Syn- to post-orogenic exhumation of metamorphic nappes: structure and thermobarometry of the western Attic-Cycladic metamorphic complex (Lavrion, Greece).

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Abstract:

The Lavrion peninsula is located along the western boundary of the Attic-Cycladic metamorphic complex in the internal zone of the Hellenic orogenic belt. The nappe stack is well exposed and made, from top to bottom, of (i) a non-metamorphic upper unit composed of an ophiolitic melange, (ii) a middle unit mainly composed of the Lavrion schists in blueschist facies, (iii) and a basal unit mainly composed of the Kamariza schists affected by pervasive retrogression of the blueschist facies metamorphism in greenschist facies. The middle unit is characterized by a relatively steep-dipping foliation associated with isoclinal folds of weakly organized axial orientation. This foliation is transposed into a shallow-dipping foliation bearing a N-S trending lineation. The degree of transposition increases with structural depth and is particularly marked at the transition from the middle to the basal unit across a low-angle mylonitic to cataclastic detachment. The blueschist facies foliation of the Lavrion schists (middle unit) is underlined by high pressure phengite intergrown with chlorite. The Kamariza schists (basal unit) contains relics of the blueschist mineral paragenesis but is dominated by intermediate pressure phengite also intergrown with chlorite and locally with biotite. Electron probe micro-analyzer chemical mapping combined with inverse thermodynamic modeling (local multi-equilibrium) reveals distinct pressure-temperature conditions of crystallization of phengite and chlorite assemblages as a function of their structural, microstructural and microtextural positions. The middle unit is characterized by two metamorphic conditions grading from high pressure (M1, 9 – 13 kbar) to lower pressure (M2, 6 – 9 kbar) at a constant temperatures of ca. 315 °C. The basal unit has preserved a first set of HP/LT conditions (M₁₋₂, 8 – 11 kbar, 300 °C) partially to totally transposed-retrogressed into a lower pressure mineral assemblage (M₃, 5 – 8.5 kbar) associated with a slight but significant increase in temperature (~350 °C).

These structural, petrologic and thermobarometric data document the tectonic evolution from construction to destruction of the Hellenic orogenic belt. The steep-dipping blueschist facies foliation, preferentially preserved at high structural level in the middle unit, is considered to reflect tectonic accretion marked by successive burial (D_1M_1) and syn-orogenic exhumation (D_2M_2) without thermal relaxation. The transposition-retrogression of the blueschist facies mineral assemblage into a shallow-dipping greenschist facies foliation associated with an increase in temperature corresponds to lateral flow of the thermally relaxed nappe stack (D_3M_3). The development of a low-angle detachment, accommodating post-orogenic exhumation of the orogenic root, is attributed to gravitational collapse of the Hellenic belt.

1. Introduction

Orogenic belts form as a consequence of lithospheric plate convergence and correspond to zones of localized crustal deformation and metamorphism (Dewey and Bird, 1970). Currently active convergent plate boundaries are characterized by crustal orogenic wedges and orogenic plateaus, but also by gravitational collapse of previously thickened crust leading to the opening of intermontane and eventually oceanic back-arc basins (Collins, 2002; Vanderhaeghe, 2012 and references therein). Metamorphic rocks exposed in the internal zone of orogenic belts record burial and exhumation under contrasted geothermal gradients (Zwart, 1967; Ernst et al., 1973; Miyashiro, 1973; Parra et al., 2002; Lanari et al., 2012). *HP/LT* metamorphic rocks are interpreted to reflect burial and exhumation without thermal relaxation, whereas *HT/MP* to *HT/LP* metamorphic rocks attest for the contribution of heat advection related to the emplacement of mafic magmas (Bergantz, 1989; De Yoreo et al., 1991; Annen and Sparks, 2002) and/or to the thermal relaxation of a radioactive orogenic crust (England and Thompson, 1986; Vanderhaeghe et al., 2003).

The Hellenides represent an emblematic example of a mountain belt formed along the Africa-Eurasia plate boundary actively convergent since more than 80 Ma (Auboin, 1973, 1976; Dewey and Sengor, 1979). Subduction and southward retreat of a single slab beneath the Aegean domain is marked by southward migration of arc magmatism (Fytikas et al., 1984) and is consistent with the lithospheric structure deciphered by seismic tomography (Spakman et al., 1988; Bijwaard et al., 1998). The internal zone of the Hellenides corresponds to exhumed metamorphic rocks designated as the Attic-Cycladic metamorphic complex (Dürr et al., 1978; Jacobshagen et al., 1978; Jacobshagen, 1986). Two distinct stages of metamorphism have been documented in the Attic-Cycladic complex (Jansen, 1973; Jacobshagen et al., 1978; Altherr et al., 1982). The first one corresponds to Eocene *HP/LT* metamorphism affecting an ophiolitic nappe and a continental margin sedimentary sequence grouped in the so-called Cycladic blueschist unit (Bonneau et al., 1978; Avigad and Garfunkel, 1991; Parra et al., 2002; Forster and Lister, 2004). The *HP/LT* metamorphic mineral paragenesis has been overprinted during Oligocene-Miocene time by *HT* metamorphism ranging from greenschist to amphibolite facies (Jansen and Schuilling, 1976; Buick and Holland, 1989) and reaching partial melting in the central part of the Cyclades (Martin, 2004; Duchêne et al., 2006; Martin et al., 2006, 2008; Kruckenberg et al., 2010, 2011; Laurent et al., 2015). The Aegean domain, characterized by a zone of low-topography marking the transition between the Hellenides and the Taurides, has been identified as a Metamorphic Core Complex similar to the ones typified in the internal zone of the North-America Cordillera based on the identification of low-angle detachments (Lister et al., 1984). Continental extension is also expressed by the activation of the Corinth rift, the most seismically active zone in Europe (Rigo et al., 1996).

Recent tectonic models for the Aegean domain invoke a period of tectonic accretion associated with thrusting and burial of tectonic units followed by a period of exhumation and thinning of the previously thickened orogenic crust (Gautier et al., 1993, 1999; Vanderhaeghe,

2004; Vanderhaeghe et al., 2007; Jolivet and Brun, 2010; Ring et al., 2010; Grasemann et al., 2012; Jolivet et al., 2013; Augier et al., 2015). Despite a general agreement on this first order conceptual model, there are several discrepancies regarding the significance of structures marking the boundaries of the Attic-Cycladic metamorphic complex and most particularly along its western boundary. Indeed, some authors interpret the western boundary of the Attic-Cycladic complex as a thrust (Ring, et al., 2003; Jolivet and Brun, 2010; Jolivet et al., 2010b; Philippon et al., 2012), others as a detachment (Skarpelis, 2007; Liati et al., 2009; Grasemann et al., 2012; Berger et al., 2013), and some as a dextral strike-slip zone in the continuity of the North Anatolian Fault (Koukouvelas and Kokkalas, 2003; Flerit et al., 2004). These discrepancies are in part related to the fact that most of these authors invoke implicitly at least partial reworking of thrusts during syn- and post-orogenic exhumation.

Most authors have based their reconstruction of the tectonic evolution of the Aegean domain on the combination of kinematic analysis of shear zones including low-angle detachments and on contrasted *P-T* conditions across tectonic contacts. To complement these previous studies, in this paper, the internal structure of metamorphic nappes and the associated mineral assemblages are documented as a function of their structural level, in order to reconstruct the tectonic-metamorphic history of the Hellenic orogenic belt from crustal thickening to gravitational collapse. The strategy is to (i) integrate scales from the region to the mineral, and (ii) obtain *P-T* conditions on mineral assemblages correlated to microtextures (core and rims) and microstructures (schistosity). In contrast to high-grade well-equilibrated metamorphic rocks, the links between mineral paragenesis and microtextures are more difficult to establish in low-grade rocks that are highly reactive to small changes in the equilibrium conditions such as pressure, temperature, oxygen fugacity and water activity. In such rocks, metamorphic transformations occur locally and are mainly driven by deformation

(Vidal et al., 2006; Lanari et al., 2012). Local equilibria are deduced using microtextural criteria and serves as basis for thermodynamic modeling. The development of complex solid solution models for chlorite and K-white mica (Vidal et al., 2005; Dubacq et al., 2010), with the improvement of a quantitative micro-mapping technique and programs (De Andrade et al., 2006; Lanari et al., 2014a) offer new opportunities to study low-grade metapelites with high-variance assemblages and to estimate local P - T conditions of crystallization.

The Lavrion peninsula, South East of Athens, is located along the western boundary of the Attic-Cycladic metamorphic complex in the internal zone of the Hellenic orogenic belt, between the Pelagonian fault, corresponding to a thrust and potentially to a syn-orogenic detachment, and low-angle post-orogenic detachments such as the West Aegean Detachment System (Grasemann et al., 2012) and the North Cycladic Detachment System (Jolivet et al., 2010b) (Fig. 1). The Lavrion area is thus a perfect target to decipher the tectonic evolution of the Hellenic orogenic belt. The goals of this study are (i) to identify the different structures of the Lavrion area, (ii) to link them to the microstructures and (iii) to calculate local P - T conditions of crystallization of the mineral assemblages according to their microstructural and microtextural positions. These results provide new data to elaborate a model for the tectonic evolution of the Hellenides from tectonic accretion to gravitational collapse.

2. Geology of the Lavrion peninsula

The Lavrion peninsula is located at 80 km to the South-East of Athens along the western boundary of the Attic-Cycladic metamorphic complex (Fig. 1). This area is characterized by a stack of polyphased metamorphic nappes composed, from top to bottom, of (i) an upper non metamorphic unit, (ii) a middle unit dominated by the Lavrion schists, and (iii) a basal unit

dominated by marbles alternating with the Kamariza schists, considered as para-autochthonous.

The upper unit is composed of serpentinites, red cherts and upper Cretaceous limestones. This non-metamorphic unit is interpreted as an ophiolitic melange with calcareous remnants thrust over the middle unit and thus considered as part of the Pelagonian nappe (Photiades and Carras, 2001). Considering the contact between upper and the middle units as a thrust is consistent with the present-day ocean over continent structural relationship. However, if one considers the juxtaposition of a non-metamorphic unit to an underlying metamorphic unit, this implies that this contact has accommodated exhumation as already proposed for the contacts located below the other remnants of the Pelagonian nappe in the Cyclades (Jolivet et al., 2010b; Grasemann et al., 2012). This point will be further considered in the general discussion regarding the tectonic evolution of the Hellenic orogenic belt.

The middle unit, also designated as the phyllite nappe or the Lavrion blueschist tectonic unit, is composed of a 100 to 250 m thick alternation of the Lavrion schists, including bands of metavolcanites, and marbles (Fig. 2). This nappe locally includes meta-ophiolites (serpentinites and metabasalts containing glaucophane with preserved pillows shape) that are capping topographic highs (Photiades and Carras, 2001). The schists and their metavolcanites are rich in muscovite, quartz, albite, chlorite, glaucophane, calcite and epidote depicting a blueschist facies metamorphic assemblage weakly retrogressed under greenschist facies conditions (Fig. 2a, b) (Photiades and Carras, 2001). In Lavrion area, metamorphic conditions of 7.0 – 7.5 kbar and 300 – 340 °C have been estimated by Baltatzis (1996) using sodic amphibole assemblage in prasinite. In the same area, pressure peak conditions of 9 – 11 kbar and 370 °C, and retrograde conditions of 6 kbar and 280 °C were derived from

thermodynamic modeling (Pseudosections) on metabasites and phyllites (Baziotis et al., 2009). The peak assemblage reported in metabasite boudins is marked by epidote, glaucophane, garnet and omphacite. At the scale of the Cyclades, the *HP/LT* metamorphism recorded by the Cycladic blueschists has yielded an Eocene age (50 – 40 Ma) and a variety of *P-T* conditions, ranging from a pressure of 12 to 22 kbars for a temperature of 450 to 550 °C (eg. Alther et al., 1982; Buick and Holland, 1989; Bröcker et al., 1993; Avigad, 1998; Trotet et al., 2001; Parra et al., 2002; Bröcker and Franz, 2005; Duchêne et al., 2006; Groppo et al., 2009). Most metabasites and metavolcanics from the middle unit of the nappe stack exposed in the Lavrion peninsula show a geochemical signature typical of MORB composition (mainly E-MORB, rarely N-MORB) but some display a calc-alkaline affinity (Photiades and Saccani, 2006). These features are consistent with a geodynamic evolution encompassing a Triassic continental rift followed by the opening of the Pindos ocean along the southern margin of the Pelagonian continent. Metabasites from the Lavrion schists also display a geochemical signature comparable to rift-related mildly alkaline basalts and an N-MORB signature and are interpreted as being generated and emplaced along an oceanic spreading center, or in an evolved back-arc basin (Baziotis and Mposkos, 2011). In contrast, Baltatzis (1996) describes LILE-enriched calc-alkaline metabasic rocks and suggests an island-arc environment. In any case, these meta-sedimentary and metavolcanics sequences were deposited on the top of the Pindos Ocean, or along a thinned continental margin.

The basal unit is composed of two marble layers separated by a schist-dominated layer up to 200 m thick designated as the Kamariza schists (Photiades and Carras, 2001). The schists are rich in muscovite, quartz, albite, calcite and chlorite with granoblastic to lepidoblastic texture. (Fig. 2c). The lower marble has a thickness reaching 300 – 350 m whereas the upper marble is mylonitic and displays a heterogeneous thickness ranging from 150 m to a few meters

(Photiades and Carras, 2001). A Triassic to lower Jurassic age has been attributed to these two marble layers on the basis of their fossils (Cordellas, 1878; Negris, 1915-19; Kober, 1929; Petrascheck and Marinos, 1953; Katsikatsos, 1977). Accordingly, these two marble layers might represent a single stratigraphic horizon repeated by an isoclinal fold (Photiades and Carras, 2001; Morin and Photiades, 2012). Previous petrological studies document a *P-T* path characterized firstly by a blueschist metamorphic stage (9 – 11 kbar, ca. 370 °C) (Baziotis et al., 2009) followed by a greenschist facies stage with *P-T* conditions ranging from 4.0 – 4.5 kbar, 340 – 360 °C (Baltatzis, 1996) to 5 – 6 kbar, up to 450 °C (Baziotis et al., 2006). This retrograde path is in line with a regional metamorphic gradient ranging from greenschist to amphibolites facies at the scale of the Cyclades, dated at ca. 25 Ma (Andriessen et al., 1979; Alther et al., 1982; Ring et al., 2001; Ring and Reischmann, 2002; Duchêne et al., 2006). Metavolcanics from the basal unit attributed to the Trias (Fig. 2d) have a calc-alkaline affinity consistent with an emplacement in a magmatic arc environment associated with the opening of a back-arc basin (Photiades and Saccani, 2006).

The contact between the basal unit and the middle unit has been described either as a thrust (Marinos and Petrascheck, 1956; Photiades and Carras, 2001), or alternatively as a low-angle detachment fault (Skarpeilis, 2007; Liati et al., 2009; Lekkas et al., 2011; Berger et al., 2013). Lekkas et al. (2011) proposed that this low-angle fault accommodated Miocene post-orogenic exhumation coeval with the emplacement of the Plaka granodioritic pluton (Pe-Piper and Piper, 2002; Stouraiti et al., 2010). Aeromagnetic data suggest that the Plaka pluton represents the exposed part of a larger batholith that might be present at depth throughout the Lavrion peninsula (Marinos and Makris, 1975; Tsokas et al., 1998). The crystallization of the granodiorite has been dated at 8.34 +/- 0.2 Ma by U/Pb on zircon (Liati et al., 2009). Relative rapid cooling of the pluton from about 350 to ca. 100 °C is constrained by K-Ar ages of 9.3 to

8.3 Ma on biotite (Marinos, 1971; Altherr et al., 1982), of 9.4 ± 0.3 Ma on K-feldspar (Tsikouras et al., 2006; Skarpelis et al., 2008), and by a 7.3 Ma apatite fission track age (Altherr et al., 1982). The emplacement of this large batholith is potentially responsible for the genesis and circulation of metal-rich fluids that could have played a major role in the deposition of mineralization in the Lavrion peninsula (Skarpelis 2002; Voudouris et al., 2008a, b; Skarpelis and Argyraki, 2009; Bonsall et al., 2011).

3. Methodology

We use a multi-method approach combining field investigations, structural, microstructural and microtextural analysis, and quantitative petrology including compositional quantitative micro-mapping and thermodynamic inverse modeling. The methods used are introduced in the following sections.

3.1 Field mapping and sampling strategy

On the field, foliation planes, stretching and mineral lineations, fold axes and faults have been systematically measured in order to document the kinematics of the main tectonic contacts as well as the internal structure of tectonic units separated by shear zones. Stretching lineations and fold axes measurements are given in trend/plunge convention, and planes in strike/dip direction following the right hand rule convention. The main lithologies have been sampled on either side of tectonic contacts in order to conduct metamorphic petrology and microtextural and microstructural analysis.

3.2 Textural and chemical analysis

Microscopic observations of the metamorphic assemblages of both Lavrion and Kamariza schists have been performed by Scanning Electron Microscopy and Electron Probe Micro-Analyzer (EPMA) at the CRPG and GeoRessources laboratories in Nancy, France. Representative samples were selected according to the occurrence of superimposed structures containing K-white mica and chlorite in order to perform further investigations by combining chemical micro-mapping and thermodynamic modeling.

3.3 Quantitative micro-mapping

In the selected samples LAV11 003b (Lavrion schists) and LAV11 020b (Kamariza schists), chlorite and K-white mica grains display complex zoning that is, at first order, correlated with their microtextural position. Compositional maps are required to capture the chemical variability of such phases at least in 2-dimensions and to establish the link between chemical variations and the observed microtextures. X-ray maps, routinely acquired using EPMA, are matrix of X-ray intensities that correspond to the number of counts recorded by the wavelength dispersive spectrometers for each pixel of the image. These semi-quantitative maps are standardized using spot analyzes as internal standards (see detailed presentation of the method in De Andrade et al., 2006) in order to generate compositional maps in oxide weight percentages.

EPMA analyzes were performed at the Institute of Geological Sciences at University of Bern, Switzerland, using a JEOL JXA 8200 instrument. Conventional spot analyzes were measured using 15 KeV accelerating voltage, 10 nA specimen current and 40 s counting time (including 2×10 s of background measurement). Standards used were wollastonite and orthose (Si for chl

and K-white mica respectively), phlogopite (K), forsterite (Mg), ilmenite (Fe in K-white mica, Ti) and almandine (Fe in chl), anorthite (Ca), spinel (Al), tephroite (Mn), albite (Na). X-ray maps were measured using 15 KeV accelerating voltage, 100 nA specimen current and 150 ms counting time per grid point.

The LS-XM map corresponding to the sample LAV11 003b (Lavrion schists) is 560×600 pixels size with a pixel width of $2 \mu\text{m}$, corresponding to an investigated area of $1120 \times 1200 \mu\text{m}$. The total acquisition time was about 31 h. The KS-XM map corresponding to the sample LAV11 020b (Kamariza schists) is 500×300 pixels size with a pixel width of $2 \mu\text{m}$, corresponding to an investigated area of $1000 \times 600 \mu\text{m}$. The total acquisition time was about 17 h.

The program XMAPTOOLS 1.6.5 (Lanari et al., 2014a) has been used for the processing that includes (i) classification (method: normalized), (ii) analytical standardization (method: auto [median approach]), (iii) structural formulae calculation (on a basis of 11 and 14 atoms of oxygen for K-white mica and chlorite respectively) and (iv) distinction of chemical groups using the tools CHEM2D and TriPLOT3D provided with XMAPTOOLS. The quality of the standardization of X-ray maps was tested: the compositions of the spot analyzes were plotted against the compositions of the corresponding pixels on the standardized maps. The compositional variability recorded by the spot analyzes is well reproduced by the compositions of the standardized maps within analytical uncertainties excepted for MnO in phengite ($0 - 0.08 \text{ wt\%}$) and CaO in chlorite ($0 - 0.05 \text{ wt\%}$). In both cases, the small variations in compositions are not recorded by the maps suggesting that Ca and Mn in chlorite and K-white mica are below detection limits for the mapping conditions used in this study.

Both LS-XM and KS-XM X-rays maps allow identifying a significant range of compositional heterogeneities in K-white mica and chlorite minerals. The compositions of the pixels of K-white mica and chlorite minerals were plotted respectively into ternary diagrams: (i) muscovite, celadonite, pyrophyllite and (ii) amesite, clinocllore + daphnite, sudoite using the modules TRIPLOT3D available in XMAPTOOLS (see Fig. 5 in Lanari et al., 2014a). The selected pixels are displayed into a map with distinct colors according to their group (light blue, blue and green for K-white mica and yellow and red for chlorite). The chemical subdivision into distinct groups is based on chemistry, but must be relevant from a microtextural and microstructural position point of view.

3.4 Thermodynamic inverse modeling

Chlorite minerals are ubiquitous in low-grade metamorphic rocks (Vidal et al., 2001). Changes in pressure, temperature, and in bulk rock composition during chlorite crystallization are responsible for a wide composition range which is mainly generated by three main substitutions (i) $\text{Fe}^{2+} = \text{Mg}^{2+}$, (ii) Tschermak, $\text{Si}, (\text{Mg}^{2+}, \text{Fe}^{2+}) = \text{Al}^{\text{IV}}, \text{Al}^{\text{VI}}$ (iii) di-trioctahedral $(\text{Mg}^{2+}, \text{Fe}^{2+})_3 = \square \text{Al}_2$ (Cathelineau and Nieva, 1985; Lanari et al., 2014b). The crystallization temperature of chlorite may be estimated using the approaches of Vidal et al., (2005; 2006) or Tarantola et al. (2009) based on the convergence of two independent equilibrium for varying $X\text{Fe}^{3+}_{\text{chl}} = \text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ (detailed procedure in Lanari et al., 2012). Temperature and $X\text{Fe}^{3+}$ are simultaneously estimated at a given pressure and a fixed water activity equal to 1. Convergence is considered to be achieved when the temperature difference between the two equilibria is less than 30 °C.

Following a similar strategy, pressure conditions have been derived from K-white mica (detailed procedure in Lanari et al., 2012). The equilibrium conditions of the quartz + water + K-white mica assemblage is represented by a divariant line in P - T space along which only the amount of water (n_{H_2O} in pfu) in the interlayer site content varies (Dubacq et al., 2010). Pressure and n_{H_2O} have been simultaneously estimated at a given temperature and a fixed water activity of 1. Computations were made using the program CHLMICA_{EQUI} v 1.5H (Lanari, 2012).

4. Results

4.1 Structural analysis of the Lavrion area along the western boundary of the Attic-Cycladic metamorphic complex

The metamorphic nappes exposed in the Lavrion peninsula (Fig. 3a) display a regional scale foliation underlined by the alternations of marble and schists layers with shallow-dipping contacts which led some authors to consider these alternations as a stratigraphic sequence (Photiades and Carras, 2001). However, a detailed structural investigation reveals that the foliation is composite and reflects a succession of transpositions associated with shearing and folding (Fig. 4)

At the panoramic scale, folds are delineated by the morphological contrast between schists and marbles. The western side of the Lavrion peninsula (Fig. 5a, b) exposes the middle unit, above the low-angle detachment, characterized by alternations of marble and the Lavrion schists underlining kilometer-scale isoclinal recumbent folds. Steep-dipping schistosity planes

and fold axial planes related to the development of the $S_{0/1-2}$ foliation are preserved along the southern part of the panoramic view (Fig. 5a, b).

In contrast, the northern part of the panorama shows the transposition of the foliation into the relatively shallow-dipping S_3 schistosity associated with boudinage of marble layers (northern part in Fig. 5a, b). This transposition into the S_3 schistosity is all the more expressed in the basal unit mainly composed of alternations of marble and the Kamariza schists representative of a lower structural level below the low-angle detachment that shapes the landscape (Fig. 5c, d).

Folds, schistosities and lineations

These structures observed at the regional scale are also identified at the outcrop and mineral scales. The oldest preserved schistosity, designated as S_1 , is relatively steeply dipping and is in an axial planar position of F_1 isoclinal folds. These F_1 folds are refolded by asymmetric F_2 folds associated with the development of an S_2 axial planar schistosity, resulting in hook-shape interferences patterns (Fig. 6a, b, c, d). The S_2 schistosity is also relatively steeply dipping. S_1 and S_2 are the dominant structures in the middle unit but they are also locally preserved in the basal unit (Fig. 6c, d, e, f, g, h).

S_1 and S_2 are transposed into a shallow-dipping S_3 schistosity associated with F_3 symmetric folds (Fig. 6c, d, e, f, g, h). Transposition is gradually more intense from the middle to the basal unit where the S_3 schistosity is the dominant structure. Nevertheless, F_1/F_2 interferences are locally preserved in more competent lithologic layers such as dolomitic marbles of the basal unit. In the middle unit, F_1 and F_2 fold axes display a disharmonic distribution, with a shallow to steep plunge in all directions but with a weakly defined maximum of fold axes at

N023/23 (5.5 % of the axes). F_3 fold axes measured in the basal unit below the detachment show a more homogeneous distribution with a dominant N-S trend and a shallow plunge (N180/13 representing 11.5 % of the fold axes). Dispersions of data around this mean pole are interpreted as relics of partially transposed F_1 and F_2 fold axes with orientations similar to the ones displayed by fold axes in the middle unit (Fig. 3b).

The development of the transposition mylonitic fabric below the detachment is also marked by the transposition of the L_1 and L_2 mineral/stretching lineations into a L_3 lineation along a NNE-SSW direction (Fig. 3b). Above the detachment, the middle unit shows relics of an L_1 and L_2 stretching lineations with an E-W direction related to the development of the S_1 and S_2 schistosity. The transposition into the S_3 schistosity is associated with rotation of the L_2 stretching lineation along a NNE-SSW direction typifying the L_3 lineation (Fig. 3b).

Dolomitic layers, included into the heterogeneous marbles, are stretched in the direction parallel and perpendicular to the lineation indicating a strain ellipsoid intermediate between plane strain and flattening. In the direction parallel to the lineation, the sigmoid-shape of dolomitic boudins is consistent with a dominant top-to-the-SSW sense of shear (Fig. 7a, c) although top-to-the-NNE sense of shear have been locally observed (Fig. 7b). There are no obvious cross-cutting relationships between these kinematic criteria suggesting that they are contemporaneous and indicating that the deformation regime is intermediate between coaxial and non-coaxial.

Low-angle mylonitic to cataclastic detachment

The contact between the basal and the middle unit is marked by a mylonitic to cataclastic marble layer underlined by a distinct morphological surface (Fig. 5c, d). The strike and dip of

the detachment, estimated from its map-scale geometry, defines a broad antiformal structure. On the eastern side of the peninsula, the mean orientation of the detachment fault is N050/04, while in the central part of the peninsula, the detachment fault is oriented N180/04. The structural position of this detachment fault was identified at Porto Ennia by Berger et al. (2013) where the mylonitic marble appears totally transposed and thinned.

This transition between the main units is marked by the presence of cataclastic zones crosscutting the mylonitic fabric of the marble. The cataclastic zones (Fig. 7c, d) are associated with numerous iron- and carbonate-veins crosscutting the mylonitic fabric. Just below the detachment, cataclastic shear zones are delineated by a yellow-brown to reddish color, which suggests that fracturing of the marble was coeval with pervasive circulation of an iron-rich fluid. In the previous work of Photiades and Carras (2001), this zone of hydrothermal alteration was interpreted as a transgressive calcareous formation.

Many faults crosscutting and offsetting marble and schists contacts of the middle unit have been identified on satellite images (available in Google Earth[®]). These faults do not appear to continue into the basal unit and are thus interpreted to be rooting into the detachment fault (Figs. 3a and 4). These faults are mainly striking WNW-ESE, consistent with a NNE-SSW direction of extension, as also suggested by orientation of the L_3 stretching lineation.

4.2 Relationship between microstructures, microtextures, metamorphic petrology and thermobarometry

Microtexture, texture and mineral paragenesis in schists of the middle and the basal units

Lavrion schists of the middle unit

The granolepidoblastic Lavrion schists (Sample LAV11 003b) is mainly composed of an assemblage of recrystallized quartz and albite with some occurrences of phyllosilicate-rich layers. Phyllosilicate layers delineate the steep-dipping S_1 and S_2 schistosity identified at outcrop-scale. The S_1 schistosity is characterized by the assemblage quartz, albite, K-white mica, chlorite, calcite, apatite, magnetite, rutile, $\pm$ pyrrhotite, zircon and tourmaline. The S_1 schistosity is folded by F_2 isoclinal folds with a S_2 schistosity in an axial planar position characterized by the assemblage K-white mica, chlorite, quartz, calcite $\pm$ apatite (Fig. 8a).

Kamariza schists of the basal unit

The Kamariza schists (sample LAV11 020b) shows a porphyroblastic texture with the presence of albite porphyroclasts and recrystallized quartz layers alternating with phyllosilicate-rich layers. Alternations of K-white mica and chlorite underline two different superimposed fabrics (Fig. 8b). Relics of a steep-dipping schistosity, attributed to S_2 , are preserved in microlithons. S_2 is folded and transposed into a S_3 shallowly dipping schistosity. S_2 is characterized by K-white mica, chlorite, quartz, albite, calcite, magnetite, rutile, apatite $\pm$ zircon, allopahane, rhabdophane-(Ce), asbolane and tourmaline. Albite porphyroclasts are wrapped into the S_3 schistosity and include K-white mica, chlorite, calcite, allopahane, and asbolane that underline the S_2 schistosity. S_3 is underlined by chlorite and K-white mica in association with quartz, calcite, magnetite, rutile $\pm$ apatite, and rhabdophane-(Ce).

In both units, late brittle deformation is evidenced by the presence of calcite and quartz veins which crosscut all the previous structures.

Chemical compositions of K-white mica and chlorite

Lavrion schists of the middle unit

The composition of chlorite minerals is centered between Fe-amesite + Mg-amesite and daphnite + clinochlore end-members (Fig. 9a). The population of chlorite is subdivided in (i) a subgroup closer to the daphnite + clinochlore end-members (LS-Chl1 in red pixels) defined by low XMg ($\text{XMg} = \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$) comprised between 0.46 to 0.48 and (ii) a subgroup closer to the amesite end-member (LS-Chl2 in yellow pixels) characterized by a higher XMg ranging between 0.48 and 0.51.

The chemical composition of K-white mica is centered along the muscovite-celadonite joint (Fig. 9a). Data spreading toward the celadonite-pyrophyllite joint correspond to analytical points straddling the boundary with other minerals and are thus considered as irrelevant. The core of K-white mica porphyroclasts display a distinct muscovite-rich composition, defining a first chemical group (LS-KWM1 in green pixels) characterized by a low Si content ($\text{Si} < 3.20$ per formula unit (pfu)) and a low Mg content ($\text{Mg} < 0.20$ pfu). K-white mica rimming muscovite porphyroclasts display a rather homogeneous phengite composition but a detailed investigation allows the distinction of two subgroups, defined as LS-KWM2 and LS-KWM3. The inner rims surrounding muscovite porphyroblasts tend to have a celadonite-rich chemical composition, marked by high Si and Mg contents (respectively > 3.50 pfu and > 0.30 pfu), which corresponds to the LS-KWM2 (in light blue pixels) chemical subgroup. Locally,

phengite neoblasts of the LS-KWM2 chemical subgroup underlining the schistosity are folded and partly recrystallized into phengite neoblasts defining the LS-KWM3 chemical subgroup in dark blue, with a chemical composition characterized by a slightly lower Si-content (close to 3.40 pfu) and Mg content (comprised between 0.25 and 0.30 pfu).

Kamariza schists of the basal unit

Chlorite compositions are centered in between the amesite and clinocllore + daphnite end-members (Fig. 9b). A first chlorite subgroup (KS-Chl1 in yellow pixels), trending toward the clinocllore-daphnite is marked by high XMg ranging between 0.59 and 0.65. This chemical composition is preserved in microlithons and in the core of chlorite porphyroclasts, in textural equilibrium with the core of K-white mica porphyroclasts (KS-KWM1 subgroup).

Rims of chlorite porphyroclasts and chlorite neoblasts underlining a shallow-dipping schistosity (KS-Chl2 in red pixels) are characterized by lower XMg ranging between 0.59 and 0.54 and trend toward amesite composition. These chlorite crystals are in textural equilibrium with phengite neoblasts and rims (KS-KWM2 subgroup) surrounding phengite porphyroclasts.

Chemical composition of K-white micas forms an elliptical spread between the celadonite and muscovite end-members (Fig. 9b). Cores of K-white mica porphyroclasts, preserved in microlithons (KS-KWM1 subgroup in light blue pixels), display a distinct celadonite-rich composition characterized by a high Si-content (> 3.49 pfu) and a high Mg content (> 0.30 pfu). The rims of K-white mica porphyroclasts and K-white mica neoblasts underlining a shallow-dipping schistosity (KS-KWM2 subgroup in dark blue pixels) show a composition

trending toward muscovite characterized by Si content ranging between 3.25 to 3.35 pfu and a relatively low Mg content (<0.26 pfu).

Five representative analyzes of each chemical group, exported from the Lavrion and the Kamariza schists chemical maps, are respectively reported in Table. 1 and Table. 2.

Thermobarometry

In order to investigate the local equilibria described in the previous section a thermodynamic inverse modeling technique was used, with the specific compositions of each chemical group.

Lavrion schists of the middle unit

Chlorite with a composition closer to the daphnite-chlinocllore end-member (LS-CHL1 subgroup) yields a temperature of 325 ± 28 °C and chlorite closer to the amesite end-member (LS-CHL2 subgroup) yields a slightly lower temperature of 300 ± 35 °C (Fig. 10a). This difference of temperature is not significant and these chlorite can also be considered as part of a single group characterized by a mean crystallization temperature of 311 ± 34 °C.

Thermodynamic modeling using K-white mica compositions determined for the Lavrion schists yields three sets of divariant curves, two of which being relatively close to each other.

According to the textural relationships observed on X-ray maps, chlorite grains do not show textures of local equilibrium with the muscovite-rich core of white mica porphyroclasts (LS-KWM1 subgroup). Accordingly, we cannot use the temperature estimates based on chlorite +

quartz + water equilibria to determine the P - T conditions recorded by these muscovite-rich cores. Phengite + quartz + H₂O equilibrium curves of (LS-KWM1) subgroups indicate that the muscovite-rich core of these porphyroclasts crystallized at a relatively low pressure. For example, a temperature of 330 °C corresponds to a pressure lower than 4 kbar (Fig. 10b).

In contrast phengite rimming porphyroclasts and present as neoblasts underlining the schistosity (subgroups LS-KWM2 and LS-KWM3) are locally in textural equilibrium with chlorite. Using the mean temperature of $311 \pm 34^\circ\text{C}$ obtained by chlorite thermometry allows estimating the corresponding pressure range for each group of phengite. The estimated pressure conditions range from 9 to 13 kbar for the phengite forming the inner rims around porphyroclasts (LS-KWM2 subgroup) and 6 to 9 kbar for the phengite neoblasts underlining the schistosity (LS-KWM3 subgroup) (Fig. 10b).

Kamariza schists of the basal unit

Cores of chlorite porphyroclasts (KS-Chl1 subgroup) yield a temperature of $298 \pm 38^\circ\text{C}$, whereas chlorite porphyroclasts rims and neoblasts (KS-Chl2 subgroup) underlining a new schistosity yield a higher temperature of $345 \pm 40^\circ\text{C}$ (Fig. 10c).

Phengite + Quartz + H₂O thermodynamic modeling for the phengite porphyroclasts and the neoblasts yields two distinct sets of divariant lines in the P - T diagram (Fig. 10d). As the chlorite KS-Chl1 are locally in textural equilibrium with the phengite KS-KWM1, the average temperature of the chlorite + quartz + H₂O equilibria is used with the phengite + quartz + H₂O equilibria to constrain the pressure conditions. The temperature of $298 \pm 38^\circ\text{C}$ obtained on chlorite porphyroclasts implies a pressure comprised between 8 and 11 kbar for phengite

porphyroclasts (KS-KWM1 subgroup). In turn, the temperature of chlorite neoblasts of 345 ± 40 °C implies a significantly lower pressure comprised between 5 and 8.5 kbar.

These P - T estimates obtained from local equilibrium are used to calculate and construct composite temperature maps for chlorite and pressure maps for K-white micas. These maps are used to illustrate the mosaic of P - T conditions formation archived by the rock at the thin section scale (Fig. 11).

5. Discussion

Field mapping, structural, microstructural, microtextural, and petrological data reported in this paper show that the Lavrion area has been affected by three main deformation/metamorphic stages associated with isoclinal folding, boudinage and schistosity development. Local P - T conditions preserved by the phyllosilicates are determined for these three different stages recorded in the Lavrion schists above the low-angle detachment and in the underlying Kamariza schists using a combination of microstructural and microtextural analyzes, detailed chemical analyzes, and thermodynamic modeling. These data serve as a basis to discuss the thermal-mechanical evolution of the Hellenic orogenic belt from its construction to its collapse integrated in the Cenozoic geodynamic context of the Eastern Mediterranean.

5.1 P - T - D paths of the Lavrion area

Above the low-angle detachment, the Lavrion schists from the middle unit comprise K-white mica porphyroclasts with muscovite-rich cores (LS-KWM1) implying crystallization at relatively low-pressure (below 4 kbar for a temperature arbitrarily fixed at 330 °C). These

porphyroclasts could either represent porphyroblasts of an alpine pre-S₁ metamorphism or detrital grains originating from the erosion of Variscan basement (Fig 11a-b). Muscovite porphyroclasts have been described in orthogneisses and phyllites exposed in Ios Island, and in the northwest Aegean and in the Rhodope Massif, and yield Variscan ages by argon thermochronology (Baldwin and Lister, 1998; Lips et al., 1998, 2000). Distinguishing between these two models would require dating of the muscovite-rich core by ³⁹Ar/⁴⁰Ar. These muscovite porphyroclasts are wrapped in phengite and chlorite neoblasts underlining the steep-dipping schistosity identified from the thin section to the regional scale in the Lavrion schists of the middle unit (Fig. 11a-b).

The steep-dipping S₁ and S₂ schistositities identified in the Lavrion schists of the middle unit, and in the Kamariza schists of the basal unit are interpreted as the succession of burial and syn-orogenic exhumation, defined as D₁M₁ and D₂M₂. In the Lavrion schists, chlorite neoblasts (LS-Chl1 and LS-Chl2) are chemically rather heterogeneous and do not present any particular textural distribution relative to phengite neoblasts, underlining the S₁ and S₂ schistositities. Accordingly, chlorite seems to have crystallized in a continuous way from 325 ± 28 °C to 300 ± 35 °C, yielding a mean temperature of 311 ± 34 °C. The spread in chemical composition of phengite neoblasts yields also a relatively large pressure range from 6 to 13 kbar. Phengite neoblasts with a celadonite-rich composition (LS-KWM2), yielding the highest pressure, tend to be localized in the inner rim surrounding muscovite porphyroclasts, and to underline the S₁ schistosity, whereas the S₂ schistosity tends to be underlined by phengite neoblasts (LS-KWM3) yielding the lowest pressure (Figs. 9a and 11a-b).

At a lower structural level, in the Kamariza schists below the low-angle detachment, the steep-dipping S₁ and S₂ schistositities associated with F₁/F₂ hook-type fold interferences are

locally preserved. At the thin section scale, S_1 and S_2 relics in microlithons yield a pressure of 8 to 11 kbar for a temperature of 298 ± 38 °C which is similar within error range to the P - T conditions recorded in the Lavrion schists at higher structural level.

Transposition of the S_1 and S_2 schistosity into a shallow-dipping S_3 schistosity yielding a slightly lower pressure of 5 to 8.5 kbar for a significantly higher temperature of 345 ± 40 °C is interpreted to represent lateral flow and post-orogenic exhumation after thermal relaxation of the nappe pile and is defined as the D_3M_3 stage (Figs. 9b and 11c-d). Transposition and retrogression are preferentially expressed in the basal unit.

Previously reported high pressure peak conditions for the Lavrion area in the blueschist facies conditions (9 – 11 kbar), attributed to the prograde path (Baziotis et al., 2009), are consistent with the D_1M_1 conditions that we estimate for the Lavrion schists (LS-KWM2).

The retrograde path associated with D_3M_3 , and characterized by an increase in temperature coeval with decompression in the greenschist facies conditions described here (5 to 8.5 kbar and 345 ± 40 °C) is consistent with P - T conditions presented by previous authors (4 – 6 kbar, 340 – 450 °C according to Baltatzis, 1996; Baziotis et al., 2006). The higher temperature estimated by previous authors for the prograde path (9 – 11 kbar, 370 °C according to Baziotis et al., 2009; 7.0 – 7.5 kbar, 300 – 340 °C, after Baltatzis, 1996) compared to the one obtained in the present study (311 ± 34 °C) could either reflect a difference in the structural position of samples and/or a difference in the re-equilibration of the minerals during the retrograde path associated with D_3 and marked by an increase in temperature, and/or the proximity with granodiorite plutons.

At the scale of the Attic-Cycladic complex, the succession of an M_1 Eocene (50 - 40 Ma) HP/LT metamorphic gradient and an M_2 Oligocene-Miocene (30 to 20 Ma) MP/MT

metamorphic gradient has also been described in the Cycladic blueschist unit (Jansen and Schuiling, 1976; Andriessen et al., 1979; Alther et al., 1982; Bonneau and Kienast, 1982; Buick and Holland, 1989; Avigad and Garfunkel, 1991; Bröcker et al., 1993; Ring et al., 2001; Parra et al., 2002; Ring and Reischmann, 2002; Forster and Lister, 2004; Duchêne et al., 2006; Baziotis et al., 2009). The peak P - T conditions recorded in the Cyclades islands, Crete and Peloponnese around 18 – 22 kbar and 500 – 550 °C (Jolivet et al., 1996; Trotet, 2000; Trotet et al., 2001, 2006; Parra et al., 2002; Groppo et al., 2009; Jolivet et al., 2010a; Fig. 12a) are higher than those measured in this study. All of these P - T conditions nevertheless align along the same geothermal gradient of ca. 10 °C/km. The lower peak P - T conditions obtained in the Lavrion peninsula suggest that this part of the nappe stack has not been buried as deep as its lateral equivalents in the Cyclades. First, this potentially reflects the fact that, in the Lavrion peninsula, directly below the Pelagonian non-metamorphic unit, only the top part of the HP/LT nappes is exposed. Moreover, this contrast in peak P - T conditions could attest for the relative impact of slab retreat on burial and exhumation of nappes. Indeed, the Lavrion peninsula is located along the edge of the Attic-Cycladic complex, in a region that has not been tectonically affected as much by slab retreat as the Aegean domain. In any case, the HP peak is always followed by a first stage of exhumation associated to a progressive decrease in pressure. For part of the nappes, this decompression is isothermal or associated with a slight decrease in temperature, as observed into the Lavrion schist and in most of the Cycladic Blueschist unit. In contrast, other parts of the nappes record an increase in temperature after some isothermal decompression, as shown in this paper for the Kamariza schists of the basal unit and also in Tinos island (Parra et al., 2002) and in Naxos island (Duchêne et al., 2006). The meaning of this succession of contrasted metamorphic gradients has been debated. Some authors invoked a heat input related to the emplacement of granodioritic plutons (Lister et al., 1984) or to the pulsative circulation of fluids (Forster and

Lister, 2005). Other authors favored the succession of syn-orogenic exhumation in a subduction channel followed by thermal relaxation and post-orogenic exhumation (Parra et al., 2002; Vanderhaeghe et al., 2007; Jolivet and Brun, 2010). It is to note that these heat sources are not mutually exclusives. Based on the results presented in the present study, we concur to the interpretation of the P - T conditions as recording a succession of (i) a first phase of tectonic accretion by syn-orogenic exhumation of subducted units without thermal relaxation and (ii) a second phase of post-orogenic exhumation following thermal relaxation of the previously thickened crust (Fig. 12b). The increase in temperature coeval with decompression and thus exhumation could result from the combined effects of (i) thermal relaxation of the thickened orogenic crust, (ii) increase in the mantle heat flux caused by slab retreat, and (iii) advection of heat associated with the emplacement of syn-tectonic magmas.

The originality of the present study comes from the identification of microstructural and microtextural position of the mineral assemblages depicting the metamorphic evolution and the integration of these structures from the thin section to the regional scales leading the identification of distinct deformation-metamorphic (D_nM_n) stages. This leads to the identification of a transposition gradient increasing with structural level. The HP/LT steep-dipping $S_{0/1-2}$ foliation and the E-W trending L_{1-2} lineation are best preserved in the middle unit above the low-angle detachment. In contrast, the basal unit, below the low-angle detachment, preserves relics of the steep-dipping foliation but is dominated by a shallow-dipping D_3 mylonitic fabric delineated by minerals indicating a lower pressure and a higher temperature.

Increasing D_3 transposition with structural level is moreover evidenced by the progressive rotation of the E-W stretching lineation of the Lavrion schists into a NNE-SSW direction at

lower structural level. The extreme expression of this transposition is the mylonitic to cataclastic low-angle detachment that records the transition from ductile to brittle deformation. This transition is dated at ca. 9 Ma by the emplacement of a syn-tectonic granodioritic pluton in the Miocene (Marinos, 1971; Altherr et al., 1982; Tsikouras et al., 2006; Skarpelis et al., 2008; Liati et al., 2009). In the Cyclades, most shear zones attributed to post-orogenic exhumation are associated with N-S to NE-SW stretching lineations and with top-to-the-N, or NE senses of shear (Buick, 1991a, b; Faure et al., 1991; Lee and Lister, 1992; Gautier et al., 1993; Gautier and Brun, 1994a, b; Jolivet and Patriat, 1999; Vanderhaeghe, 2004; Kruckenberg et al., 2011). In contrast, in the western part of the Cyclades (Kea, Kythnos, and Serifos islands and the Lavrion peninsula) previously described kinematic criteria are consistent with a top-to-the-SW sense of shear (Grasemann and Petrakakis, 2007; Brichau et al., 2010; Jolivet et al., 2010b; Grasemann et al., 2012; Berger et al., 2013). The kinematic criteria consistent with dominant top-to-the-SSW suggest that the Lavrion area is affected by deformation under a non-coaxial-dominated regime. Local top-to-the-NNE is consistent with a position at the junction between the divergent NCDS and WCDS detachment systems.

5.2 Thermal-mechanical and tectonic evolution of the Hellenic belt

The succession of D_1 , D_2 , D_3 events associated with a metamorphic gradient changing from *HP/LT* conditions to *MP/MT* and eventually *LP/HT* is typical of Phanerozoic orogens (see review in Vanderhaeghe, 2012 and references therein).

The succession of D_1M_1 and D_2M_2 events under a low-geothermal gradient is attributed to burial and syn-orogenic exhumation in a subduction channel (Agard et al., 2009; Guillot et al.,

2009; Agard et al., 2010). This results in the development of an orogenic wedge by tectonic accretion of *HP/LT* metamorphic rocks that have been successively dragged in subduction with the down going slab and then mechanically decoupled from it.

The transposition of steep-dipping S_1/S_2 schistosity into the shallow-dipping S_3 schistosity marks the transition from tectonic accretion to vertical thinning. This has also been nicely described in the Variscan belt exposed in the Iberian Massif where transposition results in the development of meter to kilometer-scale recumbent folds (Díez Fernández et al., 2013), or in the Montagne Noire (Aerden and Malavielle, 1999). Transposition is associated with the transition to an *MP/MT* metamorphic gradient. These features are interpreted as resulting from gravity-driven flow and post-orogenic exhumation of the thermally relaxed thickened orogenic crust. In this context, the increase in temperature is interpreted to reflect the combined effects of (i) an increased radioactive heat production in the thickened crust, and (ii) an increased basal heat flux caused by asthenospheric upwelling in response to slab retreat (Fig. 13).

The most favorable situation for the development of a high-temperature and gravitationally unstable orogenic belt corresponds to construction of the belt by tectonic accretion of crustal units decoupled from the down going slab in a context of slab retreat (Vanderhaeghe and Duchêne, 2010). Accordingly, for the Hellenides and the Aegean domain, we favor a model whereby the succession of (i) burial, (ii) syn-orogenic exhumation, (iii) thermal relaxation, and (iv) post-orogenic exhumation is directly related to the thermal-mechanical evolution of the orogenic crust along a retreating convergent plate boundary (Vanderhaeghe et al., 2007; Jolivet and Brun, 2010; Jolivet et al., 2013).

It is to note that folding and transposition of *HP/LT* fabrics into *MP/MT* ones is at odds with models proposing the reactivation of thrusts and syn-orogenic detachments by post-orogenic detachments implicitly proposed for the Aegean (Ring and Layer, 2003; Jolivet et al., 2010b;

Jolivet and Brun, 2010; Augier et al., 2015). During the construction phase of the orogenic belt, mechanical decoupling mainly occurs at the basement/cover transition and/or along terrane boundaries indicating that it is mainly lithologically-controlled (Vanderhaeghe and Duchêne, 2010). Thermal relaxation of the thickened crust results in a new rheological layering of the orogenic crust that is mainly thermally-controlled and leads to mechanical decoupling along the brittle/ductile transition and by the generation of a partially molten crust (Vanderhaeghe and Teyssier, 2001; Vanderhaeghe, 2012). Accordingly, decoupling levels that were at play during tectonic accretion are unlikely reactivated during gravitational collapse of the thermally relaxed orogenic crust.

6. Conclusion

Multi-scale structural and petrographical analysis of the metamorphic nappes exposed in the Lavrion peninsula allows us identifying and quantifying the different stages that characterize the thermal-mechanical evolution of the Hellenic orogenic belt from tectonic accretion to gravitational collapse. These different stages are variously recorded in the nappe stack as a function of structural level:

- 1) The Lavrion schists of the middle unit are characterized by a dominantly steeply dipping $S_{0/1-2}$ foliation bearing an E-W stretching L_{1-2} lineation partially transposed into a NNE-SSW direction. This composite foliation includes (i) a S_1 chlorite-phengite assemblage yielding a pressure of 9 – 13 kbar and a temperature of 311 +/- 34 °C, and (ii) a S_2 mineral assemblage associated with lower pressures of 6 to 9 kbar. These features are interpreted to record burial (D_1M_1) of a metasedimentary sequence

dragged with the Hellenic subducting slab, followed by isothermal decompression and syn-orogenic exhumation (D_2M_2) in the subduction channel.

- 2) The Kamariza schists, part of the basal unit juxtaposed to the middle unit along a low-angle mylonitic to cataclastic detachment, are characterized by a shallowly dipping S_3 transposition foliation and a NNE-SSW L_3 stretching lineation. Thermobarometry on relictual chlorite and phengite crystals of the S_2 schistosity, preserved in microlithons, yield a pressure of 8 – 11 kbar for a temperature of 300 °C. These P - T conditions are similar to the ones obtained for M_{1-2} mineral assemblages of the Lavrion schists located in the hanging wall of the detachment. Chlorite-phengite mineral assemblages attributed to the S_3 schistosity indicate a pressure of 5 – 8.5 kbar, lower than the one obtained on the S_2 schistosity, and associated with a significantly higher temperature of about 350 °C. These features are interpreted to accommodate thinning after thermal relaxation of the previously thickened orogenic crust and post-orogenic exhumation (D_3M_3) of its root after thermal relaxation during gravitational collapse.
- 3) Thrusts and syn-orogenic detachments, marked respectively by S_1 and S_2 , aren't reactivated but folded and eventually transposed into a low-angle mylonitic to cataclastic detachment accommodating post-orogenic exhumation of the root of the orogen across the ductile to brittle transition during gravitational collapse (D_3).

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Figures captions

Figure 1. Structural map of the western part of the Attic-Cycladic metamorphic complex (basal and middle units) at the junction between the Hellenic belt and the Aegean domain showing the spatial distribution of overprinted metamorphic facies recorded by the Cycladic Blueschist Unit. The Pelagonian fault is represented as a syn-orogenic high-angle fault accommodating exhumation of the Cycladic Blueschist and is progressively reoriented in a shallow position. The North Cycladic Detachment System (NCDS) and the West Cycladic Detachment System (WCDS) observed in Lavrion area (this study), accommodate post-orogenic exhumation of the Cycladic Blueschist Unit overprinted by greenschist to amphibolite facies metamorphism reaching partial melting as evidenced by migmatites exposed in Paros and Naxos islands. Modified after Jacobshagen (1986); Grasemann et al. (2012) and Augier et al. (2015).

Figure 2. Schematic representation of the nappe stack exposed in the Lavrion area and cross-polarized micro-photographs of selected representative samples of schists and associated metavolcanites from basal and middle units. The Upper unit is dominated by Upper Cretaceous limestones, red cherts and non-metamorphosed serpentines. The middle unit is dominated by Lavrion schists (Fig. 2a) and marbles. The basal unit is composed by Kamariza schists (Fig. 2c) and marble layers. The basal and middle units are juxtaposed along a low-angle mylonitic to cataclastic detachment. The Lavrion schists are affected by blueschist facies metamorphism whereas the Kamariza schists display a pervasive greenschist facies overprint. Mafic metavolcanic rocks are preserved as boudins in the hanging wall (Fig. 2b) and the footwall (Fig. 2d) of the detachment. Bt: biotite, Cal: calcite, Chl: chlorite, Ep: epidote, Gln: glaucophane, Ms: muscovite, Qtz: quartz.

Figure 3a. Geological map of the Lavrion peninsula (modified after Photiades and Carras, 2001). The location of photographs Figures 5 to 7 are indicated on the map. The locations of the Kamariza (LAV11 020b, green square) and the Lavrion (LAV11 003b, blue square) schists sampled for this study and used for *P-T* reconstruction are indicated. **b.** Equal angle Wulff net stereographic projection (lower hemisphere) of schistosity, fold axis, and stretching lineation of the middle unit in blue, and of the basal unit in green. The number of measurements (n) is indicated.

Figure 4. Geological cross sections from the geological map of the Lavrion peninsula (Fig. 3a) oriented W-E (A-A') and SSW-NNE (B-B') showing the relationships and the transposition of structure between the middle unit and the basal unit. The different type of foliation (S_1 , S_2 and S_3), and fold axis (F_2 , F_3) associated to the three main deformation stage are represented.

Figure 5. Panoramic views of either side of the detachment fault (localizations are given in Fig. 3a). **a-b.** Folded schists and marbles layers from the middle unit with steep-dipping schistosity (S_{1-2}) (preserved in the South) progressively transposed into a shallow-dipping schistosity (S_3) (in the North). **c-d.** Schists and marbles layers of the basal unit transposed into the shallow-dipping S_3 schistosity. The middle unit, characterized by S_{1-2} schistosity, is found above the low-angle detachment fault modeling the landscape.

Figure 6. Photographs of typical structures observed at the outcrop scale in the middle unit and in the basal unit (localizations are given in Fig. 3a). **a-b.** F_1 folds folded by asymmetric F_2 folds associated with the development of an S_2 axial planar schistosity into Lavrion schists (37°39'18.01"N; 24°1'24.13"E). **c-d.** Preserved F_1 fold and steep-dipping schistosity (S_2) into within Kamariza schists included in a more competent marble strongly transposed into the S_3 shallow-dipping schistosity (37°43'21.96"N; 24°1'27.96"E). **e.** Lavrion schists characterized by a steep-dipping schistosity S_2 affected by isoclinal F_3 folds with horizontal axial surfaces allowing the transposition into the shallow-dipping schistosity S_3 (37°39'53.71"N; 23°58'57.68"E). **f.** Mylonitic marble mainly characterized by a shallow-dipping schistosity S_3 , with relics of steep-dipping schistosity S_2 (37°44'15.32"N; 24°3'14.46"E). **g-h.** Thin section photographs of the Kamariza schists with S_2 steep-dipping schistosity preserved in microlithons and transposed into shallow-dipping S_3 associated with a top-to-the-NE sense of shear marked by the rotation of albite porphyroclasts (37°41'36.10"N; 24°0'36.23"E). Ab: albite, Cal: calcite, Chl: chlorite, Ms: muscovite, Qtz: quartz.

Figure 7. Photographs of mylonitic to cataclastic marbles underlining the low-angle detachment (localizations are given in Fig. 3a). **a.** Competent boudins of dolomitic marble wrapped into a mylonitic marble strongly affected by S_3 shallow-dipping mylonitic foliation. The sigmoid shape of the dolomitic boudins is consistent with a top-to-the-S sense of shear (37°44'15.32"N; 24°3'14.46"E). **b.** Dolomitic boudins wrapped into a mylonitic marble

strongly affected by S_3 shallow-dipping schistosity showing a top-to-the-N sense of shear (37°43'50.00"N; 24°1'57.93"E). **c.** Cataclastic shear zones included into the mylonitic fabric of the marble showing a top-to-the-S sense of shear (37°44'15.32"N; 24°3'14.46"E). **d.** Cataclastic rocks characterized by iron rich cement just below the detachment fault (37°44'24.50"N; 24°3'9.78"E).

Figure 8. Back-scattered electron photographs of thin sections of the Lavrion and Kamariza schists used to perform X-ray chemical maps (LS-XM and KS-XM area, see Fig 9). **a.** Lavrion schists thin section (sample LAV11 003b) showing chlorite and K-white mica association used to perform LS-XM chemical map (37°39'18.01"N; 24°1'24.13"E). **b.** Kamariza schists thin section (sample LAV11 020b) showing chlorite and K-white mica association used to perform KS-XM chemical map (37°41'36.10"N; 24°0'36.23"E). Ap: apatite, Chl: chlorite, FeOx: iron oxide, Mt : magnetite, K-wm: K-white mica, Qtz: quartz, Rt : rutile.

Figure 9. X-ray map and chemical analysis of K-white mica and chlorite from the Lavrion schists (Fig. 9a, LS-XM, sample LAV11 003b) and the Kamariza schists (Fig.9 b, KS-XM, sample LAV11 020b). K-white mica and chlorite chemistry are respectively reported into (left) muscovite, celadonite, pyrophyllite and (right) amesite, clinocllore + daphnite, sudoite triplot diagrams. **a.** In the Lavrion schists, according to chemical variations and microstructural position, three main subgroups of K-white mica (LS-KWM1-2-3) and two subgroups of chlorite (LS-Chl1-2) are defined. **b.** In the Kamariza schists, according to chemical variations and microstructural position, two main subgroups of K-white mica (KS-KWM1-2) and two subgroups of chlorite (KS-Chl1-2) are defined.

Figure 10. P - T estimates obtained from local equilibrium between chlorite and K-white mica for each subgroup previously identified in the LS-XM (Fig. 9a) and the KS-XM (Fig. 9b). Reconstruction of chlorite temperature pseudo-distribution (without vertical scale) from histograms of each subgroup are given for the Lavrion schists in Fig.10a and for the Kamariza schists in Fig.10c. K-white mica P - T estimates (lines) are given for the Lavrion schists in Fig.10b and for the Kamariza schists in Fig.10d. Boxes are constructed using the results of the

chlorite thermometer. For a given temperature, pressures are estimated along the corresponding K- white mica P - T equilibrium lines.

Figure 11. Microtextural map of Lavrion schists (LS-XM) and the Kamariza schist (KS-XM) indicating the modeled P - T estimates as a function of microstructural positions. Temperature calculated from chlorite showing the microstructural position with the different generations of phengite are given for the Lavrion schists (Fig.11a) and the Kamariza schists (Fig.11c). Pressure calculated from phengite showing the microstructural position with the different generations of chlorite are given for the Lavrion schists (Fig.11b) and the Kamariza schists (Fig.11d).

Figure 12. Synthetic final P - T paths recorded by the Cycladic blueschist. **a.** P - T paths recorded by the Lavrion area (Lavrion schist from the middle unit in blue and Kamariza schist from the basal unit is green) are compared to the ones measured in the Cyclades (Trotet et al., 2001; Parra et al., 2002; Groppo et al., 2009) and in the Peloponnese and Crete (multiple thin grey curves synthesized in Jolivet et al., 2010a from Jolivet et al., 1996; Trotet, 2000 and Trotet et al., 2006) **b.** Burial (D_1M_1) and the syn-orogenic exhumation (D_2M_2) were mainly recorded by the Lavrion schists. The Kamariza schists recorded syn- to post-orogenic exhumation after thermal relaxation in greenschist facies. Geothermal gradient are represented in dashes curves.

Figure 13. Schematic geodynamic model illustrating the tectonic evolution of the nappe pile exposed in the Lavrion peninsula from construction to collapse of the Aegean orogenic belt. **a.** The first step, corresponding to the burial stage (D_1M_1), is marked by the development of a S_{0-1} steep-dipping schistosity underlined by a blueschist facies mineral assemblage. **b.** The second stage (D_2M_2) corresponds to syn-orogenic exhumation of previously buried rocks in the subduction channel accommodated by syn-orogenic high-angle fault associated with the development of S_2 steep-dipping schistosity underlined by blueschist facies minerals. **c.** The last stage (D_3M_3) corresponds to a post-orogenic exhumation associated with the development of a low-angle detachment marked by transposition into S_3 shallow-dipping schistosity in greenschist facies induced by thermal relaxation. **d.** Schematic representation of the three main deformation stage affecting the nappe pile in the Lavrion area. All previous structures (thrust and syn-orogenic detachment) are folded and transposed into the S_3 shallow-dipping

schistosity. This schistosity is induced by the development of the low-angle post-orogenic detachment controlled by the thermal evolution. Gs: Greenschist facies, Amp: Amphibolite facies, Mig: Migmatite.

Table captions

Table 1. Selection of five quantified analyses and structural formulas of chlorite and K-white mica sampled into the Lavrion X-ray chemical map (LS-XM, sample LAV11 003b). Temperatures are estimated using chlorite–quartz–water thermometry. $X\text{Fe}^{3+}$ is estimated by the model and corresponds to the minimum amount of Fe^{3+} . Phengite curves are estimated using phengite-quartz-water equilibrium. Pressure range is estimated using chlorite temperature calculated from local equilibrium.

Table 2. Selection of five quantified analyses and structural formulas of chlorite and K-white mica sampled into the Kamariza X-rays map (KS-XM, sample LAV11 020b). Temperatures are estimated using chlorite-quartz-water thermometry. $X\text{Fe}^{3+}$ is estimated by the model and corresponds to the minimum amount of Fe^{3+} . Phengite curves are estimated using phengite-quartz-water equilibrium. Pressure range is estimated using chlorite temperature calculated from local equilibrium.

Lavrion schists

Metavolcanite

Upper Unit

Non-metamorphic
ophiolitic melange
and Cretaceous
limestone

Meta-ophiolites

Middle Unit

Lavrion schists

Lavrion marble

Basal Unit

Upper marble

Kamariza schists

Lower marble

Metavolcanic rocks

Kamariza schists

Metavolcanite

A (W)

A' (E)

B (SSW)

B' (NNE)

a

Lavrion schists

LS-XM

b

Kamariza schists

KS-XM

Lavrion schists

Kamariza schists

Lavrion schists

Kamariza schists

a

D₁M₁-Burial

b

D₂M₂-Syn-orogenic exhumation

c

D₃M₃-Post-orogenic exhumation

d

Chlorite										
LS-Chl1					LS-Chl2					
SiO2	26.66	25.87	26.61	26.68	26.31	26.29	26.81	26.42	26.87	27.01
TiO2	0.04	0.01	0.04	0.05	0.05	0.03	0.04	0.04	0.04	0.03
Al2O3	20.11	20.07	20.41	21.17	20.07	19.84	20.21	19.57	20.38	19.52
FeO	28.41	27.63	27.76	28.74	28.44	25.71	27.41	25.33	28.03	28.37
MnO	0.3	0.21	0.17	0.18	0.2	0.14	0.25	0.21	0.15	0.21
MgO	14.48	14.25	15.13	14.17	14.6	15.2	15.32	15.22	14.95	14.63
CaO	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02
Na2O	0.06	0.03	0.03	0.02	0.02	0.11	0.05	0.06	0.02	0.03
K2O	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
Atom site distribution (14 anhydrous oxygen basis)										
Si (T1+T2)	2.77	2.75	2.75	2.74	2.75	2.79	2.77	2.81	2.77	2.81
Al (T2)	1.23	1.25	1.25	1.26	1.25	1.21	1.23	1.19	1.23	1.19
Al (M1)	0.23	0.25	0.25	0.26	0.25	0.21	0.23	0.19	0.23	0.19
Mg (M1)	0.37	0.36	0.37	0.34	0.37	0.39	0.38	0.4	0.37	0.38
Fe (M1)	0.4	0.39	0.38	0.38	0.4	0.37	0.39	0.37	0.39	0.42
V (M1)	0	0	0	0.02	0	0.02	0	0.04	0.01	0.01
Al (M2+M3)	0.01	0.01	0	0.05	0	0.05	0	0.07	0.02	0.03
Mg (M2+M3)	1.88	1.9	1.96	1.84	1.91	2.01	1.98	2.01	1.93	1.89
Fe (M2+M3)	2.07	2.07	2.02	2.09	2.09	1.91	1.98	1.88	2.03	2.05
Al (M4)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
XFe3+	30	26	28	25	27	33	31	35	29	34
Temperature (°C)	320	340	337	329	344	310	324	296	324	300

Phengite															
LS-KWM1					LS-KWM2					LS-KWM3					
SiO2	47.88	46.56	45.59	46.86	45.45	51.25	52.12	51.59	51.78	51.31	50.26	49.94	50.79	49.87	51.27
TiO2	0.66	0.56	0.76	0.77	0.66	0.21	0.27	0.23	0.19	0.23	0.27	0.32	0.19	0.17	0.3
Al2O3	31.82	32.1	32.58	31.67	31.55	23.87	24.27	24.62	23.82	23.85	27.93	26.87	26.64	26.79	27.3
FeO	2.92	2.48	2.65	2.68	2.55	3.81	3.72	3.6	3.82	4.0	2.74	2.69	3.18	3.18	3.21
MnO	0.05	0.04	0.04	0.05	0.04	0.04	0.06	0.04	0.04	0.03	0.09	0.05	0.04	0.04	0.04
MgO	1.78	1.66	1.79	1.48	1.78	3.64	3.46	3.61	3.42	3.1	2.76	3.03	3.08	3.15	3.12
CaO	0.17	0.17	0.15	0.14	0.23	0.14	0.17	0.22	0.15	0.17	0.17	0.16	0.13	0.2	0.21
Na2O	0.31	0.37	0.34	0.23	0.35	0.05	0.08	0.02	0.14	0.12	0.13	0.16	0.12	0.17	0.17
K2O	9.93	9.59	10.0	10.1	9.93	9.71	10.02	9.89	9.93	9.86	9.91	10.08	10.36	9.86	9.86
Atom site distribution (11 anhydrous oxygen basis)															
Si (T1+T2)	3.19	3.16	3.1	3.18	3.14	3.52	3.53	3.5	3.54	3.53	3.38	3.4	3.43	3.4	3.41
Al (T2)	0.81	0.84	0.9	0.82	0.86	0.48	0.47	0.5	0.46	0.47	0.62	0.6	0.57	0.6	0.59
Mg (M1)	0.02	0.02	0.02	0.01	0.02	0.03	0.01	0.03	0.02	0.01	0.02	0.01	0.02	0.03	0.03
Fe (M1)	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
V (M1)	0.97	0.96	0.95	0.99	0.97	0.95	0.98	0.96	0.97	0.98	0.97	0.98	0.97	0.95	0.96
Al (M2+M3)	1.69	1.73	1.71	1.71	1.7	1.46	1.46	1.47	1.46	1.47	1.6	1.56	1.54	1.55	1.55
Mg (M2M3)	0.16	0.15	0.16	0.14	0.17	0.34	0.33	0.34	0.33	0.31	0.26	0.29	0.29	0.29	0.28
Fe (M2M3)	0.15	0.12	0.13	0.15	0.13	0.2	0.2	0.19	0.21	0.22	0.14	0.15	0.17	0.16	0.16
K (A)	0.84	0.83	0.87	0.87	0.87	0.85	0.87	0.86	0.87	0.87	0.85	0.88	0.89	0.86	0.84
Na (A)	0.04	0.05	0.04	0.03	0.05	0.01	0.01	0.0	0.02	0.02	0.02	0.02	0.02	0.02	0.02
V (A)	0.1	0.11	0.08	0.09	0.06	0.13	0.11	0.12	0.1	0.11	0.12	0.09	0.08	0.11	0.13

Chlorite										
KS-Chl1					KS-Chl2					
SiO2	27.02	26.28	26.71	26.89	26.75	26.47	26.13	26.02	26.09	25.99
TiO2	0.1	0.07	0.1	0.09	0.09	0.09	0.04	0.07	0.09	0.08
Al2O3	20.19	20.23	20.78	20.61	20.35	21.67	21.2	22.11	21.88	22.05
FeO	20.21	19.77	18.42	19.53	20.67	20.58	21.09	19.74	19.19	20.82
MnO	0.09	0.11	0.12	0.12	0.1	0.1	0.15	0.12	0.13	0.13
MgO	18.75	18.32	19.55	18.97	18.38	18.3	17.93	18.05	18.22	17.59
CaO	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01
Na2O	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.01
K2O	0.03	0.05	0.04	0.04	0.03	0.04	0.03	0.05	0.05	0.04
Atom site distribution (14 anhydrous oxygen basis)										
Si (T1+T2)	2.72	2.72	2.7	2.72	2.7	2.8	2.78	2.77	2.79	2.79
Al (T2)	1.28	1.28	1.3	1.28	1.3	1.2	1.22	1.23	1.21	1.21
Al (M1)	0.28	0.28	0.3	0.28	0.3	0.2	0.22	0.23	0.21	0.21
Mg (M1)	0.42	0.42	0.4	0.41	0.39	0.48	0.46	0.48	0.47	0.46
Fe (M1)	0.27	0.28	0.25	0.24	0.26	0.29	0.28	0.25	0.27	0.29
V (M1)	0.04	0.03	0.06	0.06	0.05	0.04	0.04	0.04	0.04	0.03
Al (M2+M3)	0.08	0.05	0.11	0.12	0.09	0.08	0.08	0.08	0.09	0.07
Mg (M2+M3)	2.39	2.37	2.39	2.42	2.33	2.43	2.43	2.54	2.46	2.39
Fe (M2+M3)	1.51	1.56	1.47	1.43	1.55	1.47	1.47	1.34	1.42	1.51
Al (M4)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
XFe3+	43	39	41	41	39	28	27	21	26	25
Temperature (°C)	298	312	314	305	309	346	358	367	344	351

Phengite										
KS-KWM1					KS-KWM2					
SiO2	51.55	52.55	51.93	52.16	51.0	47.87	48.48	49.07	48.25	48.76
TiO2	0.4	0.29	0.26	0.32	0.36	0.41	0.45	0.33	0.37	0.4
Al2O3	25.07	25.37	25.74	25.11	25.36	28.89	28.85	29.48	29.05	28.87
FeO	2.79	2.73	2.55	2.76	2.6	2.63	3.14	2.48	2.93	2.28
MnO	0.03	0.02	0.02	0.04	0.03	0.02	0.03	0.04	0.02	0.03
MgO	3.23	3.53	3.26	3.51	3.46	2.94	2.57	2.48	3.0	2.69
CaO	0	0	0	0	0	0	0	0	0	0
Na2O	0.17	0.29	0.13	0.22	0.18	0.19	0.25	0.3	0.25	0.17
K2O	9.63	9.43	10.13	9.95	9.5	10.37	10.31	10.35	10.51	10.67
Atom site distribution (11 anhydrous oxygen basis)										
Si (T1+T2)	3.51	3.52	3.5	3.51	3.49	3.27	3.29	3.3	3.27	3.31
Al (T2)	0.49	0.48	0.5	0.49	0.51	0.73	0.71	0.7	0.73	0.69
Mg (M1)	0.01	0.02	0.01	0.01	0.02	0.04	0.02	0.02	0.04	0.01
Fe (M1)	0	0.01	0	0	0.01	0.02	0.02	0.01	0.02	0.01
V (M1)	0.99	0.97	0.99	0.99	0.97	0.95	0.96	0.97	0.94	0.98
Al (M2+M3)	1.52	1.52	1.54	1.51	1.53	1.6	1.6	1.64	1.59	1.62
Mg (M2M3)	0.32	0.33	0.32	0.34	0.33	0.26	0.24	0.23	0.26	0.26
Fe (M2M3)	0.16	0.14	0.14	0.15	0.14	0.13	0.16	0.13	0.14	0.12
K (A)	0.84	0.81	0.87	0.85	0.83	0.9	0.89	0.89	0.91	0.92
Na (A)	0.02	0.04	0.02	0.03	0.02	0.03	0.03	0.04	0.03	0.02
V (A)	0.14	0.16	0.11	0.12	0.15	0.07	0.07	0.07	0.06	0.05