

# HP-LT metamorphism in Elba Island: Implications for the geodynamic evolution of the inner Northern Apennines (Italy)

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1	HP-LT metamorphism in Elba Island: implications for
2	the geodynamic evolution of inner Northern
3	Apennines (Italy)
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14	
15	Abstract
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17 The inner Northern Apennines (*i.e.*, northern Tyrrhenian Sea and southern Tuscany) is 18 an Alpine chain affected by high-P metamorphic condition during its evolution. 19 Although the Elba Island is structurally located close to the Adria-Europe suture zone, 20 no evidence of high-P metamorphism has been here documented. This led to consider 21 it as a sector of the orogeny developed in a low P-context. This paper accounts for a 22 new finding of high-P and low-T metamorphism documented in metabasite rocks 23 embedded in the Cretaceous calcschist of eastern Elba Island. Mineral composition of metabasite includes Gln+Cpx+Ep+Ab+Act+Qtz+Ilm±Ti-oxide±Spn and it is indicative 24 25 of a former equilibration in the epidote blueschist subfacies and subsequent retrogression in the greenschist facies. Metamorphic peak occurred at P= 0.9-1.0 GPa 26

27 and T=330-350°C. Tectonic discrimination using immobile elements in the metabasite 28 does not point to an oceanic setting. As a consequence, the metasedimentary 29 succession containing metabasite is interpreted as belonging to the Tuscan contintental domain and not to the Ligurian-Piedmont Ocean, as previously 30 interpreted. Our results have two significant implications: (i) the tectonic stacking of 31 32 the Elba Island units did not occur in a low-pressure context; (ii) the Elba Island is now reconciled in the tectonic and metamorphic evolution of the inner Northern 33 Apennines. 34

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#### 38 1. Introduction

Northern Apennines is an eastward verging alpine belt deriving from the convergence
and subsequent collision between Adria microplate and Corsica-Sardinia massif,
believed of African and European pertinence, respectively (Molli, 2008 with references
therein).

43 Evidence of high-P metamorphic conditions have been detected, both in
44 metasiliciclastic rocks and metabasite, along a roughly W-E transect, from the Tuscan
45 Archipelago up to the exhumed Metamorphic Complex cropping out in southern
46 Tuscany (Fig.1).

Data from metasediments indicate P-T values (Fig.1) of 1.0-1.5 GPa and  $\leq$  350 °C, in the Tuscan Archipelago (Rossetti et al., 1999; Rossetti et al., 2001). Differently, inland, the P-values are slightly lower, between 0.6 – 1.2 GPa and T is in the range 350–420 °C (Kligfield et al., 1986; Theye et al., 1997; Giorgetti et al., 1998; Elter and Pandeli, 2002; Brogi and Giorgetti, 2012). High-P metamorphism is dated at Late Oligocene-Early Miocene, on the basis of <sup>40</sup>Ar/<sup>39</sup>Ar radiometric method (Brunet et al. 2000). Higher and older thermobaric conditions are recorded in north-eastern Corsica where P-T values up to 2 GPa and 380°C have been detected and referred to Eocene (Jolivet et al., 1998; Brunet et al., 2000) and Oligocene (Rossetti et al., 2015). These data are associated to westward verging thrusts (Fig.1) involving the oceanic rocks presently exposed in the Alpine Corsica.

Thus, along the Corsica-Tuscany W-E transect (Fig.1), the Elba Island represents the westernmost outcropping evidence of tectonic units verging to the east (Trevisan, 1950), as it is the case of the Apennine belt. In addition, and as further on described, the structure of the Elba Island is characterised by the superimposition of continental units over the oceanic ones, the latter already stacked on the continental successions (Pertusati et al., 1993 with references).

This fact, therefore, enforced the interpretation that the collisional suture between the 65 European and African plates passes close to the Elba Island (Keller and Pialli, 1990; 66 Pandeli et al., 2001; Balestrieri et al., 2011). However, although studies on Si-content 67 in phengite suggested high-P occurrence (Pandeli et al., 2001), the lack of a mineral 68 69 assemblage confirming high-P and low-T metamorphic conditions, makes this 70 interpretation weak, thus accounting for orogenic (Late Oligocene-Early Miocene) deformation developed under low-P metamorphic conditions (Keller and Coward, 71 1996; Garfagnoli et al., 2005; Musumeci and Vaselli, 2012). For this reason, Elba 72 73 Island resulted a distinctive case with respect to the surrounding areas, with fallouts 74 on the supposed evolution of the Northern Tyrrhenian Basin (Bonini et al., 2014).

In this paper we document for the first time, the occurrence of a high-P mineral assemblage in metabasite interlayered to Cretaceous calcschist (Acquadolce Unit *Auctt.*). We conclude that high-P and low-T metamorphism affected the whole tectonic pile of the Elba Island, at least up to the Early Burdigalian, as suggested by Deino et al. (1992) age measurements, thus reconciling the evolution of the Elba Island with the Northern Apennines.

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### 83 **2. Geological framework**

84 The geodynamic process leading to the Northern Apennines orogenesis determined the eastward stacking of several tectonic units belonging to oceanic and continental 85 paleogeographic domains. These are: (a) the Ligurian Units, consisting of remnants of 86 87 Jurassic oceanic crust, with the Jurassic-Cretaceous cover (Ligurian Units) and Cretaceous-Oligocene turbidites (Sub-Ligurian Units); these units were thrust 88 89 eastwards over the Tuscan Nappe during Late Oligocene-Early Miocene times; (b) the 90 inner Tuscan Domain, made up of a complete sedimentary succession of evaporitic, 91 platform, pelagic and foredeep environments, ranging in age from Late Trias to Early Miocene. During Early Miocene, the Tuscan succession was internally deformed and 92 93 detached from its substratum along the late Triassic evaporite level, giving rise to the 94 Tuscan Nappe. This latter stacked over the external Tuscan domain, that was deformed in isoclinal folds and duplex structures, under metamorphic conditions from 95 the blueschist to the greenschist facies (Carmignani and Kligfield, 1990; Carmignani 96 97 et al., 1994; Jolivet et al., 1998; Rossetti et al., 2002; Molli, 2008; Brunet et al., 2000; Brogi and Giorgetti, 2012). During Early-Middle Miocene (Jolivet et al., 1990; 98 Carmignani et al., 1995; Brunet et al., 2000) the tectonic framework changed and an 99 100 eastward migrating extension affected the inner Northern Apennines (i.e., northern 101 Tyrrhenian Sea and southern Tuscany). Extension continuously developed through 102 time, although two main events can be distinguished (Barchi, 2010 with references 103 therein). The first one, occurred during Miocene, determined the lateral segmentation 104 of the more competent levels within the previously stacked tectonic units and the 105 consequent superimposition of the Ligurian Units (at the top of the tectonic pile) on 106 the deeper basal detachment levels. These are within the late Triassic evaporite and 107 the Palaeozoic phyllite (Bertini et al., 1991; Baldi et al., 1994), and, consequently, the

108 stair-case geometry of the faults gave rise to bowl-shaped structural depressions 109 where Langhian-Messinian marine to evaporitic and continental sediments deposited 110 (Brogi and Liotta, 2008). The second extensional event (Pliocene-Quaternary) 111 determined normal faults crosscutting the previously developed compressional and 112 extensional structures, thus defining tectonic depressions filled up by Pliocene to 113 Quaternary marine and continental sediments (Bossio et al., 1993). Since Late 114 Miocene, extension is accompanied by anatectic magmatism with minor mantle contribution (Peccerillo, 2003). 115

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#### 117 **2.1. Elba Island geological framework**

Integrating previous papers (Trevisan, 1950; Keller and Pialli, 1990; Pertusati et al., 1993; Bortolotti et al., 2001 with references therein) with the data here further on illustrated, we distinguish seven main tectonic units, belonging both to continental and oceanic environments and forming the tectonic pile of the Elba Island (Fig.2). The deeper outcropping continental unit (continental unit 1, Fig.3) is made up of early Carboniferous micaschist (Musumeci et al., 2011) and its Triassic-Jurassic siliciclastic and carbonatic cover (Porto Azzurro Unit, in Pandeli et al., 2005).

The 2nd continental unit (Fig.3) is made up of a complete succession of metamorphic 125 126 rocks consisting of middle Ordovician porphyroids (Ortano porphyroids, Musumeci et al., 2011) above which Mesozoic continental to marine metasediments crop out 127 128 (Duranti et al., 1992). The latter are late Triassic to Jurassic metacarbonates, calcschist and metaradiolarite passing to a Cretaceous succession made up of 129 130 calcschist and phyllite with levels of metasiltstone and metasandstone. Calcschist 131 represents the base of the succession and contains discontinuous lenses of metabasite 132 (Fig.3), the main focus of this paper. The third continental unit (Fig.3) consists of low-133 grade metamorphic rocks including late Carboniferous phyllite, overlain by Triassic continental quartzite and phyllite, marine ?Triassic-?Jurassic marble and by the 134

135 Cretaceous-Oligocene carbonatic and terrigenous metasedimentary succession 136 (Bortolotti et al., 2001). Finally, the forth continental unit (Fig.3) is related to the 137 Tuscan Nappe, composed of late Triassic, locally vacuolar and fragmented calcareous dolostone, overlain by Jurassic marine carbonate and Cretaceous-Oligocene 138 calcareous and marly pelagic sediments. The oceanic unit 1 (Fig.3) is interposed 139 140 between the second and the third continental units by means of out-of-sequence 141 thrust (Keller and Pialli, 1990; Pertusati et al., 1993; Keller and Coward, 1996) 142 referred to Early Burdigalian (Deino et al., 1992; Pertusati et al., 1993). This unit is a 143 tectonic slice made up of Jurassic ophiolite. Finally, the oceanic units 2 and 3 (Fig.3) 144 consist of remnants of the Jurassic ophiolite, Jurassic radiolarite and Cretaceous-Eocene calcareous and terrigenous sediments, with levels of ophiolitic breccias. After 145 the stacking of the tectonic pile, the Elba Island was affected by Miocene extensional 146 147 structures and magmatism (Fig.2), giving rise to the emplacement of Monte Capanne (about 7.0 Ma, Westerman et al., 2004), and Porto Azzurro (about 6 Ma, Maineri et al. 148 149 2003 and Musumeci et al. 2011) laccolith-pluton-dyke granitic complexes (Dini et al. 150 2002), respectively located to the West and East sides of the Island (Fig.2). 151 Regionally, magma emplacement and cooling (Caggianelli et al., 2014) determined thermo-metamorphic aureolas (Barberi and Innocenti, 1965; Duranti et al., 1992; 152 Rossetti et al., 2007) and low-P mineral assemblage resetting the older metamorphic 153 paragenesis related to the collisional event (Duranti et al., 1992; Pertusati et al., 154 155 1993). Moreover, a diffuse hydrothermalism determined Fe-ore deposits (Tanelli, 1983; Tanelli et al., 2001), particularly in the Eastern Elba Island. In this framework, 156 157 it was surprising to find relic high-pressure metamorphic paragenesis still preserved in 158 metabasite lithons, embedded in the calcshist of the Continental unit 2 (Fig.3).

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**3 - Rock fabric** 

The sampling area (Fig.4 and Fig. 5A) is structurally located in the lower part of the Cretaceous succession of the continental unit 2 (Fig.3). Here, lenses of metabasite, from few cm to about 2 m thick (Fig. 5B), are embedded in calcschist, mainly along the main schistosity, gently NW-dipping (Fig.5C-5D). The metabasite is laterally segmented at different scales (Fig. 5E-H), indicating the pervasiveness of the deformation. The rock fabric is characterized by the presence of porphyroclasts of mafic minerals within a chloritic matrix (Fig.5I) and by S/C structures.

In calcschist, the main foliation, generally parallel to  $S_0$  (Fig.5), is locally deformed by 168 169 tight and isoclinal folds with  $\approx 304/30$  plunging hinge lines (Fig. 6A-B). These folds, 170 characterised by the lack of an axial plane foliation, account for thermal conditions favoring plastic behavior. The stretching lineation is well defined by elongated calcite 171 crystals, NW-SE trending (Fig. 6C). The mineral association (Fig. 6D) on main 172 173 schistosity is made up of Cal+Dol+Qtz+Bt+Ms+Chl±Ti-FeOxides±Ab±Ap±Ep (mineral 174 abbreviations after Kretz, 1983 and Bucher and Frey, 1994). Close to this study outcrop (Fig.4), few tens of meter southwards, muscovite on the main foliation has 175 been dated through <sup>40</sup>Ar/<sup>39</sup>Ar method at 19.68±0.15 Ma (Deino et al., 1992). A new 176 177 deformation episode affected the previous structures, determining local open and SEverging folds. 178

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#### 180 **4. evidence of HP metamorphism**

Main evidence of high-P and low-T metamorphic conditions are from the metabasite embedded in the calcschist. The nature of the parental material of the metabasite was ascertained by XRF analyses for three rock samples. Results in Table 1 indicate low contents in SiO<sub>2</sub> (down to 43.60 wt. %) and K<sub>2</sub>O (down to 0.56 wt. %) and high contents in MgO (up to 9.92 wt. %) and Na<sub>2</sub>O (up to 3.49 wt. %). Finally, a wide variation in CaO (from 6.28 to 12.36 wt. %) and elevated values of L.O.I. (up to 9.25 wt. %) can be noted. Classification of these rocks was performed by the Winchester

188 and Floyd (1977) diagram based on immobile elements distribution, as modified by 189 Pearce (1996; 2014). In Fig. 7, the analysed rocks are in the field of basalt, near the 190 boundaries with the andesite/basaltic andesite and alkali basalt fields, resulting 191 different from N-MORB and the well known ophiolitic lavas of Troodos and Semail (Pierce, 2014). The mineralogical composition of the metabasite includes 192 193 *Gln+Cpx+Ep+Ab+Act+Qtz+Ilm±Ti-oxide±Spn*. It is indicative of former equilibration 194 in the epidote blueschist subfacies (Evans, 1990) and later retrogression in the 195 greenschist facies. Metabasite has a fine grain size and sometimes a mylonitic fabric 196 characterized by clinopyroxene porphyroclasts set in a matrix mainly made up of 197 glaucophane and epidote + chlorite. Clinopyroxene porphyroclasts are typically rounded and fragmented (Fig.8A-C), probably representing relics of former magmatic 198 diopside and augite. They usually appear brownish and rare portions apparently 199 unaffected by alteration characterized by bright interference colors. Elongated 200 glaucophane crystals, recognizable for the pale lavender color shades, are 201 202 preferentially oriented along the main foliation (Fig.8C) and wrap around 203 clinopyroxene porphyroclasts (Fig.8D). Glaucophane is present also in the strain 204 shadows and in the fractures of the stretched porphyroclasts (Fig.8A-B). Epidote occurs in minor amounts with respect to glaucophane and is represented by small 205 grains, occasionally with lamellar twinning, of both clinozoisite and pistacite. It is 206 occasionally zoned with clinozoisite cores and pistacite rims, a texture reflecting the 207 208 transition to lower pressure conditions. Ilmenite and, if present, Ti-oxide, are 209 scattered throughout the rock, showing a variable grain size. Sometimes, ilmenite can 210 be surrounded by sphene (Fig. 8E). Rock portions characterized by the abundance of 211 chlorite, epidote, sphene and Ti-oxide, when glaucophane and clinopyroxene relics are 212 scarce (Fig.8E), indicate that later retrogression was non-pervasive and took place in 213 the greenschist facies (Fig.8E). Another common textural evidence of retrogression is

214 represented by albite blasts enclosing glaucophane and by the presence of215 calcite±actinolite veins crosscutting the main foliation (Fig. 8F).

In Table 2 microprobe analyses and structural formulae of selected minerals, representative of the metabasite assemblage in sample C19, are provided. We focus hereafter on those mineral phases (*i.e.*: glaucophane, clinopyroxene, epidote) used to constrain the P-T conditions of the epidote blueschist subfacies metamorphism.

Blue-amphibole nomenclature was defined according to Leake (1997) by using the software Probe-Amph (Tindle et al., 1994). It was established that all Na-amphibole analyses can be attributed to glaucophane (Fig.9A). Content in glaucophane molecula  $X_{Gin}$ , calculated as  $AI^{VI}/[Fe^{3+} + AI^{VI}]$  ranges from 0.65 to 0.86. Ca-amphibole analyses are related to Fe-actinolite with average  $X_{Mg}$  of 0.78.

225 Clinopyroxene nomenclature was defined following Morimoto et al. (1988) and using 226 the PX-NOM software (Sturm, 2002). Clinopyroxene porphyroclasts surrounded by glaucophane fibres can be classified in most cases as omphacite and secondly as 227 aegirine-augite (Fig. 9B). For these types, content in jadeite molecula ranges from 228 229 0.24 to 0.33, indicating their involvement in the high-pressure metamorphic reactions. 230 However, a smaller number of analyses, generally pertaining to isolated porphyroclasts (Fig.9C) without external glaucophane fibres, can be classified as 231 diopside (average  $X_{Mq}$ =0.80) and, in one case, as augite ( $X_{Mq}$ =0.65). Therefore, they 232 233 can be ascribed to magmatic clinopyroxene relics. Epidote is represented by both 234 clinozoisite- and pistacite-rich terms. The content in pistacite molecula (X<sub>Ps</sub>) has been calculated by Fe/[(Al-4)+Fe] on the basis of  $\Sigma O = 25$ . It results that clinozoisite is 235 characterized by a minimum value of  $X_{Ps}$  = 0.09 and pistacite by a maximum value of 236  $X_{Ps} = 0.82$ . Interestingly, in the matrix of two metabasites, microanalyses allowed to 237 238 recognize the presence of anorthite with composition very close to pure calcic plagioclase end-member (Table 2). Anorthite was probably generated from a former 239 lawsonite in response to the later heating produced at low-P conditions by the 240

241 emplacement of the Porto Azzurro monzogranite pluton, as an effect of the reaction 242 lawsonite=anorthite+ $H_20$ .

The mineral compositional data from metabasite were used for a preliminary estimation of the P-T conditions in the epidote-blueschist metamorphic subfacies. To this end, we considered the pyroxene porphyroclasts with omphacite composition  $(\max X_{Jd} = 0.33)$  and glaucophane (max  $X_{Gin} = 0.86$ ).

We firstly used the approach described by Sturm (2002) based on the albite =jadeite 247 + quartz equilibrium, experimentally determined by Holland (1980). This calibration 248 249 was obtained for temperatures higher than blueschist facies but, according to Sturm 250 (2002), extrapolation to lower temperatures produces small uncertainties in P values and can provide acceptable preliminary estimates. Therefore, considering the 251 maximum content of jadeite molecula ( $X_{Jd}$ =0.33) in omphacite, pressure values 252 253 ranging from 0.95 to 1.10 GPa are obtained if the field of the epidote blueschists 254 subfacies by Tsujimori and Ernst (2013) is considered (Fig.10). Indeed, the relatively low content of epidote in the metabasite and the suspected former presence of 255 lawsonite, now replaced by anorthite, point to a peak P-T condition in the 256 257 neighbourhood of the transition from lawsonite- to epidote-blueschist subfacies. According to Zhang et al. (2009), blueschists of NW China crossed this transition 258 during subduction at temperatures close to 350 °C. In Fig.10 the isopleth related to 259 the observed maximum content in jadeite molecula meets the transition line between 260 261 the two subfacies at a T of c. 330 °C, corresponding to a pressure of c. 0.95 GPa. Lower P estimates (Fig.10) are obtained on the basis of the Na-amphibole 262 composition. By following the calibration of Maruyama et al. (1986) and by plotting 263 264 the isopleth related to the maximum content in glaucophane molecula in the field of 265 epidote blueschist subfacies, a value of pressure slightly above 0.7 GPa is estimated. 266 This result may indicate that, after the peak pressure condition, glaucophane re-267 equilibrated in a later stage during the exhumation.

A confirmation of the high-pressure metamorphic event was obtained from SEM-EDS analyses revealing the presence of white mica (Fig. 11A) with an elevated content in celadonite molecula ( $X_{Cel}=0.5$  and Si=3.5 a.p.f.u.) in metabasite sample RMT3 (Table 3). However, although it accounts for high-P conditions, the lack of a limiting mineral assemblage in equilibrium with phengite (*i.e.*: K-feldspar, quartz, Mg/Fe silicates) precludes quantifying pressure by a geobarometric approach.

Another indication in favor of the high-pressure metamorphism comes from a phengite-bearing quartzite (sample RIO6B) in the Torre Giove locality (Fig. 2, 11B and Table 3). The main schistosity is defined by Qtz+Ms+ Kln±Cal ± Fe-Ti oxide. In some cases, detrital grains of white mica are surrounded by aggregates of newly-formed flakes of phengite (Fig. 11B) with Si content of about 3.5 a.p.f.u. (Table 3).

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### 281 **5. Discussion and Conclusions**

The metasedimentary succession where we have found metabasite, has been 282 differently interpreted through time. According to Trevisan (1950), Barberi et al. 283 284 (1969), Perrin (1975) and Keller and Pialli (1990), it is considered as part of the sedimentary succession belonging to the Tuscan Domain. Differently, Duranti et al. 285 286 (1992) and Pertusati et al. (1993) interpreted the ophiolite slice (*i.e.* the oceanic unit 1 in Fig. 3) and the underlying metasedimentary succession, where the study 287 288 metabasite is embedded, as belonging to the same overturned Jurassic-Cretaceous 289 oceanic succession of the inner Ligurian Domain (Pertusati et al., 1993). This unit was 290 later affected by contact metamorphism during the emplacement of the Porto Azzurro 291 monzogranite (Duranti et al., 1992). Pandeli et al. (2001) followed this interpretation 292 and suggested that this succession can be related to the Piedmont Ocean sedimentary 293 evolution.

Our data indicate that the composition of the metabasite rocks (Fig.7) is not compatible with an oceanic setting, *i.e.* the Ligurian-Piedmont Ocean. Thus, we sustain that the hosting metasediments cannot be related to the sedimentary succession of the ophiolite slice (oceanic unit 1 in Fig. 3). The latter instead is tectonically located above the calcschist (Fig.2). As a consequence, and as already proposed by the previously cited Authors, the metasedimentary succession under discussion should be linked to the Tuscan domain (Fig.3).

Mineral association and P-T conditions indicate an equilibration of the metabasite in the epidote blueschist subfacies with a pressure peak of 0.9-1.0 GPa. Metamorphic studies (Fig.1) carried out in the inner Northern Apennines indicate an eastward decrease of pressure (Rossetti et al. 2002 with references therein), from 1.3-1.6 GPa (Gorgona and Giglio Islands, Fig.1) to 0.8-1.0 GPa (southern Tuscany), as obtained on metasediments with Fe-Mg silicates (Giorgetti et al., 1998; Rossetti et al, 1999; Rossetti et al., 2001; Agard et al., 2000).

A comparison between P-values obtained for metasediment and metabasite parageneses from other localities of inner Northern Apennines (Fig.1), indicates that the metamorphic peak in metabasites is encompassed between 0.6 and 0.8 GPa (T= 275-350°C). Instead, P-values obtained from metasediments range from 0.8 to 1.5 GPa (T=350-420°C) in six out of seven localities. Thus it can be inferred that metabasites usually provide peak estimates lower than metasediments.

Although in the Elba Island pressure estimate is slightly higher (P=0.9-1.0 Gpa; T=330-350°C) than those obtained for the other metabasites, we interpret all the barometric values in the same tectono-metamorphic framework of the inner Northern Apennines. On this basis, the result provided by the Elba Island metabasite has two significant implications: (i) the tectonic stacking of the Elba Island units did not occur in a low-P context, as supposed by Pertusati et al. (1993) and, more recently, by Musumeci and Vaselli (2012); (ii) the Elba Island is now reconciled in the tectonic and metamorphic evolution of the Northern Apennines. Furthermore, it results that its stratigraphic and metamorphic evolution is significantly similar to the one described for the Gorgona Island, suggesting that the interpretation of the Gorgona calcschist as a part of the Piedmont Ocean (Capponi et al., 1990; Pandeli et al., 2001; Rossetti et al., 2001) should be revised.

Finally, considering reasonable that the high content of Si in phengite from the Monte 326 Giove area is a further evidence of high-P conditions, it derives that continental units 327 2 and 3 (Fig. 3) have been affected by high P-metamorphism too. Consequently, it 328 329 can be inferred that also the oceanic unit 1, interposed between the continental unit 2 330 and 3 (Fig.3 and 4), underwent metamorphism in high-P conditions. The absence of a 331 corresponding paragenesis, is probably an effect of the thermal perturbation produced by the emplacement of the Porto Azzurro monzogranite (Pertusati et al., 1993; 332 333 Bortolotti et al., 1994).

As it regards the timing of metamorphism, we have in the area two different 334 radiometric ages: Brunet et al. (2000) dated muscovite on the main schistosity of 335 calcschist cropping out in the Gorgona Island (Fig.1), obtaining 25.5±0.3 Ma by 336 <sup>40</sup>Ar/<sup>39</sup>Ar geochronology; by the same method, Deino et al. (1992) dated the 337 muscovite, grown on the main schistosity of the calcschist of the Elba Island (Fig.4), 338 339 providing a radiometric age of 19.68±0.15 Ma. Assuming that the study metabasite and hosting calcschist record the same deformational event and considering that both 340 341 glaucophane in metabasite, and white mica in calcschist, are syn-kynematic, we suggest that the radiometric ages are indicative for the high-P metamorphic event. 342 343 We can therefore assess that the high-P conditions occurred during the late 344 Oligocene-early Burdigalian time interval.

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#### 566 **CAPTIONS**

567

Figure 1 - Structural sketch map of Tuscany (inner Northern Apennines) with location
of the HP-LT mineralogical assemblages in metabasite (black circle) and other
rock types (metasediments). The P-T values from Rio Marina (no.11) are
presented in this paper; other data Kligfield et al. (1986); Theye et al. (1997);
Giorgetti et al. (1998); Rossetti et al. (1999); Brunet et al. (2000); Rossetti et
al. (2001); Elter and Pandeli, (2001); Brogi and Giorgetti (2012).

574

575 Figure 2 - Geological sketch map of the Elba Island. The relationships between the 576 tectonic units are highlighted as described in the text. The location of the 577 phengite - and glaucophane-bearing rocks is also indicated.

578

Figure 3 – Tectono-stratigraphic columns showing the seven tectonic units belonging 579 580 both to continental and oceanic environments and forming the tectonic pile of the 581 Elba Island. From right to left, and from the bottom in each column: oceanic unit 582 3:  $b\Sigma$  = Breccia of ophiolitic rocks; LC = limestone and shale (Palombini Shales) 583 Fm); C = shale (Varicoluored shales Fm); S = sandstone and shale (Ghiaieto 584 Sandstones Fm); Sc = sandstone and marlstone (Marina di Campo Fm); Ts = shale with limestone and marlstone (Colle Reciso Fm). Oceanic unit 2:  $\Sigma$  = 585 586 ophiolite; J = radiolarite (Mt. Alpe Cherts Fm); Cl = calcilutite and cherty limestone (Nisportino Fm); L = cherty limestone (Calpionella Limestones Fm); LC 587

588 = limestone and shale (Palombini Shales Fm). Continental unit 4: Ev = 589 Evaporite (Calcare Cavernoso Fm); M = massive and cherty limestone and 590 dolostone (Pania di Corfino Fm, Mt. Cetona Fm, Calcare Massiccio Fm, Grotta 591 Giusti Limestones, Rosso Ammonitico Fm, Limano cherty Limestones Fms); Mp= 592 marls (Posidonia Marlstones Fm); MI = varicolored shales (Cavo Fm). Continental 593 unit 3: Bphy = black phyllite (Rio Marina Fm); Q = quartzite and phyllite (Verruca Fm, Mt. Serra quartzite Fm); M = marble (Valle Giove Limestones Fm; 594 Capo Pero Limestone Fm; Capo Castello Calcschists Fm); Mc = cherty marble; Cs 595 596 = calcschist and phyllite (Varicoloured Sericitic Schist Fm); Ms = metasandstone 597 and phyllite (Pseudomacigno Fm). Continental unit 2: P = porphyroids, quartzite 598 and phyllite (Ortano Unit); Q = quartzite; M = massive and cherty limestone and dolostone (Valdana marble Fm); Mp = marls (Posidonia Marlstones Fm); J = 599 600 radiolarite; Phy = calcschist with interbedded metabasite (Mb) and phyllite 601 (Acquadolce Unit). Oceanic unit 1:  $\Sigma$  = ophiolite. Continental unit 1: Mc = micaschist (Mt. Calamita Fm); Q = quartzite and phyllite (Quarziti di Barabarca 602 603 Fm); M = dolostone (Crystalline dolostone and dolomitic limestone Fm). 604 Formational names after Bortolotti et al. (2001) and Garfagnoli et al. (2005). The stars indicate the location of the analysed samples. 605

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607 Figure 4 - Geological map and cross sections of the Rio Marina area.

608

Figure 5 - A) panoramic view of the sampling area; B) lenses of metabasite embedded
in calcshist; C) metabasites lenses located mainly along the main schistosity,
gently NW-dipping; D) detail of metabasite lens; E-H) metabasite laterally
segmented at different scales indicating the pervasiveness of the deformation; I)
rock fabric characterized by the presence of porphyroclasts of mafic minerals
within a chloritic matrix.

616 Figure 6 - A-B) tight and isoclinal folds with  $\approx 304/30$  plunging hinge lines deforming 617 the meian foliation in calcschists; C) stretching lineation well defined by 618 elongated calcite crystals, NW-SE trending; D) SEM-BSE (scanning electron 619 microscopy-back scattered electron) image showing the textural characteristics 620 and paragenesis of micaschists. Mineral abbreviations after after Kretz (1983) and Bucher and Frey (1994). D) SEM-BSE (scanning electron microscopy-back 621 scattered electron) image showing the textural characteristics and paragenesis of 622 623 micaschists. Mineral abbreviations after after Kretz (1983) and Bucher and Frey 624 (1994).

625

Figure 7 - Immobile elements TAS proxy diagram (Pearce, 2014). Grey area indicates the field of ophiolitic lavas from Troodos (Cyprus) and Semail (Oman) as reported by Pearce (2014). The metabasite under study (white circles) in comparison to Troodos and Semail lavas show a more pronounced alkaline affinity.

631

Figure 8 - Micrographs of a metabasite sample (plane polarised light in A-E and 632 crossed polars in F). A) Rounded porphyroclast of clinopyroxene with strain 633 shadow filled by glaucophane; B) Stretched and fractured porphyroclast of 634 635 clinopyroxene. Fracture is filled by glaucophane fibres grown parallel to the stretching direction; C) Elongated well-developed glaucophane crystals, mostly 636 oriented along the main foliation between clinopyroxene porphyroclasts; D) 637 Glaucophane fibres wrapping around porfiroclasts of clinopyroxene; E) Rock 638 639 portion affected by retrogression in greenschist facies as shown by the widespread chlorite and by the corona of sphene around ilmenite; F) Late calcite 640

vein cross-cutting at high angle the main foliation. Mineral symbols from Kretz(1983).

643

Figure 9 - A) Classification diagram of Na-Amphiboles in metabasite (after Leake et
al., 1997). B) Classification diagram for Ca-Na pyroxenes in the metabasite
according to Morimoto et al. (1988); Q = wollastonite+enstatite+Ferrosilite. C)
Classification diagram for Ca-Fe-Mg pyroxenes in the metabasite by Morimoto et
al. (1988).

649

650 Figure 10 - P-T diagram showing approximate metamorphic conditions (circles) for the 651 Elba Island blueschists constrained by mineral assemblage and composition of omphacite (yellow) and glaucophane (lilac). X<sub>Jd</sub> isopleth calculated with the aid of 652 653 the Sturm (2002) software on the basis of Ab = Jd + Qtz equilibrium calibrated by Holland (1980). X<sub>GIn</sub> isopleth from calibration by Maruyamaet al. (1986). 654 Subfacies boundaries by Tsujimori and Ernst (2013) and some relevant equilibria 655 have been shown. Metamorphic facies and sub-facies abbreviations: L-Bs = 656 657 lawsonite blueschist; E-Bs = epidote blueschist; Gs = greenschist; E-Am = epidote - amphibolite; Am = amphibolite; Amph-Ec = amphibole eclogite. 658 659 Mineral stability boundary and equilibria: Gln-in = stability boundary of glaucophane by Maresch (1977); Omph-in = stability boundary of omphacite-in a 660 jadeite-enriched MORB (MORB+ in Tsujimori and Ernst, 2013); Ab = Jd + Qtz by 661 Tsujimori and Ernst (2013); Lws = An +  $H_2O$  by Crawford and Fyfe (1965). 662 Mineral abbreviations according to Kretz (1983). 663

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665 Figure 11 - SEM-BSE (scanning electron microscopy-back scattered electron) images:666 A) RMT3 metabasite sample with glaucophane (Gln), clinopyroxene (Cpx) and

667 phengite (Phe). B) Phengite (Phn) from Torre Giove quartzite; phengite is more 668 celadonite -rich in the rim (lighter color).

669

- 670 Table 1 XRF analyses of three metabasites samples.
- 671

Table 2 - Representative analyses of Metabasite (sample C19). Beam width was 672 673 approximately of 1 µm. Table 2. Mineral abbreviations according to Kretz (1983) 674 Bucher Frey (1994): Gln=glaucophane; Act=actionolite; and and 675 Omph=omphacite; Agt=aegirine-augite; Di=diopside; Aug=augite; Clz=clinozoisite; Ps=pistacite. Analyses were performed on the JEOL 8200 676 microprobe, at the University of Milan, operating in WDS/EDS with an 677 accelerating voltage of 15 kV and 5 nA current. Beam width was approximately 678 679 of 1 µm.

680

Table 3 - Selected SEM/EDS analyses of phengites in metabasite (sample RMT3) and
 quartzite (RIO6B). Analyses were performed on the Philips XL30 SEM at the
 University of Siena, operating in EDS/EDAX with an accelerating voltage of 20
 kV.

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finding of HP-LT metamorphism in Elba Island implications for the geodynamic evolution of N.Apennines revision of the tectonic units involved in the N.Appennine stacking

Tabl	e1
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		C19	RMT2	RMT3
W	vt.%			
S	iO <sub>2</sub>	44.84	43.60	44.15
Т	CiO <sub>2</sub>	1.15	0.84	1.03
A	$l_2O_3$	17.04	13.72	15.23
F	eO <sub>t</sub>	10.52	7.96	9.45
Ν	/InO	0.16	0.09	0.12
Ν	/IgO	9.92	7.29	9.55
C	CaO	6.28	12.36	9.80
Ν	$a_2O$	2.10	3.49	3.11
K	$C_2O$	0.58	1.04	0.59
Р	$P_2O_5$	0.14	0.13	0.14
L	.O.I.	6.86	9.25	6.68
Т	ot	99.58	99.75	99.85
р	pm			
Ň	Ji	139	91	133
C	Cr	287	199	265
V	7	193	111	157
R	Rb	40	46	26
S	r	234	483	445
E	Ba	21	104	46
Y	7	24	17	22
Z	Źr	106	91	105
Ν	Jb	8	7	7
L	a	23	7	10
C	Ce	70	27	38

	<b>Amphiboles</b>		Clinopyroxenes			Feldspars		<u>Epid</u>	Epidotes		
	Gln	Act	Omph	Agt	Di	Aug	Ab	An	Clz	Ps	
wt.%											
SiO <sub>2</sub>	58.08	57.28	55.20	54.00	51.63	52.13	68.36	42.51	39.27	37.87	30.03
TiO	0.22	0.03	0.10	0.01	1.00	0.03	0.01	0.01	0.12	0.06	0.02
	9.63	1.06	7.20	3.26	2.15	4.44	19.50	36.79	32.55	22.28	20.74
$Cr_2O_2$	5.00	0.04	0.28	0.19	0.02		20.00		0.02	0.09	0.03
FeQ.	9 76	6.89	9 36	9.86	6 71	13 69	0.07	0 17	1 4	12 55	14 26
MnO	0.17	0.00	0.13	0.23	0.19	0.22	0.07	0.17	0 03	0 11	0.38
MaO	10.56	18 47	7 44	9 90	15 04	14 23	0.01	0.01	0.05	0.11	20.97
CaO	1 09	11 20	11 65	15 19	21 64	13 22	0.01	19.80	23 55	22.18	0.06
	6.16	0.86	7 3/	5 33	0.36	0.35	11 68	0.05	0.01	0.03	0.00
	0.10	0.00	0.04	0.04	0.30	0.55	11.00	0.03	0.01	0.03	0.01
	0.02	0.05	0.04	0.04	0.05	0.11	00 66	0.05	0.01	0.02	0.00 96 E9
TÜL	93.08	90.14	90.74	90.01	90.70	90.42	99.00	99.37	97.02	95.22	00.30
ΣΟ	23	23	6	6	6	6.066	8	8	25	25	28
Si	8.063	8.087	2.011	2.004	1.929	1.982	2.994	1.982	6.027	6.320	5.986
Al <sup>IV</sup>					0.071	0.018	1.008	2.024			2.014
Al <sup>VI</sup>	1.576	0.176	0.309	0.143	0.024	0.181			5.895	4.387	2.864
Ti	0.022	0.004	0.003		0.028	0.001			0.014	0.008	0.003
Cr		0.004	0.008	0.006	0.001				0.002	0.012	0.005
Fe	1.133	0.813	0.289	0.306	0.210	0.435	0.003	0.007	0.180	1.751	2.377
Mn	0.020	0.036	0.004	0.007	0.006	0.007			0.004	0.016	0.064
Ma	2.190	3.885	0.404	0.558	0.838	0.806	0.001	0.001	0.014	0.007	6.231
Ca	0.163	1.693	0.455	0.604	0.866	0.538	0.001	0.989	3.872	3.966	0.013
Na	1.658	0.234	0.519	0.391	0.026	0.026	0.992	0.005	0.003	0.010	0.004
ĸ	0.003	0.005	0.002	0.002	0.001	0.005		0.002	0.002	0.004	0.020
Fe <sup>3+</sup>	0.266	0.024	0.175	0.227	0.017						
Fe <sup>2+</sup>	0.867	0.789	0.110	0.079	0.193	0.435					
ΣCat	14.827	14.938	4.000	4.000	4.000	4.000	4.998	5.009	16.013	16.480	19.581
X <sub>GIn</sub>	0.86										
XJd			0.33	0.15							
X <sub>Wo</sub>					0.45	0.30					
X <sub>En</sub>					0.47	0.45					
X <sub>Fs</sub>					0.11	0.25					
X <sub>Q</sub>			0.48	0.62							
X <sub>Ae</sub>			0.19	0.24							
X <sub>Ps</sub>									0.09	0.82	
X <sub>An</sub>							0.00	1.00			
X <sub>Ab</sub>							1.00	0.00			
Х <sub>Ма</sub>	0.72	0.83	0.70	0.88	0.81	0.65					

	Metabasite RMT3	Quartzite RIO6A
wt.%		
SiO <sub>2</sub>	52.69	51.65
TiO <sub>2</sub>	0.15	0.19
$AI_2O_3$	24.61	23.77
FeOt	3.34	5.93
MnO	0.12	0.11
MgO	4.97	2.98
CaO	0.18	0.11
Na <sub>2</sub> O	0.12	0.08
K <sub>2</sub> O	9.66	10.96
lot	95.85	95.//
ΣΟ	11	11
Si	3.49	3.50
Al <sup>IV</sup>	0.50	0.50
Al <sup>VI</sup>	1.42	1.40
Ti	0.01	0.01
Fe	0.19	0.34
Mn	0.00	0.00
Mg	0.49	0.30
Ca	0.01	0.01
iva	0.01	0.01
K SCat	0.81	0.94
ZCal	0.95	7.02
X <sub>Cel</sub>	0.50	0.50



Figure2 Click here to download high resolution image









FIGURE 5

Figure6 Click here to download high resolution image



Figure7 Click here to download high resolution image



### Figure8 Click here to download high resolution image



#### Figure9 Click here to download high resolution image





FIGURE 10

