,b), and are those that best preserve the peak blueschist facies assemblage among all the investigated samples and show only a weak contact metamorphic imprint.

4.1  |  Metabasite

The metabasite contains, with decreasing modal content, amphibole+chlorite+clinopyroxene+epidote+albite+titanite+quartz+calcite. The microstructures of this rock are characterized by large, brownish clinopyroxene porphyroclasts (grain size: 0.2–2 mm), surrounded by a green to blue matrix made up of fine-grained amphibole+chlorite+epidote+quartz (grain size: 2–5 µm–100 µm; Figure 5a). Clinopyroxene porphyroclasts are partially replaced by very fine-grained intergrowths of chlorite+titanite+albite+quartz+amphibole, the latter also occurring in strain shadows around or in fractures within the porphyroclasts (Figure 5b). The prismatic shape of clinopyroxene, only locally preserved (Figure 5a), suggests that these porphyroclasts were originally primary constituents of the igneous protolith, in agreement with Bianco et al. (2015). However, SEM-EDS analyses carried out during this work and microprobe analyses reported by Bianco et al. (2015, 2019) reveal an omphacitic composition, demonstrating re-equilibration during blueschist facies metamorphism.

The foliation is heterogeneous and very poorly developed, and is mostly defined by the preferred orientation of amphibole and chlorite grains (Figure 5a). Unfoliated domains are characterized by irregular patches of epidote, titanite, albite and quartz.

Amphibole is zoned, showing a dark to lavender blue Na-rich core (Na-amphibole), surrounded by a pale green rim of Ca-amphibole (Figure 5c). Na-amphibole is commonly associated with clinopyroxene porphyroclasts (Figure 5b) and forms acicular to prismatic (~0.1 to 1 mm grain size) grains in the matrix (Figure 5c). Ca-amphibole forms a thin, euhedral rim around Na-amphibole grains as well as tiny, acicular grains (~10 to 50 µm) localized in the chlorite-rich matrix (Figure 5c). Epidote grains have euhedral to anhedral habits, ranging in size from 2–5 µm to ~100 µm (Figure 5d). In general, epidote is zoned and characterized by a relatively Fe-poor core (clinozoisite) surrounded by a ‘pistacitic’ Fe-rich rim (e.g. Figure S5). However, epidote grains with complex zoning patterns are also present. Pseudomorphs of rhomb-hedral lawsonite grains (~10 to 100 µm grain size) occur in the matrix, and as inclusions in epidote and albite (Figure 5e). Lawsonite has been replaced by aggregates of clinozoisite–epidote, and quartz (Figure 5e; concentration maps of major elements are available in Figures S6 and S7), as also reported by Bianco et al. (2019). Albite forms irregular patches, roughly 50–100 µm across, displaying a strongly lobate shape at the contact with partially resorbed Na-amphibole grains and sharp, straight boundaries at the contact with Ca-amphibole, epidote and titanite grains (Figure 5f). Titanite occurs as euhedral grains and clusters, ranging in size from 5–10 µm up to 200 µm (e.g. Figure 5f). Quartz and chlorite grains are distributed in the matrix (Figure 5d,e,f). Calcite grains locally occur in clusters but are the major component of veins crosscutting the sample.

To summarize, it is possible to distinguish an early metamorphic assemblage, documented by relic lawsonite, Na-amphibole, clinozoisite and clinopyroxene, from a later overprinting assemblage of albite+Ca-amphibole+Fe-epidote+chlorite+titanite+quartz. The relic mineral assemblage can be further subdivided into an earlier stage with lawsonite
formation and a later stage when lawsonite was pseudomorphed by clinzoisite. Na-amphibole is inferred to have been present during both stages.

4.2 | Calcschist

The calcschist consists of 80%–90% calcite (estimated on thin sections with ImageJ), organized in layers ranging in thickness between some hundreds of micrometres and the millimetre. Other mineral phases (given in decreasing modal content) are chlorite, white mica, albite, epidote, Na-amphibole, titanite, quartz, and accessory apatite, rutile, zircon, and tourmaline (in modal order). The non-carbonatic phases are concentrated in thin (10–20 µm, up to 100–200 µm) lepidoblastic layers, defining the main metamorphic foliation of the sample (Figure 6a). Chlorite, white mica and Na-amphibole share a common shape preferred orientation in these layers (Figure 6a). Subparallel white mica and chlorite also occur as single grains within calcite layers, defining the foliation therein (Figure 6a,b). Stacks of chlorite and white mica, intricately intergrown and oriented at high angle to the foliation in local crenulations, are also present (Figure 6c).

The calcite grains are 1–3 mm across with amoeboid shapes and lobate grain boundaries, that contain deformed mechanical twins and bands of smaller, recrystallized...
grains (grain size: 20–100 μm) with granoblastic microstructure (Figure 6b). The preferred orientation of both large calcite grains and bands of recrystallized grains contributes to define the foliation within calcite-rich domains (Figure 6b).

The grain size of chloride and white mica varies generally between 5 and 50 μm. Na-amphibole grains (grain size: 0.1–1.0 mm) display prismatic to fish-shaped habits and commonly contain inclusions of quartz, calcite, rutile, and apatite. Na-amphibole is very commonly boudinaged along the main foliation, with calcite+quartz located interstitially between boudins (Figure 6d). Epidote (grain size: 10–200 μm) forms euhedral grains, localized in the chlorite + white mica-rich matrix (Figure 6d,e). As shown in Figure 6e, epidote can contain allanite cores with oscillatory zoning, interpreted as detrital cores (see also Figures S15 and S17).

Albite is present as large porphyroclasts (up to 1–2 mm), synkinematically with respect to the main foliation, containing poikiloblastic inclusions of calcite, quartz, epidote, Na-amphibole, white mica, chlorite and titanite (Figure 6f). Na-amphibole within albite is partially resorbed, whereas titanite and epidote are in textural equilibrium with albite (Figure 6g). Small albite rims are also commonly present around Na-amphibole grains (e.g. Figure 6h). Very tiny quartz grains and aggregates, commonly organized in very thin layers (<10–50 μm thickness), are dispersed within the chlorite + white mica matrix (e.g. Figure 6e,h). Titanite (grain size: 10–100 μm), apatite and zircon (grain size: 5–50 μm) commonly display euhedral shapes (e.g. Figure 6e). Titanite commonly contains poikiloblastic inclusions of quartz and rutile (e.g. Figure 6e). The few rutile grains present in the matrix (grain size: 10–50 μm) are preserved as anhedral aggregates partially overgrown by titanite (Figure 6e,h). Thus, rutile was probably stable at peak conditions.

Based on microstructural relationships, the peak mineral assemblage, represented by Na-amphibole+rutile+quartz, was overprinted by albite+epidote+titanite+quartz. Matrix white mica and chlorite are interpreted as being present throughout the metamorphic evolution of the investigated calcschists, since they occur also in stacks crosscut by the main foliation (Figure 6c).

5 | MINERAL CHEMISTRY

The chemical composition of minerals in the selected samples was determined using a CAMECA SX100 electron microprobe (EMP) equipped with five WDS spectrometers and an EDS system at the Institut für Mineralogie und Kristallchemie (Universität Stuttgart). Analytical conditions for spot analyses were 15 kV accelerating voltage, 15 nA beam current, 20 s counting time on peak and background each, and 1 μm spot size. The standards used were wollastonite (Si, Ca), Al₂O₃ (Al), Fe₂O₃ (Fe), MnTiO₃ (Mn, Ti), albite (Na), orthoclase (K), olivine (Mg) and barite (Ba). Structural formulae of minerals were recalculated considering 14 oxygen equivalents for chlorite, 11 for white mica, 23 for amphibole, 12.5 for epidote, 8 for feldspar, 5 for titanite and 4 for rutile. The Fe³⁺ content of amphibole was recalculated using PROBE-AMPH (Tindle & Webb, 1994) and MINCALC-V5 (Bernhardt, 2007).

Na- and Ca-amphibole were classified using the classification scheme by Deer, Howie, and Zussman (1992), and white mica based on the Al⁶⁺-Al⁴⁺ diagram by Bousquet, Goffé, Vidal, Oberhänsli, and Patriat (2002). Concentration maps for major elements (Ca, Fe, Mn, Mg, Al, Na) were also produced by stepwise movements of the thin section under the electron beam; counting times per step were 100 ms. Representative mineral analyses are shown in Tables 1 and 2. All analyses, and their location, are available in the Supporting information to this article (Sections S1–S4).

5.1 | Metabasite

The amphibole composition is highly variable from Na-amphibole in the core to Ca-amphibole (actinolite) in the rim (Figure 7a). Na-amphibole shows a wide chemical variability from ‘crossite’ to glaucophane (Figure 7b) with Si = 7.76–7.97 per formula unit (p.f.u.), X_Mg (=Mg p.f.u./[Fe+Mg p.f.u.]) = 0.52–0.65, and X_Na (=Na p.f.u./[Na+K+Ca p.f.u.]) = 0.86–0.98. ‘Crossite’ was
### TABLE 1  Representative mineral analyses in the metabasite sample (IESP3SP56).

|             | Epidote |            |     |        |          |                |                |                |                |                | Amethyst       |                |                |                |                |                |                |
|-------------|---------|------------|-----|--------|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|             | core    | rim        |     | core   | rim      | matrix        | Chlorite       | Albite         | Titanite       |                |                |                |                |                |                |                |
| Analysis    | 17      | 20         | 14  | 72     | 2        | 33            | 28             | 87             | 96             | 5              | 90             | 32             | 97             | 27             | 62             |
| SiO₂        | 42.80   | 39.02      | 37.61| 37.54  | 56.45    | 58.83         | 56.36          | 55.62          | 54.15          | 28.40          | 29.68          | 68.96          | 68.34          | 31.81          | 30.23          |
| TiO₂        | 0.16    | 0.31       | 0.05| 0.07   | 0.14     | 0.06          | 0.01           | 0.00           | 0.04           | 0.00           | 0.00           | 0.02           | 0.00           | 0.00           | 37.03          |
| Al₂O₃       | 34.62   | 31.17      | 24.76| 22.28  | 7.88     | 11.01         | 0.80           | 1.10           | 2.37           | 18.93          | 19.37          | 19.06          | 18.86          | 1.58           | 0.69           |
| FeOtot      | 0.49    | 2.69       | 9.97| 12.98  | 15.35    | 10.45         | 10.28          | 10.01          | 12.39          | 18.78          | 15.74          | 0.41           | 0.27           | 0.60           | 0.57           |
| MnO         | 0.00    | 0.07       | 0.08| 0.06   | 0.11     | 0.12          | 0.17           | 0.26           | 0.19           | 0.35           | 0.34           | 0.03           | 0.00           | 0.04           | 0.01           |
| MgO         | 0.02    | 0.06       | 0.23| 0.01   | 9.79     | 10.16         | 17.53          | 17.72          | 15.90          | 21.56          | 21.27          | 0.02           | 0.02           | 0.03           | 0.05           |
| CaO         | 19.85   | 24.48      | 23.01| 23.12  | 0.72     | 0.41          | 12.25          | 11.54          | 11.45          | 0.19           | 0.19           | 0.15           | 0.11           | 27.68          | 28.32          |
| BaO         | 0.00    | 0.02       | 0.00| 0.00   | 0.00     | 0.00          | 0.02           | 0.00           | 0.01           | 0.04           | 0.00           | 0.01           | 0.00           | 1.21           | 1.25           |
| Na₂O        | 0.28    | 0.00       | 0.01| 0.01   | 0.06     | 0.01          | 0.03           | 0.05           | 0.10           | 0.06           | 0.03           | 11.98          | 12.16          | 0.16           | 0.08           |
| K₂O         | 0.02    | 0.00       | 0.00| 0.00   | 6.22     | 7.06          | 0.43           | 0.84           | 0.87           | 0.03           | 0.03           | 0.05           | 0.05           | 0.02           | 0.02           |
| Total       | 98.24   | 97.82      | 95.72| 96.08  | 96.71    | 98.09         | 97.88          | 97.14          | 97.46          | 88.35          | 86.63          | 100.7          | 99.83          | 100.2          | 100.5          |
| Si           | 3.16    | 2.99       | 3.00| 3.01   | 7.86     | 7.98          | 7.95           | 7.87           | 7.72           | 2.87           | 2.99           | 3.00           | 3.00           | 3.00           | 1.04           |
| Al           | 3.01    | 2.81       | 2.33| 2.11   | 1.29     | 1.76          | 0.13           | 0.18           | 0.40           | 2.25           | 2.30           | 0.98           | 0.98           | 0.06           | 0.03           |
| Ti           | 0.01    | 0.02       | 0.00| 0.00   | 0.00     | 0.00          | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.91           |
| Fe²⁺        | 0.00    | 0.00       | 0.00| 0.00   | 0.74     | 0.89          | 1.07           | 0.84           | 1.08           | 1.59           | 1.33           | 0.00           | 0.00           | 0.02           | 0.02           |
| Fe³⁺        | 0.03    | 0.17       | 0.67| 0.87   | 1.05     | 0.29          | 0.14           | 0.35           | 0.40           | 0.00           | 0.00           | 0.01           | 0.01           | 0.00           | 0.00           |
| Mn           | 0.00    | 0.00       | 0.01| 0.00   | 0.01     | 0.01          | 0.02           | 0.03           | 0.02           | 0.03           | 0.03           | 0.00           | 0.00           | 0.00           | 0.00           |
| Mg           | 0.00    | 0.01       | 0.03| 0.00   | 2.03     | 2.05          | 3.69           | 3.73           | 3.38           | 3.24           | 3.19           | 0.00           | 0.00           | 0.00           | 0.00           |
| Ca           | 1.57    | 2.01       | 1.97| 1.99   | 0.11     | 0.06          | 1.85           | 1.75           | 1.75           | 0.02           | 0.02           | 0.01           | 0.01           | 0.97           | 1.00           |
| Ba           | 0.00    | 0.00       | 0.00| 0.00   | 0.00     | 0.00          | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.02           |
| Na           | 0.04    | 0.00       | 0.00| 0.00   | 1.68     | 1.86          | 0.12           | 0.23           | 0.24           | 0.01           | 0.01           | 1.01           | 1.03           | 0.01           | 0.00           |
| K            | 0.00    | 0.00       | 0.00| 0.00   | 0.01     | 0.00          | 0.01           | 0.01           | 0.02           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           | 0.00           |
| Analysis | Core | 149 | 150 | 151 | 152 | 153 | 154 | 155 | 156 | 157 | 158 | 159 | 160 | 161 | 162 |
|----------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SiO₂      | 56.76| 57.17| 58.03| 52.44| 51.77| 51.74| 52.02| 52.50| 28.51| 37.63| 37.96| 68.85| 30.78|     |     |
| TiO₂      | 0.21 | 0.12 | 0.09 | 0.06 | 0.06 | 0.06 | 0.06 | 0.08 | 0.06 | 0.07 | 0.07 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al₂O₃     | 5.47 | 5.74 | 10.25| 9.03 | 24.55| 25.29| 24.72| 25.07| 24.38| 18.41| 19.21| 22.03| 21.59| 20.30| 19.49|
| Cr₂O₃     | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe₂O₃     | 16.66| 16.26| 11.26| 0.93 | 2.29 | 3.77 | 2.07 | 2.43 | 2.19 | 1.29 | 1.85 | 1.53 | 1.23 | 1.46 | 1.53 |
| MnO       | 0.10 | 0.11 | 0.39 | 0.51 | 0.10 | 0.08 | 0.11 | 0.12 | 0.12 | 0.92 | 0.97 | 0.00 | 0.00 | 0.00 | 0.00 |
| MgO       | 10.64| 10.24| 10.92| 9.92 | 11.26| 11.26| 11.26| 11.26| 11.26| 11.26| 11.26| 11.26| 11.26| 11.26| 11.26|
| CaO       | 0.27 | 0.15 | 0.26 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| BaO       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na₂O      | 6.98 | 6.82 | 7.41 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 | 7.27 |
| K₂O       | 0.01 | 0.02 | 0.00 | 0.00 | 10.79| 11.24| 11.18| 11.18| 11.18| 11.18| 11.18| 11.18| 11.18| 11.18| 11.18|
| Total     | 97.31| 96.63| 97.52| 95.56| 95.84| 95.84| 95.84| 95.84| 95.84| 95.84| 95.84| 95.84| 95.84| 95.84| 95.84|
| Si         | 7.90 | 7.99 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 | 7.90 |
| Al         | 0.90 | 0.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 |
| Ti         | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Cr⁷⁺       | 0.67 | 0.76 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 |
| Fe³⁺       | 1.09 | 1.06 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |
| Mn         | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Ca         | 0.04 | 0.02 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Ba         | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na         | 1.88 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 | 1.85 |
| K          | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
analysed mainly in the core, whereas glaucophane occurs closer to the rim (Table 1). The chemical variation of the actinolitic rim is characterized by Si = 7.66–7.95 p.f.u., Ca = 1.69–1.85 p.f.u., Mg = 0.63–0.78 and Na = 0.11–0.33 p.f.u. The calculated \( X_{\text{Mg}} = \text{Mg} / (\text{Mg} + \text{Fe}^2+) \) increases from 0.36 to 0.75 in the Na-amphibole core to 0.66–0.90 in the actinolitic rim, accompanying the increase in \( X_{\text{Mg}} \). In all amphiboles, K, Ti and Mn content proportions are always near zero (below 0.02–0.03 p.f.u.; Table 1).

Clinozoisite–epidote generally displays direct zoning with \( \text{Fe}^3+ = 0.0–0.4 \) p.f.u. in the core to \( \text{Fe}^3+ = 0.4–0.9 \) p.f.u. in the rim (Figure 7c). However, some grains are characterized by complex intergrowths of \( \text{Fe}^3+ \)-poor and \( \text{Fe}^3+ \)-rich clinozoisite–epidote. K, Na, Ti, Mg and Mn contents are close to zero in all the analysed epidote grains. Chlorite displays \( \text{Si} = 2.80–3.00 \) p.f.u., \( \text{Al} = 2.22–2.34 \) p.f.u., and \( X_{\text{Fe}} = \text{Fe} / (\text{Fe} + \text{Mg}) \) (Table 2). Albite is nearly pure in composition with \( \text{Ca} < 0.01 \) p.f.u. and \( \text{K} \) close to zero (Table 1). Titanite contains 0.5%–1.5% wt% \( \text{Al}_2\text{O}_3 \) (Table 1). The major potassium-bearing phase in the sample is phengitic white mica that occurs, intergrown with chlorite, in clinopyroxene pseudomorphs. Analyses of phengite were all poor because of the very fine grain size. No preserved relics of clinopyroxene and lawsonite were found in this study.

**5.2 | Calcschist**

Chlorite, white mica, epidote and albite in the calcschist are relatively homogeneous in composition (see below), whereas Na-amphibole displays concentric zoning from core to rim (Figure 8a), related to a sharp increase in Mg (Figure 8b) and, in particular, Mn (Figure 8c) towards the rim, accompanied by a very slight increase in Na (Figure 8d) and a decrease in Fe. Mn is also heterogeneously distributed in chlorite, with local, relatively high peaks observed in some grains (Figure 8b).

The composition of Na-amphibole ranges from ‘crossite’ in the core to glaucophane in the rim (Figure 9a). The zoning from crossite to glaucophane is accompanied by an increase in \( X_{\text{Mg}} \) from 0.49 to 0.66 (Figure 9b), in Al from 0.62 to 1.64 p.f.u., and in MnO from nearly 0 to 0.08 p.f.u. (Figure 9c). The MnO content ranges from 0.10–0.20 (core) to 0.45–0.65 wt% (rim) (Table 2). \( X_{\text{Fe}} \) increases from roughly 0.40–0.64 (core) to 0.59–0.65 in the rim (Table 2). White mica is phengitic, halfway between the muscovite and celadonite end-members, and seems to display a certain solid-solution towards a trioctahedral mica component (Figure 9d). As the extent of this miscibility clearly exceeds that experimentally found by Massonne & Schreyer (1986), we interpret the observed composition as contamination by intergrown chlorite (e.g. Figure 6c). The composition of phengite is largely \( \text{Si} = 3.45–3.51 \) p.f.u., \( X_{\text{Fe}} = 0.26–0.33 \) (Figure 9e), and \( X_{\text{Na}} < 0.03 \). Chlorite is characterized by \( \text{Si} = 2.83–3.04 \) p.f.u., \( \text{Al} = 2.20–2.30 \) p.f.u., \( X_{\text{Fe}} = 0.28–0.31 \) (Figure 9f), and MnO contents between 0.2 and 1.1 wt% (Table 2).

Epidote compositions are close to the pistacite end-member, \( \text{Ca}_2\text{Al}_2\text{Fe}^3+\text{Si}_3\text{O}_{12}(\text{OH}) \), with \( \text{Al} = 1.87–2.10 \) p.f.u. and \( \text{K}, \text{Na}, \text{Ti}, \text{Mg} \) and Mn contents close to zero (Table 2). The allanitic cores of epidote show oscillatory zoning with \( \text{La}_2\text{O}_3 \),...
Ce₃O₃ and Y₂O₃ contents between 0.5 and 10.2 wt%, 0.1 and 5.7 wt%, and 0 and 0.7 wt% respectively (Table 2). Albite is pure with Ca and K contents close to zero. Titanite displays Al₂O₃ contents consistently near ~1 wt% (Table 2).

6 | PSEUDOSECTION MODELLING

The bulk-rock chemistry of samples IESP3SP53 (calcscist) and IESP3SP56 (metabasite) was determined by X-ray fluorescence spectroscopy (XRF) using a Panalytical PW2400 spectrometer at the Institut für Mineralogie und Kristallchemie at Universität Stuttgart. The carbonate fraction of the ground sample IESP3SP53 was previously removed by reaction with diluted HCl, based on the lack of microstructural evidence of metamorphic reactions between the silicate and carbonate minerals (more details below). FeO (and Fe₂O₃) was analysed by wet chemical titration at the Università di Padova, Italy. The bulk composition of the samples (shown as wt% in Table 3) was recalculated to fit the MnO–Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–O₂ (MnNCKFMASHTO) system, used for pseudosection modelling (Table 3). In particular, P₂O₅ was fractionated as apatite, together with corresponding amounts of CaO.

Pseudosections were calculated using PERPLE_X 6.8.6 (Connolly, 2005, 2009) and the hp02ver.dat thermodynamic data set (Connolly & Kerrick, 2002; Holland & Powell, 2001). The solution models used were: Gt(HP)–garnet, St(HP)–staurolite, Ctd(HP)–chloritoid, Pheng(HP)–phengitic mica, Ep(HP)–epidote, Omph(HP)–clinopyroxene, Chl(HP)–chlorite (Holland & Powell, 1998), Mica(M)–paragonitic mica, Stlp(M)–stilpnomelane (Massonne, 2010), Opx(HP)–orthopyroxene (Powell & Holland, 1999), MtUl(A)–magnetite (Andersen & Lindsley, 1988), feldspar–ternary feldspar (Fuhrman & Lindsley, 1988), Bio(TCC)–biotite (Tučmanová, Connolly, & Cesare, 2009) and the ideal IlGkPy-ilmenite, Carp–carpholite, hCrd–cordierite, and T–talc models. The low-T amphibole models Namph(M) (Kryza et al., 2011), Act(M) (Massonne & Willner, 2008), and GItTrTsMr (Liu, Liu, Theye, & Massonne, 2009) were tested in different pseudosections. Namph(M) considers the compositional variability of sodic amphibole in the tremolite–glaucophane–riebeckite–Mg-riebeckite space, Act(M) in the tremolite–actinolite–glaucophane–Mg-riebeckite space,
**FIGURE 9** Mineral chemistry of the calcschist (IESP3SP53): (a) Classification of Na-amphibole in the Fe$^{3+}$(Fe$^{3+}$+Al$^{VI}$+Ti)–Fe$^{2+}$(Fe$^{2+}$+Mg+Mn) space following Deer et al. (1992); (b, c) Compositional variability of Na-amphibole in the (b) Mg/(Fe$^{2+}$+Fe$^{3+}$+Mg)–Fe$^{3+}$(Fe$^{3+}$+Al$^{VI}$+Ti) and (c) Mg/(Fe$^{2+}$+Fe$^{3+}$+Mg)–Mn p.f.u. spaces. (d) Classification of white mica based on the Al$^{VI}$ p.f.u.–Al$^{IV}$ p.f.u. diagram by Bousquet et al. (2002). (e, f) Compositional variability of (e) white mica (phengite) and (f) chlorite in the $X_{Fe} = Fe/(Fe+Mg)$–Si p.f.u. space. White mica end-member abbreviations after Siivola & Schmid (2007).

**TABLE 3** Bulk-rock composition from XRF analyses and wet chemical titration of the investigated samples (left columns), recalculated from the MnNCKFMASHTO system (right columns), expressed in wt%.

| Analysis          | Metabasite (IESP3SP56) | Calcschist (IESP3SP53) | Metabasite (IESP3SP56) | Calcschist (IESP3SP53) |
|-------------------|------------------------|------------------------|------------------------|------------------------|
| SiO$_2$           | 48.55                  | 53.30                  | SiO$_2$                | 50.89                  | 55.99                  |
| TiO$_2$           | 1.15                   | 0.90                   | TiO$_2$                | 1.21                   | 0.94                   |
| Al$_2$O$_3$       | 18.28                  | 16.52                  | Al$_2$O$_3$            | 19.16                  | 17.36                  |
| FeO               | 4.04                   | 4.01                   | FeO                    | 7.79                   | 8.28                   |
| Fe$_2$O$_3$       | 3.78                   | 4.76                   | O$_2$                  | 0.39                   | 0.45                   |
| MnO               | 0.13                   | 0.21                   | MnO                    | 0.13                   | 0.22                   |
| MgO               | 8.34                   | 9.15                   | MgO                    | 8.74                   | 9.61                   |
| CaO               | 8.26                   | 2.34                   | CaO                    | 8.47                   | 2.46                   |
| Na$_2$O           | 2.73                   | 2.62                   | Na$_2$O                | 2.86                   | 2.76                   |
| K$_2$O            | 0.32                   | 1.84                   | K$_2$O                 | 0.33                   | 1.94                   |
| P$_2$O$_5$        | 0.13                   | 0                      | P$_2$O$_5$             | —                      | —                      |
and GIiT TsMr in the glaucophane–tremolite–tschermakite–Mg-riebeckite space. The fluid phase was taken as pure H2O, and set in excess, based on the extensive presence of epidote in both samples, which is stable only at very low values of $X_{CO_2} (=CO_2\text{ mol.}\%/[CO_2+H_2O\text{ mol.}\%])$ in a hydrous fluid (see Bucher & Grapes, 2011; Bucher-Nurminen, Frank, & Frey, 1983). The inferred presence of substantial lawsonite at peak conditions in the metabasite, also implies that water was in excess (see Clarke, Powell, & Fitzherbert, 2006).

Additionally, we tested the effect of $X_{CO_2}$ on the stability of amphibole and epidote in preliminary $P$–$X_{CO_2}$ pseudosections at $T = 300, 350$ and $400\degree$C (those for $T = 350\degree$C are reported in Figures S21 and S22). Epidote, amphibole, lawsonite and titanite are stable for $X_{CO_2} < 0.01–0.05$ in the 0.2–2.2 GPa pressure range, thus validating our assumption of a virtually CO2-free fluid.
A first-order limitation for pseudosection modelling in the metabasite sample is represented by the wide chemical and textural variability of the observed mineral phases (amphibole and epidote for instance; Figure 7), which suggests that the rock is characterized by grain-scale disequilibria and element partitioning that make thermodynamic modelling using pseudosections challenging. In any case, we tentatively calculated $P-T$ pseudosections to obtain insights into the metamorphic evolution of the metabasites.

In order to describe in detail the mineralogical variability of Na- and Ca-amphibole in the sample, we calculated two $P-T$ pseudosections for the $P-T$ range $0.2–1.4$ GPa and $300–500^\circ C$ using either Namph(M) (Figure 10a and simplified version in Figure 10b) or Act(M) (Figure 10c and simplified version in Figure 10d). The GITYTsMr model, which was used in preliminary pseudosections, is not suitable for the here relevant low-$T$ amphiboles, as it predicts significant proportions of the tschermak component even for $T < 400^\circ C$.

The phase diagrams calculated with either Namph(M) or Act(M) are fairly similar in first order (Figure 10b,d). Considering the $T = 300–400^\circ C$ temperature interval, both diagrams predict lawsonite+amphibole occurring at $P > 0.9–1.2$ GPa, epidote+amphibole at $P = 0.5–1.2$ GPa, and albite+epidote below 0.5–1.2 GPa, whereas garnet-bearing fields occur at higher temperatures, above 380–420°C (Figure 10b,d). The main differences regard the $P-T$ fields of amphibole, omphacite and paragonite.

The Namph(M) model, for instance, limits the $P-T$ field of amphibole to blueschist facies conditions (plagioclase-free fields; Figure 10b). In most of the plagioclase-bearing fields, biotite appears as Fe–Mg-bearing phase (Figure 10a). On the other hand, the Act(M) model stabilizes amphibole in most of the greenschist facies fields (Figure 10d) and limits the biotite-bearing fields to higher temperatures (Figure 10d). This is not surprising since Namph(M) considers only tremolite Ca-amphibole end-members that would be stable at greenschist facies conditions (e.g. Bucher & Grapes, 2011), whereas an additional Ca-amphibole end-member is included in Act(M). The composition of amphibole, calculated with Namph(M), is characterized by a high proportion of glaucophane component for most of the blueschist facies, and an increase in the riebeckite component towards the lawsonite- and the plagioclase-bearing fields (Figure 10a). These compositions are comparable to those observed for Na-amphiboles in the sample (Figure 7b). However, $X_{Gl}$ is always $>0.55$ and ‘true’ Ca-amphiboles never appear (Figure 10a). Differently, the Act(M) model predicts amphibole compositions with low $X_{Na} <0.6$ for pressures between 0.6 and 1.0 GPa and ‘true’ sodic compositions never appear, even at $P > 1.0–1.4$ GPa (Figure 10c).

Another direct consequence of the choice of the models is that omphacite is stable at epidote-blueschist facies conditions with Namph(M) (Figure 10b), while Act(M) stabilizes paragonite towards higher pressures (Figure 10d). The change in the modes of these phases can be seen in Figure 11 along modal profiles calculated at $T = 350^\circ C$ and varying pressure. They predict similar modal proportions of epidote, chlorite, quartz,
albite, titanite, phengite, rutile and biotite. The modes of albite and epidote approach zero towards the greenschist–blueschist facies and the epidote-blueschist to lawsonite-blueschist facies transition respectively. Instead of epidote, lawsonite appears as a major constituent with a ~20% modal proportion (Figure 11a,b). In both cases, the disappearance of albrite is accompanied by a strong increase in amphibole and paragonite. Around 9% of paragonite is predicted using the Namph(M) model (Figure 11a), whereas this percentage increases to ~20% using Act(M) in the epidote-blueschist facies (Figure 11b). On the other hand, only a very small proportion of omphacite appears using the Namph(M; Figure 11a). In any case, clinopyroxene does not occur or in very small modal proportions in the calculated pseudosections. This is consistent with the textural evidence of amphibole, chlorite and epidote, overgrowing clinopyroxene, which is very likely an igneous relic (Figure 5b). The local omphacitic pyroxene spectrum (Figure S6), also reported by Bianco et al. (2015, 2019), might be to some extent the result of local equilibria. Finally, we note that the use of Namph(M) results in higher proportions of stilpnomelane towards high pressure (up to 12%; Figure 11a), compared to the Act(M) model (Figure 11b).

Taking into account the limitations of the solid-solution models, Namph(M) can be tentatively used to describe the variability of glaucophane–crossite amphibole in the blueschist facies, whereas Act(M) can be used to constrain the actinolite–tremolite amphibole at greenschist facies conditions. Considering the phase diagram calculated with Namph(M), lawsonite is stable in the presence of Na-amphibole beyond 0.7–1.3 GPa in the 300–400°C temperature range (Figure 10a). Many lawsonite-bearing P–T fields are also characterized by rutile as part of the assemblage, which was not observed. The pseudomorphing of lawsonite by epidote and quartz can be related to the transition from the lawsonite- to the epidote-bearing fields during the P–T evolution of the sample. The assemblage epidote+phengite+Na-amphibole+chlorite+titanite+quartz is stable together with paragonite and omphacite over a wide range of P–T conditions between 0.6 and 1.3 GPa and 300 and 470°C (Figure 10a). Paragonite, which was not found in the sample, was likely obliterated by retrograde metamorphism, notably by the growth of albite. The stability field of garnet provides an upper temperature limit at $T = 400–500^\circ$C at $P = 1.0–1.4$ GPa. The wide chemical variability of Na-amphibole suggests that this mineral continuously grew over a wide range of P–T conditions, likely in the lawsonite- to the epidote-bearing fields, hindering the possibility to precisely link Na-amphibole growth to a particular P–T range. We tentatively plotted isopleths for the $X_{Fe}$ content of chlorite in the phase diagram calculated with Namph(M) (Figure 10a); however, the observed $X_{Fe}$ range of chlorite (0.26–0.34) is predicted to be stable at 0.5–0.9 GPa at the transition from plagioclase-absent to plagioclase-bearing fields. Hence, chlorite likely re-equilibrated during retrograde metamorphism (Figure 10a).

The greenschist facies assemblage epidote+phengite+plagioclase (albite)+Ca-amphibole+chlorite+titanite+quartz occurs at $P = 0.2–0.8$ GPa and $T = 300–420^\circ$C (Figure 10c). At higher temperature, biotite, rutile and hematite join the mineral assemblage at the expense of titanite and phengite.

Based on the modelled mineral assemblage and mineral chemistry, it is not possible to precisely constrain the $P$–$T$ path of the metabasite. The preserved paragenesis suggests, however, a progressive evolution from early, blueschist facies metamorphism (lawsonite- to epidote-blueschist facies) to later, greenschist facies metamorphism. The lack of garnet indicates a maximum metamorphic temperature of 380–420°C. The former presence of lawsonite suggests a peak pressure above 0.8–1.3 GPa.

### 6.2 Calcschist

As a first approach, we calculated a preliminary H$_2$O-saturated $P$–$T$ phase diagram in the $P$–$T$ range of 0.2–2.2 GPa at 300–600°C using the analysed bulk-rock composition and the FeO–Fe$_2$O$_3$ content obtained by wet chemical titration (Figure S23). Since this sample is characterized only by Na-amphibole, we used the Namph(M) to model this phase. In the calculated diagram, quartz is stable across the entire $P$–$T$ range and titanite is present at $T < 420^\circ$C and $P < 0.8$ GPa, while rutile occurs at higher pressures and temperatures. Na-amphibole occurs in all plagioclase-absent $P$–$T$ fields and, in the presence of albitic plagioclase, in a restricted $P$–$T$ range between 0.2 and 0.6 GPa and 300 and 400°C. Garnet appears in the HP–HT part of the diagram (red line in S23, above 0.6–1.4 GPa at 360–540°C), whereas phengite is present in all $P$–$T$ fields except at LP–HT conditions (yellow line in Figure S23; beyond ~480°C at 0.2–1.6 GPa). However, low modal contents (<1–2 vol.%) of hematite, which was not observed, occur in most of the fields, coexisting with rutile or titanite. This indicates that the chosen Fe$_2$O$_3$ content, obtained by wet chemical titration, is too high, probably due to late oxidation of the rock.

Therefore, we calculated a series of $P$–$X$ pseudosections at fixed temperature ($T = 300, 350$ and 400°C) for the 0.6–2.0 GPa pressure range and $X(Fe^{3+})=Fe^2O_3/(FeO+Fe_2O_3)$ between 0 (i.e. all Fe considered divalent) and 0.48 (i.e. value obtained by wet chemical titration) to constrain an appropriate $X(Fe^{3+})$ value for this sample. Temperatures above 400°C are unlikely because the preliminary diagram predicts garnet to be stable in most of the lawsonite-bearing fields for $T > 360–420^\circ$C (Figure S23). We used the composition of phengite, in terms of $X_{Fe}$ and Si p.f.u., to quantitatively constrain the $P$–$T$ conditions of equilibrium of the investigated sample. Phengite is, indeed, characterized in the rock by a very narrow compositional range with Si = 3.45–3.51 p.f.u. and $X_{Fe} = 0.26–0.33$ (Figure 9e).
As shown in Figure 12 for 350°C, hematite is stable for \(X(\text{Fe}^{3+})\) between 0.4 and 0.5, whereas rutile and titanite appear for \(X(\text{Fe}^{3+}) < 0.4\) above and below \(P = 1.0–1.2\) GPa respectively. The observed phengite Si p.f.u. and \(X_{\text{Fe}}\) isopleths intersect in the phengite-amphibole+stilpnomelane+paragonite+chlorite+lawsonite+quartz+rutile field, for a restricted \(X(\text{Fe}^{3+})\) range between 0.05 and 0.15. At this interval and in the pressure range 0.6–2.0 GPa, rutile is the stable Ti phase, whereas titanite occurs at lower pressures (hematite is absent). A similar \(X(\text{Fe}^{3+})\) range was estimated from the analysis of the pseudosections calculated for other temperatures than 350°C. Therefore, we calculated several \(P-T\) pseudosections for \(X(\text{Fe}^{3+}) = 0.05, 0.10\) and 0.15. In Figure 13a, we show the pseudosection corresponding to \(X(\text{Fe}^{3+}) = 0.10\), while a simplified version is presented in Figure 13b.

In this diagram, garnet appears in the presence of lawsonite above 360–420°C (Figure 13a,b). Na-amphibole occurs in the plagioclase- and garnet-absent fields for \(P\) above 0.6–0.8 GPa and \(T\) below 360–460°C. Rutile is present above 1.0–1.2 GPa in the lawsonite field, whereas titanite is the predominant Ti phase in the epidote-+Na-amphibole-bearing fields and in the presence of plagioclase (Figure 13a,b). Excluding garnet-bearing fields, the calculated phengite isopleths intersect for Si p.f.u. = 3.45–3.50 and \(X_{\text{Fe}} = 0.26–0.32\) in the \(P = 1.5–1.8\) GPa and \(T = 320–370°C\) range (violet shaded field in Figure 13a). At such conditions, the metamorphic assemblage is phengite+Na-amphibole+stilpnomelane+paragonite+chlorite+lawsonite+quartz+rutile, and even carpholite for \(P > 1.6–1.8\) GPa. At slightly higher temperatures (330–390°C), the assemblage consists of phengite+amphibole+paragonite+chlorite+lawsonite+quartz+rutile (Figure 13a). As shown in the modal profile at \(T = 350°C\) in Figure 13c, the sample should have contained non-negligible modal proportions of lawsonite (7%–11%), stilpnomelane (up to 3%) and paragonite (1%–3%) in the 1.5–1.7 GPa pressure range. Moreover, for \(P > 1.8\) GPa, up to 25% of stilpnomelane, and up to 15% of carpholite should have been present (Figure 13c). The presence of lawsonite pseudomorphs in the associated metabasite (see Figure 5e and Bianco et al., 2019) suggests that lawsonite was probably also present in the calcschist. Another indication of the former presence of lawsonite is provided by the glauco- phase- rich amphibole rim, which, according to pseudosection modelling, is predicted to be stable at \(P > 1.0–1.4\) GPa, chiefly in the lawsonite- and rutile-bearing fields. Similarly, any former paragonite might have been consumed during the retrograde path during the growth of other Na-bearing phases (i.e. albite). The Mn-enrichment in the glauco- phase-rich rim and in some chlorite grains (Figure 8c) provides indirect chemical evidence of the total (or partial) breakdown
of one (or more) Mn-rich phase(s) during equilibration of the amphibole rim. Stilpnomelane and carpholite are common Mn-bearing phases in HP–LT rocks (see e.g. Deer et al., 1992). Consequently, it is likely that the studied calcschist passed through the stilpnomelane- and carpholite-bearing fields at \( P = 1.6–1.8 \) GPa, in the presence of phengite with \( \text{Si p.f.u.} = 3.45–3.50 \), and reached, after stilpnomelane (and/or carpholite) breakdown, the phengite (Si p.f.u. \( \sim 3.45 \)) + amphibole + paragonite + chlorite + lawsonite + quartz + rutile field, registered by the amphibole rim at \( P = 1.5–1.6 \) GPa (Figure 13a). Following this interpretation, the crossite core of amphibole, on the other hand, likely equilibrated on the prograde path or at peak conditions, in the presence of carpholite and/or stilpnomelane. We exclude that the glaucophane rim grew due to the breakdown of lawsonite, as lawsonite usually does not store much Mn (see e.g. Fornash, Whitney, & Seaton, 2019), and lawsonite breakdown is commonly linked to epidote growth (e.g. Evans, 1990).
The metabasite layers range in thickness between few centimetres and some metres.

2. The metacarbonate lenses hosting the metabasites display high modal contents of glauconephane, epidote, titanite, chlorite and albite, with chlorite being more abundant than potassic white mica (Figure 6). Typical blueschist facies parageneses in metapelitic rocks are characterized by relatively high abundances of K-, Al- and Fe–Mg-bearing phases, such as white mica, chlorite and chloritoid over Na- and Ca-bearing phases (e.g. Theye et al., 1997; Theye, Seidel, & Vidal, 1992). Indeed, chemical analyses of the studied metapelitic fraction of the calcschist (Table 3) reveal high Ca, Na, Ti and Mg, and relatively low K content, which is untypical for a standard pelagic shale (see e.g. Carmichael, 1989). Rather, it suggests an input of detrital material from a basic igneous source to the sedimentary protolith of the calcschist.

3. Detrital allanite (Figure 6e) is present in the calcschists and is modally more abundant than other detrital heavy minerals, such as zircon. Allanite displays monotonous zoning and euhedral habit (Figure 6e) suggesting that grains of this mineral originated from a fairly restricted igneous source.

Based on the considerations listed above, the Acquadolce metabasites and metacarbonates can be interpreted as associated extrusive magmatic bodies and metavolcanoclastic sequences deposited in a carbonatic sedimentary basin. The source of detrital allanite could be an associated igneous source, which is not outcropping. Detailed investigations of allanite may offer the potential to provide additional geochemical and geochronological details on the age and characteristics of the volcanic events preserved in the investigated rock record. A similar sequence in the Northern Appennines is found in the Middle Triassic succession of the Punta Bianca and Massa Units (see Figure 1a), where the association of carbonates, alkaline metabasites and metabreccias was interpreted as evidence of a ‘failed’ Middle Triassic rift (Martini, Rau, & Tongiorgi, 1986). We therefore suggest that the investigated metabasite was emplaced in the Triassic sequences of the Adria continental margin. The associated marbles and calcschist could be, as a whole, representative of the Triassic–Jurassic passive margin sequences of the Adria margin (e.g. Boccaletti et al., 1971).

The problem that arises from this interpretation is how these—likely Mesozoic—rocks became entrained in the Oligocene foredeep deposits of the Acquadolce Subunit. Although new geochronological constraints on the metacarbonatic–metabasic sequences are required, we propose that these carbonate–metabasite lenses were part of an original volcano-sedimentary sequence that was disrupted by tectonic processes during underplating and subsequent exhumation, developing competent lenses surrounded by incompetent
Schists. Similar examples of entrainment of competent lithologies in a more-deformed matrix are well documented in exhumed blueschist- and eclogite facies terrains worldwide and have been linked to shearing during subduction (e.g. Angiboust et al., 2011; Kotowski & Behr, 2019; Kurz, Neubauer, & Dachs, 1998).
7.2 | \(P-T\) constraints from petrographic observations and pseudosection modelling

In the Acquadolce Subunit, HP–LT parageneses are well preserved in metabasite and hosting calc schist. Field, petrographic and pseudosection modelling data document the progressive evolution of the Acquadolce Subunit from lawsonite-blueschist to epidote-blueschist and greenschist facies conditions, in agreement with Bianco et al. (2019). The reconstructed evolution is summarized in Figure 14a. The detailed analysis of metamorphic assemblages and pseudosection modelling in the calc schist constrain the peak \(P-T\) conditions of the investigated rocks to 1.5–1.8 GPa and 320–370°C in the lawsonite-blueschist facies (stage 1 in Figure 14a), based on phengite isoplothe s. From the pseudosection modelling we infer that lawsonite, paragonite, stilpnomelane and/or carpholite were likely present as part of the peak metamorphic assemblage in the calc schist (stage 1 in Figure 14a). Lawsonite was not found in the calc schist. However, lawsonite pseudomorphs (Figure 5e; examples in Angiboust, Langdon, Agard, Waters, & Chopin, 2012; López-Carmona et al., 2014; Tsujimori, Sisson, Liou, Harlow, & Sorensen, 2006) were found in the metabasite (e.g. Figure 5e; stage i–ii in Figure 14a) and also reported by Bianco et al. (2019). Paragonite, which is also predicted to be stable in most blueschist facies fields above 0.6–1.0 GPa (Figures 10, 11, 13), was not found, as its presence was likely erased by the retrograde growth of albite, both in the metabasite and the calc schist (Figures 5f and 6f). In this sense, it is possible that some of the resorbed pseudomorphs found in albite could have represented former paragonite grains (e.g. Figure 6g).

The strong zoning in Mn of Na-amphibole in the calc schist is likely related to the breakdown of stilpnomelane and/or carpholite close to peak metamorphic conditions (stage 2 in Figure 14a), consistent with a clockwise prograde evolution in the lawsonite-blueschist facies (Figure 14a). Although no precise constraints on the retrograde \(P-T\) path are available, the zoning of amphibole from glaucophane–crossite to actinolite (Figure 7a,b; stage i–ii in Figure 14a) and epidote from clinozoisite to Fe-epidote (Figure 7c) in the metabasite, and the blastesis of albite overgrowing Na-amphibole (stage 3 and ii in Figure 14a) indicate retrograde metamorphism along a path from epidote-blueschist to greenschist facies conditions (e.g. Brown, 1977; Davis & Whitney, 2006; Evans, 1990). Maximum metamorphic temperatures of 380–420°C can be estimated based on the lack of garnet in both the metabasite and the calc schist (Figures 10a and 13a), thus indicating that the retrograde path was nearly isothermal or characterized by a slight increase in temperature only.

Our \(P-T\) estimates are significantly different from those by Bianco et al. (2015), obtained using the jadeite-in-omphacite geobarometer (0.7–0.9 GPa; 330–350°C). This is because the jadeite-in-omphacite geobarometer provides only minimum pressures. On the other hand, Bianco et al. (2019), were unable to precisely constrain the peak \(P-T\) conditions of the Acquadolce metabasite, due to its strong chemical and textural heterogeneities. These authors inferred reasonably \(P > 1.6\) GPa and significantly higher temperatures (450–500°C), based on (a) the former presence of lawsonite and (b) the lack of garnet, which in their modelling, using the Mn-free NCFMASHTO system, appears above 550°C. However, Mn stabilizes garnet towards low temperature conditions (Mahar, Baker, Powell, Holland, & Howell, 1997; Spear & Cheney, 1989; Symmes & Ferry, 1992; here: 380–420°C). Our modelling of the Acquadolce metabasite (Figure 10) demonstrates, indeed, that such a rock, with strongly zoned amphibole (Figure 7a,b) and clinozoisite–epidote (Figure 7c), is currently of limited use for pseudosection modelling, which requires discernable chemical and textural equilibria.

To summarize, based on the present study, the Acquadolce Subunit experienced nearly isothermal exhumation from peak \(P-T\) conditions of 1.5–1.8 GPa at 320–370°C (see \(P-T\) path in Figure 14a). Assuming a rock density of 2.8 g/cm³, the estimated peak pressures indicate maximum depths in the range of 42–50 km. Peak metamorphic conditions were likely attained c. 18–20 Ma (\(40\text{Ar}/39\text{Ar}\) white mica age: Deino et al., 1992; \(40\text{Ar}/39\text{Ar}\) glauconaphane age: Bianco et al., 2019). Late Miocene contact metamorphism in the Acquadolce Subunit occurred at a maximum pressure of 0.2 GPa (Duranti et al., 1992), corresponding to 5–6 km depth, and was dated at 7–6 Ma (Musumeci et al., 2011, 2015; Viola et al., 2018). Based on the data above, we can estimate an average exhumation rate of 2.5–3.7 km/Ma, which is consistent with those of exhumed blueschist facies continental units elsewhere (e.g. Ring & Glodny, 2010).

7.3 | Implications for early continental collision in the Northern Apennines

In the Northern Tyrrhenian Sea, typical HP–LT ocean-derived units, characterized by metaophiolites and their metasedimentary cover, are found on the Islands of Gorgona and Giglio and in the Argentario promontory (Elter & Pandeli, 2002; Orti, Morelli, Pandeli, & Principi, 2002; Rossetti et al., 1999; Theye et al., 1997). Both on Giglio and in the Argentario, HP–LT oceanic units are tectonically stacked over HP–LT carpholite-bearing continental units (Theye et al., 1997). Other HP–LT continental units are found on the mainland, where the HP–LT event is typically recorded by chloritoid- or carpholite-bearing rocks (e.g. Giorgetti et al., 1998; Lo Pò & Braga, 2014; Molli et al., 2000). Based on the present study, the Acquadolce Subunit is also a HP–LT
continental unit consisting of interleaved metasedimentary and metabasic rocks.

All these units represent scattered remnants of ocean- and continent-derived units that experienced blueschist facies metamorphism at pressures ranging between 0.7–0.9 GPa and 1.5–1.8 GPa and temperatures between 300 and 420°C (Figure 14b). The highest pressures are recorded by the oceanic units on the Island of Gorgona (Jolivet et al., 1998) and the continental units on the Island of Elba (this work; Figure 14b). The coupling of HP–LT oceanic and continental units implies that, during the Oligocene–early Miocene interval, continental units shared a similar subduction history with oceanic units in the subduction channel and reached greater depths than previously reported, and attaining metamorphic conditions comparable to those of the subducted oceanic units (i.e. Gorgona island; Jolivet et al., 1998). Based on the available ⁴⁰⁴Ar/³⁹°Ar radiometric ages, both continental and oceanic units experienced coeval subduction, exhumation and tectonic stacking in a short time span (10–15 million years), between 21 and 6 Ma (Figure 14b; Bianco et al., 2019; Brunet et al., 2000; Deino et al., 1992), which implies rapid subduction of continental units and subsequent tectonic coupling with oceanic units during exhumation.

In particular, the estimated P–T values for the Acquadolce Subunit are comparable to those reported for some continental units of the western Alps metamorphosed under blueschists- to eclogite facies conditions, belonging to the Brianzonoese zone and the Penninic units. For example, peak P–T conditions of 1.5 GPa at 500°C have been estimated for glaucophane-bearing micaschist from the Ambin–south Vanoise massif (Ganne, Bussy, & Vidal, 2003), 1.8–2.0 GPa at 490°C for garnet–chloritoid-bearing micaschists of the Gran Paradiso massif (Chopin, 1981; Le Bayon, Pitra, Balleure, & Bohn, 2006), and 1.2–1.3 GPa at 425–475°C for blueschist facies metasediments of the Combin Unit (Cartwright & Barnicoat, 2002). Significantly lower pressure conditions have been recorded by the continental unit of Alpine Corsica: for instance, the Permian metarhyolites of the Tenda Massif experienced P–T conditions ranging between 0.8 GPa at 300°C and 1.1 GPa at 500°C (Tríbuzio & Giacomini, 2002) and the Corte slices between 0.8 and 1.4 GPa at 200–350°C (Di Rosa, Meneghini, Marroni, Hobbs, & Vidal, 2019).

Comparison between HP–LT conditions in the western Alps and in the Tyrhenian sector of the Northern Apennines suggests that, despite being more recent (Western Alps: 47–33 Ma; Beltrando, Campagnoni, & Lombardo, 2010 and references therein; Northern Apennines: 27–16 Ma; Brunet et al., 2000; Kligfield et al., 1986), the subduction of the Adriatic margin in the Northern Apennines is comparable in depth reached with those of the European margin in the Alps. In both subduction zones, continental crust was involved and experienced P–T conditions related to geothermal gradients of 6–7.5°C/km. All these features shed new light on the evolution of the hinterland sector of the Northern Apennines, which experienced subduction and exhumation under a very low geothermal gradient, comparable with the 5–10°C/km reported for oceanic subduction zones (Zheng & Chen, 2016).

### 7.4 Implications for exhumation processes in the Northern Apennines

In the Northern Apennines metamorphic units are exposed at the base of the nappe stack, at the core of dome-like structures, known as antiformal stacks. The exhumation of these units has been interpreted mostly as the result of (a) post-orogenic extension (Carmignani et al., 1994; Carmignani & Kligfield, 1990) or (b) a combination of syn-orogenic extension and post-orogenic extension (Jolivet et al., 1998; Molli et al., 2018).

The present-day setting of the hinterland sector of the Northern Apennines is characterized by extensional seismicity (e.g. Pondrelli et al., 2006), affecting a thinned continental crust (20–25 km at the Tyrrenhenian side; Cassinis et al., 2005). This crust is marked by high heat flow, magmatism (e.g. Della Vedova, Vecellio, Bellani, & Tinivella, 2008; Serri et al., 1993), and the presence of wedge-top basins or intermontane basins that have been interpreted as graben fills (see Bonini et al., 2014 for a review). Based on the present-day regime, many authors have suggested long-lasting (post–early Miocene) crustal thinning (e.g. Brogi, Lazzarotto, Liotta, & Ranalli, 2005; Brogi, 2008; Le Breton, Handy, Molli, & Ustaszewski, 2017; Liotta & Ranalli, 1999), favouring a scenario of post-orogenic exhumation in metamorphic core complexes (Carmignani & Kligfield, 1990). In this framework, Bianco et al. (2019) addressed extensional tectonics as the main driver of exhumation of the HP–LT blueschists of the Island of Elba. However, geodetic, geophysical and geodynamic models all suggest that the present geodynamic framework (crustal thickness, seismicity, stress field and thermal structure of the lithosphere) of the Tyrrenhenian sector of Italy can be extrapolated only to the last 2.5 Ma (Faccenna, Becker, Miller, Serpelloni, & Willett, 2014).

On the other hand, several authors (Carosi et al., 2004; Jolivet et al., 1998; Molli et al., 2000; Storti, 1995) noticed that a scenario of pure post-orogenic extension cannot explain (or can only in part explain) many metamorphic and structural features observed in the HP–LT metamorphic units of the Northern Apennines. Jolivet et al. (1998) first suggested that the nearly isothermal exhumation gradient observed in the HP–LT units (e.g. Giorgetti et al., 1998; Rossetti et al., 1999; Theye et al., 1997) indicates
syn-orogenic extrusion (examples in Jolivet & Brun, 2010; Law, Searle, & Godin, 2006). Consequently, Jolivet et al. (1998) suggested that this process occurred during the Oligocene–Miocene in the Northern Tyrrenian Sea before post-orogenic back-arc extension took place. Syn-orogenic extrusion was also proposed by Molli et al. (2000) and Carosi et al. (2004) to explain the occurrence of higher-grade metamorphic rocks of the Massa Unit (0.6–0.8 GPa at 420–500°C), sandwiched between the non-metamorphic Tuscan nappe and the Apuan Unit (0.4–0.6 GPa at 360–420°C) in the Apuan Alps. More recently, Molli et al. (2018) also suggested that the Massa Unit was exhumed in a syn-orogenic setting, due to a combination of deep duplexing and later post-orogenic extension. Both E- and W-verging structures, which have been interpreted as related to syn-orogenic exhumation or gravitational instabilities during underplating of units in the wedge, are preserved in many areas of the Northern Apennines (Clemenzi et al., 2014; Massa et al., 2017; Storti, 1995).

Top-to-the-E detachment fault systems, such as the Zuccale Fault on Elba (Collettini & Holdsworth, 2004; Musumeci et al., 2015; Smith, Holdsworth, Collettini, & Pearce, 2011) or the Tellaro Detachment in the La Spezia area (see e.g. Clemenzi et al., 2015) were considered as post-orogenic structures driving the exhumation of metamorphic rocks. However, not only the interpretation of these structures as detachments has been questioned (see Musumeci et al., 2015; Viola et al., 2018), but the total slip measured on these fault systems ranges between 5 and 10 km and thus their contribution for vertical exhumation is minimal (see examples in Ring & Glodny, 2010). High-\(T\) contact metamorphism (Figure 14b) linked to emplacement of plutons, previously interpreted as post-orogenic magmatism (Jolivet et al., 1998), occurred at very low-\(P\) conditions (\(P < 0.2\) GPa; Duranti et al., 1992; Musumeci & Vaselli, 2012; Papeschi et al., 2019) and was coeval with contractional tectonics (e.g. Musumeci et al., 2015; Papeschi et al., 2017; Viola et al., 2018). Moreover, this study highlights that high-\(T\) metamorphism overprints blueschist facies rocks that were already exhumed to very shallow levels (Figure 2).

Based on the new metamorphic data from Elba presented here, showing rapid (c. 15 Ma) and cold exhumation of blueschist facies rocks, we, thus, suggest that syn-orogenic extrusion, not post-orogenic extension, was the main process responsible for the exhumation of HP–LT metamorphic units in the hinterland part of the Northern Apennines orogen (Figure 14b). W-verging folds and shear zones, which are documented in many areas of the Northern Apennines (e.g. Gianmarino & Giglia, 1990; Storti, 1995) might have accommodated the extrusion of the deeper units in the orogenic wedge within an overall contractional setting with general E-verging kinematics.

8 | CONCLUSIONS

This study documents Oligocene–early Miocene blueschist facies metamorphism in the Acquadolce Subunit from eastern Elba (Northern Apennines, Italy), showing that:

1. The Acquadolce Subunit records peak lawsonite-blueschist facies metamorphism at \(P = 1.5–1.8\) GPa and \(T = 320–370°C\) c. 21–19 Ma, followed by nearly isothermal exhumation through the epidote-blueschist and albite-greenschist facies at maximum temperatures of 380–420°C. Peak assemblages were likely characterized by the presence of carpholite and/or stilpnomelane, as suggested by Mn-zoning of glaucophane that likely developed after their breakdown. The 6–7 Ma contact metamorphic overprint occurred at 0.2 GPa, when these rocks were already exhumed, indicating a time frame of at most c. 15 Ma for exhumation.

2. Metacarbonates contain detrital metabasic material and albite grains suggesting deposition together with the associated metabasites in a basin that received volcanoclastic input. Lithostratigraphic correlations indicate a possible Triassic age for these rocks, which likely correlate with the metabasite-hosting metacarbonates of the Massa Unit. These rocks might have become enclosed in early Oligocene metapelites due to boudinage or formation of a tectonic mélange in the subduction channel.

3. The underthrusting of the continental Acquadolce Subunit to pressures of 1.5–1.8 GPa indicates deep involvement of continental crust in the Apennines in subduction along cold geothermal gradients of 5–10°C/km. Reached depths are comparable to oceanic units as well as exhumed Europe-derived continental units from the Alps. Retrograde metamorphism along a cold and isothermal gradient supports exhumation by syn-orogenic extrusion, rather than post-orogenic extension.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

**Table S1.** List of the investigated samples, as they appear on SESAR (https://app.geosamples.org/). Minerals in assemblage and accessories are in modal order from high to low. The classification follows the IUGS recommendations for the nomenclature of metamorphic rocks. Abbreviations after Siivola and Schmid (2007).

**Section S1.** Spot and area location—Sample IESP3SP56.

**Section S2.** Spot and area location—Sample IESP3SP53.

**Section S3.** Mineral chemistry—Sample IESP3SP56.

**Section S4.** Mineral chemistry—Sample IESP3SP53.

**Section S5.** Phase equilibria modelling.

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