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Giancarlo Molli [1]

GEOLOGY OF THE ALPI APUANE AND THEIR MARBLES: AN UPDATE OVERVIEW

Abstract - G. Molli, *Geology of the Alpi Apuane and their marbles: An update overview.*

The Alpi Apuane are renowned globally for their marble deposits, notably the famed white Carrara marble, quarried there for over two millennia. The occurrence of marble within a region predominantly composed of non-metamorphic rock types has captivated geological interest since the early 19th century. Consequently, this area was the site of Italy's earliest modern geological maps and remains a crucial zone for structural and tectonic research. Following a general tectonic introduction, this study provides a current geological synthesis of the Alpi Apuane, emphasizing structures, tectono-metamorphic development, and the chronology of deformation events. Furthermore, the microstructural variability of the marbles will be illustrated and correlated with the different kinematic and dynamic stages of the wedge at the crustal scale.

Key words - Alpi Apuane, marbles, structural geology, tectonics, Apennines, Italy

Riassunto - G. Molli, *Geologia delle Alpi Apuane e dei loro marmi: una revisione aggiornata.*

Le Alpi Apuane sono rinomate a livello mondiale per i loro giacimenti di marmo, in particolare per il famoso marmo bianco di Carrara, estratto in quest'area da oltre due millenni. La presenza del marmo in una regione caratterizzata prevalentemente da rocce non metamorfiche ha suscitato interesse geologico fin dall'inizio del XIX secolo. Di conseguenza, le Alpi Apuane sono state oggetto delle prime carte geologiche moderne in Italia e da sempre rappresentano una zona cruciale per la ricerca geologico-strutturale e la comprensione dell'evoluzione tettonica della catena appenninica. Dopo un'introduzione tettonica regionale, questo studio fornisce una sintesi delle ricerche geologiche più recenti delle Alpi Apuane, sottolineando le strutture, lo sviluppo tettono-metamorfico e la cronologia degli eventi deformativi. Viene inoltre illustrata la variabilità microstrutturale dei marmi e correlata con le diverse fasi cinematiche e dinamiche di sviluppo della catena Appenninica.

Parole chiave - Alpi Apuane, marmi, geologia strutturale, tettonica, Appennino, Italia

Introduction and regional tectonic frame

A unique morpho-structural domain exists in the northernmost portion of the Italian peninsula, extending from the Gulf of La Spezia to Monte Pisano (Federici & Raggi, 1975). This area, part of the inner northwestern Apennines (Fig. 1), encompasses the Alpi Apuane a mountain range rising to approximately 2000 m near the coast (Baroni *et al.*, 2015). The Alpi Apuane has long intrigued naturalists due to its distinctive topography and the unusual presence of marble within an area of predominantly non-metamorphic rock-units.

The discovery of fossils (bivalvs and ammonites) at the beginning of '800 by Girolamo Guidoni (1794-1870), in the reliefs surroundings of La Spezia and in the Alpi Apuane, and their correct attribution to the Mesozoic (Secondary at that time) make this region special in the historical development of research and geological maps for the entire Apennines (Molli, 2023). As matter of facts the region represents at the end of the 19th century the first largest area of the entire Italian peninsula mapped at a scale of 1:25000 by Zaccagna and Lotti (1879-1897) in the frame of the first edition of the Italian geological map project.

These detailed maps provided the basis for cross-sections that supported the earliest nappe interpretations for the Apennines. In these models, developed by Lencewicz (1917) and subsequently reproposed by Ippolito (1950) and Elter (1960), the Alpi Apuane play a key role being recognized as a tectonic window showing the lowermost structural units of the Apennines nappe stack.

Cross-section in Fig. 1 shows at a crustal scale the Alpi Apuane within the Northern Apennines tectonic frame. In the section it is possible to recognize a system of uppermost units (Ligurian and sub-Ligurian) representing the remnants of the pre-collisional accretionary wedge below which the distal Adria continental margin was underplated. In the internal zones of the range two main groups of Adria-derived units may be distinguished (Elter, 1975; Carmignani & Kligfield, 1990):

1. The Tuscan Nappe which consists of Mesozoic carbonate rocks and Tertiary deep-water and turbiditic sequences that are almost everywhere detached from their original basement (only locally recognized see Molli *et al.*, 2020) along the décollement levels of the former Carnian and Norian evaporites and dolostones of the "Calcare Cavernoso" (Conti *et al.*, 2020; Cornamusini *et al.*, 2024);

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2. The Tuscan metamorphic units showing a Mesozoic–Tertiary metasedimentary sequences, like that of the Tuscan Nappe, which rest locally on a Permian cover or directly overlie a low-grade Variscan basement (Conti *et al.*, 2020). The peak metamorphic conditions and some differences in the Mesozoic to Tertiary metasedimentary sequences allowed to differentiate various metamorphic tectonic units (Molli 2023 and ref.).

The stratigraphic sequences and the marble-types

The lithostratigraphic successions observable in Alpi Apuane record the complete sedimentary evolution from breakup of Pangaea (Permian and Triassic) with rifting of the old Variscan crust to drifting (from late Jurassic onward) associated with basin deepening and widening of the Ligurian Tethys ocean. The inversion of the Europe-Adria plates kinematics brings during the Tertiary to the Apennines orogenesis (Elter, 1975; Bernoulli, 2001; Carmignani & Kligfield, 1990; Conti *et al.*, 2020 and references therein).

The exposed pre-Mesozoic basement observable in the Alpi Apuane (Massa and Apuane units) (Fig. 2) includes low-grade Variscan units (Conti *et al.*, 1991). These mainly contain albite-bearing chloritic phyllites and quarzites with lenses of mafic metavolcanics and calcareous schists (Lower Phyllites), felsic metavolcanics and metavolcanoclastic rocks (Porphyroids and porphyritic schists), metasandstones, quarzites and phyllites (Upper Phyllites), graphitic schists and Orthoceras bearing dolostone. These units are considered as part of a Cambrian to Silurian succession, classically correlated with the Palaeozoic units of central-southern Sardinia (Conti *et al.*, 1991; Pandeli *et al.*, 1994). During Late Carboniferous/early Permian a regional scale trans-extensional regime (Rau, 1990; Molli *et al.*, 2020) affected the Adria crust. This history is recorded by the different Permian deposits recognized in the Massa unit (Patacca *et al.*, 2011; Conti *et al.*, 2020) and in the eastern Alpi Apuane (Fornovolasco area) and by the intrusions of early Permian subvolcanics felsic bodies which may be observed in Fornovolasco as well as in the Sant'Anna di Stazzema areas (Vezzoni *et al.*, 2018; Pieruccioni *et al.*, 2023). Evidence of a later crustal attenuation is provided by the Anisian-Ladinian extensional basin sequences in the Massa unit where marine platform sediments (Diplopora-bearing marbles) are associated with alkaline basaltic flows and breccias. This sequence well studied in the nearby area of Punta Bianca testifies a Mid-Triassic aborted rifting stage affected the future Adria-plate (Elter & Federici, 1964; Federici, 1966; Martini *et al.*, 1986; Storti, 1995).

The Upper Ladinian(?)-Carnian sedimentation is then witnessed by continental to marine deposits (Conti *et al.*, 2020) locally observable at the base of shallow water carbonates (Carnian (?)-Norian Dolomites of the "Grezzoni Fm.") or dolomite-evaporites sequences (Calcare Cavernoso) formed during the renewal of the rifting process. Shallow water carbonate deposi-

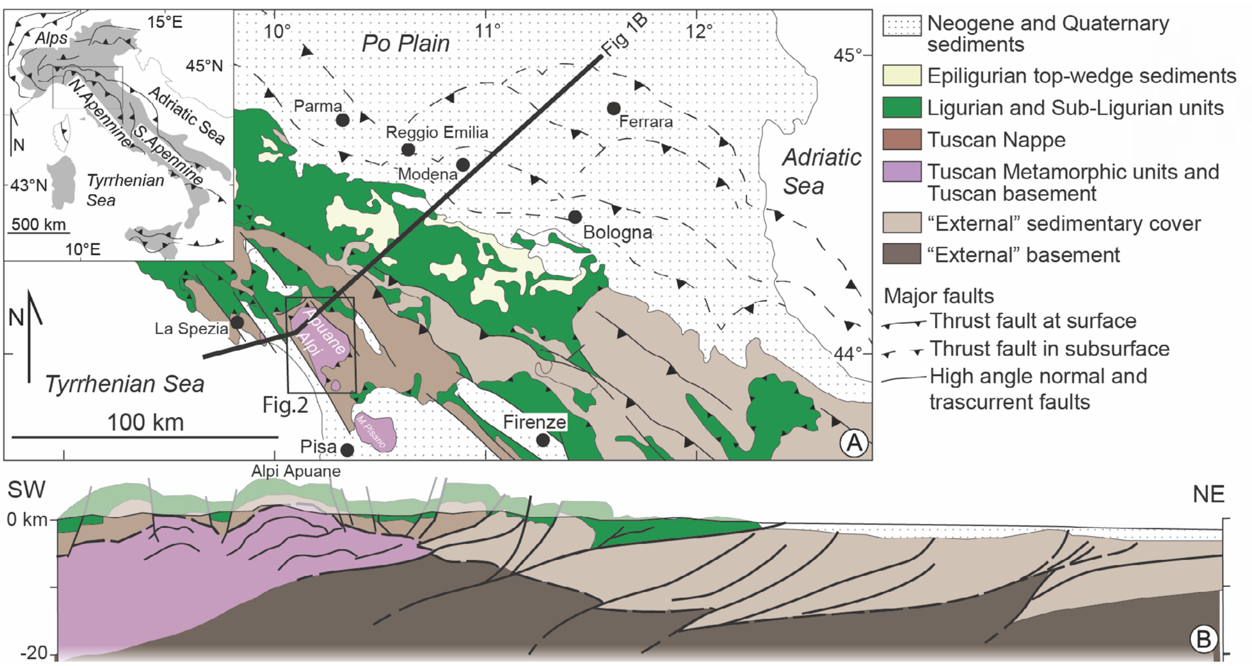

Figure 1. Tectonic map of the Northern Apennines, with crustal scale (b) cross section (modified after Molli, 2008).

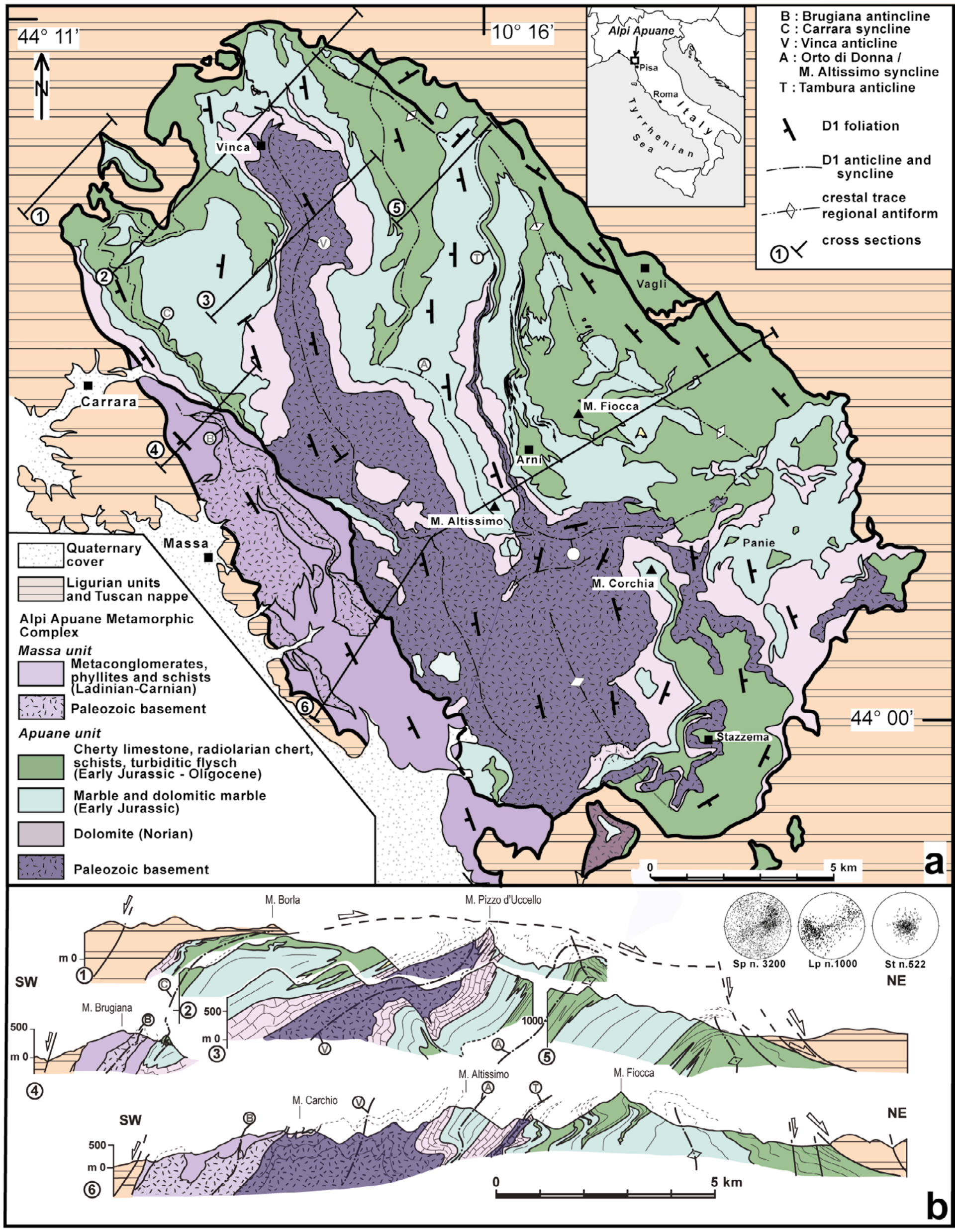

Figure 2. (a) Simplified geological-structural map and (b) composite cross sections across the Alpi Apuane. The dashed lines show the axial traces of the major D1 and D2 folds. Equal area lower hemisphere stereograms show the poles to the main foliation (Sp), stretching lineation (Lp), and the poles of late crenulation cleavage (St).

tion occurred all over the Tuscan continental margin (Calcare Massiccio platform) during the Rhaetian to early Liassic, locally interrupted by uplift, emersion and development of slope breccias (Rhaetian-Liassic boundary). Early to Middle Jurassic block faulting and progressive subsidence of the continental margin were associated with the dismembering of the carbonate platforms and the oceanization of the Ligurian Tethys (Malm) far west (Marroni *et al.*, 2017). Drowning of carbonate platform is then testified by Middle Jurassic-Cretaceous to Cenozoic pelagic carbonates and shales grading upward to Oligocene lower Miocene sandstones and shales (Pseudo-Macigno Fm).

The variability in the stratigraphy in the different areas of Alpi Apuane (Carmignani *et al.*, 1987; Coli & Fazzuoli, 1992; Conti *et al.*, 2020) relates to the syn-sedimentary extensional history started within Anisian-Ladinian as recorded in the main different stratigraphic sequences between Massa and Apuane units. The sin-sedimentary extensional history continued in the Carnian (Vinca Fm.'s facies variability, Fig. 3), and then in the Norian-Rhaetian (lagoonal metalimestones and black marbles "Nero di Colonnata" of the Western Apuane as opposite to a carbonate platform Megalodon-bearing marbles, Seravezza Breccia and Chloritoid Schists of the Central-Eastern Apuane).

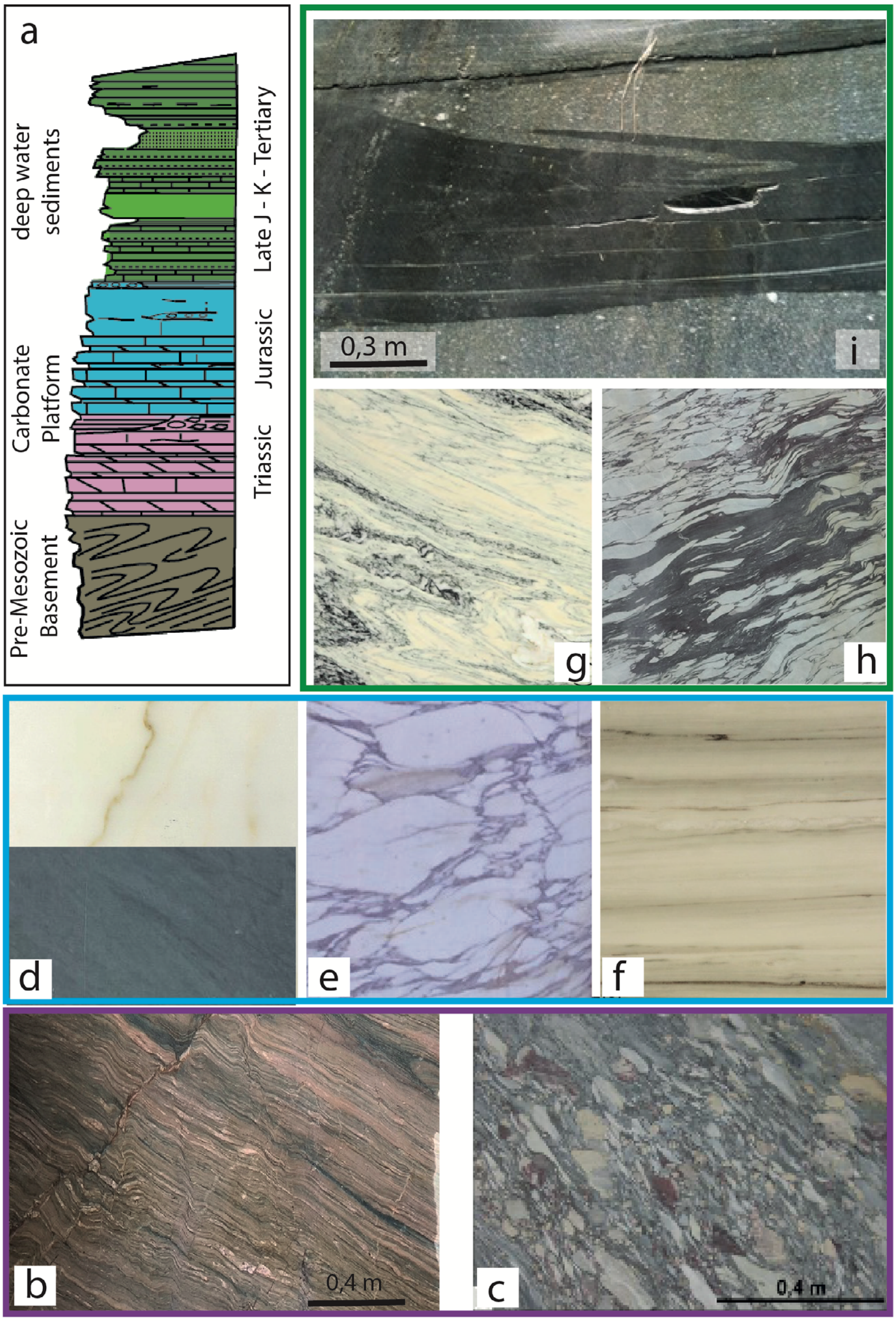

Figure 3. (a) General stratigraphic sequence of the Apuane unit with some characteristic rock-types quarried as ornamental stones. In particular: b) Carnian impure marble part of the Vinca Fm. quarried as “Rosso Rubino”; (c) Breccia di Seravezza, Late Rhaetian scree-breccia also known with the historical name of “Breccia Medicea”; (d) “Carrara marble”: variety “Statuario” (upper part) and “Bardiglio” (grey marble) in the lowermost part; (e) marble breccia variety of “Arabescato”; (f) impure marble quarried with the name of “Zebrino”. This rock types occupy the stratigraphic position of the “Rosso Ammonitico” between Massiccio and Calcare Selcifero in the un-metamorphic Tuscan succession; (g) impure marble “Cipollino”; (h) Breccia Rossa, characteristic rock-units of the eastern Alpi Apuane, typical of “condensed” stratigraphic sequences; (i) PseudoMacigno Fm. quarried in the southernmost Alpi Apuane with the name of “Pietra del Cardoso”.

The Jurassic sequences well witness the presence of different paleoenviroments related to lagoons, tidal channels and emerged areas (White marble, Veined marble, Statuario) as well island-bounding scarps, documented by the Arabescato (Fig. 3e) and other marble breccias including paleokarsts remnants (Fig. 4a). Some other kinds of the marble breccias (Fig. 4b,c,d) may be related to paleofractures forming Neptunian dykes and in some cases damage zones of paleofaults locally mineralized by basement-derived fluids (marble variety of the Paonazzo).

The demise and drowning of Jurassic carbonate platform toward deep-water condition of sedimentation is recorded in different but coeval lithostratigraphic

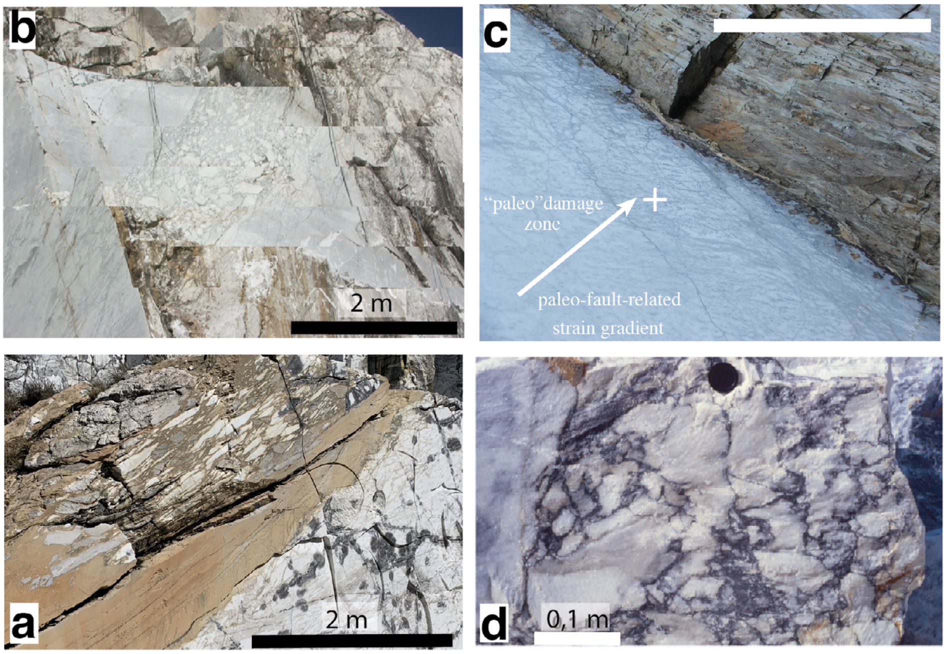

Figure 4. (a) Paleokarst and related marble breccias (Morlungo quarry); (b) Fault-related neptunian-dyke, Pianza quarry; c) Veined marble interpreted as paleo-fault damage zone and related paleo-fault breccias; (c) marble variety of "Paonazzo" a breccia-variety characterized by Fe- and Mn-rich mineralized matrix.

terms explaining the variabilities in Late Jurassic-Tertiary sequences in the different parts of the Alpi Apuane giving way to the variable kinds of "Cipollino" and a red-greenish-coloured variety of marble breccia (Breccia Rossa in Carmignani *et al.*, 2007) (Fig. 3f,g). The end of history in the metasedimentary sequence exposed in the Alpi Apuane is recorded by the silicilastic turbidites of the Pseudo-Macigno Fm. (Conti *et al.*, 2020) a fine to coarse grain metasandstone-metasiltstones and black slates quarried as "Pietra del Cardoso" with the local merceological name (Fig. 3i).

D1 deformation and the distribution of the Jurassic marbles

Map and cross-sections of Fig. 2 illustrate the large-scale structures in the Alpi Apuane metamorphic core which is characterized by kilometer- to hectometer-scale folds (main phase folds or D1) affecting the Paleozoic basement rocks and their Mesozoic to Cenozoic metasedimentary cover sequence (Carmignani *et al.*, 1985). In the northwestern part of the Alpi Apuane, the first-order structure is represented by the east-facing M. Brugiana antiform-anticline in the Massa unit. In its northernmost exposures, between Massa and Carrara, this structure has a core of Paleozoic basement and limbs exposing Ladinian-Carnian continental to marine sequences (Patacca *et al.*, 2011; Di Vincenzo *et al.*, 2022).
Below the Massa unit, the Apuane unit shows two regional-scale structures, the Carrara syncline resting above a major east-facing fold, the Vinca-Forno anticline, with a core of Paleozoic basement. These two regional-scale structures are separated by minor (hectometer-scale) antiform-synform pairs, the Pianza and Vallini folds, with stretched limbs and the core of Jurassic marbles and cherty metalimestone, respectively. Below the Vinca-Forno anticline a second kilometric scale D1 isoclinal fold structure can be observed, the M. Tambura anticline, as the previous ones cored by Paleozoic basement rocks. The two major antiform-anticlines are separated by the Mesozoic metasediments of the Orto di Donna-M. Altissimo-M. Corchia synclines (Fig. 2). The M. Tambura anticline and the Orto di Donna-M. Altissimo synclines close to their southernmost exposures (Fig. 2) are characterized by a nearly 90° change in orientation of fold axes (Carmignani & Giglia, 1977; Carmignani *et al.*, 1978; Meccheri *et al.*, 2008; Molli & Meccheri, 2012), which defines the so-called "Virgazione di Arni" (Giglia, 1967) that will be discussed further. Below the M. Tambura anticline in the north-eastward part of the Alpi Apuane an high strain domain (Eastern Alpi Apuane) is characterized by tight to isoclinal folds (anticlines and synclines pairs) associated with pluridecameter-thick mylonitic zones affecting the whole sequence, from Jurassic-marble to Tertiary Pseudomacigno Fm.
A main planar anisotropy (S1 foliation) of S-L type can be recognized across all the Alpi Apuane as the axial plane foliation of the isoclinal decimeter to kilometer scale folds (Fig. 5). This foliation has a composite origin (Carmignani & Kligfield, 1990; Molli & Meccheri, 2000) and bears a WSW-ENE trending mineral and extension lineation (Fig. 2) which appears to be parallel to the long axes of the stretched pebble clasts in marble breccias and in quarzitic metaconglomerates. D1 fold

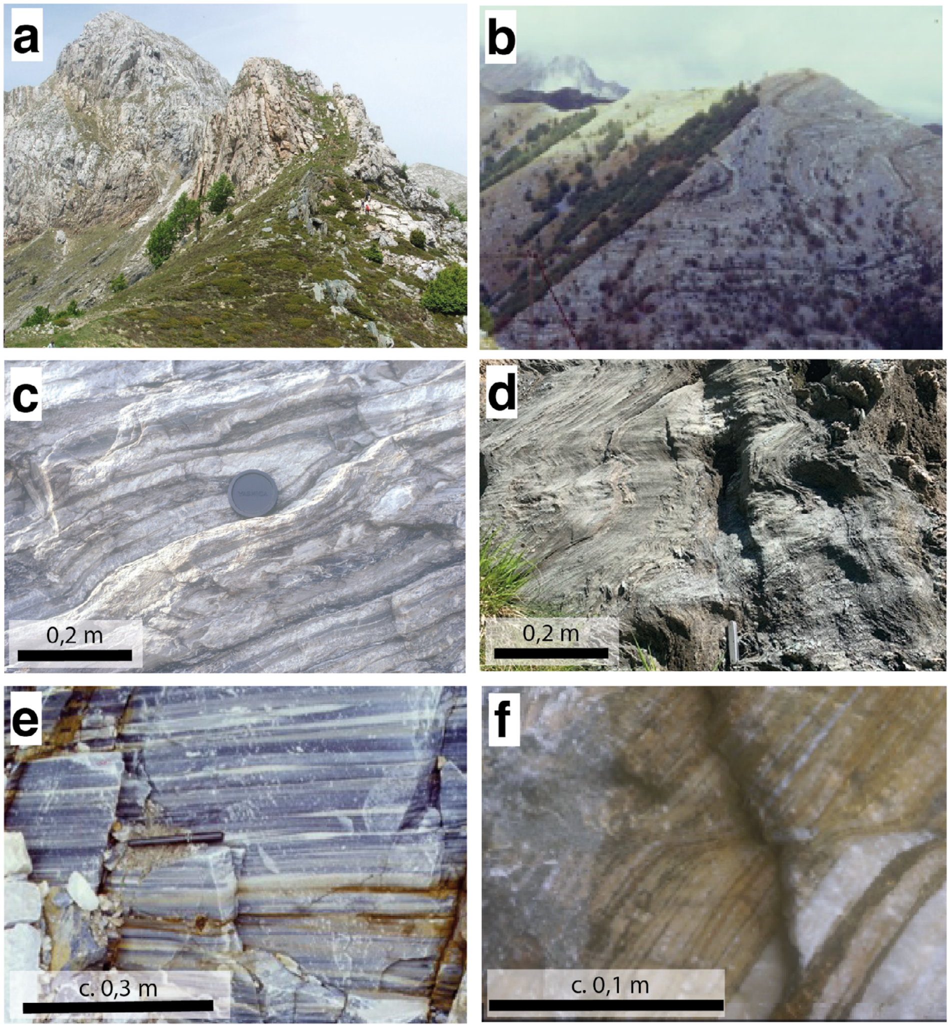

Figure 5. (a) Panoramic view, looking north, from Foce di Giovo, northern Alpi Apuane. Two plurihectometer-scale folds in the hinge zone of the km-scale D1 Vinca-Forno Anticline are visible. D1 folds are refolded by D2 folds with a horizontal fold axial plane. Dark green Paleozoic schists making cuspides within the metadolstones of the Grezzoni Fm.; (b) D2 west-vergent cascade-folds affecting the Grezzoni metadolostone in the normal limb of Vinca-Forno Anticline (Cima D'Uomo, Colonnata). (c) D1 meter-scale isoclinal fold and related axial planar foliation, overprint by D2 cleavage (Cherty metalimestone of Mt.Uccelliera); (d) meter-scale open D2 folds associated with a sub-horizontal crenulation cleavage (Scisti Sericitici Fm., Arni valley, eastern Alpi Apuane); (e) calc-mylonites derived from cherty metalimestones within a Late D1 shear zone. Colonnata valley, Carrara western Alpi Apuane; (f) decimeter-scale D2 shear zone in impure marble, Forno valley inland of Massa (for detailed microstructural description and fabric-types evolution see Oesterling *et al.*, 2007).

axes in the western area mainly trend NW-SE and are sub-horizontal (but see the area around Ponti di Vara, inland of Carrara) with a D1 lineation plunging down-dip within the main foliation at 90° from fold axis. In the north-eastern region, below the Mt.Tambura anticline, fold axes are parallel to sub-parallel to the down-dip stretching lineation and highly non-cylindric sheath folds appear (Carmignani & Giglia, 1984; Carmignani & Kligfield, 1990). This relationship between fold axis and stretching lineation has been proposed as an example of passive rotation of early formed folds into the extension direction in the higher strained domains during progressive simple shear (Kligfield *et al.*, 1981). The deformation geometries, strain patterns and kinematic data allowed to interpret the D1 history as the result of: (1) underthrusting and early nappe stacking within the Apenninic collisional wedge; (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (Carmignani & Kligfield, 1990; Molli *et al.*, 2000).

Structural heritage and D1 deformation

The development of the large scale D1 structures is strongly controlled by the original paleotectonic setting and its lateral heterogeneities documenting the important role of structural inheritance (Molli & Meccheri, 2012). In the geological literature of the Alpi Apuane the concept of paleotectonic heritage can be traced back to Zaccagna (1897) and occurs throughout the literature until the '60s (e.g. Giglia, 1967; Nardi, 1969). More recently it was appreciated and illustrated by Carmignani *et al.* (1978), Kligfield (1979), Kligfield *et al.* (1981), Carmignani *et al.* (1987), Carmignani & Kligfield (1990) who clearly suggested a direct relationship between orogenic structures and Norian–Cretaceous paleotectonic ones. For these authors the first order folds of the Alpi Apuane (i.e. the "Vinca-Forno" and "Tambura" anticlines) were related to the geometry of the Mesozoic sedimentary basins and intervening highs of the external Tuscan domain (Elter,1975). According to Carmignani *et al.* (1987) and

Carmignani & Kligfield (1990), the lateral and vertical thickness variabilities in the Mesozoic stratigraphy of the rifted Tuscan continental margin controlled the localization of the ramps in "prograde" ramp-flat tectonics, whose structures were successively modified at deeper structural levels in the metamorphic realm. This proposal has been slightly modified in the interpretation by Molli & Meccheri (2012), who applied a "modified overthrust model" proposed for the Helvetic nappes by Casey & Dietrich (1997) and used by Butler *et al.* (2006a; 2006b), Bellahsen *et al.* (2012) as key to understand inversion tectonic-styles at mid-crustal depth. The interpretation considers the role of paleofault-related vertical thickness variabilities in the Mesozoic stratigraphy of the rifted Adria continental margin and the kinematic evolution of the investigated structures (Fig. 6). A localization of the low-amplitude initial folds by pre-existing fault domains may have served to create initial buckling instabilities associated with heterogeneous pure-shear basement deformation. During progressive fold amplification, a modification of the initial buckle folds was produced by shearing with formation of the major regional folds later refolded during the antiformal stacking (and D2 deformation see below) ending with the presently observable Alpi Apuane architecture (see Fig. 2, 6, 7). Molli & Meccheri (2012) underlined the point that, if the original buckling was controlled by the pattern of preexisting faults (Fig. 7d), the presence of fault segmentation and transfer zones might bring to a deviation of the velocity discontinuities with the frontal fold axis would become nearly parallel to the bulk shortening direction (Calassou *et al.*, 1993; Konstantinovskaya *et al.*, 2007) giving way to a transversal trend of folds. This was considered as the origin of the early stage of regional transversal trend of folding which would have been further modified by shearing leading to the antiapenninic "rotated" trends sub-parallel to the regional stretching lineation at kilometer-scale in the "Virgazione di Arni" (Carmignani & Giglia, 1983; Molli & Vaselli, 2006).

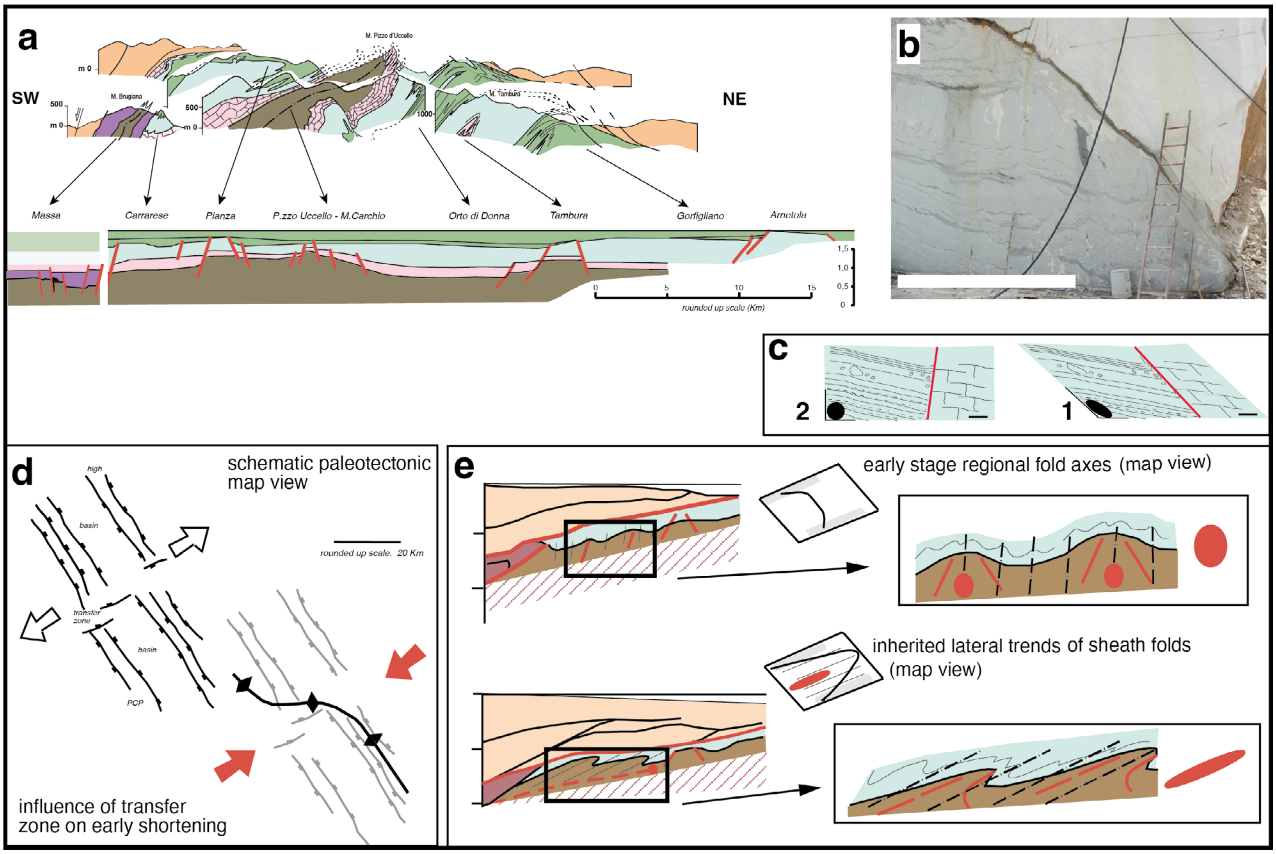

Figure 6. (a) General cross-section of the Alpi Apuane showing the regional-scale structures and their relationships with the original paleogeography modified after Carmignani *et al.* (1987) and Carmignani & Kligfield (1990); (b) White marble thrust above stratified impure pale greenish marble, scale bar ca.2,5 m. Figured are details of thrust plane and meter-scale east-vergent folds developed in the footwall of the thrust; (c): c1 schematic line drawing showing the present-day geometry and lithology of the outcrop. Based on the local finite strain data and a simple shear strain path the original geometry can be reconstructed (c2); (d) schematic paleotectonic map view showing the possible segmentation of the former basin and transfer zones as well as their influence during the early "inversion"-related shortening; (e) regional tectonic frame with close up of vertical profiles and map views of early normal fault- controlled buckling during underthrusting of the external Tuscan Domain (Alpi Apuane zone) and later modification by shearing to produce the recumbent Alpi Apuane D1-fold structures.

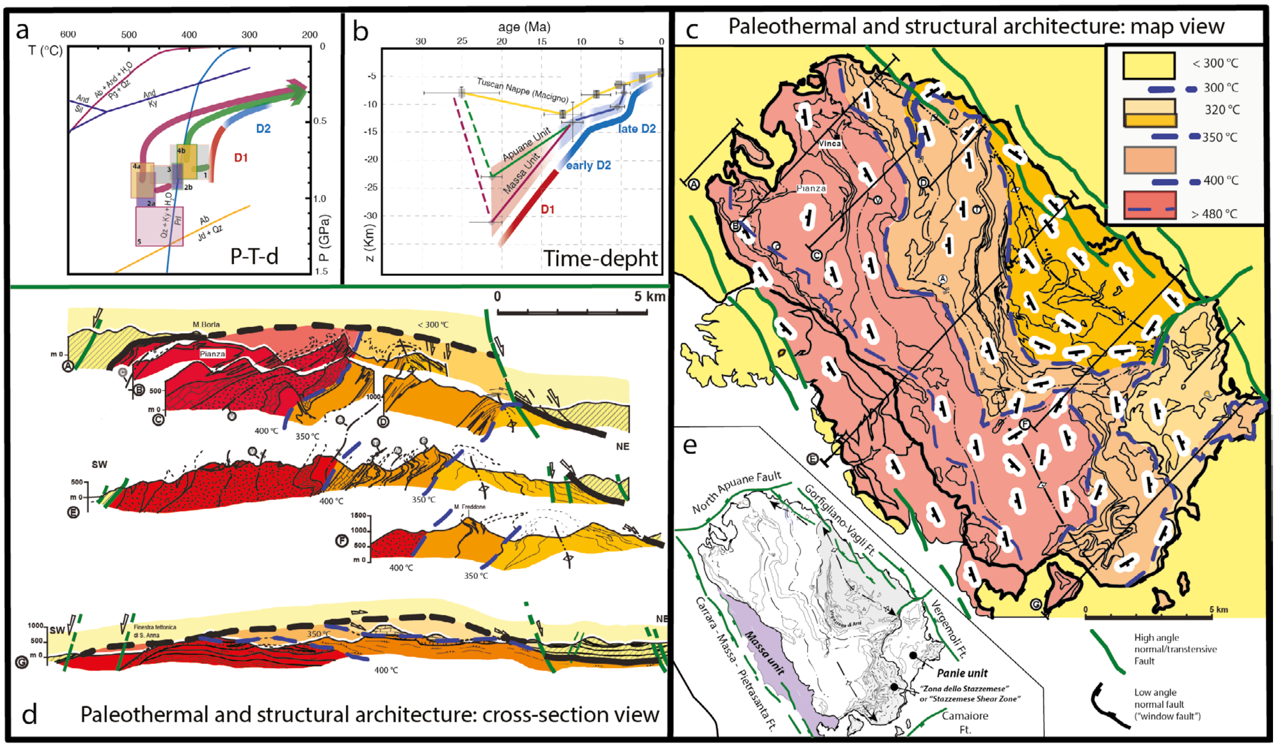

Figure 7. (a) P-T estimates and paths for the Apuane and Massa units. Data used for boxes 1-4 are derived from quantitative classical thermo-barometry as well as pseudosections (Franceschelli *et al.*, 1986; Jolivet *et al.*, 1998; Molli *et al.*, 2000; Papeschi *et al.*, 2023). Data used to define box 4 also include temperatures based on Raman spectroscopy on carbonaceous material (RSCM) (Molli *et al.*, 2018). Red and blue lines outline the relative timing of deformation for D1 and D2 with changing metamorphic conditions. For more details see Di Vincenzo *et al.*, 2022; (b) Time-depth paths of the Massa and Apuane units and of the overlying Tuscan nappe (Macigno) modified after Fellin *et al.*, 2007 including data in Di Vincenzo *et al.*, 2022; (c) Paleothermal architecture of the Alpi Apuane metamorphic core complex in map view; (d) paleothermal architecture at window-scale in cross-sections view; (e) overall structural architecture of the Alpi Apuane metamorphic core. Also indicated and named the main boundary faults around the metamorphic core.

D2 DEFORMATION AND THE REWORKING OF THE EARLY STRUCTURES

All the D1 structures and tectonic contacts are overprinted by later structures of different generations and styles collectively referable to the regional D2 event. The early structures, syn-metamorphic, are represented by variously sized high strain zones and well-developed folds mainly associated with a low dipping to sub-horizontal axial planar foliation (S2), of crenulation type (Figs. 2, 5b,d). After these early generations of folds and shear zones, Late D2 structures formed. These are mainly represented by upright kinks and different generations of brittle faults (the earlier with a low angle attitude as opposite to the younger at a high angle) that accommodate the most recent tectonic history.

As documented since the end of '70s (Carmignani *et al.*, 1978; Carmignani & Giglia, 1979; Carmignani & Kligfield, 1990) a complex D2 mega-antiform with Apenninic trending axis (nearly N 130°-170°), and corresponding to the entire width of the Alpi Apuane window, refold the early-formed D1 structures (Fig. 7). All around the antiform, second order asymmetric folds facing away from the dome crests are described. At the scale of the whole Alpi Apuane, large scale reverse drag-folds having "S" and "Z" sense of asymmetries can be observed on the southwestern and northeastern flanks, respectively. These structures form series of folds at different scale (from centimeters to kilometers) with variable morphologies related to rock competence and structural position within the folded multilayer but also from the characters of the previously developed D1 structures.

For this early D2 deformation, different and alternative interpretations were proposed in the literature.

A first model, frame the D2 history during a continuous shortening regime in which superimposed folding occurred (Carmignani *et al.*, 1978; Kligfield, 1979; Boccaletti *et al.*, 1983; Carosi *et al.*, 2002). In this model-groups may be also inserted the '90s proposal of Jolivet *et al.* (1998) which envisaged the south-west verging folds as related to local shear zones conjugate to the major top-to-the-northeast thrusts, accommodating rotation of intra "Apuane" rigid domains within the major top-to-the-northeast contractional shearing. Differently, Carmignani & Kligfield (1990), proposed a kinematic model in which the D2 structures were related with conjugate top-to-the northeast and top-to-the southwest shear zones, in which cascade-type folds were produced within an overall extensional crustal kinematics.

As alternative to all the previously mentioned models, the one first proposed by Carmignani & Giglia (1979) and more recently reproposed by Molli *et al.* (2022) based on strain fringes analyses, abides the only requirement necessary for the development of D2 deformation and strain features: a roughly vertical shortening of medium to steeply oriented layers. The vertical shortening-initiated buckle instabilities in more competent units and layer-parallel shearing on the limbs of previously developed Late D1 antiforms with an asymmetry related to the orientation of pre-existing composite layering and early isoclinal fold structures. This general architectural pattern is presently recognized as typical of region undergoing crustal scale extension/transtension (Froitzheim, 1992; Carosi *et al.*, 1996; Arden & Malavieille, 1999; Fossen et al., 2013) and therefore may be considered as a key signature for geodynamic interpretations.

The Late D2 deformation history is then associated with cataclastic low-angle normal faults with the major structures localized by the reactivation of the window fault (Calcare Cavernoso Auct.) and their footwall splays, few hundreds of meters below the main fault (Conti e*t al.*, 2020; Pieruccioni *et al.*, 2018).

This Late D2 low angle normal faults are overprinted by a further generation of structures related with deformation at shallower crustal depth. The Alpi Apuane are indeed an homogeneous regional scale brittle 'low strain' domain surrounded by large displacement faults (boundary faults) to the east, west, north and south. These high angle boundary faults (see Fig. 7e) divide the Alpi Apuane from the surroundings tectonic depressions of Lunigiana, Garfagnana, Versilia and Camaiore (Molli *et al.*, 2021 and references). Deformations associated with the boundary faults are witnessed by damage zones of variable width toward the external parts of the tectonic window and within the metamorphic core by an immature intra Alpi Apuane fault network. This fault network, characterized by a very low degree of interconnection, shows low displacement (from meter to pluridecameter) along every single structure. This is the reason why the brittle structures were neglected or missed in most of the available geological maps, although they are very important and significant for the quarrying activity, hydrogeology and karst network development (Piccini *et al.*, 2003; Cortopassi *et al.*, 2007; Isola *et al.*, 2021; Molli *et al.*, 2015).

The metamorphic history and paleothermal architecture

Regional scale differences in peak of metamorphism were envisaged in the Alpi Apuane since the mid of eighties (Di Pisa *et al.*, 1985; Franceschelli *et al.*, 1986). In metapelites of the Massa Unit metamorphic peak conditions (Fig. 7) are associated with kyanite + chloritoid + phengitic muscovite assemblages and related to ~1.0 GPa and 420-500°C (Franceschelli *et al.*, 1986; Jolivet *et al.*, 1998; Molli *et al.*, 2002; Di Vincenzo *et al.*, 2022; Papeschi *et al.*, 2023). In the Apuane Unit the peak assemblages of pyrophyllite + chloritoid + chlorite + phengitic muscovite in metapelites indicate peak metamorphism in the pressure range of 0.4-0.6 GPa and temperatures ranging between 350 and 450°C in different structural positions (Franceschelli *et al.*, 1986; Jolivet *et al.*, 1998; Molli *et al.*, 2002).

RSCM thermometry allowed to refine the T distribution at the scale of the entire region in the different pre-Mesozoic rock-units and in Mesozoic to Tertiary ones. The pre-Mesozoic basement rocks show a mean peak RSCM T of 445 °C whereas a mean of 386 °C is found in the metasedimentary Mesozoic to Tertiary cover (Molli *et al.*, 2018). The distribution of peak T at the scale of the whole Alpi Apuane (Fig. 7c) indicates a systematic arrangement with respect to the overall architecture of the regional structures. The north-west part of the Alpi Apuane is characterized by a SW to NE decrease of peak temperature from 495 °C in the west to 357 °C in the central and 336 °C in the easternmost position. A difference of 125 °C is observed with a structural distance of ~8 km, outlying an inverted field metamorphism with a T gradient of ~20°/km. The thermal architecture combined with the structural ones indicate an overall "contractional" model of antiformal stacking suggesting an orogenic wedge dominated by material advection realized by underplating of more external units (Molli *et al.*, 2018). In the south-east part of the Alpi Apuane (Fig. 7c) an "extensional" core-complex type thermal architecture and an apparent normal-type gradient is observed with transition from temperatures higher than 500 °C to less than 300 °C (projected base of the Tuscan Nappe) in less than 1,5 km (e.g. cross-section G). This thermal architecture, however, could be only apparent since the exposed geometrically deepest and cooler levels represented in the eastern Alpi Apuane are not at the surface due to the 3D dome shape structural architecture previously illustrated.

Age of deformation and exhumation history

Based on the geochronological data (Kligfield *et al.*, 1986; Di Vincenzo *et al.*, 2022), the available thermochronology (Abbate *et al.*, 1994; Fellin *et al.*, 2007) and geological constrains (Carmignani & Kligfield, 1990; Molli *et al.*, 2002; Molli *et al.*, 2021) the following deformation age and exhumation history may be reconstructed (Di Vincenzo *et al.*, 2022):

1. onset of metamorphism and deformation in the exposed units of the Alpi Apuane region may be constrained as having a minimum age of 20-21 Ma (Aquitanian/Burdigalian boundary), as documented by 40Ar-39Ar data for the composite D1 foliation and related structures in the western parts of the Alpi Apuane (i.e., Massa unit). This is in line with the recently acquired data in the close area of Punta Bianca (Montomoli *et al.*, 2024) as well as at regional scale in the Adria-derived Tuscan metamorphic units in Southern Tuscany (Bianco *et al.*, 2015; Giuntoli & Viola, 2024).
2. D1 deformation, consistently with its composite character, occurred during a protracted (at least ~6.5 Ma) metamorphic evolution, lasting from the Aquitanian/Burdigalian to the Langhian/Serravallian boundary. A possible West-East diachronism for the development of D1 foliation is suggested by the minimum age of ~14.4 Ma obtained for the development of the D1 foliation in the easternmost sample of the Apuane Unit (Arni valley). Such a diachronism in the development of D1 structures appear to be significant from a wedge kinematic viewpoint being consistent with the West-East sense of transport, the stacking of the various units, and their internal deformation at the scale of the whole metamorphic core.
3. D2 deformation shows a common temporal evolution at the scale of the entire Alpi Apuane region and is recorded for a duration of at least ~2.5 Ma, starting not after the upper Serravallian and ending in the middle Tortonian, at ~10.5 Ma.

Interpreting the early D2 deformation structures, with their architectures and kinematics features as marking the switch from crustal contraction to crustal extension (Carmignani & Kligfield, 1990; Molli *et al.*, 2018), point (3) constraints the onset of the genuine lithospheric scale extensional history in this portion of the inner northern Apennines as developed since the upper Serravallian (~12.5-12.0 Ma) and recorded until c. 10 Ma (youngest Ar/Ar ages associated to the D2 fabrics in the Massa unit Di Vincenzo *et al.*, 2022).
The available thermochronological data in Abbate *et al.* (1994) and Fellin *et al.* (2007) allowed to complete the timing of deformation and exhumation from the middle-upper crust (temperature c. 300 °C) up to the surface (Fig. 7a,b). The data regards the thermal evolution of the Tuscan Nappe in its uppermost stratigraphic term of Macigno Fm. (the only lithotype useful for fission tracks dating) and for the metamorphic units the Palaeozoic volcanic-volcanoclastic of Porphyroids and Porphyric Schists as well as the siliciclastic rock-units of the Pseudomacigno Fm. The data show the vertical path of the tectonic units, analysed through the temperature ranges of 250, 200, 120, 70 °C (respectively the closure temperatures for fission tracks in the Zr, He-Zr, Ap, He-Ap; Fellin *et al.*, 2007).
Using the available cooling ages data sets, the time-depth path in Fig. 7b may be reconstructed. This suggests that after the first stage of exhumation (pre-7 Ma), c. 3.6 ± 0.5 km of tectonic unroofing of the Alpi Apuane core occurred in a narrow time interval between approximately 7 and 5 Ma (Upper Tortonian-Messinian). After this, the Alpi Apuane core and the Tuscan nappe were jointly exhumed as a single body. This occured by the activity of boundary faults and erosion. The presence of metamorphic pebbles from the Alpi Apuane core in the early Pliocene Garfagnana, and Lunigiana intramontane basins (Molli *et al.*, 2021 and references) indicate that at c. 2,5 Ma the Alpi Apuane core rocks were at the surface in agreement with the U/Pb radiometric age of speleothems (Isola *et al.*, 2021).

Marble microstructures as record of the tectonic history of the inner NA

After the pioneering studies reported in Zaccagna (1932) and Bonatti (1938) the microstructures of Alpi Apuane marbles was the object of investigations by Crisci *et al.*, (1975), Di Pisa *et al.*, (1985) and Coli (1989a). Considering the main microstructural features and relationships with mesoscopic field structures (foliations, folds and shear zones), the marbles microstructures were subdivided by Molli *et al.*, (2000a) into three main group-types (Fig. 8) interpreted respectively product of:

a) static recrystallization (type A microfabric);
b) dynamic recrystallization (type B microfabric, further subdivided into two types B1 and B2);
c) reworking during the late stage of deformation (type C microfabric).

These distinctions represent the end-member of a wide range of transitional types which in some cases can be observed superimposing each other (see detailed description in Molli & Heilbronner, 1999; Molli *et al.*, 2000; Oesterling *et al.*, 2007).

– The statically recrystallized microfabric or "annealed-type" (type-A microfabric) is characterized by equant polygonal grains (granoblastic or "foam" microstructure, Fig. 8a,b,c), with straight to slightly curved grain boundaries that meet in triple points at angles of nearly 120°. C-axis orientations show a random distribution or a weak crystallographic preferred orientation. These microfabrics are

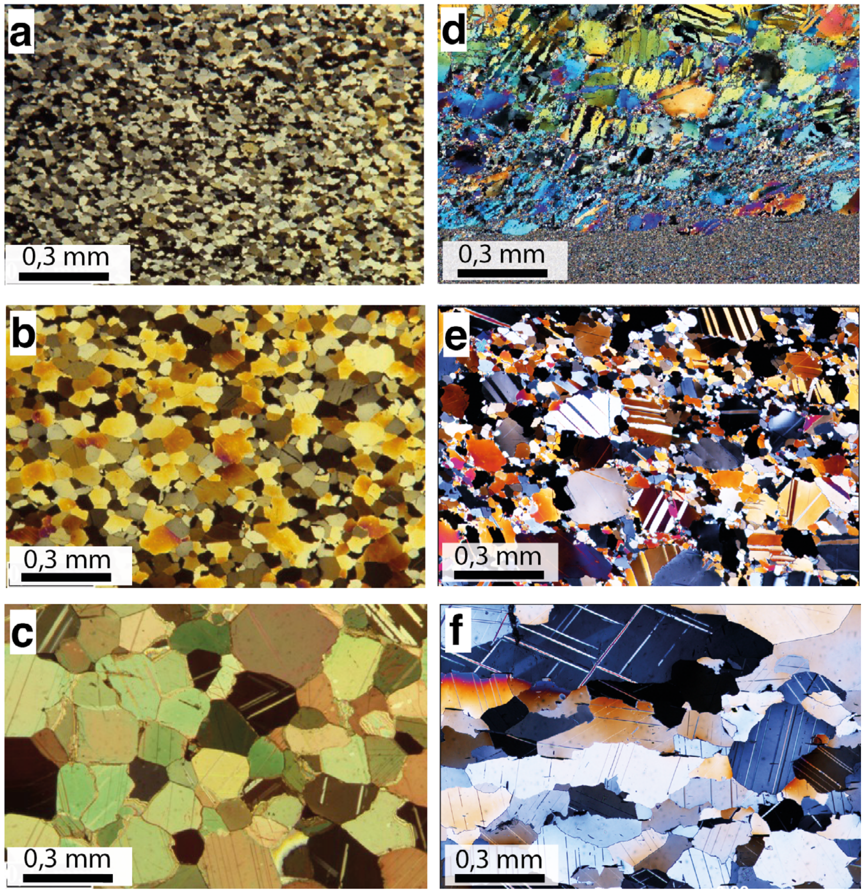

Figure 8. Marbles microstructures a,b,c: Statically recrystallized or annealed microstructure (Type A). Sample (a) from the Pania unit, southern Alpi Apuane, structural domain characterized by RSCM temperature of 320 °C; sample (b) from the eastern Alpi Apuane, domain characterized by RSCM of 360 °C; sample (c) from the western Alpi Apuane, domain characterized RSCM of 480 °C. Dynamic recrystallized microstructures (Type B): (d) sample coming from a millimeter-scale rim tapering the main slip surface of an High Angle Normal Fault (Late D2 history;) (e) Type B2-microstructure related to D2 shear zones, localized deformation during the switch from crustal-scale contraction to crustal-scale extension (early D2); (f) Type B1-microstructure related to a Late D1 shear zone, localized deformation during the antiformal stacking.

observable in marble levels belonging to km-scale D1 isoclinal folds, where also minor parasitic folds developed. The presence of such microstructures within D1 folds indicates that the grain growth which produced type A microfabric occurred after the main D1 folding phase and obliterated all earlier syntectonic microstructures associated with folding. However, the presence of a texture in some samples of impure marbles may be related to the pre-annealing deformation history (Leiss & Molli, 2003). Marbles with annealed microstructure can be observed in the western, central and eastern parts of the Alpi Apuane, with a medium grain size decreasing from west to east (300-150 µm to 100-80 µm) and from geometrically deeper to higher structural levels in well agreement with the paleothermal architecture (Fig. 8a,b,c).

– The dynamically recrystallized microfabrics (type-B microfabrics) were differentiated in two main groups, the first one (type B1) exhibiting strong shape preferred orientation, coarse grains and lobate grain boundaries whereas the second show microstructures with shape preferred orientation, smaller grain size and predominantly straight grain boundaries (type B2). Fig. 8e,f shows representative examples of the two types of microfabrics. These two types of microstructures are both interpreted as related to high strain and high temperature (300-400 °C) crystal plastic deformation mechanisms (dislocation creep regime). Whereas grain boundary migration recrystallization can be considered as predominant in type B1 microfabric, an important contribution of both rotation recrystallization and grain boundary migration has been inferred to prevail in type B2 microfabric (Molli *et al.*, 2000; Oesterling *et al.*, 2007).
– Twinned microfabric (type-C microfabric). The third type of microfabric is related to low-strain and low-temperature crystal plastic deformation mechanisms. Characterized by thin straight e-twins, it occurs in all the marble outcrops of the Alpi Apuane region, overprinting both type A and type B microfabrics. It is mostly developed in coarse grained marble. This microstructural-type has been also found associated to the marbles involved in the damage zones of late high angle normal to oblique slip faults where are associated to extremely localized (millimeter-scale) recrystallized microstructures (Fig. 8d) tapering their principal slip surfaces (Molli *et al.*, 2011; Molli, 2016).

Final remarks

The Alpi Apuane represent one of the key areas for understanding the geologic evolution of the Northern Apennines as well documented by the literature of the last of two centuries. During the 1970's the area was the ground of the first applications of modern structural geology with the recognition of superimposed foliations and structures (Carmignani & Giglia 1975; Pertusati *et al.*, 1977; Kligfield, 1979; Boccaletti & Gosso, 1980; Boccaletti *et al.*, 1983), stretching fabrics and sheath folds (Carmignani *et al.*, 1978) and the studies of finite strain (Kligfield *et al.*, 1981). Moreover in the Alpi Apuane the first pioneering geochronological study by Giglia & Radicati di Brozolo (1970) was realized and after that one of the first world-wide attempts of radiometric dating of superimposed low-grade foliations (Kligfield *et al.*, 1986). During '90s the papers of Coli (1989), and above all, Carmignani & Kligfield (1990) underlined and linked the late stage of syn-metamorphic history of the Alpi Apuane to the extensional geodynamics characteristic of the Apennines-Tyrrhenian system. This make the Alpi Apuane a key and unique area of the Apennines where it is possible to track and document how the Adria continental crust was deformed at depth during the phases of continental subduction, but also how it record of the different stages of the syn- and post-collisional extension from the depth of the middle crust (c. 10-15 km) up to the surface. As matter of facts this complete cycle of the Apennines orogenic evolution may be also traced and followed by the microstructural variability of the Alpi Apuane marbles which document, as successive footprints, the different kinematics and dynamic stages of the Apennines wedge at the crustal scale.

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Conflict of interest statement

The author declares that he has no conflict of interest neither known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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