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

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Abstract

The inner Northern Apennines (*i.e.*, northern Tyrrhenian Sea and southern Tuscany) is an Alpine chain affected by high-P metamorphic condition during its evolution. Although the Elba Island is structurally located close to the Adria-Europe suture zone, no evidence of high-P metamorphism has been here documented. This led to consider it as a sector of the orogeny developed in a low P-context. This paper accounts for a new finding of high-P and low-T metamorphism documented in metabasite rocks embedded in the Cretaceous calcschist of eastern Elba Island. Mineral composition of metabasite includes $Gln+Cpx+Ep+Ab+Act+Qtz+Ilm\pm Ti\text{-oxide}\pm Spn$ and it is indicative of a former equilibration in the epidote blueschist subfacies and subsequent retrogression in the greenschist facies. Metamorphic peak occurred at $P= 0.9\text{-}1.0\text{ GPa}$

27 and $T=330-350^{\circ}\text{C}$. 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
30 continental domain and not to the Ligurian-Piedmont Ocean, as previously
31 interpreted. Our results have two significant implications: (i) the tectonic stacking of
32 the Elba Island units did not occur in a low-pressure context; (ii) the Elba Island is
33 now reconciled in the tectonic and metamorphic evolution of the inner Northern
34 Apennines.

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38 **1. Introduction**

39 Northern Apennines is an eastward verging alpine belt deriving from the convergence
40 and subsequent collision between Adria microplate and Corsica-Sardinia massif,
41 believed of African and European pertinence, respectively (Molli, 2008 with references
42 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).

47 Data from metasediments indicate P-T values (Fig.1) of 1.0-1.5 GPa and $\leq 350^{\circ}\text{C}$, in
48 the Tuscan Archipelago (Rossetti et al., 1999; Rossetti et al., 2001). Differently,
49 inland, the P-values are slightly lower, between 0.6 – 1.2 GPa and T is in the range
50 350–420 $^{\circ}\text{C}$ (Kligfield et al., 1986; Theye et al., 1997; Giorgetti et al., 1998; Elter and
51 Pandeli, 2002; Brogi and Giorgetti, 2012). High-P metamorphism is dated at Late
52 Oligocene-Early Miocene, on the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric method (Brunet et al.
53 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 European and African plates passes close to the Elba Island (Keller and Pialli, 1990; Pandeli et al., 2001; Balestrieri et al., 2011). However, although studies on Si-content in phengite suggested high-P occurrence (Pandeli et al., 2001), the lack of a mineral assemblage confirming high-P and low-T metamorphic conditions, makes this interpretation weak, thus accounting for orogenic (Late Oligocene-Early Miocene) deformation developed under low-P metamorphic conditions (Keller and Coward, 1996; Garfagnoli et al., 2005; Musumeci and Vaselli, 2012). For this reason, Elba Island resulted a distinctive case with respect to the surrounding areas, with fallouts 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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2. Geological framework

The geodynamic process leading to the Northern Apennines orogenesis determined the eastward stacking of several tectonic units belonging to oceanic and continental paleogeographic domains. These are: (a) the Ligurian Units, consisting of remnants of Jurassic oceanic crust, with the Jurassic-Cretaceous cover (Ligurian Units) and Cretaceous-Oligocene turbidites (Sub-Ligurian Units); these units were thrust eastwards over the Tuscan Nappe during Late Oligocene-Early Miocene times; (b) the inner Tuscan Domain, made up of a complete sedimentary succession of evaporitic, platform, pelagic and foredeep environments, ranging in age from Late Trias to Early Miocene. During Early Miocene, the Tuscan succession was internally deformed and detached from its substratum along the late Triassic evaporite level, giving rise to the Tuscan Nappe. This latter stacked over the external Tuscan domain, that was deformed in isoclinal folds and duplex structures, under metamorphic conditions from the blueschist to the greenschist facies (Carmignani and Kligfield, 1990; Carmignani 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; Carmignani et al., 1995; Brunet et al., 2000) the tectonic framework changed and an eastward migrating extension affected the inner Northern Apennines (i.e., northern Tyrrhenian Sea and southern Tuscany). Extension continuously developed through time, although two main events can be distinguished (Barchi, 2010 with references therein). The first one, occurred during Miocene, determined the lateral segmentation of the more competent levels within the previously stacked tectonic units and the consequent superimposition of the Ligurian Units (at the top of the tectonic pile) on the deeper basal detachment levels. These are within the late Triassic evaporite and 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
115 contribution (Peccerillo, 2003).

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117 **2.1. Elba Island geological framework**

118 Integrating previous papers (Trevisan, 1950; Keller and Piali, 1990; Pertusati et al.,
119 1993; Bortolotti et al., 2001 with references therein) with the data here further on
120 illustrated, we distinguish seven main tectonic units, belonging both to continental
121 and oceanic environments and forming the tectonic pile of the Elba Island (Fig.2). The
122 deeper outcropping continental unit (continental unit 1, Fig.3) is made up of early
123 Carboniferous micaschist (Musumeci et al., 2011) and its Triassic-Jurassic siliciclastic
124 and carbonatic cover (Porto Azzurro Unit, in Pandeli et al., 2005).

125 The 2nd continental unit (Fig.3) is made up of a complete succession of metamorphic
126 rocks consisting of middle Ordovician porphyroids (Ortano porphyroids, Musumeci et
127 al., 2011) above which Mesozoic continental to marine metasediments crop out
128 (Duranti et al., 1992). The latter are late Triassic to Jurassic metacarbonates,
129 calcschist and metaradiolarite passing to a Cretaceous succession made up of
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
134 continental quartzite and phyllite, marine ?Triassic-?Jurassic marble and by the

135 Cretaceous-Oligocene carbonatic and terrigenous metasedimentary succession
136 (Bortolotti et al., 2001). Finally, the fourth continental unit (Fig.3) is related to the
137 Tuscan Nappe, composed of late Triassic, locally vacuolar and fragmented calcareous
138 dolostone, overlain by Jurassic marine carbonate and Cretaceous-Oligocene
139 calcareous and marly pelagic sediments. The oceanic unit 1 (Fig.3) is interposed
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-
145 Eocene calcareous and terrigenous sediments, with levels of ophiolitic breccias. After
146 the stacking of the tectonic pile, the Elba Island was affected by Miocene extensional
147 structures and magmatism (Fig.2), giving rise to the emplacement of Monte Capanne
148 (about 7.0 Ma, Westerman et al., 2004), and Porto Azzurro (about 6 Ma, Maineri et al.
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
152 thermo-metamorphic aureolas (Barberi and Innocenti, 1965; Duranti et al., 1992;
153 Rossetti et al., 2007) and low-P mineral assemblage resetting the older metamorphic
154 paragenesis related to the collisional event (Duranti et al., 1992; Pertusati et al.,
155 1993). Moreover, a diffuse hydrothermalism determined Fe-ore deposits (Tanelli,
156 1983; Tanelli et al., 2001), particularly in the Eastern Elba Island. In this framework,
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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160 **3 - Rock fabric**

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

168 In calcschist, the main foliation, generally parallel to S_0 (Fig.5), is locally deformed by
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
171 favoring plastic behavior. The stretching lineation is well defined by elongated calcite
172 crystals, NW-SE trending (Fig. 6C). The mineral association (Fig. 6D) on main
173 schistosity is made up of $Cal+Dol+Qtz+Bt+Ms+Chl\pm Ti-FeOxides\pm Ab\pm Ap\pm Ep$ (mineral
174 abbreviations after Kretz, 1983 and Bucher and Frey, 1994). Close to this study
175 outcrop (Fig.4), few tens of meter southwards, muscovite on the main foliation has
176 been dated through $^{40}Ar/^{39}Ar$ method at 19.68 ± 0.15 Ma (Deino et al., 1992). A new
177 deformation episode affected the previous structures, determining local open and SE-
178 verging folds.

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180 **4. evidence of HP metamorphism**

181 Main evidence of high-P and low-T metamorphic conditions are from the metabasite
182 embedded in the calcschist. The nature of the parental material of the metabasite was
183 ascertained by XRF analyses for three rock samples. Results in Table 1 indicate low
184 contents in SiO_2 (down to 43.60 wt. %) and K_2O (down to 0.56 wt. %) and high
185 contents in MgO (up to 9.92 wt. %) and Na_2O (up to 3.49 wt. %). Finally, a wide
186 variation in CaO (from 6.28 to 12.36 wt. %) and elevated values of L.O.I. (up to 9.25
187 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
192 (Pierce, 2014). The mineralogical composition of the metabasite includes
193 $Gln+Cpx+Ep+Ab+Act+Qtz+Ilm\pm Ti\text{-oxide}\pm Spn$. 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
198 rounded and fragmented (Fig.8A-C), probably representing relics of former magmatic
199 diopside and augite. They usually appear brownish and rare portions apparently
200 unaffected by alteration characterized by bright interference colors. Elongated
201 glaucophane crystals, recognizable for the pale lavender color shades, are
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
205 occurs in minor amounts with respect to glaucophane and is represented by small
206 grains, occasionally with lamellar twinning, of both clinozoisite and pistacite. It is
207 occasionally zoned with clinozoisite cores and pistacite rims, a texture reflecting the
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 of
 215 calcite±actinolite veins crosscutting the main foliation (Fig. 8F).
 216 In Table 2 microprobe analyses and structural formulae of selected minerals,
 217 representative of the metabasite assemblage in sample C19, are provided. We focus
 218 hereafter on those mineral phases (*i.e.*: glaucophane, clinopyroxene, epidote) used to
 219 constrain the P-T conditions of the epidote blueschist subfacies metamorphism.
 220 Blue-amphibole nomenclature was defined according to Leake (1997) by using the
 221 software Probe-Amph (Tindle et al., 1994). It was established that all Na-amphibole
 222 analyses can be attributed to glaucophane (Fig.9A). Content in glaucophane molecule
 223 X_{Gln} , calculated as $Al^{VI}/[Fe^{3+} + Al^{VI}]$ ranges from 0.65 to 0.86. Ca-amphibole analyses
 224 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
 227 glaucophane fibres can be classified in most cases as omphacite and secondly as
 228 aegirine-augite (Fig. 9B). For these types, content in jadeite molecule ranges from
 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
 231 porphyroclasts (Fig.9C) without external glaucophane fibres, can be classified as
 232 diopside (average X_{Mg} =0.80) and, in one case, as augite (X_{Mg} =0.65). Therefore, they
 233 can be ascribed to magmatic clinopyroxene relics. Epidote is represented by both
 234 clinozoisite- and pistacite-rich terms. The content in pistacite molecule (X_{Ps}) has been
 235 calculated by $Fe/[(Al-4)+Fe]$ on the basis of $\Sigma O = 25$. It results that clinozoisite is
 236 characterized by a minimum value of $X_{Ps} = 0.09$ and pistacite by a maximum value of
 237 $X_{Ps} = 0.82$. Interestingly, in the matrix of two metabasites, microanalyses allowed to
 238 recognize the presence of anorthite with composition very close to pure calcic
 239 plagioclase end-member (Table 2). Anorthite was probably generated from a former
 240 lawsonite in response to the later heating produced at low-P conditions by the

241 emplacement of the Porto Azzurro monzogranite pluton, as an effect of the reaction
242 lawsonite=anorthite+H₂O.

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

247 We firstly used the approach described by Sturm (2002) based on the albite =jadeite
248 + quartz equilibrium, experimentally determined by Holland (1980). This calibration
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
251 and can provide acceptable preliminary estimates. Therefore, considering the
252 maximum content of jadeite molecula (X_{Jd}=0.33) in omphacite, pressure values
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
255 low content of epidote in the metabasite and the suspected former presence of
256 lawsonite, now replaced by anorthite, point to a peak P-T condition in the
257 neighbourhood of the transition from lawsonite- to epidote-blueschist subfacies.
258 According to Zhang et al. (2009), blueschists of NW China crossed this transition
259 during subduction at temperatures close to 350 °C. In Fig.10 the isopleth related to
260 the observed maximum content in jadeite molecula meets the transition line between
261 the two subfacies at a T of c. 330 °C, corresponding to a pressure of c. 0.95 GPa.
262 Lower P estimates (Fig.10) are obtained on the basis of the Na-amphibole
263 composition. By following the calibration of Maruyama et al. (1986) and by plotting
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.

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

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

279

280

281 **5. Discussion and Conclusions**

282 The metasedimentary succession where we have found metabasite, has been
283 differently interpreted through time. According to Trevisan (1950), Barberi et al.
284 (1969), Perrin (1975) and Keller and Pialli (1990), it is considered as part of the
285 sedimentary succession belonging to the Tuscan Domain. Differently, Duranti et al.
286 (1992) and Pertusati et al. (1993) interpreted the ophiolite slice (*i.e.* the oceanic unit
287 1 in Fig. 3) and the underlying metasedimentary succession, where the study
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.

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

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

308 A comparison between P-values obtained for metasediment and metabasite
309 parageneses from other localities of inner Northern Apennines (Fig.1), indicates that
310 the metamorphic peak in metabasites is encompassed between 0.6 and 0.8 GPa (T=
311 275-350°C). Instead, P-values obtained from metasediments range from 0.8 to 1.5
312 GPa (T=350-420°C) in six out of seven localities. Thus it can be inferred that
313 metabasites usually provide peak estimates lower than metasediments.

314 Although in the Elba Island pressure estimate is slightly higher (P=0.9-1.0 GPa;
315 T=330-350°C) than those obtained for the other metabasites, we interpret all the
316 barometric values in the same tectono-metamorphic framework of the inner Northern
317 Apennines. On this basis, the result provided by the Elba Island metabasite has two
318 significant implications: (i) the tectonic stacking of the Elba Island units did not occur
319 in a low-P context, as supposed by Pertusati et al. (1993) and, more recently, by
320 Musumeci and Vaselli (2012); (ii) the Elba Island is now reconciled in the tectonic and

321 metamorphic evolution of the Northern Apennines. Furthermore, it results that its
322 stratigraphic and metamorphic evolution is significantly similar to the one described
323 for the Gorgona Island, suggesting that the interpretation of the Gorgona calcschist as
324 a part of the Piedmont Ocean (Capponi et al., 1990; Pandeli et al., 2001; Rossetti et
325 al., 2001) should be revised.

326 Finally, considering reasonable that the high content of Si in phengite from the Monte
327 Giove area is a further evidence of high-P conditions, it derives that continental units
328 2 and 3 (Fig. 3) have been affected by high P-metamorphism too. Consequently, it
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
332 by the emplacement of the Porto Azzurro monzogranite (Pertusati et al., 1993;
333 Bortolotti et al., 1994).

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

345

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CAPTIONS

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).

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

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

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

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

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.

615

616 Figure 6 - A-B) tight and isoclinal folds with $\approx 304/30$ plunging hinge lines deforming
617 the main 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)
621 and Bucher and Frey (1994). D) SEM-BSE (scanning electron microscopy-back
622 scattered electron) image showing the textural characteristics and paragenesis of
623 micaschists. Mineral abbreviations after after Kretz (1983) and Bucher and Frey
624 (1994).

625

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

631

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

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

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); $Q = \text{wollastonite} + \text{enstatite} + \text{Ferrosilite}$. C) Classification diagram for Ca-Fe-Mg pyroxenes in the metabasite by Morimoto et al. (1988).

Figure 10 - P-T diagram showing approximate metamorphic conditions (circles) for the Elba Island blueschists constrained by mineral assemblage and composition of omphacite (yellow) and glaucophane (lilac). X_{Jd} isopleth calculated with the aid of the Sturtevant (2002) software on the basis of $Ab = Jd + Qtz$ equilibrium calibrated by Holland (1980). X_{Gln} isopleth from calibration by Maruyama et al. (1986). Subfacies boundaries by Tsujimori and Ernst (2013) and some relevant equilibria have been shown. Metamorphic facies and sub-facies abbreviations: L-Bs = lawsonite blueschist; E-Bs = epidote blueschist; Gs = greenschist; E-Am = epidote - amphibolite; Am = amphibolite; Amph-Ec = amphibole eclogite. Mineral stability boundary and equilibria: Gln-in = stability boundary of glaucophane by Maresch (1977); Omph-in = stability boundary of omphacite in a jadeite-enriched MORB (MORB+ in Tsujimori and Ernst, 2013); $Ab = Jd + Qtz$ by Tsujimori and Ernst (2013); $Lws = An + H_2O$ by Crawford and Fyfe (1965). Mineral abbreviations according to Kretz (1983).

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

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

Table 1 - XRF analyses of three metabasites samples.

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

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.

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

Table1

| | C19 | RMT2 | RMT3 |
|--------------------------------|-------|-------|-------|
| wt. % | | | |
| SiO ₂ | 44.84 | 43.60 | 44.15 |
| TiO ₂ | 1.15 | 0.84 | 1.03 |
| Al ₂ O ₃ | 17.04 | 13.72 | 15.23 |
| FeO _t | 10.52 | 7.96 | 9.45 |
| MnO | 0.16 | 0.09 | 0.12 |
| MgO | 9.92 | 7.29 | 9.55 |
| CaO | 6.28 | 12.36 | 9.80 |
| Na ₂ O | 2.10 | 3.49 | 3.11 |
| K ₂ O | 0.58 | 1.04 | 0.59 |
| P ₂ O ₅ | 0.14 | 0.13 | 0.14 |
| L.O.I. | 6.86 | 9.25 | 6.68 |
| Tot | 99.58 | 99.75 | 99.85 |
| ppm | | | |
| Ni | 139 | 91 | 133 |
| Cr | 287 | 199 | 265 |
| V | 193 | 111 | 157 |
| Rb | 40 | 46 | 26 |
| Sr | 234 | 483 | 445 |
| Ba | 21 | 104 | 46 |
| Y | 24 | 17 | 22 |
| Zr | 106 | 91 | 105 |
| Nb | 8 | 7 | 7 |
| La | 23 | 7 | 10 |
| Ce | 70 | 27 | 38 |

Table2

| | <u>Amphiboles</u> | | <u>Clinopyroxenes</u> | | | | <u>Feldspars</u> | | <u>Epidotes</u> | | <u>Chlorite</u> |
|--------------------------------|-------------------|--------|-----------------------|-------|-------|-------|------------------|-------|-----------------|--------|-----------------|
| | Gln | Act | Omph | Agt | Di | Aug | Ab | An | Clz | Ps | |
| wt. % | | | | | | | | | | | |
| SiO ₂ | 58.08 | 57.28 | 55.20 | 54.00 | 51.63 | 52.13 | 68.36 | 42.51 | 39.27 | 37.87 | 30.03 |
| TiO ₂ | 0.22 | 0.03 | 0.10 | 0.01 | 1.00 | 0.03 | 0.01 | 0.01 | 0.12 | 0.06 | 0.02 |
| Al ₂ O ₃ | 9.63 | 1.06 | 7.20 | 3.26 | 2.15 | 4.44 | 19.50 | 36.79 | 32.55 | 22.28 | 20.74 |
| Cr ₂ O ₃ | | 0.04 | 0.28 | 0.19 | 0.02 | | | | 0.02 | 0.09 | 0.03 |
| FeO _t | 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 | 0.30 | 0.13 | 0.23 | 0.19 | 0.22 | | | 0.03 | 0.11 | 0.38 |
| MgO | 10.56 | 18.47 | 7.44 | 9.90 | 15.04 | 14.23 | 0.01 | 0.01 | 0.06 | 0.03 | 20.97 |
| CaO | 1.09 | 11.20 | 11.65 | 15.19 | 21.64 | 13.22 | 0.03 | 19.80 | 23.55 | 22.18 | 0.06 |
| Na ₂ O | 6.16 | 0.86 | 7.34 | 5.33 | 0.36 | 0.35 | 11.68 | 0.05 | 0.01 | 0.03 | 0.01 |
| K ₂ O | 0.02 | 0.03 | 0.04 | 0.04 | 0.03 | 0.11 | | 0.03 | 0.01 | 0.02 | 0.08 |
| Tot | 95.68 | 96.14 | 98.74 | 98.01 | 98.76 | 98.42 | 99.66 | 99.37 | 97.02 | 95.22 | 86.58 |
| ΣO | 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 ^{IV} | | | | | 0.071 | 0.018 | 1.008 | 2.024 | | | 2.014 |
| Al ^{VI} | 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 |
| Mg | 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 |
| K | 0.003 | 0.005 | 0.002 | 0.002 | 0.001 | 0.005 | | 0.002 | 0.002 | 0.004 | 0.020 |
| Fe ³⁺ | 0.266 | 0.024 | 0.175 | 0.227 | 0.017 | | | | | | |
| Fe ²⁺ | 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 _{Gln} | 0.86 | | | | | | | | | | |
| X _{Jd} | | | 0.33 | 0.15 | | | | | | | |
| X _{Wo} | | | | | 0.45 | 0.30 | | | | | |
| X _{En} | | | | | 0.47 | 0.45 | | | | | |
| X _{Fs} | | | | | 0.11 | 0.25 | | | | | |
| X _Q | | | 0.48 | 0.62 | | | | | | | |
| X _{Ae} | | | 0.19 | 0.24 | | | | | | | |
| X _{Ps} | | | | | | | | | 0.09 | 0.82 | |
| X _{An} | | | | | | | 0.00 | 1.00 | | | |
| X _{Ab} | | | | | | | 1.00 | 0.00 | | | |
| X _{Mg} | 0.72 | 0.83 | 0.70 | 0.88 | 0.81 | 0.65 | | | | | |

Table3

| | Metabasite RMT3 | Quartzite RIO6A |
|--------------------------------|--------------------|--------------------|
| wt. % | | |
| SiO ₂ | 52.69 | 51.65 |
| TiO ₂ | 0.15 | 0.19 |
| Al ₂ O ₃ | 24.61 | 23.77 |
| FeO _t | 3.34 | 5.93 |
| MnO | 0.12 | 0.11 |
| MgO | 4.97 | 2.98 |
| CaO | 0.18 | 0.11 |
| Na ₂ O | 0.12 | 0.08 |
| K ₂ O | 9.66 | 10.96 |
| Tot | 95.85 | 95.77 |
| ΣO | 11 | 11 |
| Si | 3.49 | 3.50 |
| Al ^{IV} | 0.50 | 0.50 |
| Al ^{VI} | 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 |
| Na | 0.01 | 0.01 |
| K | 0.81 | 0.94 |
| ΣCat | 6.95 | 7.02 |
| X _{Cel} | 0.50 | 0.50 |

Figure1
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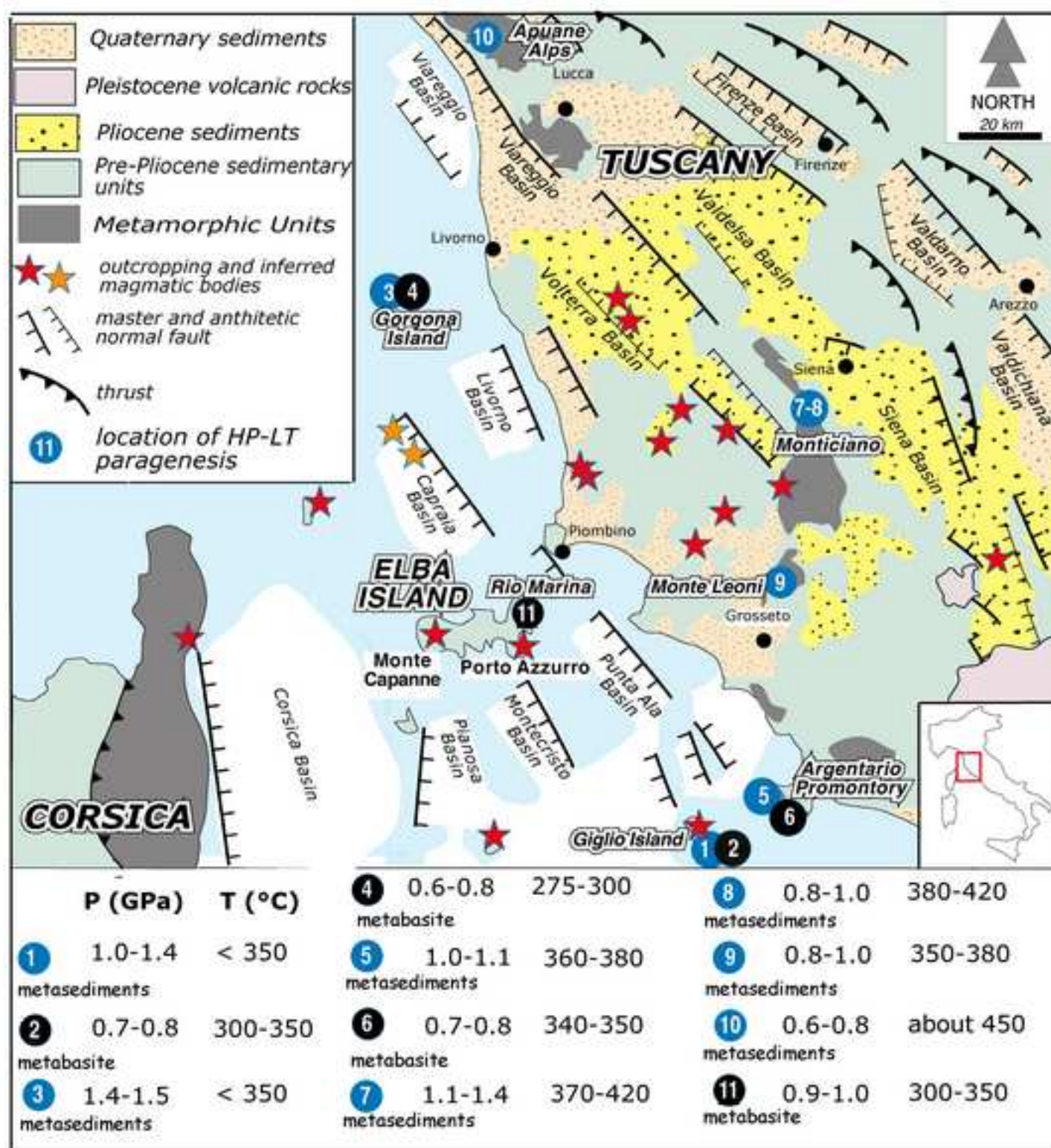


FIGURE 1

Figure2

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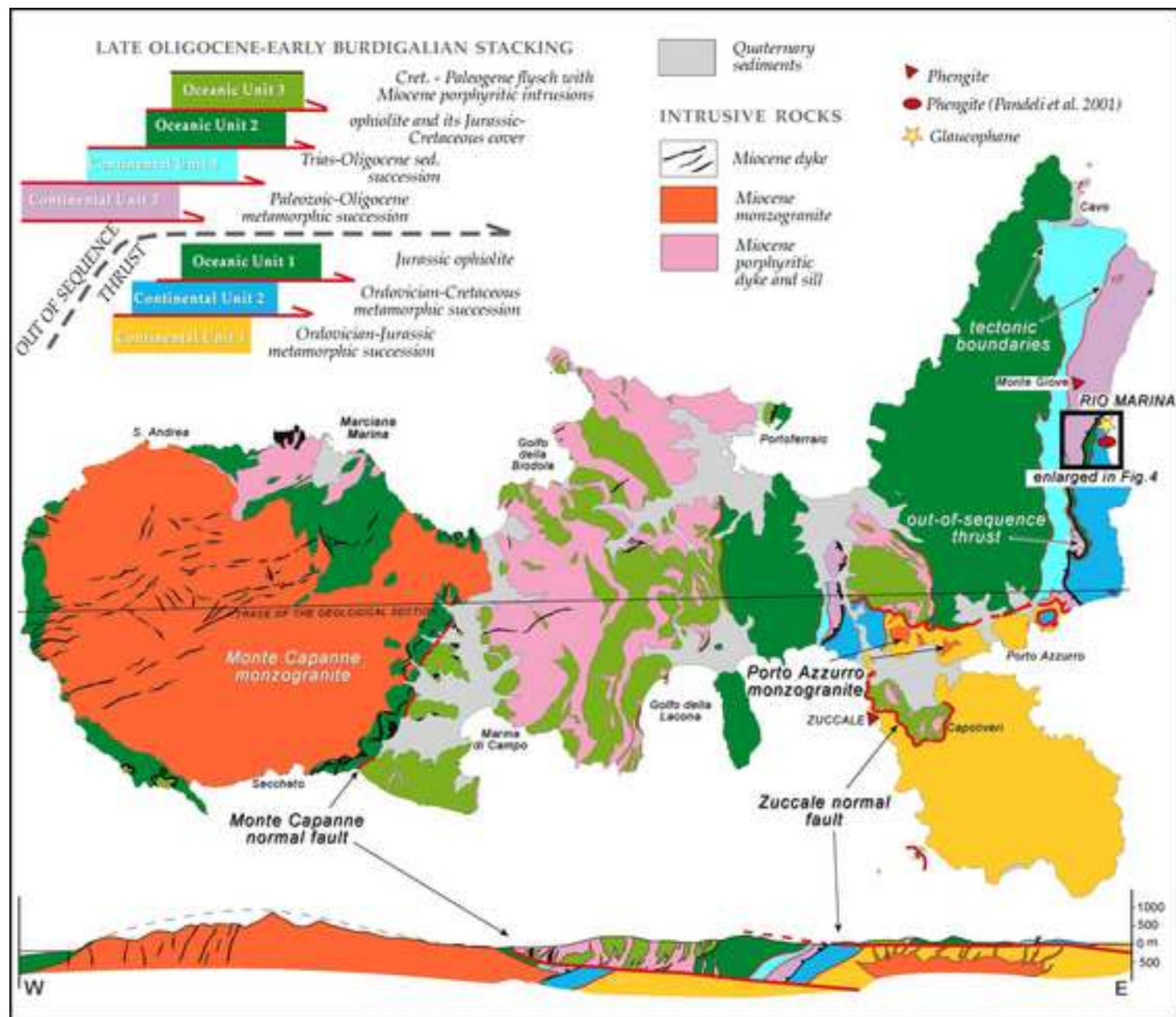


FIGURE 2

Figure3

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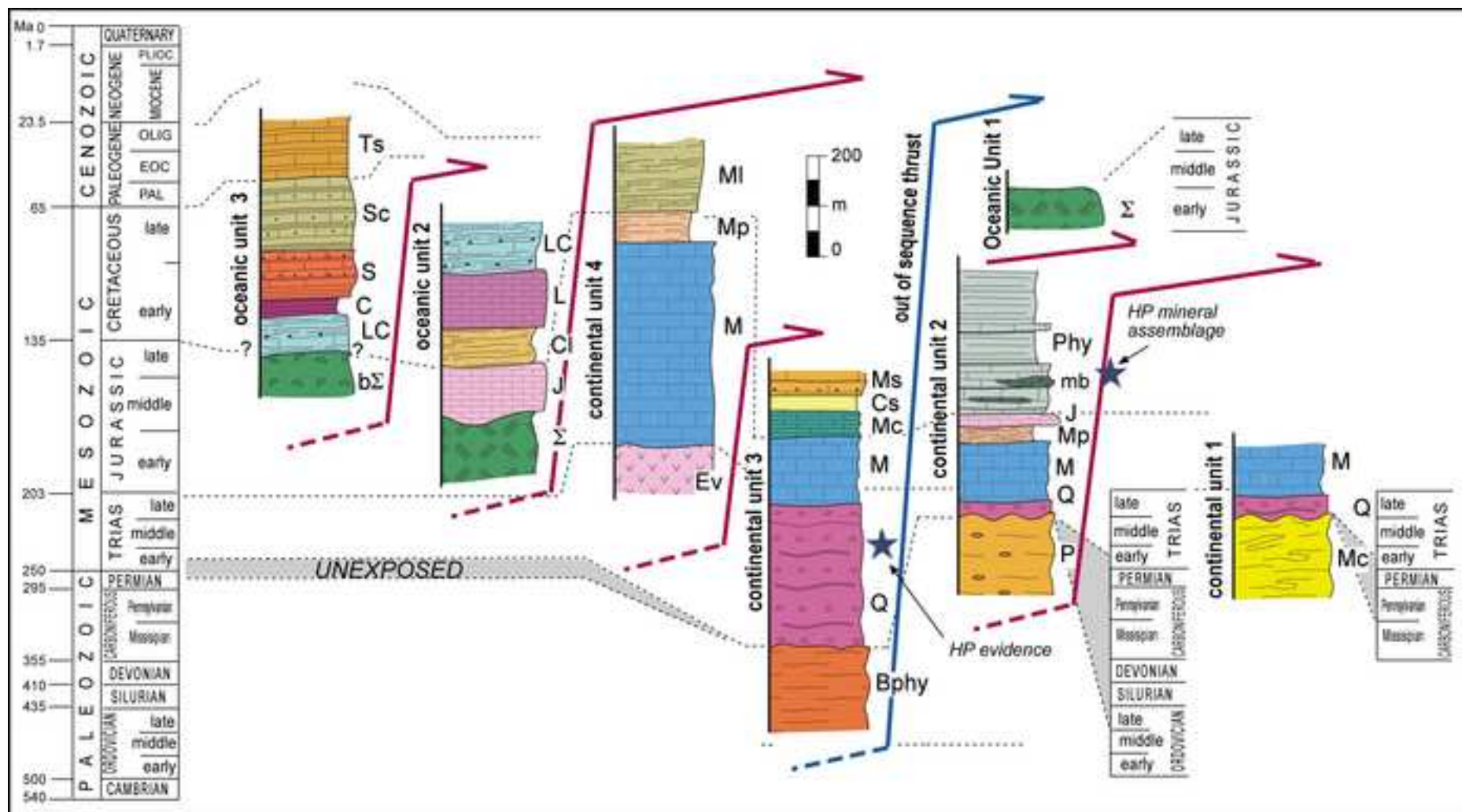


FIGURE 3

Figure4

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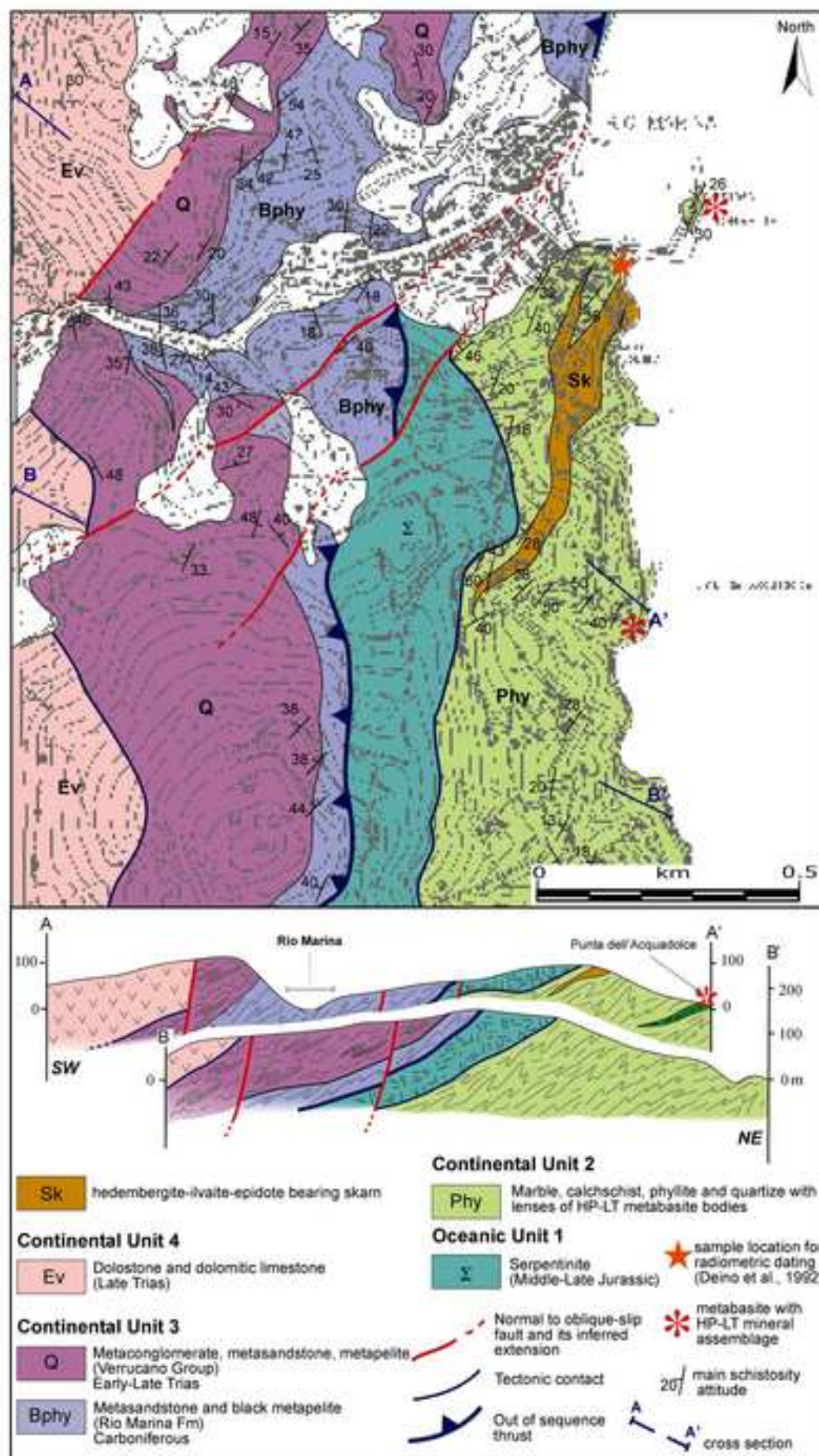


FIGURE 4

Figure5
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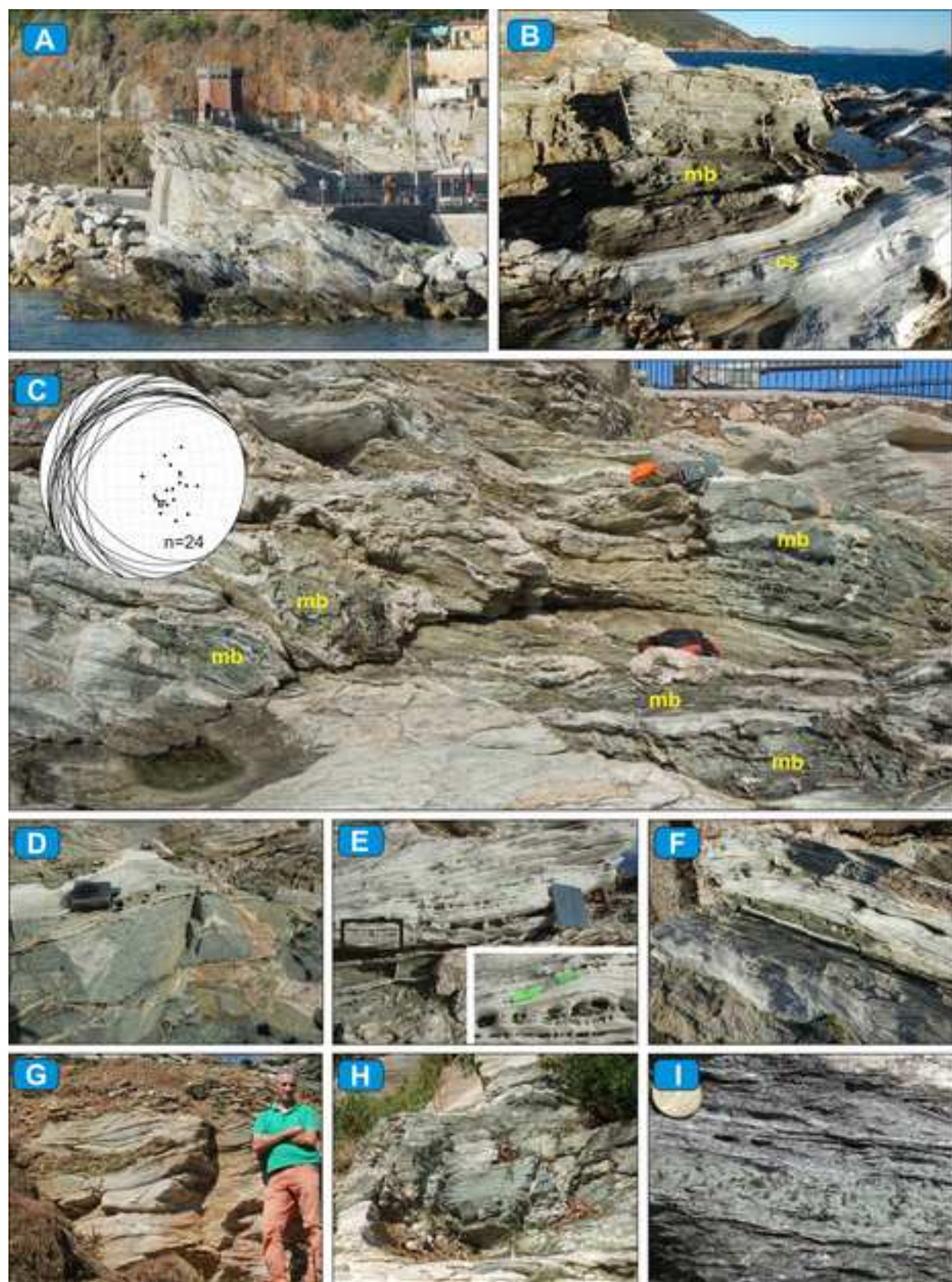


FIGURE 5

Figure6

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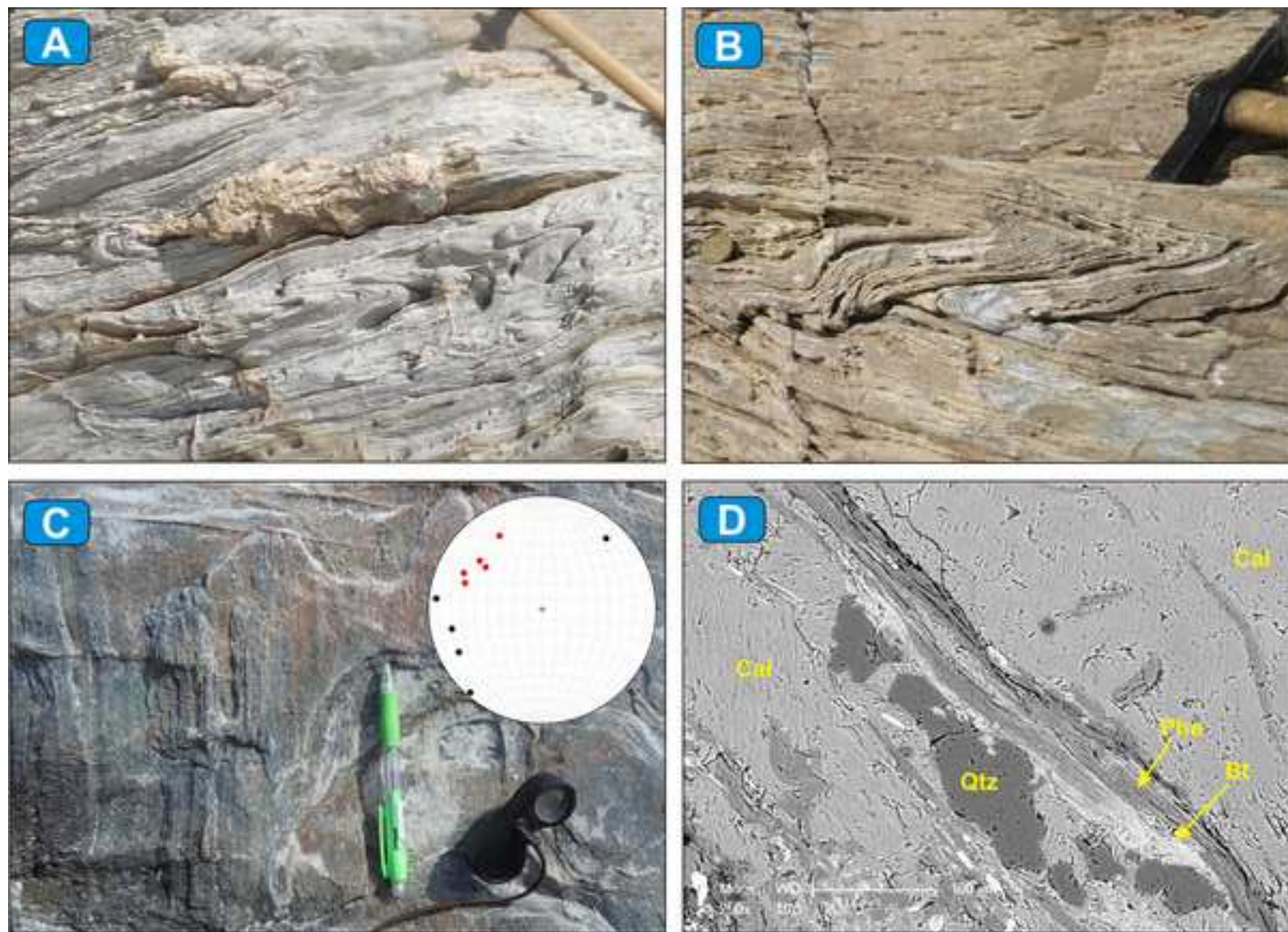


FIGURE 6

Figure7
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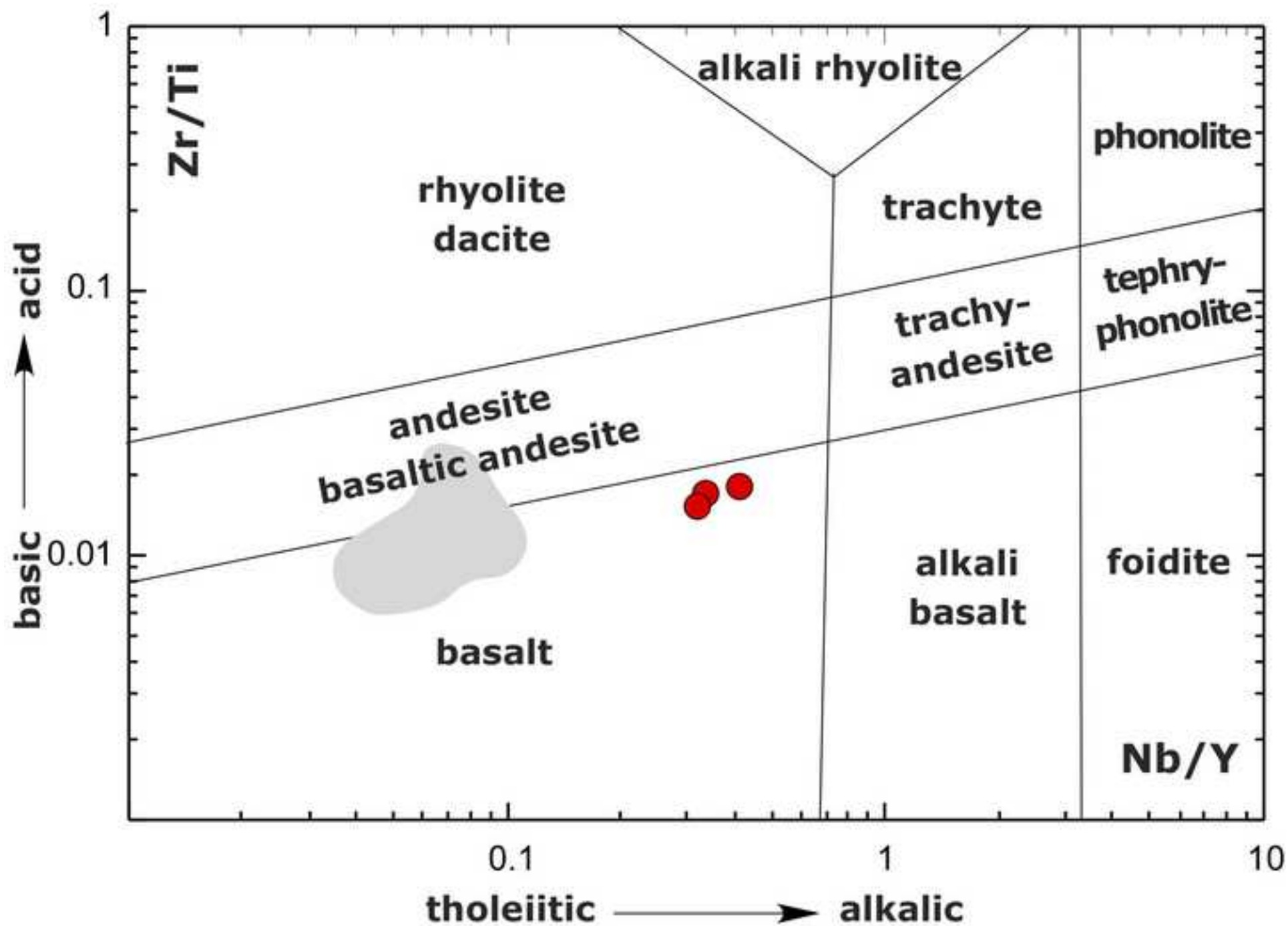


Figure8
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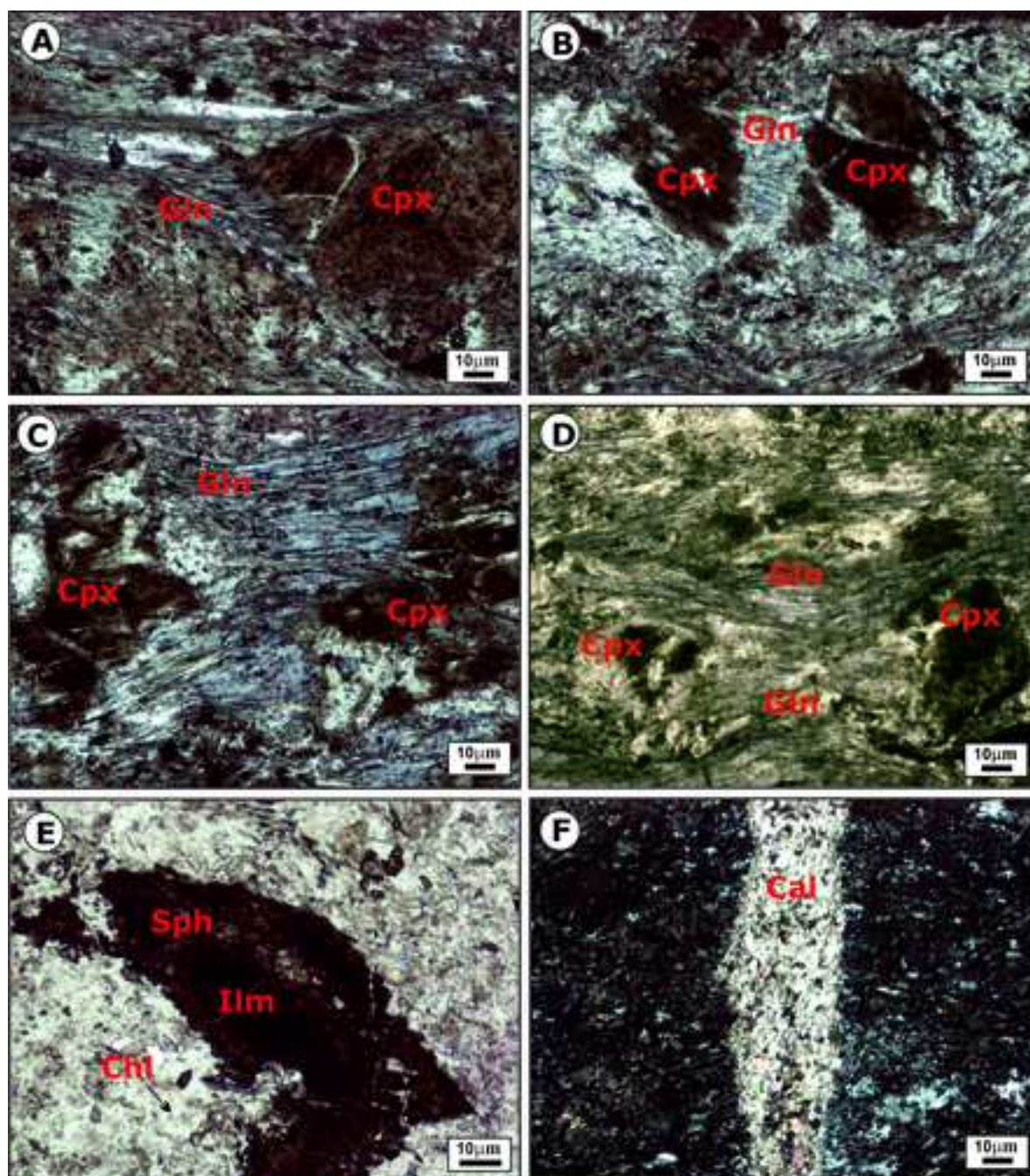


FIGURE 8

Figure9
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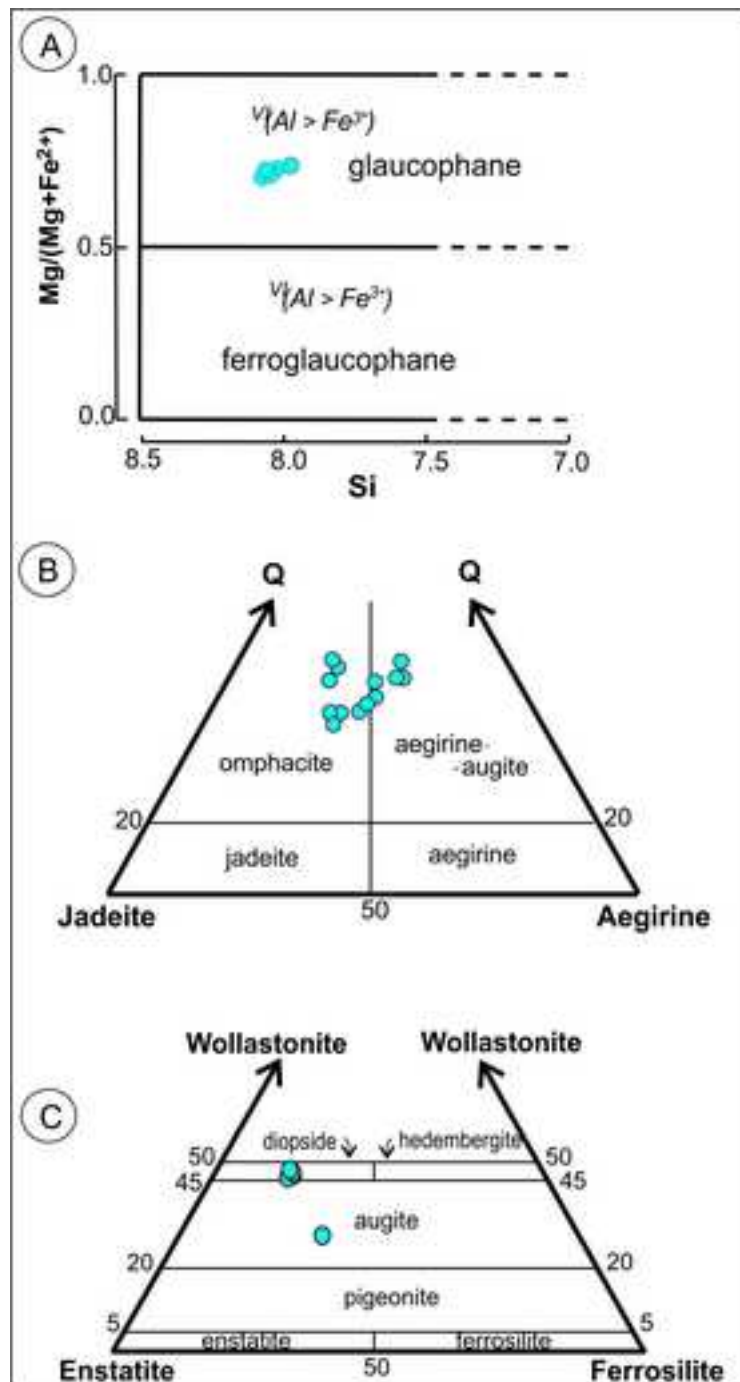


FIGURE 9

Figure10
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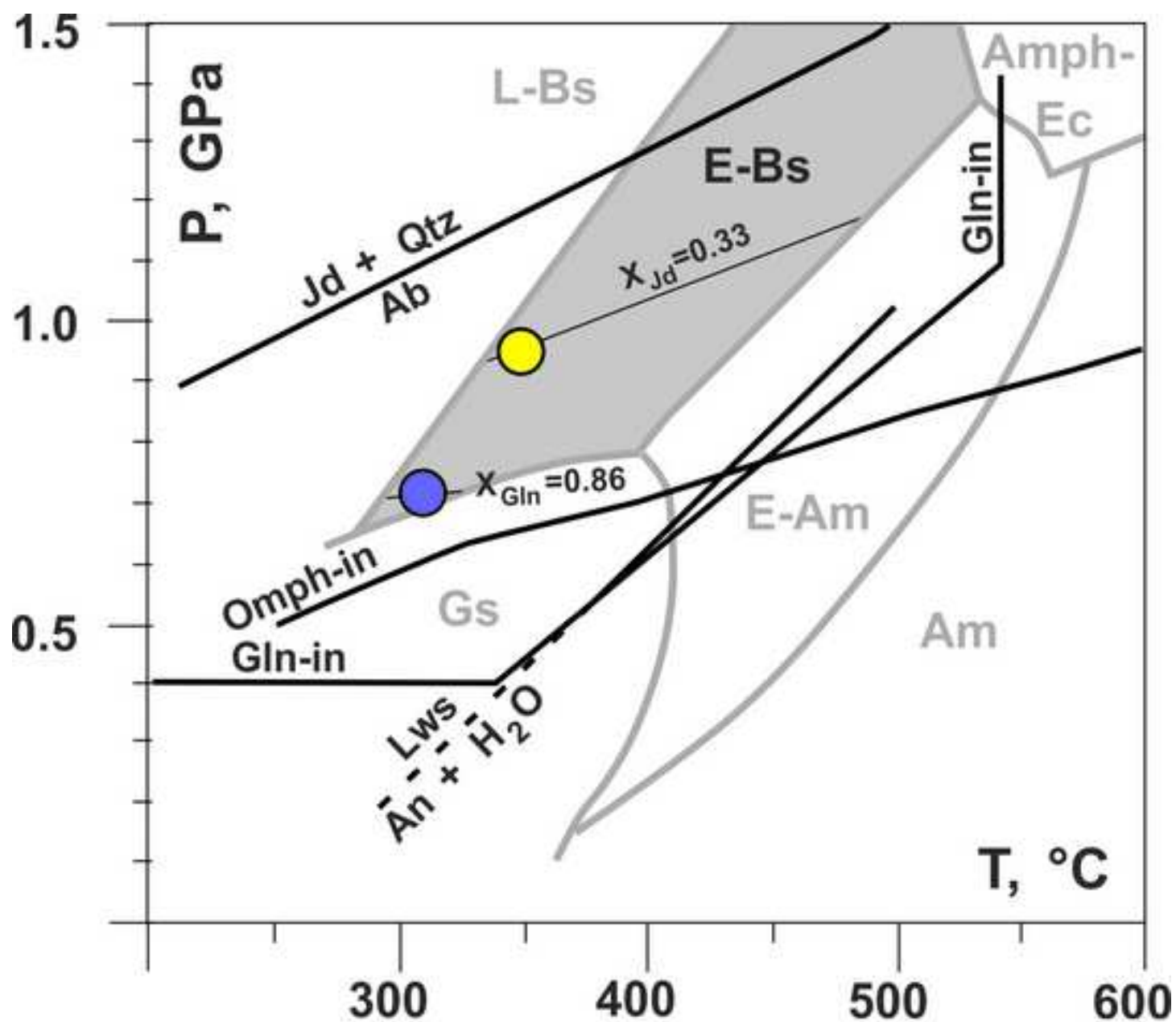


FIGURE 10

Figure11

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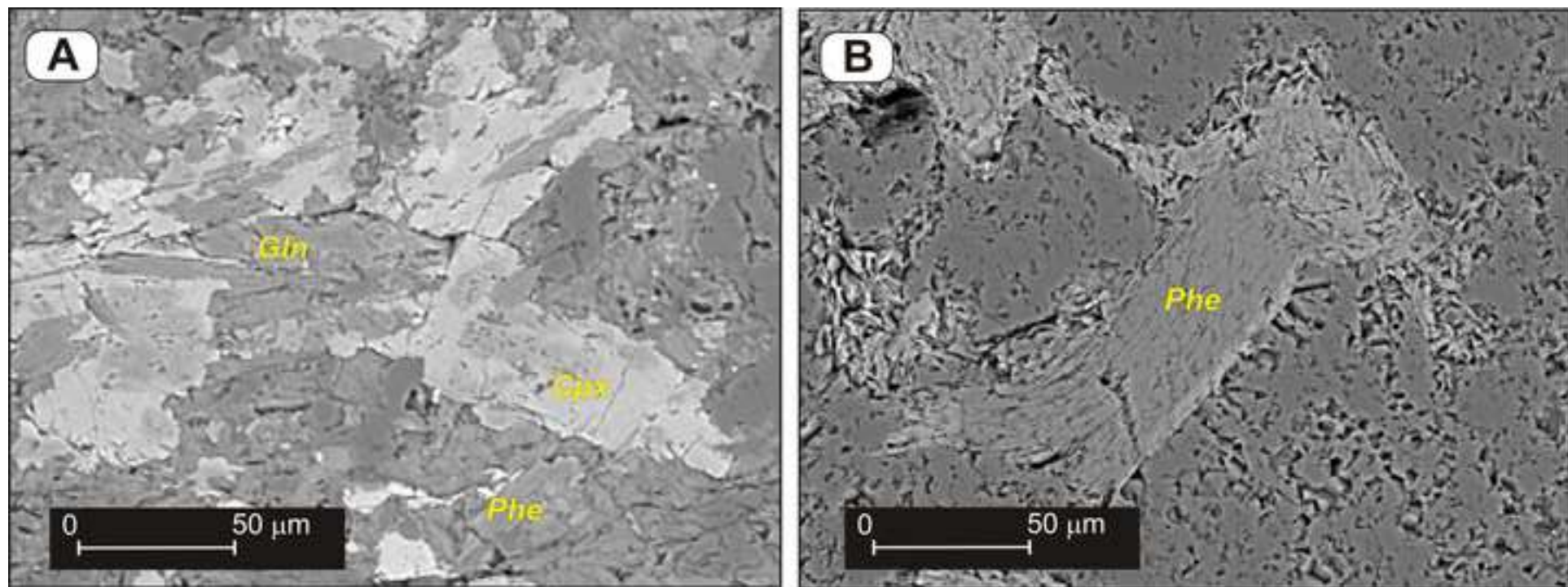


FIGURE 11