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1 Strain localization in a fossilized subduction channel: insights from  
2 the Cycladic Blueschist Unit (Syros, Greece)

3

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14 Abstract:

15

16 Syros Island is worldwide known for its preservation of HP-LT parageneses in the  
17 Cycladic Blueschist Unit (CBU) providing one of the best case-studies to understand the  
18 tectonometamorphic evolution of a subduction channel. Conflicting structural interpretations  
19 have been proposed to explain the geological architecture of Syros, in part reflecting a lack of  
20 consensus about the tectonic structure of the CBU. In this study, the geological and  
21 tectonometamorphic maps of Syros have been entirely redrawn in order to decipher the  
22 structure of a fossilized subduction channel. Based on structural and petrological observations,  
23 the CBU has been subdivided into three subunits separated by major ductile shear zones. New  
24 observations of the Vari Unit confirm that it rests on top of the CBU through a detachment or  
25 exhumation fault. While retrograde top-to-the E/NE shearing overprinting prograde

26 deformation is widespread across the island, the prograde deformation has been only locally  
27 preserved within the less retrograded units. We show that after the prograde top-to-the S/SW  
28 shearing deformation, the CBU was exhumed by an overall top-to-the E/NE shearing from the  
29 depth of the eclogite-facies all the way to the depth of the greenschist-facies and finally, to the  
30 brittle crust. The exhumation process encompassed the syn-orogenic stage (contemporaneous  
31 of subduction, within the subduction channel - Eocene) to the post-orogenic stage  
32 (contemporaneous with the formation of the Aegean Sea - Oligocene to Miocene). From syn-  
33 orogenic to post-orogenic exhumation, deformation progressively localized toward the base of  
34 the CBU, along large-scale ductile shear zones, allowing the preservation of earlier HP-LT  
35 structures and HP-LT metamorphic parageneses. Finally, this study brings new insights on the  
36 tectonometamorphic evolution of a subduction channel showing how strain localizes during  
37 the history of an accretionary complex, both during the prograde and retrograde history.

38

#### 39 Keywords

40 Subduction channel; High-pressure low-temperature metamorphism; Strain localization;  
41 Ductile shear zone; Cycladic Blueschist Unit; Syros Island

42

#### 43 Highlights

- 44 1) New geological and tectonometamorphic maps of Syros (Cyclades, Greece)
- 45 2) The Cycladic Blueschist Unit (CBU) was exhumed by an overall top-to-the east shearing
- 46 3) The CBU was exhumed as separate subunits with distinct P-T evolutions
- 47 4) Exhumation process encompassed syn- to post-orogenic stage
- 48 5) During exhumation, strain localized downward along major extensional shear zones

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## 51 1) Introduction

52

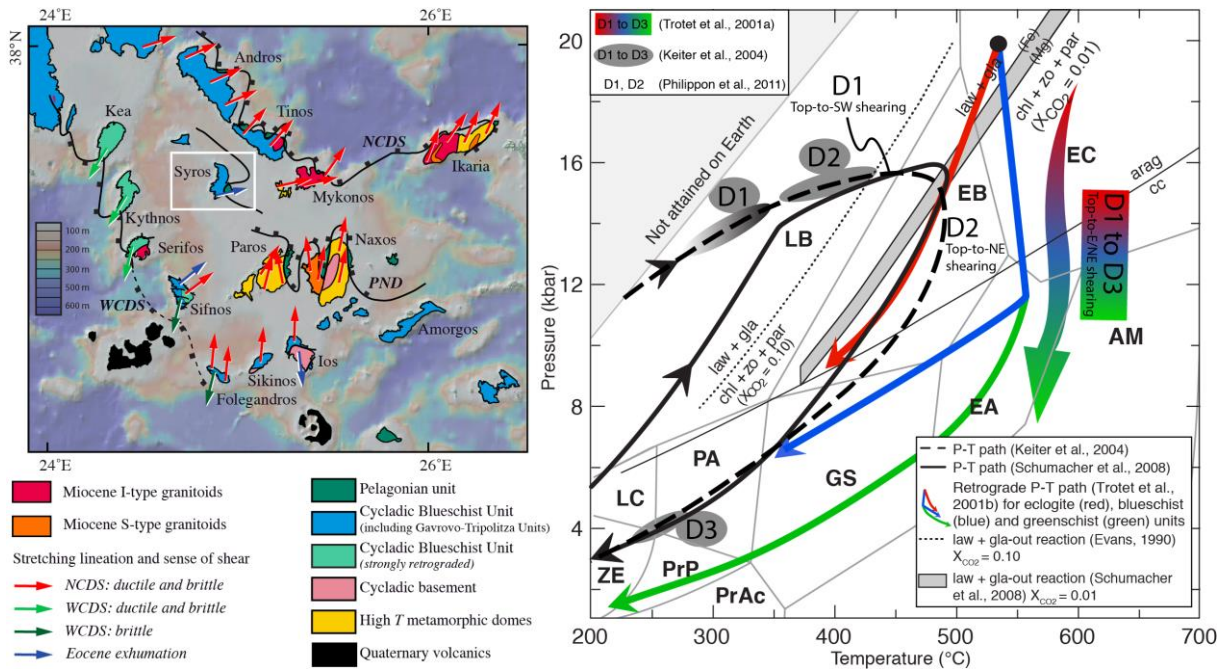
53 High-pressure low-temperature (HP-LT) metamorphic rocks are generally attributed to  
54 former subduction zones. Intense retrograde deformation often overprints the early prograde  
55 events, but in some key-areas, the prograde and metamorphic peak deformation can provide  
56 insights on the tectonometamorphic history of a subduction zone (Alpine Corsica: [Brunet et](#)  
57 [al., 2000](#); [Vitale-Brovarone et al., 2011](#); Norwegian Caledonides: [Austrheim and Griffin,](#)  
58 [1985](#); [Andersen et al., 1994](#); [Labrousse et al., 2004](#); [Terry and Heidelbach, 2006](#); [Raimbourg](#)  
59 [et al., 2005](#); Himalaya: [Burg et al., 1983](#); [Liou et al., 2004](#); [Epard and Steck, 2008](#); New  
60 Caledonia: [Bell and Brothers, 1985](#); Aegean domain: [Keiter et al., 2004, 2011](#); [Philippon et al.,](#)  
61 [2011](#)).

62 The Aegean domain and specifically the Cyclades Archipelago, form a natural  
63 laboratory for studying a former subduction zone. Syros Island, located in the central part of  
64 the Cyclades (Fig. 1a), is worldwide known for its spectacular preservation of deformed HP-  
65 LT metamorphic rocks such as eclogites and is considered to be the type locality of  
66 glaucophane ([Hausmann, 1845](#)). Rocks of this island have been the focus of many  
67 petrological, geochronological and structural studies, leading to different interpretations  
68 regarding: 1) the overall geometry of the CBU, 2) metamorphic peak conditions and 3) the  
69 role of major tectonic contacts (Fig. 1b; [Trotet et al., 2001a, 2001b](#); [Rosenbaum et al., 2002](#);  
70 [Ring et al., 2003](#); [Keiter et al., 2004, 2011](#); [Schumacher et al., 2008](#); [Philippon et al., 2011](#);  
71 [Soukis and Stöckli, 2013](#)). Despite excellent outcropping conditions, these differences are  
72 sometimes drastic, thus hindering our understanding of this classical example of a fossilized  
73 subduction channel.

74 This paper focuses on the tectonometamorphic evolution of the Cycladic Blueschist  
75 Unit. New maps and profiles are here further discussed in terms of their situation within the

76 subduction channel. We demonstrate a progressive top-to-the E/NE continuum of deformation  
 77 from eclogite- to greenschist-facies. Most of the deformation completely overprinted the  
 78 prograde subduction-related deformation. However, we highlight areas where syn-burial  
 79 tectonometamorphic features are preserved. In addition, we confirm the existence of the Vari  
 80 Detachment recently challenged by Philippon et al. (2011) as an extensional detachment  
 81 partly responsible for the exhumation of the CBU. Finally, deep-seated subduction processes  
 82 are then discussed in the framework of the Hellenic subduction zone.

83



84  
 85 Figure 1: Localization of the studied area and Pressure-Temperature-deformation paths of Syros available in  
 86 literature. a) Tectonic map of the Cyclades showing the major tectonic structures such as the North Cycladic  
 87 Detachment System (NCDS), the West Cycladic Detachment System (WCDS) and the Paros-Naxos Detachment  
 88 (PND), as well as kinematic indicators, after Jolivet et al. (2015). b) Representation of the different calculated P-  
 89 T paths for the CBU in Syros. D1, D2 and D3 phases of deformation after Trotet et al. (2001a, 2001b), Keiter et  
 90 al. (2004), Philippon et al. (2011) highlight the conflicting prograde or retrograde interpretations of the main  
 91 deformation observed on Syros. Facies: AM, amphibolite; EA, epidote-amphibolite; EB, epidote-blueschist; EC,  
 92 eclogite; GS, greenschist; LB, lawsonite-blueschist; LC, lawsonite-chlorite; PA, pumpellyite-actinolite; PrAc,  
 93 prehnite-actinolite; PrP, prehnite-pumpellyite; ZE, zeolite (after Peacock, 1993). Lawsonite + glaucophane-out  
 94 reactions after Evans (1990) and Schumacher et al. (2008).

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## 99 2) Geological setting

100

### 101 2.1) Tectonometamorphic evolution of the Cycladic Blueschist Unit

102

103         The Aegean domain, part of the eastern Mediterranean Sea, experienced a two steps  
104 tectonometamorphic evolution. Firstly, the late Cretaceous-Eocene formation of the  
105 Hellenides-Taurides chain resulted from the subduction and collision of the Apulian  
106 microcontinent with Eurasia (Bonneau and Kienast, 1982; Dercourt et al., 1986; van  
107 Hinsbergen et al., 2005). The entrance of the Apulian crust in the subduction zone led to an  
108 episode of crustal thickening and syn-orogenic exhumation of HP-LT metamorphic units such  
109 as the Cycladic Blueschist Unit (CBU; Fig. 1a; Blake et al., 1981; Bonneau and Kienast, 1982;  
110 Jolivet et al., 2003, 2004; Brun and Faccenna, 2008; Jolivet and Brun, 2010; Ring et al., 2010).  
111 Secondly, post-orogenic extension in the Rhodope from 45 Ma and in the Aegean Sea from  
112 35 Ma was associated with the retreat of the African slab (Jolivet and Faccenna, 2000; Brun  
113 and Sokoutis, 2010; Jolivet and Brun, 2010; Ring et al., 2010). In the Aegean domain, part of  
114 western Anatolia and in the Rhodope Massif, back-arc extension of the previously thickened  
115 crust was accommodated by several regional-scale detachments such as the North Cycladic  
116 Detachment System (NCDS) or the West Cycladic Detachment System (WCDS) (Fig. 1a;  
117 Jolivet et al., 2010; Grasemann et al., 2012).

118         Located in the center of the Aegean domain, the Cyclades correspond to the deepest  
119 exhumed parts of the Hellenides-Taurides chain and are mainly composed by the CBU (Fig.  
120 1a). This unit is mainly made of marbles, metapelites and metabasites all showing peak P-T  
121 conditions in the blueschist- or eclogite-facies (Blake et al., 1981; Bonneau, 1984; Okrush and  
122 Bröcker, 1990; Avigad and Garfunkel, 1991; Trotet et al., 2001b; Schumacher et al., 2008).  
123 The CBU experienced alpine tectonic and metamorphic evolution, with an early burial in HP-

124 LT conditions reaching ~18-20 kbar and 500-550 °C (Fig. 1b; Dürr et al., 1978; Bröcker and  
125 Enders, 2001; Trotet et al., 2001b; Parra et al., 2002; Tomaschek et al., 2003; Augier et al.,  
126 2015) during the Eocene (~50-35 Ma; Tomaschek et al., 2003; Putlitz et al., 2005; Lagos et al.,  
127 2007). During the Oligocene and for the whole Miocene, this event was followed by LP-HT  
128 greenschist- to amphibolite-facies overprint of variable intensity (Fig. 1a; Altherr et al., 1979,  
129 1982; Wijbrans and McDougall, 1986; Buick, 1991; Keay et al., 2001; Vanderhaeghe, 2004;  
130 Duchêne et al., 2006; Bröcker et al., 2013; Beaudoin et al., 2015). On top of the CBU, the  
131 Upper Cycladic Unit (UCU) corresponds to the uppermost parts of the nappe stack. The UCU  
132 is composed of Permian to Mesozoic metasediments, minor orthogneisses and ophiolites  
133 equilibrated in greenschist- to amphibolite-facies metamorphic conditions during the  
134 Cretaceous, sometimes covered with Oligocene to Miocene sediments (Sanchez-Gomez et al.,  
135 2002; Kuhlemann et al., 2004; Lecomte et al., 2010; Menant et al., 2013). Structurally below  
136 the CBU, the Cycladic Continental Basement (CCB) crops out as large-scale tectonic  
137 windows on several islands in the central and southern part of the Cyclades (Fig. 1a; e.g.  
138 Paros, Naxos, Ios or Sikinos; Andriessen et al., 1987). This unit is composed of Variscan  
139 orthogneisses enveloped by metasediments that locally retain metamorphic relics of  
140 amphibolite-facies assemblages suggesting a complex pre-alpine history (Bonneau and  
141 Kienast, 1982; Andriessen et al., 1987; Keay, 1998; Photiades and Keay, 2003; Gupta and  
142 Bickle, 2004; Huet et al., 2009; Augier et al., 2015). Late exhumation stages of both the CBU  
143 and the CCB were accompanied by emplacement of syn-tectonic Miocene intrusions (i.e.  
144 Tinos, Mykonos, Ikaria, Naxos, Serifos, Lavrio; Fig. 1a; Jansen, 1973; Altherr et al., 1982;  
145 Faure et al., 1991; Lee and Lister, 1992; Altherr and Siebel, 2002; Pe-Piper et al., 2002;  
146 Grasmann and Petrakakis, 2007; Iglseider et al., 2009; Bolhar et al., 2010; Lecomte et al.,  
147 2010; Stouraiti et al., 2010; Denèle et al., 2011; Laurent et al., 2015; Rabillard et al., 2015).

148

## 149 2.2) Geology of Syros

150

151 Located in the central part of the Aegean domain, Syros is mainly composed by the  
152 CBU except for the Vari Unit (Fig. 2a). Vari Unit, composed of greenschist mylonites and  
153 orthogneiss, corresponds to a distinct tectonic unit attributed to UCU, separated from the CBU  
154 by the Vari Detachment (Trotet et al., 2001a; Keiter et al., 2004, 2011; Soukis and Stöckli,  
155 2013). The basal part of the CBU crops out in the southwestern part of the island and is  
156 mainly composed of albitic micaschists and rare gneisses (e.g. the Komito gneiss; Fig. 2a;  
157 Hecht, 1985). Structurally above, the central part of Syros is dominated by alternating  
158 sequences of marble and micaschist layers (Fig. 2a). In this area, metabasites are a minor  
159 component and often occur as dismembered boudins intercalated within the metamorphic  
160 series. Conversely, in other parts of the island and especially in the north, metabasites form  
161 the dominant lithology and often occur as kilometer-scale massive bodies (e.g. Hecht, 1985;  
162 Keiter et al., 2004, 2011; Philippon et al., 2011). Metabasites are locally turned into massive  
163 eclogite-facies rocks but also occur as blueschist- or greenschist-facies rocks (Trotet et al.,  
164 2001a).

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## 166 2.3) Pressure-Temperature-time evolution

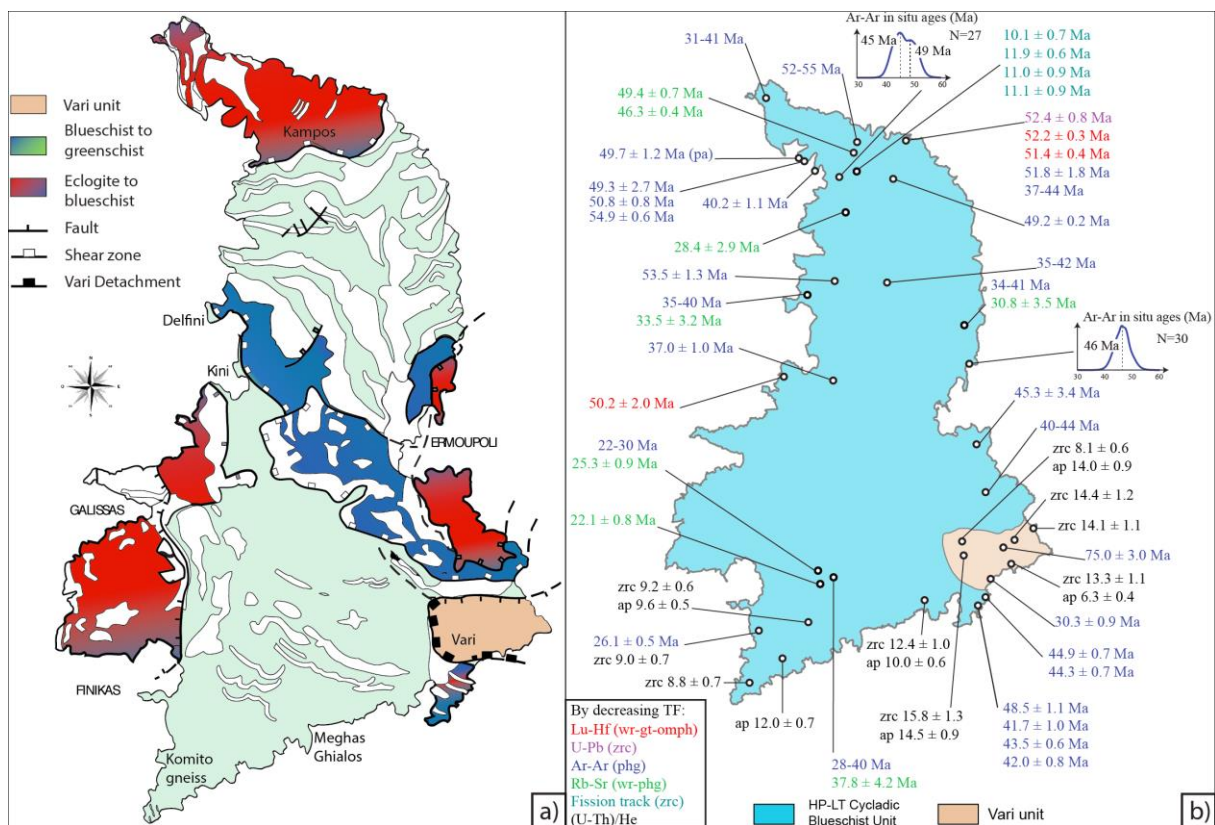
167

168 Petrological studies yielded contrasting estimates for metamorphic peak conditions  
169 from 15-16 kbar and 500°C (Schliestedt et al., 1987; Okrusch and Bröcker, 1990; Avigad and  
170 Garfunkel, 1991; Schmädicke and Will, 2003; Schumacher et al., 2008) to 19-20 kbar and  
171 525-550°C (Fig. 1b; Trotet et al., 2001b; Groppo et al., 2009; Dragovic et al., 2012; Ashley et  
172 al., 2014). Timing and duration of this subduction-related P-T evolution have been quite well  
173 constrained since the 1980s, using a large panel of isotopic systems such as K-Ar,  $^{40}\text{Ar}/^{39}\text{Ar}$ ,



174 Rb-Sr, U-Pb, Lu-Hf, Sm-Nd systems on various minerals (Fig. 2b; Altherr et al., 1979, 1982;  
 175 Andriessen et al., 1979; Wijbrans and McDougall, 1986; Maluski et al., 1987; Wijbrans et al.,  
 176 1990; Bröcker et al., 1993, 2013; Bröcker and Franz, 1998, 2006; Bröcker and Enders, 1999;  
 177 Tomaschek et al., 2003; Putlitz et al., 2005; Lagos et al., 2007; Huet, 2010; Dragovic et al.,  
 178 2012). Studies attempting to date the burial culmination led to ca. 53-49 Ma ages (Tomaschek  
 179 et al., 2003; Putlitz et al., 2005; Lagos et al., 2007). Then, the retrogression in the greenschist-  
 180 facies has been dated between 25 and 21 Ma (Bröcker et al., 2013). Final exhumation stages  
 181 of the CBU were recently constrained by low-temperature thermochronological tools between  
 182 12 and 8 Ma (Fig. 2b; Ring et al., 2003; Soukis and Stöckli, 2013).

183



184

185 Figure 2: Previous geological and geochronological works on Syros. a) Metamorphic map of Syros showing the  
 186 main tectonic structures, after Trotet et al. (2001a). b) Compilation of previous geochronological data calculated  
 187 after U-Pb (Bröcker & Enders, 1999; Tomaschek, et al., 2003), Lu-Hf (Lagos, et al., 2007), <sup>40</sup>Ar/<sup>39</sup>Ar (Maluski et  
 188 al., 1987; Tomaschek, et al., 2003; Putlitz et al., 2005; Huet, 2010; Bröcker et al., 2013), Rb-Sr (Bröcker &  
 189 Enders, 2001; Bröcker et al., 2013), (U-Th)/He (Soukis and Stöckli, 2013) and fission track methods (Ring et al.,  
 190 2003).

191

192

## 193 2.4) Main controversies

194

195 The relative importance of the prograde and retrograde deformations, compression *vs*  
196 extension, syn-orogenic *vs* post-orogenic exhumation is still debated. Hecht (1985) elaborated  
197 the geological map of Syros at the scale 1: 50000 and interpreted all basal contacts of  
198 metabasites as tectonic, mostly as thrusts, contradicting the initial interpretation of metabasite  
199 occurrences as olistoliths within a flysch sequence (Bonneau et al., 1980a, 1980b; Blake et al.,  
200 1981). Recently, Keiter et al. (2011) remapped the entire island at the scale 1: 25000. These  
201 authors argued that an important result of their study is the identification of a significant late  
202 brittle deformation on Syros that was so far poorly constrained. In parallel, Philippon et al.  
203 (2011) reinterpreted the geological map of Syros, based on the original map of Hecht (1985).  
204 These authors disconfirmed the existence of the Vari Detachment, correlating the Vari and  
205 Komito gneisses and repositioning the Vari Unit at the base of the CBU. Soukis and Stöckli  
206 (2013) challenged this conclusion, restoring the original interpretation of Gautier (1995),  
207 Trotet et al. (2001a) or Ring et al. (2003), thus recognizing the juxtaposition of the Vari Unit  
208 onto the CBU by the Vari Detachment. A second controversy relates to the regional and  
209 tectonic significance of the deformation recorded by HP-LT rocks. According to Trotet et al.  
210 (2001a), the main deformation phase is retrograde and was acquired during exhumation of the  
211 CBU from eclogite- to greenschist-facies (D1 to D3; Fig. 1b). For these authors, exhumation  
212 occurred during a continuum of top-to-the E/NE shearing deformation from the early Eocene  
213 (syn-orogenic exhumation) to the early Miocene (post-orogenic exhumation). In contrast,  
214 Keiter et al. (2004, 2011) interpreted the main deformation event affecting the CBU as  
215 prograde, implying therefore a rigid body exhumation of the whole structure (D1 to D3; Fig.  
216 1b). Finally, Philippon et al. (2011) describe two distinct ductile phases of deformation (Fig.

217 1b), i) a first top-to-the SW prograde deformation (D1) and, ii) a second extensional top-to-  
218 the NE penetrative shear (D2) affecting the entire CBU.

219 As long as these discrepancies are not addressed, the deep processes and long-term  
220 evolution of the CBU in the subduction channel will remain poorly understood.

221

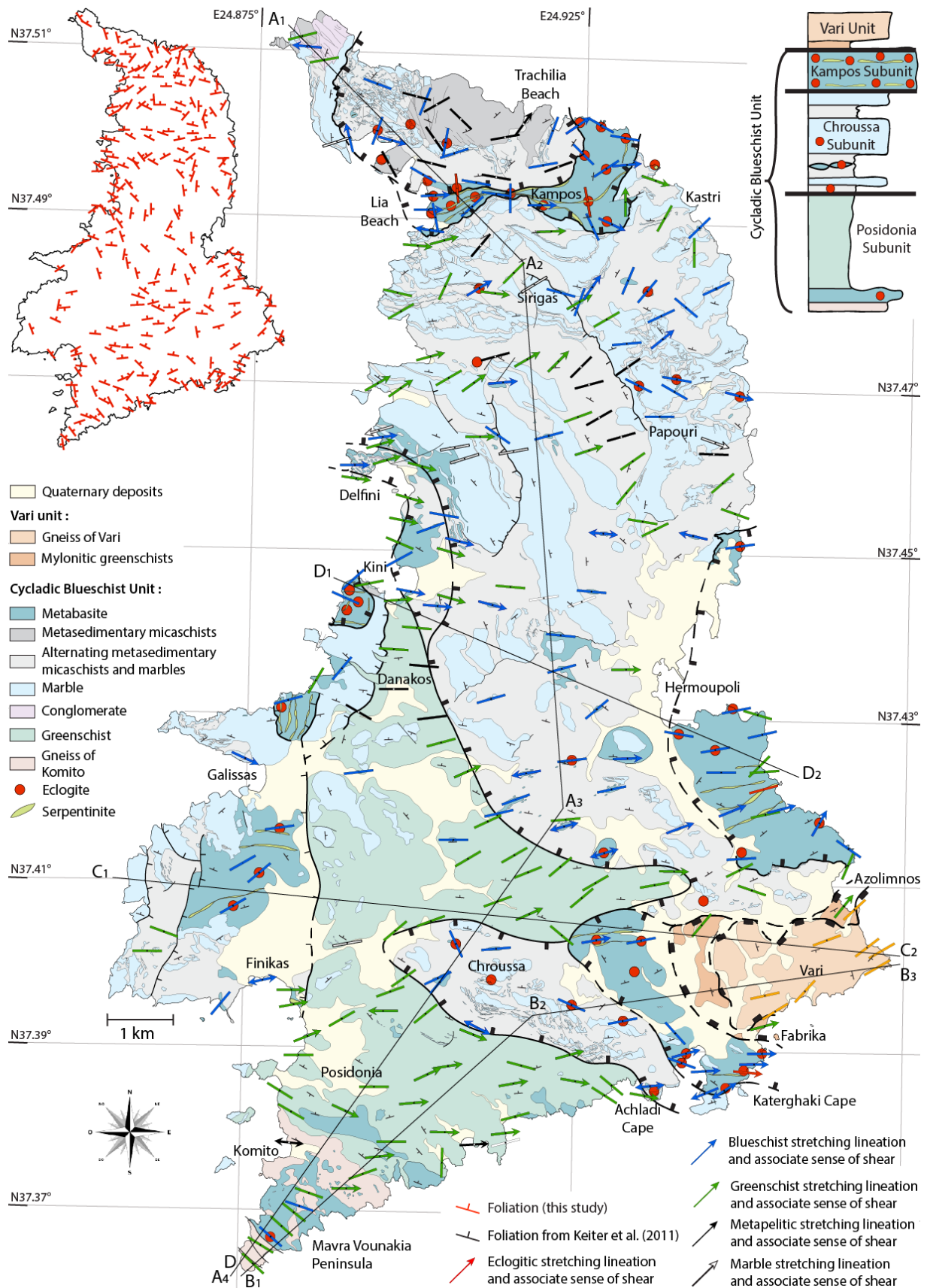
### 222 3) A new geological map of Syros

223

#### 224 3.1) Method and mapping technique

225

226 In order to complement existing geological maps and put constraints on the geometry  
227 of Syros, the whole island has been remapped based on field observations and satellite-images  
228 interpretation (Fig. 3). Lithology and tectonic boundaries have been redrawn following our  
229 observations all over the island. For mutual comparison, the color code of the legend is the  
230 same as in the geological map of Keiter et al. (2011), with simplified lithologic subdivisions  
231 for the purpose of our tectonometamorphic study. Calcitic and dolomitic marbles were  
232 merged together into a unique metacarbonate comprehensive unit. Similarly, further  
233 subdivisions within the mafic protoliths were abandoned. Anyway, principal occurrences of  
234 serpentinite and eclogite are reported on the map (Fig. 3). Additionally, the finite strain  
235 markers were studied as well as the link with the metamorphic record. Results are given on  
236 figure 3.



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Figure 3: New geological map of Syros showing the main tectonic structures and lithologic distributions (geometry of the Vari Unit after Soukis and Stöckli, 2013). Cross-sections are traced with black lines and highlight the architecture of Syros. Planar (foliation planes) and linear (stretching lineations) fabrics are represented with their associated metamorphic facies. Also shown are the localities cited in the text.



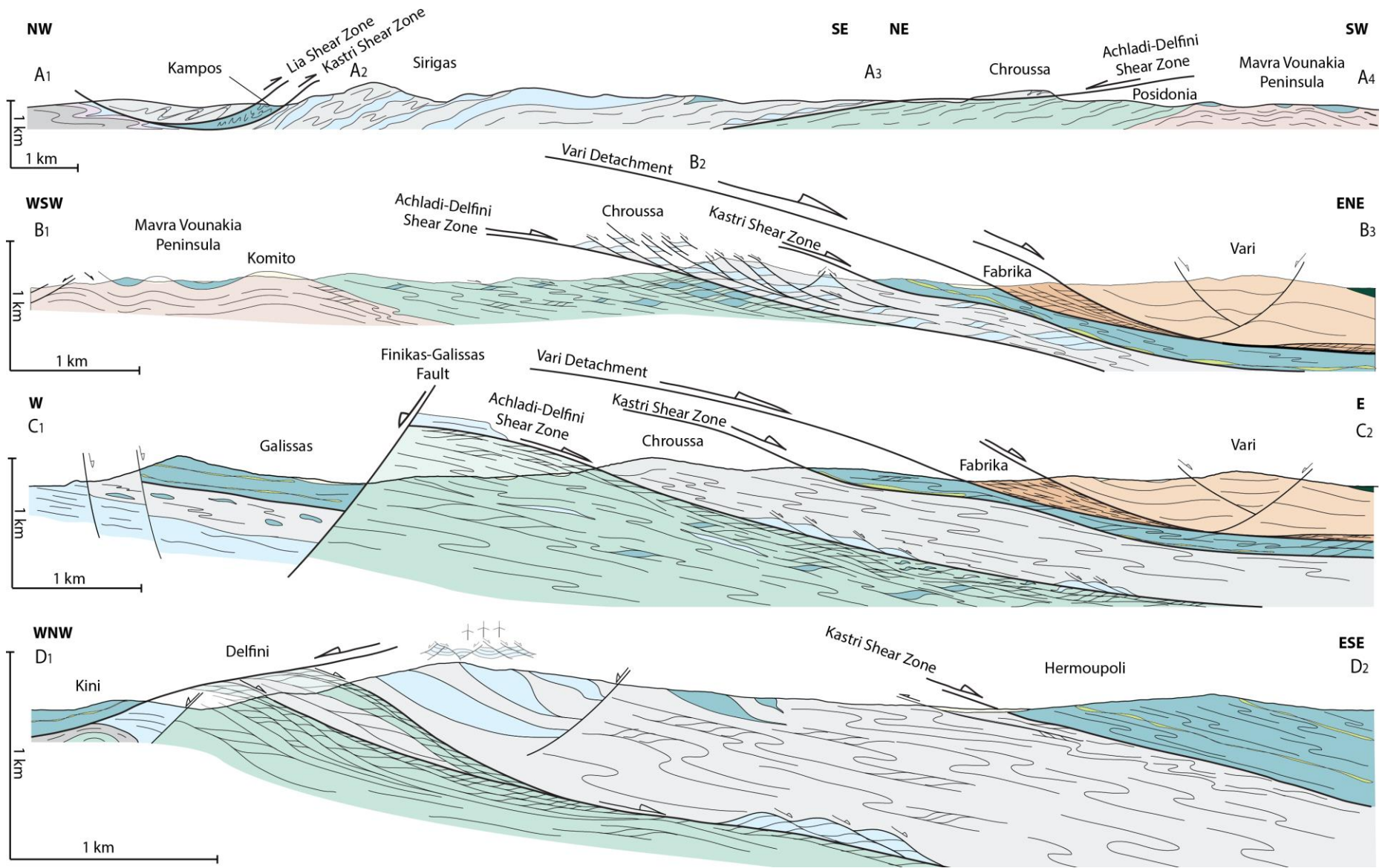


Figure 3 (continue)

### 244 3.2) Large-scale structure

245

246 From a lithological point of view, our new geological map does not significantly differ  
247 from the one of Keiter et al. (2011) with only few areas where minor changes are reported; the  
248 map thus seems relatively robust. As examples of differences, we highlight larger outcrops of  
249 metabasites in several parts of the island, like in Mavra Vounakia peninsula or near the  
250 Delfini Bay (Fig. 3).

251 The most obvious changes are related to the structural aspects in a broad sense, and  
252 particularly the way the metamorphic sequence is structured in coherent units. Our approach  
253 consisted first in the identification of high strain zones (i.e. major shear zones) where  
254 deformation is concentrated, and second, in the recognition of subunits characterized by their  
255 lithological content and metamorphic record. This mapping approach allows us redefining the  
256 stack of the CBU, subdividing it in three subunits delimited by major shear zones, which are  
257 from bottom to top:

258 1) Posidonia Subunit, which is lithologically subdivided in two parts: the structurally lower  
259 felsic gneiss of Komito with intercalated boudins of metabasite, overlain by albitic  
260 micaschists, few metabasites and thin marble layers (Fig. 3). The entire basal unit has been  
261 overprinted in the greenschist-facies with only few areas preserving high-pressure relics in  
262 centimeter-scale mafic boudins (Fig. 3). The Achladi-Delfini Shear Zone delimits the  
263 Posidonia Subunit from the upper Chroussa Subunit.

264 2) Chroussa Subunit, which is composed of a lithostratigraphic sequence of alternating  
265 micaschists, thick marble layers and metabasites (Fig. 3). Although some areas are more  
266 overprinted in the greenschist-facies, blueschist-facies parageneses are well preserved in this  
267 subunit. Fresh eclogites are sometimes preserved in the core of metabasic boudins of any  
268 scale (Fig. 3). The Kastri Shear Zone delimits the Chroussa Subunit from the upper Kampos

269 Subunit.

270 3) Kampos Subunit, which is mainly composed of a mélange of metabasites, including  
271 metagabbros, metabasalts, and locally still visible remains of metapillow-lavas (see [Keiter et](#)  
272 [al., 2011](#) for details) wrapped by strongly foliated metapelites and/or serpentinites. Within this  
273 subunit, eclogite- and blueschist-facies parageneses are preserved, with only few narrow  
274 zones overprinted in the greenschist-facies (Fig. 3). The Vari Detachment delimits the top of  
275 Kampos Subunit, and at larger scale the entire CBU, from the upper Vari Unit.

276 Finally, the Vari Unit is formed from bottom to top by a greenschist mylonitic unit and  
277 the gneiss of Vari intruding amphibolite-facies metabasites (see also Soukis and Stöckli,  
278 2013). High-pressure rocks were not recognized in the Vari Unit.

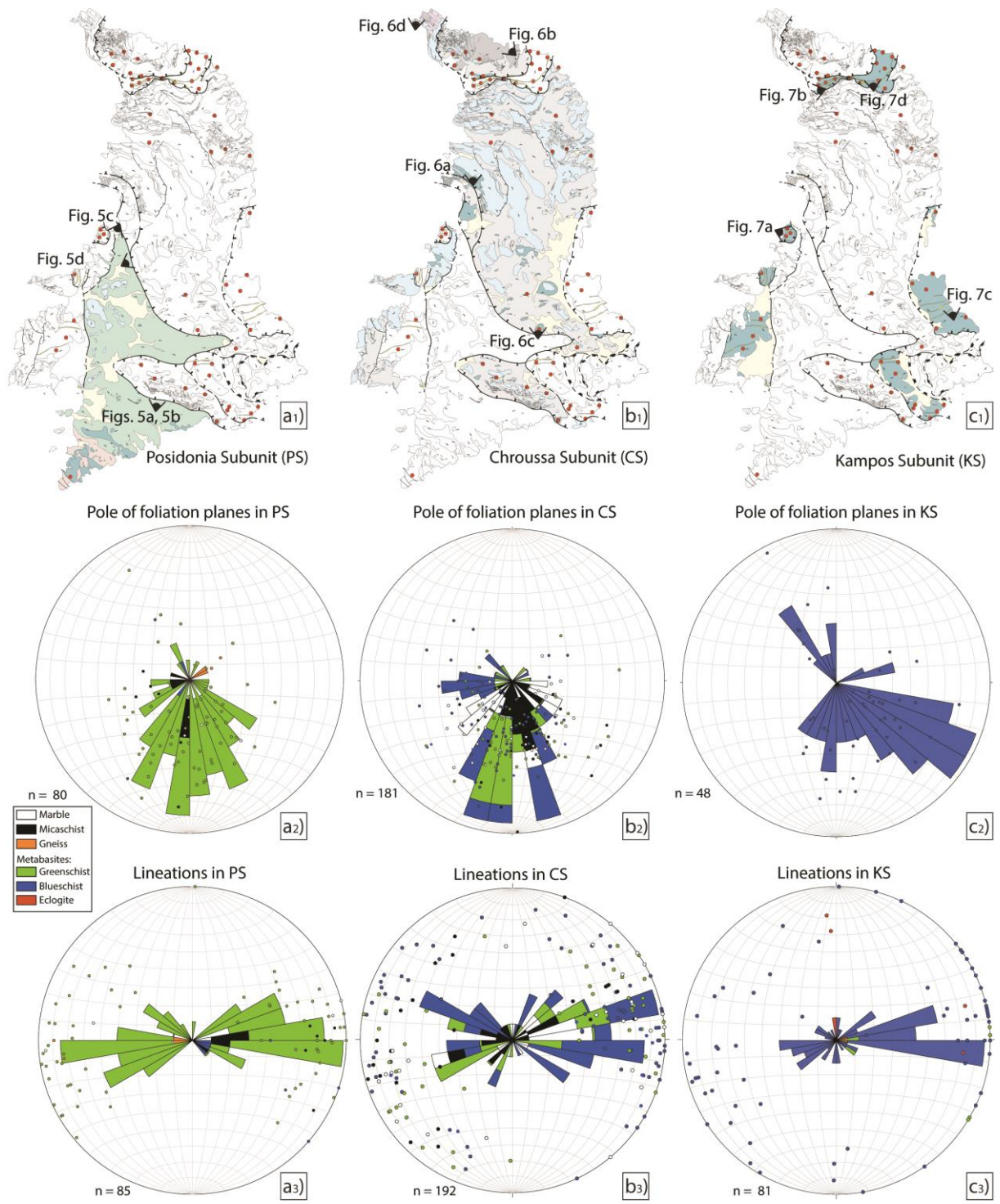
279

280 4) Deformation and metamorphic record in the CBU

281

282 Finite strain markers were studied throughout the island. In parallel, physical conditions  
283 of the deformation were evaluated by the recognition of syn-kinematic minerals in  
284 metabasites and other types of lithologies. All three subunits experienced HP-LT imprint in  
285 the eclogite-facies conditions. This initial record is however unevenly distributed. In this  
286 section we explore the relationships between the preservation/retrogression of HP-LT  
287 parageneses and the relative intensity of deformation.

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Figure 4: Stereograms of the planar and linear fabric measured on Syros and their associated metamorphic facies or lithology if mineralogy does not allow identifying the metamorphic-facies. a<sub>1</sub>, b<sub>1</sub>, c<sub>1</sub>) Geological maps highlighting respectively the Posidonia, Chroussa and Kampos subunits and localizing the pictures displayed on the figures 5, 6 and 7. a<sub>2</sub>, b<sub>2</sub>, c<sub>2</sub>) Rose diagram of the poles of foliation planes in each subunit. a<sub>3</sub>, b<sub>3</sub>, c<sub>3</sub>) Rose diagram of stretching lineations in each subunit.



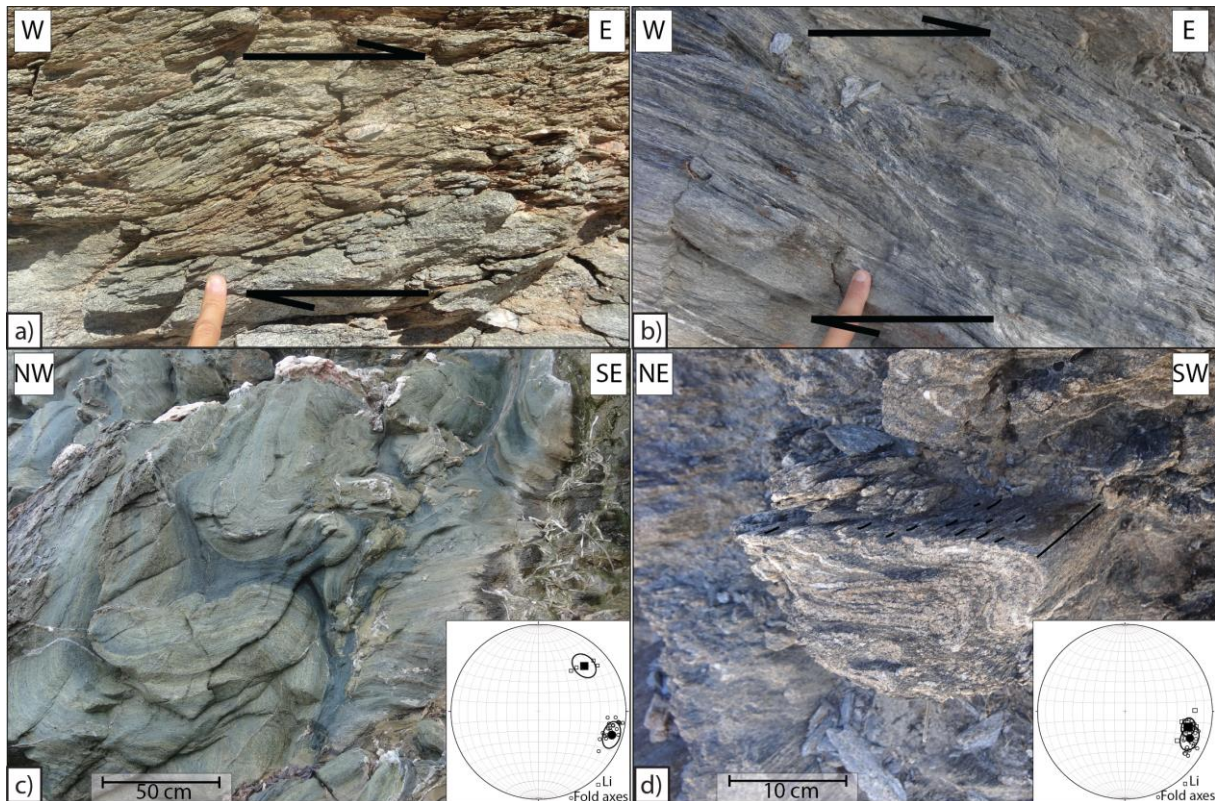
298 4.1) Posidonia Subunit

299

300 Foliation in Posidonia Subunit dips shallowly toward NNW to NNE (Fig. 4a). A syn-  
301 greenschist facies stretching lineation is observed almost systematically, marked by the  
302 stretching of syn-kinematic chlorite and/or albite in rocks showing only greenschist  
303 parageneses (Fig. 4a). Syn-blueschist lineations were observed in only four outcrops (Fig. 3).  
304 For each of these areas, HP-LT markers are preserved within up to a few meters thick mafic  
305 to ultra-mafic boudins hosted in greenschist-facies rocks. The trend of stretching lineations  
306 varies between N60°E to N100°E with a dominant E-W orientation (Fig. 4a). Foliation planes  
307 and stretching lineations measured in the Mavra Vounakia Peninsula (Fig. 3) are slightly  
308 different from those observed in the rest of Posidonia Subunit. There, foliation planes  
309 measured in gneiss and metabasites are NW-SE trending with oscillating dip direction toward  
310 the NE or SW and carried stretching lineations oriented between N120°E and N140°E (Fig. 3).

311 In Posidonia Subunit, markers of non-coaxial ductile deformation are observed as  
312 shear bands, sigma-clast systems, drag folds or asymmetric boudinage. For more than 90% of  
313 visited outcrops, these markers indicate a consistent syn-greenschist top-to-the east sense of  
314 shear (Figs. 3, 5a, 5b). Additionally, the rocks of Posidonia Subunit are tightly to isoclinally  
315 folded, with fold axes either parallel or perpendicular to the stretching direction (Figs. 5c, 5d).

316



317  
 318 Figure 5: Syn-greenschist top-to-the east shearing characterizing the Posidonia Subunit. Localization of pictures  
 319 is showing on figure 4a<sub>1</sub>. a, b) Syn-greenschist top-to-the east shear bands (GPS coordinate: 37°23'16.2'' /  
 320 24°54'21.5'') c) Greenschist folds characterized by orthogonal fold axes compared to syn-greenschist stretching  
 321 lineations (GPS coordinate: 37°26'40.5'' / 24°53'53.8''). Data are plotted on the stereogram. d) Parallel fold  
 322 axes and syn-greenschist stretching lineations observed in the contact zone with the Chroussa Subunit near the  
 323 village of Danakos (GPS coordinate: 37°26'06'' / 24°54'05.1''). Data are plotted on lower hemisphere  
 324 stereograms.

325

#### 326 4.2) Chroussa Subunit

327

328 Chroussa Subunit consists of a succession of marble layers, micaschists and  
 329 metabasites, showing both syn-blueschist and syn-greenschist deformation (Fig. 4b).  
 330 Measured foliation planes shallowly dip to north (Fig. 4b) with local variations. Within  
 331 blueschist-facies rocks, a group of N-S striking foliation planes dips eastward (Fig. 4b). Two  
 332 other orientations of foliation planes were measured in marbles, dipping toward the NE or the  
 333 NW (Fig. 4b). As for Posidonia Subunit, only a few foliation planes dip southward. The  
 334 planar fabric observed in Chroussa Subunit is often associated with a stretching lineation  
 335 marked by glaucophanes needles in blueschist-facies rocks and chlorite and/or albite pods in

336 greenschist-facies rocks (Fig. 4b). Overall, the bulk of measured stretching lineations shows a  
337 constant orientation with a rather low dispersion between N70°E and N100°E. A subordinate  
338 N20°E set of lineations is observed in blueschist-facies rocks (Fig. 4b).

339         Rocks of Chroussa Subunit are strongly deformed at all scales. Markers of non-coaxial  
340 ductile deformation are similar to those observed in Posidonia Subunit. Likewise, this subunit  
341 shows top-to-the E/NE ductile deformation for both syn-blueschist and syn-greenschist  
342 markers (Figs. 6a, 6b, 6c). In the northern part of Syros, near Trachilia Beach, top-to-the  
343 northeast shear bands affecting lawsonite pseudomorphs in metapelites occur (Fig. 6b). In few  
344 places, we observed in the Chroussa Subunit shear bands or asymmetric boudinage showing  
345 retrograde top-to-the west deformation (Figs. 3, 6c). Folds are also common in Chroussa  
346 Subunit showing curved axes locally parallel to the stretching lineation and axial closures like  
347 in sheath folds (Fig. 6d).

348

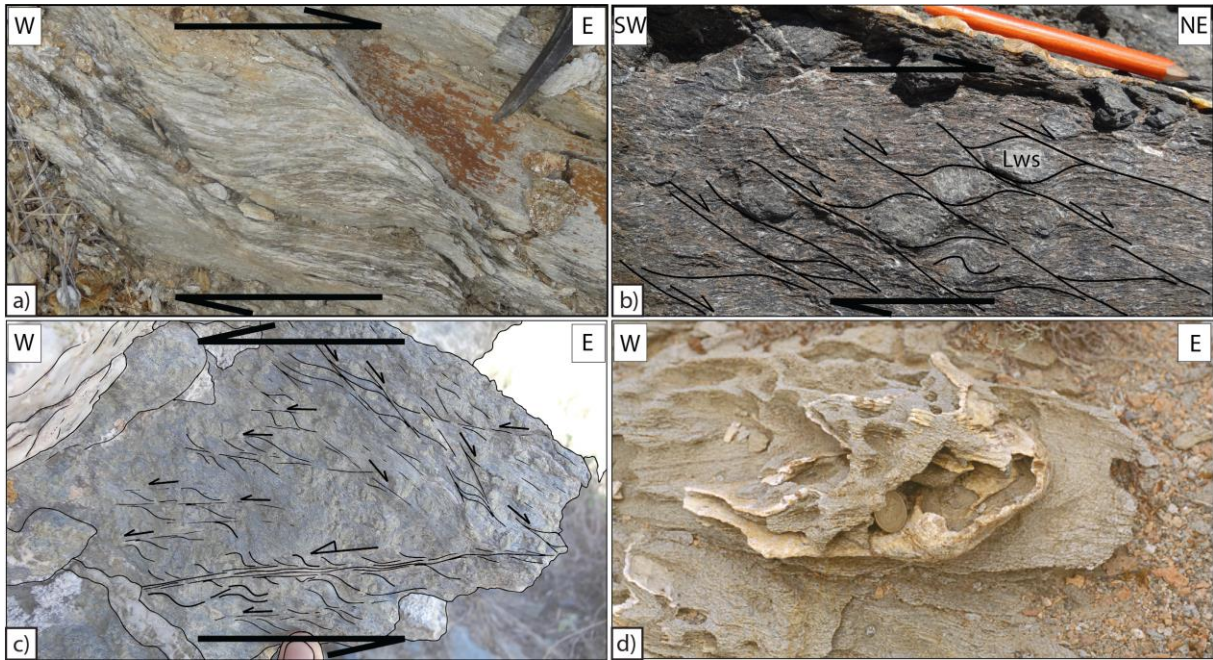
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351

352





353  
 354 Figure 6: Shearing criteria observed in Chroussa Subunit. Outcrop location is shown on figure 4a<sub>2</sub>. a) Syn-  
 355 greenschist top-to-the east shear bands (GPS coordinate: 37°28'24.1'' / 24°55'11.6''). b) Top-to-the northeast  
 356 shear bands affecting preserved pseudomorphs of lawsonite (GPS coordinate: 37°30'07.9'' / 24°54'54.4''). c)  
 357 Retrograde top-to-the west shearing observed locally in the Chroussa Subunit (GPS coordinate: 37°24'49.3'' /  
 358 24°55'45.5''). The steep shear planes are secondary shear zones rotating top west with an antithetic sense of  
 359 shear. d) Curved axis fold observed in micaschists, sub-parallel to the stretching lineation and showing closure  
 360 typical of sheath fold (GPS coordinate: 37°30'39.4'' / 24°52'39.3'').

361

362

### 363 4.3) Kampos Subunit

364

365 Kampos Subunit displays rocks equilibrated in eclogite- and blueschist-facies.

366 Foliation planes dip toward north or northwest (Fig. 4c). Stretching lineations are mainly

367 oriented between N70°E and N100°E and dominantly marked by elongated glaucophane

368 minerals along a main stretching direction (Fig. 4c). N-S syn-blueschist stretching lineations

369 are common in the metabasites near Kampos village (Figs. 3, 4c). In some outcrops (e.g. Kini,

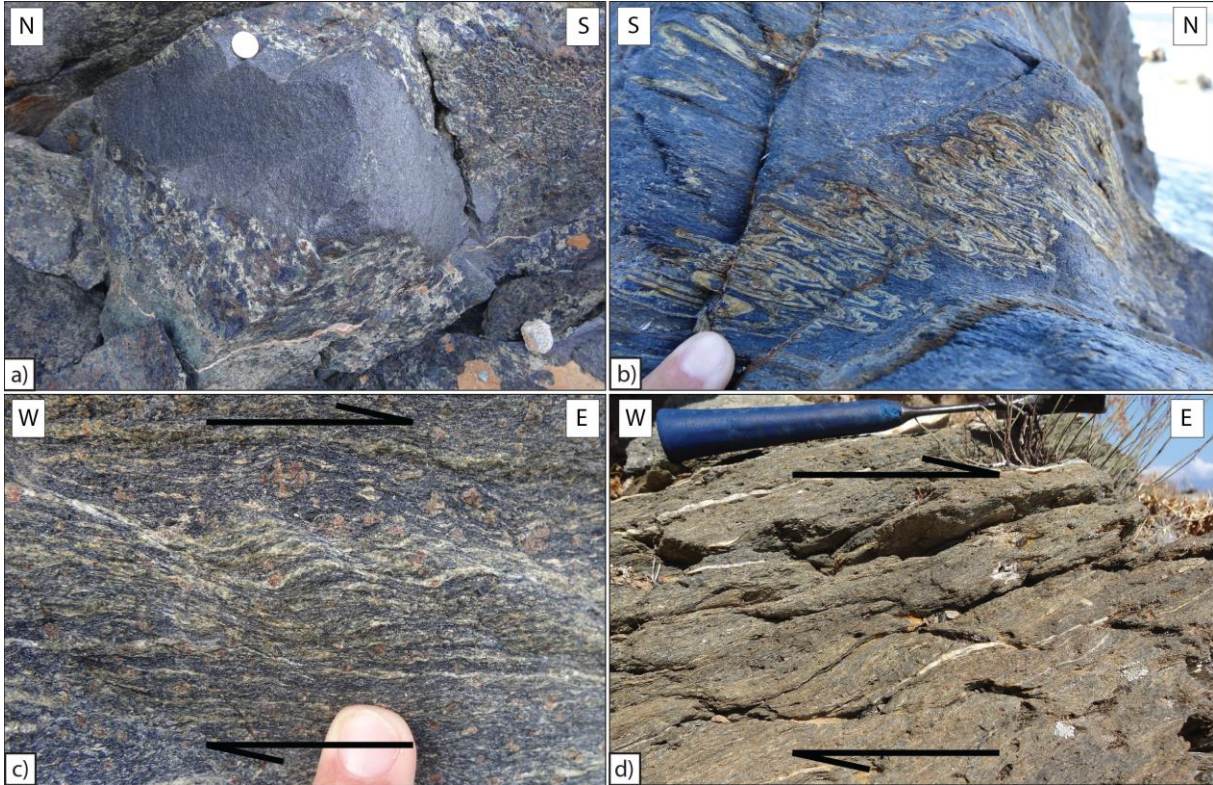
370 Kampos or near the airport), metabasite bodies show only incipient deformation with

371 preserved metapillow-lavas or metabasaltic dykes crosscutting metagabbros (Fig. 7a).

372 Conversely, in others outcrops, rocks experienced intense top-to-the-east shearing recorded

373 during retrogression of eclogites in blueschist-facies conditions (Fig. 7). This characteristic

374 top-to-the east ductile deformation increases up-section toward the contact with Vari Unit,  
375 defining a single strain gradient accompanied by a gradient of eclogite retrogression.  
376



377  
378 Figure 7: Intense syn-eclogite to blueschist-facies deformation of Kampos Subunit illustrating top-to-the east  
379 sense of shear. Localization of pictures is showing on figure 4a<sub>3</sub>. a) Metabasaltic dyke cross-cutting a massive  
380 metagabbro unit showing no deformation (GPS coordinate: 37°26'43.6'' / 24°53'20.4''). b) Isoclinal folds  
381 characterized by sub-horizontal axes parallel to the stretching lineation. These folds show intense thinning during  
382 shearing with pure shear component during deformation (GPS coordinate: 37°29'19.2'' / 24°54'03.4''). c, d)  
383 Syn-blueschist top-to-the east shearing affecting high-pressure metabasites (GPS coordinate: c) 37°25'05.3'' /  
384 24°57'42.9'' d) 37°29'22.6'' / 24°55'42.1'').

385  
386

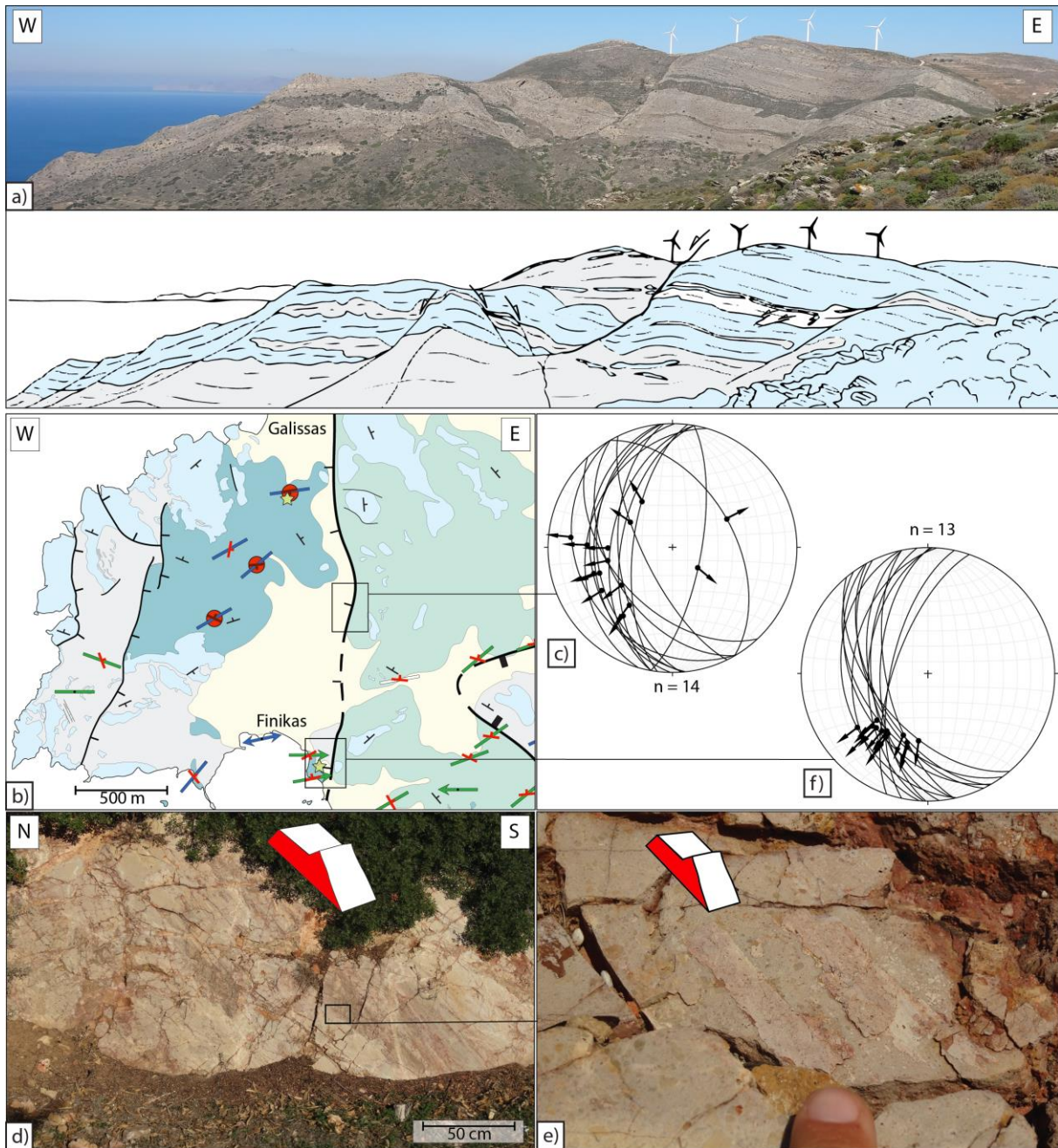
#### 387 4.4) Brittle deformation

388

389 Ductile features are affected by late, sometime pervasive, brittle deformation recorded  
390 in all units by both low and high-angle normal faults. These normal faults are well exposed  
391 near Sirigas where they offset two large boudinaged marble layers (Fig. 8a). Two normal  
392 faults, occurring between Sirigas and Papouri and close to Kini, reach the critical size to be  
393 followed at map scale (Fig. 3). Near Galissas (see location on Fig. 8b), the strongly

394 retrogressed rocks of Posidonia Subunit are in contact with the HP-LT blueschist- and  
395 eclogite-facies metabasites of Kampos Subunit (Figs. 3, 8b). Quaternary slope deposits cover  
396 this contact. Along the road between Finikas and Galissas, a west-dipping fault zone with  
397 cataclasites and striations crops out for about 50 m-long, showing oblique normal kinematics  
398 with top-to-the W-SW sense of movement (Figs. 8b, 8c, 8d, 8e). On top of this fault plane, a  
399 3-4 m-thick brittle fault gouge is observed. Moreover, south of Finikas, we observed normal  
400 faults trending N-S with similar top-to-the southwest kinematics (Fig. 8b, 8f). These two  
401 outcrops characterize a 4 km-long late brittle normal fault, the Finikas-Galissas Fault (Figs. 3,  
402 8b).





403  
 404 Figure 8: Field photographs of observed brittle normal faults. a) Panorama (Chroussa Subunit) showing coeval  
 405 top-to-the east and west ductile-brittle to purely brittle normal faults. b) Zoom of the geological map showing  
 406 location of outcrops along the Finikas-Galissas Fault. c) Associated stereogram showing measured brittle normal  
 407 fault planes that indicate top-to-the W/SW kinematic. d) Brittle fault plane observed along the main road  
 408 between Finikas and Galissas. e) Zoom on the striated fault plane showing the normal sense of motion. f)  
 409 Stereogram showing brittle normal fault planes measured near Finikas village that indicate top-to-the southwest  
 410 kinematic.

411

412

413

414

415

416 5) Geometry, kinematics and metamorphic conditions of the major contacts

417

418         If the Vari Detachment has already been described in previous works ([Soukis and](#)  
419 [Stöckli, 2013](#)), some of the major contacts described below were so far either neglected (i.e.  
420 Achladi-Delfini Shear Zone), or not fully understood in previous works. The new map,  
421 supported by field data and satellite observation, allows us to identify their main  
422 characteristics and role in the island overall architecture.

423

424 5.1) Posidonia-Chroussa subunits contact: the Achladi-Delfini Shear Zone

425

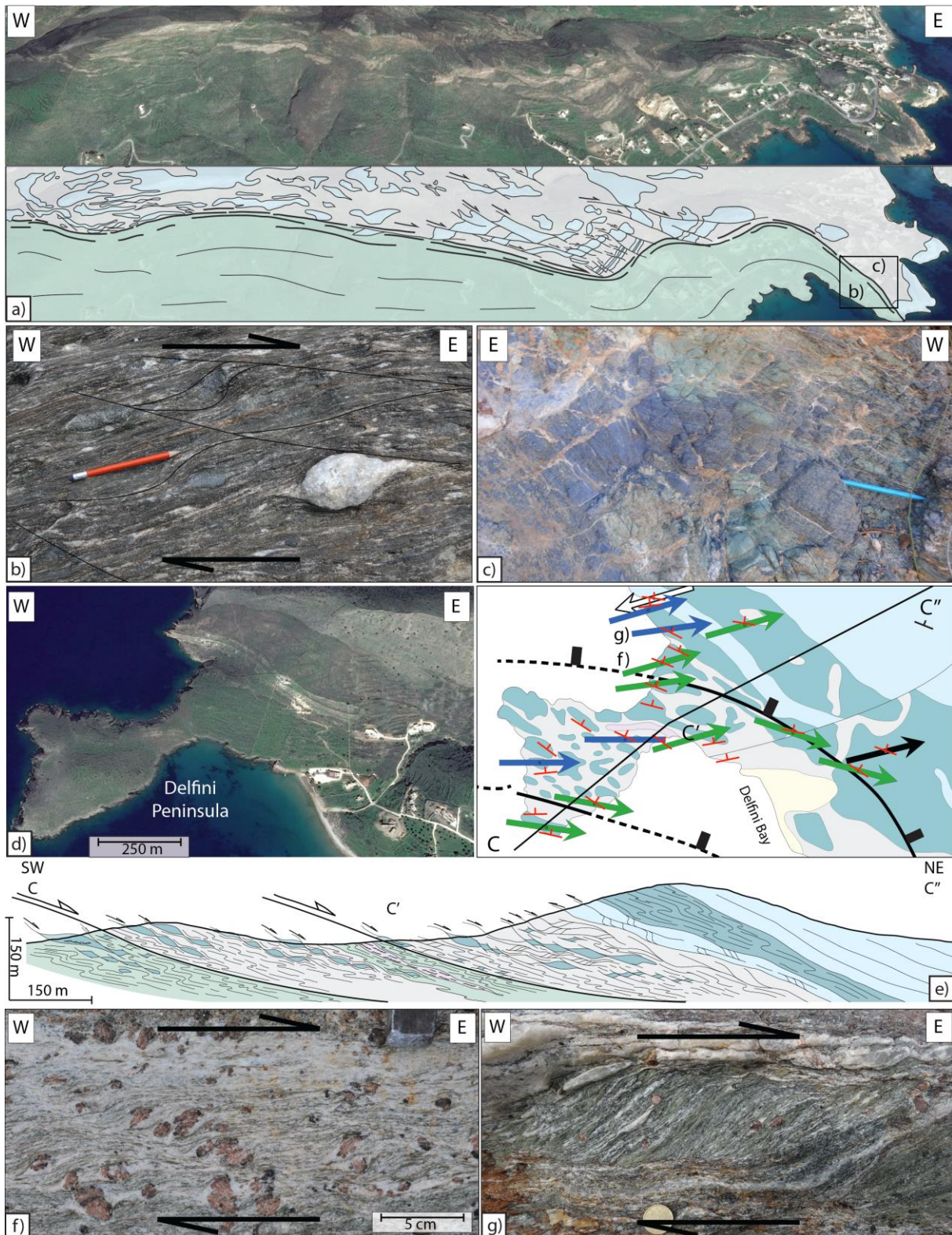
426         The Posidonia-Chroussa subunits contact is exposed between Achladi Cape and  
427 Delfini (Fig. 9, see location on Fig. 3). In its southern limit, the trace of the shear zone can be  
428 followed over more than 3 km in the landscape, shown by the non-coaxial deformation of  
429 marbles layers (Fig. 9a). Some marble layers are affected by brittle normal faults, while others  
430 are boudinaged and separated by ductile shear zones rooting in the contact between Chroussa  
431 and Posidonia subunits. Whatever the regime of deformation and the physical conditions that  
432 prevailed, ductile or brittle, clear top-to-the east deformation is observed in the form of a thick  
433 shear zone (Fig. 9a). Below, the intensity of greenschist-facies retrogression increases in the  
434 vicinity of the shear zone, where metabasites are turned into chlorite-albite prasinites in which  
435 former HP-LT imprint is not detectable in the field. For example, west of Cape Achladi along  
436 the southern coast of the island, rocks of the Posidonia Subunit are strongly overprinted by  
437 greenschist-facies parageneses. At the cape, a metaconglomerate of Posidonia Subunit  
438 consisting of basic and calcitic pebbles embedded in heavily retrogressed metapelitic matrix  
439 crops out just below the contact. Within this metaconglomerate, pebbles are ductilely sheared  
440 with a top-to-the east kinematic (Fig. 9b). Structurally a few meters above, a ca. 20 m-long



441 outcrop of preserved blueschist-facies metabasite is associated with eclogite boudins (Fig. 9c).  
442 This sharp transition from well-preserved blueschists and eclogites above strongly retrograded  
443 rocks below also supports the presence of a major shear zone between the Posidonia and  
444 Chroussa subunits, named in this study the Achladi-Delfini Shear Zone.

445         Furthermore, the same contact between Posidonia and Chroussa subunits is exposed  
446 around Delfini Bay that is bounded to the west by a small peninsula (Fig. 9d). Along a SW to  
447 NE transect through Delfini peninsula, two blue- to greenschist-facies shear zones are  
448 observed (Figs. 9d, 9e). Top-to-the east kinematic indicators such as shear bands, sigmoidal  
449 pressure shadows on garnets or drag folds associated with crystallization of syn-kinematic  
450 chlorite and albite are observed within the Delfini peninsula (Figs. 9f, 9g). These two  
451 metamorphic transition zones, distant of ca. 500 m, define the contact between Posidonia and  
452 Chroussa subunits. These shear zones have each accommodated a part of the total  
453 displacement and can be considered at large-scale as a single structure, the Achladi-Delfini  
454 Shear Zone (Fig. 3).

455         Despite poorer outcrop conditions within the island, the trace of this contact was  
456 followed by combining structural and metamorphic observations, looking especially for the  
457 preservation of HP-LT minerals. These field observations were strengthened by detailed  
458 analysis of aerial pictures. At map-scale, the resulting geometry of the Achladi-Delfini Shear  
459 Zone shows a sinuous contact extending over 13 km through the island (Fig. 3).



460  
 461 Figure 9: The top-to-the east Achladi-Delfini Shear Zone. a) Satellital image of the Achladi-Delfini Shear Zone  
 462 observed above Achladi Cape and its interpretation showing top-to-the east sense of shear. b) Top-to-the east  
 463 shearing in a greenschist metaconglomerate unit located just below the contact. c) Structurally few meters above,  
 464 in the Chroussa Subunit, massive glaucophanites are observed with eclogitic boudins. d) Satellital image of the  
 465 Delfini peninsula and its geological interpretation. e) Geological cross-section through the Delfini peninsula  
 466 illustrating the architecture of the Achladi-Delfini Shear Zone. f) Top-to-the east kinematic indicators observed  
 467 in retrogressed greenschist-facies rocks. g) Syn-blueschist top-to-the east shearing observed in the Chroussa  
 468 Subunit.

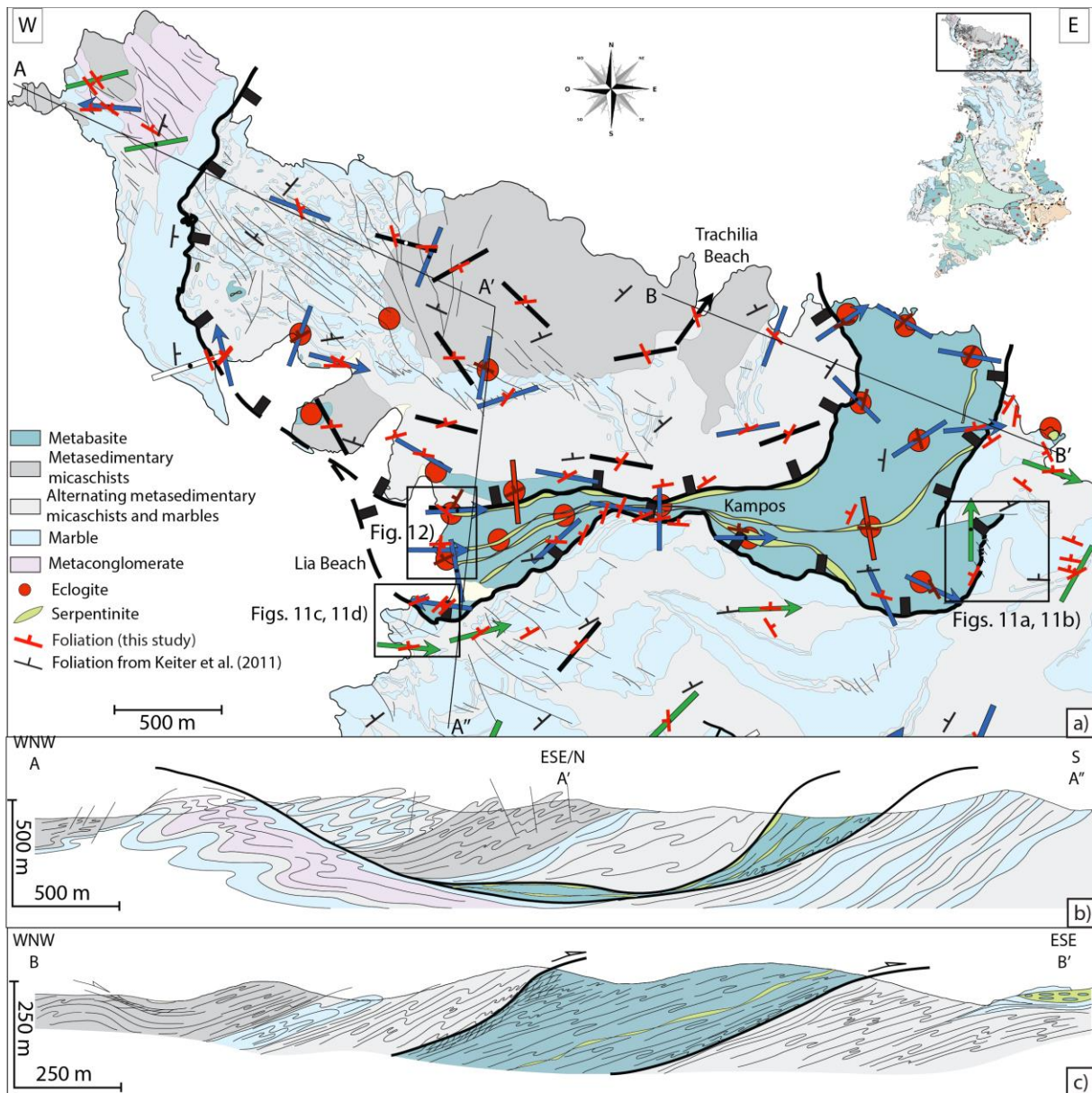
469 5.2) Chroussa-Kampos subunits contact: the Kastri and Lia Shear Zones

470

471           The contact between Chroussa and Kampos subunits is well exposed in the northern  
472 part of the island, along the Kampos metabasite belt (Fig. 10; see also [Keiter et al., 2004,](#)  
473 [2011](#)). This metabasic unit shows an E-W orientation and dips toward the north on the  
474 western side. It strikes more N-S dipping westward in its eastern half (Fig. 10). The northern  
475 and southern contact zones of the Kampos Subunit, i.e. the basal and roof contacts, are nicely  
476 exposed along the coast, especially on the way to Lia Beach (Fig. 10).

477

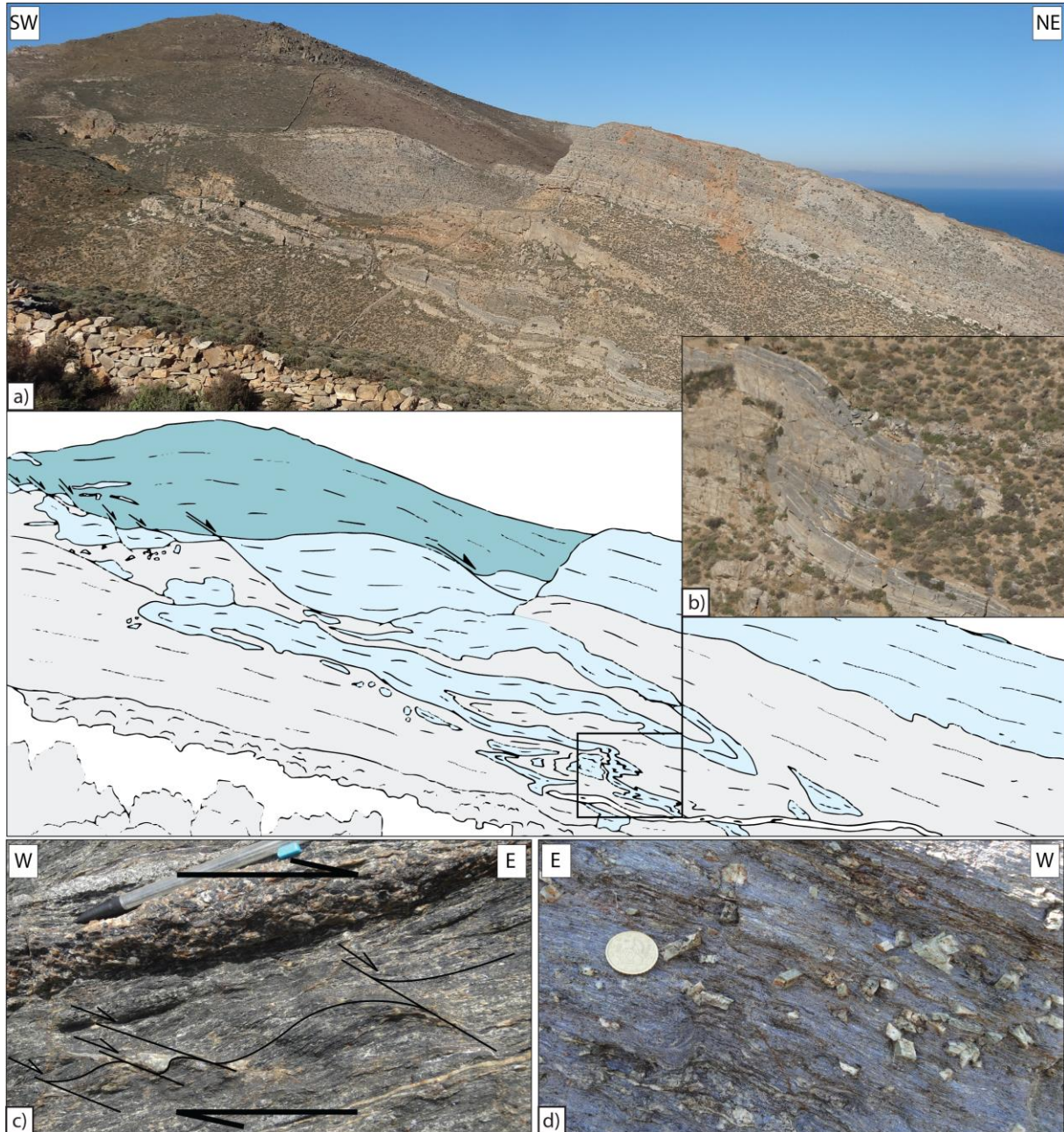




478  
 479 Figure 10: Geological architecture of the northern part of Syros. a) Geological map showing locations of cross-  
 480 sections and figures 12 and 13. b) Cross-section illustrating the organization and deformation of structures. Note  
 481 that large shear zones surround the western part of the Kampos metabasite belt. c) Detailed cross-section of the  
 482 eastern part of the Kampos metabasite belt.  
 483  
 484

485 The basal contact of Kampos Subunit with Chroussa Subunit can be seen in the  
 486 landscape near Kastri (Fig. 11a). At the contact, the marble layers of Chroussa Subunit are  
 487 boudinaged and sheared, some of them showing large-scale sigmoids (Fig. 11a). These  
 488 structures define a large-scale top-to-the northeast shear zone, named in this study the Kastri  
 489 Shear Zone. Just below the contact, tightly folded marble intercalations occur as a result of  
 490 intense shearing along this major shear zone (Fig. 11b). In contrast to the Kampos Subunit

491 that preserved eclogite- to blueschist-facies parageneses, rocks of the Chroussa Subunit are  
 492 strongly overprinted in greenschist-facies conditions all along the contact (Figs. 11c, 11d).  
 493

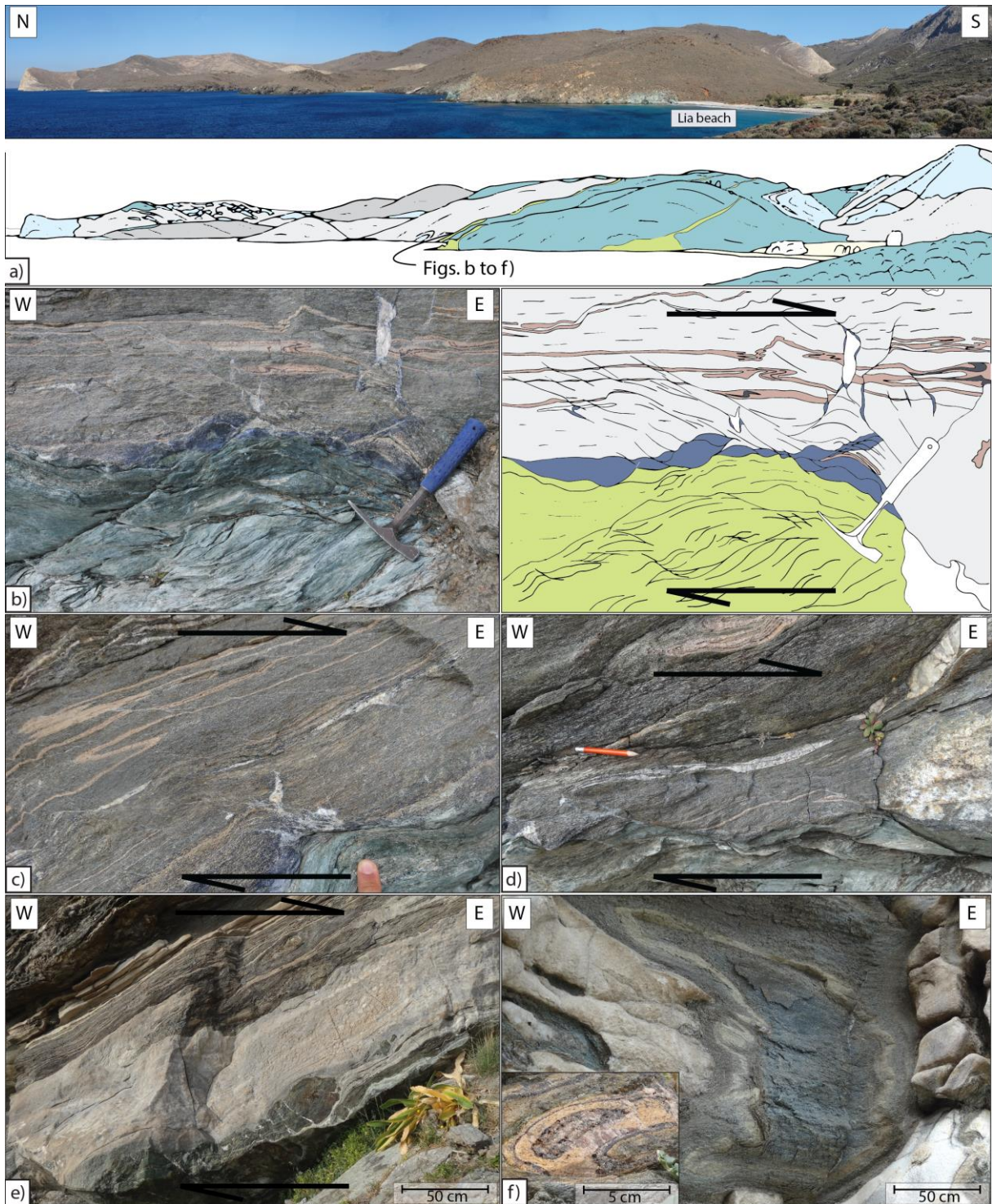


494  
 495 Figure 11: Basal contact of the Kampos metabasite belt: the Kastri Shear Zone. Pictures are located on the Fig.  
 496 12. a) Field view and its interpretation of the eastern part of the Kastri Shear Zone. Large-scale asymmetric  
 497 boudins of marble are observed in the contact zone and show top-to-the northeast sense of deformation. b) Zoom  
 498 showing the intense folding of black marbles below this contact. c) Directly below the contact, the Chroussa  
 499 Subunit is highly retrogressed and displays syn-greenschist top-to-the east sense of shear. d) High-pressure  
 500 glaucophanites bearing lawsonite pseudomorphs are well preserved up to the contact on Lia Beach.  
 501



502           Although the Kampos Subunit composes the upper structural part of the CBU, a klippe  
503 with a lithology similar to Chroussa Subunit is observed above the Kampos metabasite belt  
504 (Fig. 10). The contact zone between this klippe and the roof of the Kampos metabasite belt  
505 displays intense deformation and occurs between foliated serpentinite and metapelite (Figs.  
506 12a, 12b). The foliation is parallel to the contact and is cut by a significant number of east-  
507 dipping shear zones decorated with syn-kinematic glaucophanes (Figs. 12b, 12c, 12d). This  
508 shear zone also shows asymmetrical boudins of metabasites included in a sigmoidal foliation  
509 compatible with top-to-the east shearing deformation and folds with curved axes mostly  
510 parallel to the stretching lineation, suggesting sheath folds (Figs. 12e, 12f). All these  
511 structures define the existence of a major syn-blueschist top-to-the east shear zone located at  
512 the roof of the Kampos metabasite belt, which we called the Lia Shear Zone.

513



514  
 515 Figure 12: Roof contact of the Kampos metabasite belt. a) Field view of the western part of the Kampos  
 516 metabasite belt and its geological interpretation. b, c, d) This contact is characterized by serpentinites below and  
 517 metapelites on top, both affected by top-to-the east syn-blueschist shear bands. e) Asymmetric boudinage of a  
 518 metabasite layer included in a sigmoidal foliation compatible with top-to-the east shearing deformation. f) Folds  
 519 with curved axes sub-parallel to the stretching lineation and showing closed contour building the typical eye-  
 520 structure of sheath folds.

521

522

### 523 5.3) CBU-Vari Unit contact: the Vari Detachment

524

525 The contact between the CBU and Vari Unit is a debated topic in literature. The contact  
526 itself is hidden by Quaternary deposits and probably affected by late normal faults. However,  
527 field investigations into the footwall unit, i.e. the CBU, allow proposing new arguments on  
528 the internal architecture of the Vari Detachment from bottom to top as it crops out from Cape  
529 Katerghaki to Vari (Fig. 13).

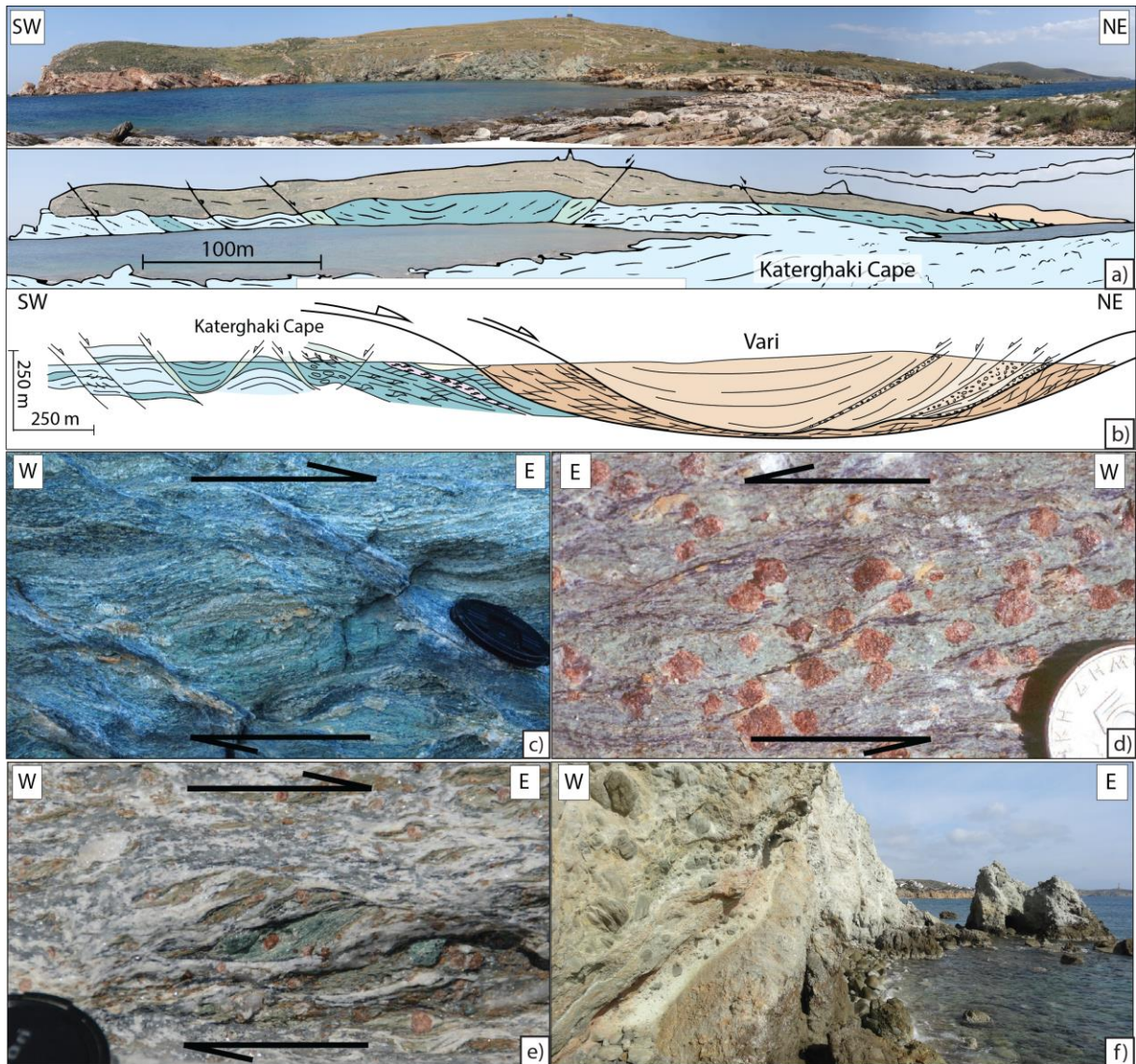
530 Below the contact, trending parallel to the stretching lineation, the whole section is  
531 characterized by a shallow northeast-dipping foliation showing that Vari Unit structurally  
532 overlain Kampos Subunit (Figs. 13a, 13b). As the rest of Kampos Subunit, these mafic rocks  
533 preserve HP-LT metamorphic parageneses such as eclogites and blueschists (see also [Trotet et](#)  
534 [al., 2001a](#)), and display a gradient of retrogression from eclogite- to blueschist-facies toward  
535 the contact. Indeed, the southwestern part of Cape Katerghaki (see location on Fig. 3) is  
536 composed of 10 m-thick massive eclogite bodies, which are more and more retrogressed in  
537 the blueschist-facies toward Vari Unit. All along this gradient, rocks show evidence of syn-  
538 eclogitic stretching reworked by syn-blueschists top-to-the east ductile shearing with HP-LT  
539 minerals such as glaucophanes decorating shear zones (Figs. 13c, 13d). South of Fabrika  
540 beach, structurally 20-30 m below the contact, a metaconglomerate composed of eclogitized  
541 mafic pebbles comprised within a marble matrix show top-to-the east sense of shear (Fig. 13e).  
542 Conjugate northeast-striking normal faults displace the inherited high-pressure structure by a  
543 few tens of meters. This may be due to conjugate normal faults (Figs. 13a, 13b).

544 Just above the contact and within the Vari Unit, mylonitic greenschists are observed,  
545 displaying only greenschist-facies metamorphism without any evidence of prior HP-LT stage,  
546 in contrast with the greenschist-facies metamorphic rocks observed in the bulk of the CBU.  
547 These rocks are strongly foliated and top-to-the E/NE shear criteria are observed such as



548 sigmoidal pressure shadows on pyrite showing top-to-the east kinematic in the north of  
549 Fabrika beach, and top-to-the northeast shear bands south of Azolimnos village. On top of  
550 these greenschist-facies mylonites, the Vari orthogneiss shows a plano-linear ductile fabric  
551 with a stretching lineation oriented N70°E, intercalated in some places with fine-grained  
552 amphibolites. This unit is affected by brittle deformation, expressed as several 10 m-thick  
553 zones of cataclasites cutting through the orthogneiss (Fig. 13f; see also [Soukis and Stöckli,](#)  
554 [2013](#)). Several E-W trending normal faults are observed in this area, cutting across the  
555 orthogneiss foliation at distance from the contact with the CBU, at variance with Philippon et  
556 al.'s ([2011](#)) interpretation of the regional structure. Our interpretation is confirmed at larger  
557 scale. Philippon et al. (2011) correlated the Vari basement lithologies with the so-called  
558 gneiss observed in the lower part of our Posidonia Unit, but we have seen that Posidonia Unit  
559 has seen the same peak of metamorphism as the other CBU of Syros with the local  
560 preservation of blueschists- or eclogite-facies metabasites while the Vari Unit has never been  
561 through HP-LT conditions.

562



563  
 564 Figure 13: The Vari Detachment. a) Field photography showing that the CBU is structurally below the Vari Unit.  
 565 b) Cross-section showing the architecture of the Vari Detachment and its top-to-the east sense of motion. c, d, e)  
 566 Below the Vari Detachment, rocks of the CBU display a significant number of top-to-the east syn-blueschist  
 567 shear bands affecting eclogites. f) Large-scale cataclastic zones observed upon the Vari Detachment within the  
 568 gneiss of Vari.

569  
 570

## 571 6) Discussion

572

573 Although our new geological map matches the one of Keiter et al. (2011) from a  
 574 lithological point of view, its structural interpretation is drastically different. This is  
 575 particularly evident in the analysis of large-scale geometries, unit and subunit subdivisions

576 and in the analysis of metamorphic record, which allowed us to identify several orders of  
577 shear zones due to strain localization.

578

579 6.1) What is left of the original nappe structure of the Cycladic Blueschist Unit?

580

581         We have recognized three distinct tectonic subunits composing the CBU in Syros,  
582 from top to base, the Kampos, Chroussa and Posidonia subunits, all resting structurally below  
583 the Vari Unit, which shows no evidence of HP. These subunits are characterized by their  
584 lithology and predominant metamorphic facies as seen in the field. All three subunits have  
585 seen the P-T conditions of the eclogite-facies but they have been subjected to different  
586 degrees of retrogression during exhumation. Following our observations, we propose a new  
587 metamorphic map based upon the study of predominant metamorphic facies, as well as on  
588 kinematic indicators and their relation to metamorphic parageneses (Fig. 14). This map, where  
589 colors correspond to the predominant metamorphic facies, displays the first-order distribution  
590 of the main parageneses.

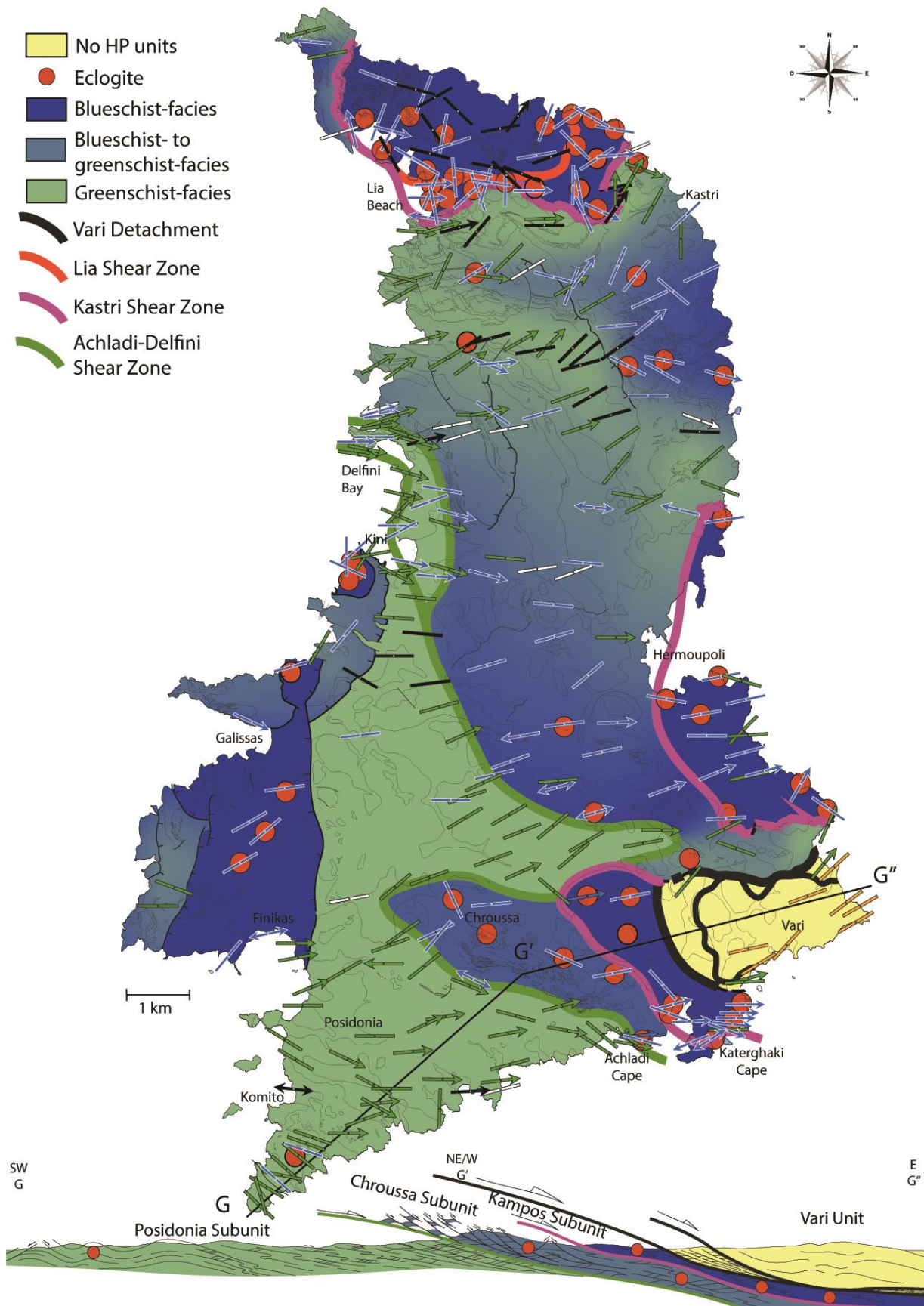
591         The recognition of remains of eclogite within all three subunits implies that Kampos,  
592 Chroussa and Posidonia subunits have all undergone a HP-LT metamorphic event in the  
593 eclogite-facies. It ensues that local blueschist- or greenschist-facies rocks abundance is  
594 retrograde. The degree of retrogression, whether it occurred under blueschist and/or  
595 greenschist metamorphic conditions, is entirely different. Retrogression increases from top to  
596 bottom of the CBU, which points to important differences in the P-T-time evolution of the  
597 different subunits during exhumation, as previously proposed by Trotet et al. (2001b). The  
598 imprint of deformation during exhumation has been different in each of these subunits,  
599 intense in the lowermost Posidonia Subunit (where the entire subunit has been sheared and  
600 pervasively retrogressed), weaker in the uppermost Kampos Subunit (where blueschist- and

601 then greenschist-facies deformation is localized along preferential shear zones). The Achladi-  
602 Delfini Shear Zone best shows this contrast. These features are similar to those observed on  
603 Sifnos (Roche et al., submitted) and seem characteristic of the large-scale structure acquired  
604 by the CBU within the subduction channel before those rocks were reworked by greenschist-  
605 facies deformation during Oligocene to Miocene extension. We now discuss the  
606 tectonometamorphic evolution of the subunits within the subduction channel.

607         The apparent inverse metamorphic gradient defined by the transition from the  
608 preserved high-pressure Kampos Subunit to the strongly retrograded Posidonia Subunit raises  
609 petrological questions. Indeed, very different P-T histories were so far published for Syros in  
610 terms of peak P-T conditions and shape of retrograde P-T path (Fig. 1b). Exhumation  
611 scenarios with a single retrograde P-T path for the whole CBU (Keiter et al., 2004, 2011;  
612 Schumacher et al., 2008) cannot explain the different degrees of retrogression observed in the  
613 CBU. Maximum P-T conditions around 15kbar and 500°C (Schumacher et al., 2008) just  
614 fringe the eclogite-facies (Fig. 1b) while eclogites are abundantly observed on Syros as well  
615 as on Sifnos (Trotet et al., 2001a). To justify these apparent contradictions, Schumacher et al.  
616 (2008) hypothesized that eclogites of Syros are the product of an earlier metamorphic event  
617 and were juxtaposed with the rest of the CBU by tectonic contacts. As result of our  
618 observations, the presence of eclogite boudins and lenses in all subunits cropping out on Syros,  
619 except the Vari Unit, does not fit the interpretation of Schumacher et al. (2008). An  
620 alternative explanation would be that the glaucophane-bearing marbles studied by  
621 Schumacher et al. (2008) were formed during the retrograde path in P-T conditions for which  
622 this assemblage is in equilibrium or that the amphibole mineralogy and stability is chemically  
623 buffered by the lithology. Indeed, much of the blueschist-facies parageneses on Syros are syn-  
624 kinematic and show top-to-the east sense of shear and clearly postdates the eclogite-facies.  
625 Consequently, our structural observations best fit the petrological analyses of Trotet et al.

626 (2001b), for whom all subunits of the CBU attained the same metamorphic peak in the P-T  
627 field of eclogite-facies, and followed different retrograde P-T paths, leading to different grade  
628 of retrogression in the CBU during the continuous activity of large-scale top-to-the east shear  
629 zones between Kampos, Chroussa and Posidonia subunits all over the exhumation (Fig. 1b).  
630 According to this interpretation, the tectonic history and the metamorphic path to the surface  
631 differ from the one envisaged by Keiter et al. (2004, 2011), who suggested rigid block  
632 exhumation mechanisms of the whole CBU as a single block. It remains true however that  
633 deformation progressively localized during exhumation along shear zones and that entire parts  
634 of the islands escape from the low-temperature deformation, these domains are those where  
635 the HP-LT parageneses are best preserved, as discussed in the next section.





636  
 637 Figure 14: New metamorphic map of Syros showing an apparent inverse metamorphic gradient. The G-G'' cross-  
 638 sections represent a synthetic view over the overall tectonometamorphic structure of Syros. The architecture of  
 639 the CBU is subdivided here in three subunits separated by large-scale shear zones. Note that in our interpretation,  
 640 the Vari Detachment juxtaposed with a top-to-the east motion the CBU and the uppermost Vari Unit.

641 6.2) Prograde or retrograde deformation?

642

643 A number of previous structural studies reported that prograde deformation is  
644 observed in Syros (Rosenbaum et al., 2002; Keiter et al., 2004, 2011; Philippon et al., 2011).  
645 Some of these studies postulated that this deformation took place just before or during peak  
646 metamorphism with no or only local retrograde deformation (Rosenbaum et al., 2002; Keiter  
647 et al., 2004, 2011). Three main arguments are presented in the literature. 1) The observation  
648 of deformed pseudomorphs of lawsonite: Philippon et al. (2011) noted that these  
649 pseudomorphs are always sheared with top-to-the S/SW kinematics and they correlated this  
650 sense of shear with subduction-related prograde thrusting. 2) The presence of large thrust  
651 zones, often described at the base of metabasic units. 3) The widespread preservation of  
652 aragonite pseudomorphs supports the view that no pervasive retrograde deformation occurred  
653 subsequently to the main prograde to peak metamorphism deformation event. The frequent  
654 presence of aragonite pseudomorphs in the Kampos Subunit, for instance in  
655 metaconglomerates, indeed shows that no significant deformation occurred at those places in  
656 the greenschist-facies and that parts of this subunit were exhumed as rigid bodies once they  
657 had exited blueschist-facies conditions (Schumacher et al., 2008).

658 Our study shows that the three subunits composing the CBU are each separated by  
659 top-to-the E/NE shear zones (Figs. 3, 14). This top-to-the E/NE deformation event observed  
660 within the entire volume of the CBU on Syros also affects lawsonite pseudomorphs (Fig. 6b)  
661 in contradiction with Philippon et al.'s observations (2011). Therefore, these structures are not  
662 only markers of prograde deformation, but also characterize early retrograde deformation.  
663 Indeed, taking into account the new lawsonite + glaucophane out reaction calculated for Fe-  
664 Mg end-member at  $X_{CO_2} = 0,01$  (Schumacher et al., 2008), and the P-T path of Trotet et al.

665 (2001b), it appears that lawsonite could have been sheared with top-to-the east sense of shear  
666 during the first exhumation stages (Fig. 1b).

667         Geometry of the basal contact of the Kampos metabasite belt is quite complex and  
668 interpreted differently in previous studies. On one hand, Trotet et al. (2001a) describe this  
669 contact as a ductile detachment. For these authors, this contact is marked in the field by an  
670 apparent metamorphic gap between retrograded greenschist-facies rocks below the  
671 detachment and preserved eclogite- and blueschist-facies above (Fig. 2a). On the other hand,  
672 Keiter et al. (2004, 2011) and Philippon et al. (2011) described this contact as a large prograde  
673 thrust related to the subduction phase. Although Keiter et al. (2004) challenged the existence  
674 of a sharp metamorphic transition through this contact, we confirm this observation of Trotet  
675 et al. (2001a). Indeed, the contact zone is clearly marked by retrogression of the upper part of  
676 the underlying Chroussa Subunit over a 100 m-thick greenschist-facies shear zone. Moreover,  
677 all shear criteria observed within this shear zone are top-to-the E/NE, in agreement with syn-  
678 greenschist retrograde sense of shear observed within the Achladi-Delfini Shear Zone deeper  
679 down in the CBU. This does not preclude the possibility that the Kampos-Chroussa subunits  
680 contact is originally a thrust as it superimposes the Kampos Subunit, which is mostly  
681 ophiolitic, on top of the Chroussa Subunit, which is mostly made of metasediments. Our  
682 interpretation is that this thrust has been later reactivated as a major top-to-the east shear zone  
683 during exhumation. In the same way, we interpret the klippe of Chroussa Subunit, which is  
684 structurally positioned above the Kampos metabasite belt (Fig. 10), as thrusting onto the  
685 Kampos Subunit during the late prograde phase of subduction or during the early phase of  
686 exhumation. Indeed, this klippe corresponds lithologically to the Chroussa Subunit but shows  
687 only eclogite to blueschist parageneses as the Kampos Subunit (Fig. 14). Our observations  
688 show that this thrust was reactivated only in the blueschist-facies forming the Lia Shear Zone



689 (Fig. 12). Then the klippe and the Kampos metabasite belt may have followed, as a single unit,  
690 the same exhumation history.

691 In agreement with Trotet et al. (2001a), one of the major results of our study is the  
692 observation of a pervasive continuum of top-to-the E/NE deformation from P-T conditions of  
693 the metamorphic peak (eclogite-facies) to late stages of retrogression in the blueschist- and  
694 then greenschist-facies. In contrast to Rosenbaum et al. (2002), and Keiter et al. (2004, 2011),  
695 we conclude that a large part of the deformation in Syros was acquired during exhumation and  
696 that this deformation was heterogeneously distributed and preferentially localized along  
697 extensional shear zones.

698 However, it is also clear that locally, criteria of prograde or peak-metamorphism  
699 deformations are preserved. Different structures are most notably inconsistent with a  
700 pervasive top-to-the E/NE retrograde shearing. First, the orientation of stretching lineations is  
701 distinctly scattered in subunits best preserving eclogite and blueschist-facies parageneses (i.e.  
702 Chroussa and Kampos subunits; Figs. 3, 4). Indeed, a group of N-S oriented lineations and  
703 top-to-the S/SW kinematic indicators, already observed by Philippon et al. (2011), can be  
704 found in Kampos Subunit. Then, at a larger-scale, the N-S orientation of the Kampos  
705 metabasite belt (see Keiter et al., 2004, 2011) is inconsistent with E-W oriented deformation  
706 and top-to-the E/NE sense of shear. All these structures appear to be related with a N-S  
707 oriented shearing event and not with the retrograde top-to-the E/NE continuum of  
708 deformation described in this study. A plausible explanation would be that these structures  
709 were acquired during an early N-S oriented prograde event in the subduction channel, leading  
710 to formation of large thrust planes between units that are now found preserved in the highly  
711 metamorphic Kampos and Chroussa subunits. This interpretation is consistent with top-to-the  
712 S/SW prograde sense of shear described by Philippon et al. (2011). Such peak-metamorphic  
713 structures were later reactivated as weak contact zones during exhumation, within a top-to-the

714 E/NE non-coaxial regime progressively localizing strain toward the lower structural parts of  
715 the CBU. These features are discussed in the context of the heterogeneous localization of  
716 deformation during exhumation of the CBU.

717

718 6.3) Localization of deformation during exhumation

719

720 The roof contact of the Kampos metabasite belt is only marked by syn-blueschist  
721 deformation, showing that this shear zone was deactivated early in the exhumation process,  
722 and that the deformation localized progressively in the basal contact of Kampos Subunit,  
723 which is characterized by syn-greenschist deformation. In contrast with Posidonia Subunit,  
724 Chroussa Subunit is not totally retrogressed in the greenschist-facies and shows large portions  
725 characterized by the predominance of blueschist-facies parageneses. Once again, this feature  
726 illustrates the progressive localization of deformation during exhumation toward the base of  
727 the CBU, i.e. toward Posidonia Subunit. Finally, the Achladi-Delfini Shear Zone is currently  
728 characterized by syn-greenschist deformation that has overprinted the entire volume of  
729 Posidonia Subunit.

730 Progressive localization of deformation toward the base of the CBU in Syros during  
731 exhumation is linked with a younging of apparent ages towards the south, from Kampos (45-  
732 50 Ma, syn-orogenic period) to Posidonia subunits (20-35 Ma, post-orogenic period),  
733 especially shown by  $^{40}\text{Ar}/^{39}\text{Ar}$  and Rb/Sr data on white micas (Fig. 2b; [Maluski et al., 1987](#);  
734 [Tomaschek, et al., 2003](#); [Putlitz, et al., 2005](#); [Huet, 2010](#); [Bröcker et al., 2013](#)). A possible  
735 explanation would be that structurally downward strain localization leads to partial resetting  
736 of isotopic systems or even recrystallization in the lowermost units. This migration of  
737 deformation could be enhanced by different factors such as intense fluid circulations in the  
738 basal part of the CBU and/or increased thermal influx at the base of the metamorphic pile

739 (Matthews and Schliestedt, 1984; Schliestedt and Matthews, 1987; Avigad, 1993; Trotet et al.,  
740 2001b). This localization could be also linked to the different lithologies composing the CBU  
741 on Syros, less and less resistant to deformation toward the base, passing from massive  
742 metabasite in Kampos Subunit to a succession of thick marble layers and metapelites in  
743 Chroussa Subunit and finally metapelites in Posidonia Subunit. During cooling of  
744 metamorphic units, this inherited rheological heterogeneity may have enhanced the downward  
745 localization of deformation toward the weak rheological units. So, while Posidonia Subunit  
746 has been deformed until the P-T conditions of the greenschist-facies, the Kampos Subunit and  
747 parts of the Chroussa Subunit have been only deformed during the first steps of exhumation.  
748 This participated to the local preservation of prograde markers of deformation seen today,  
749 allowing detailed petrological and structural information to be retrieved on the prograde  
750 subduction-related phase of deformation.

751

752 6.4) Thrusting, exhumation and extension

753

754 The contacts between Kampos, Chroussa and Posidonia subunits have a polyphase  
755 history. The first stage corresponds to the stacking of units by thrusting (i.e. nappe stacking),  
756 probably during the prograde evolution and at the pressure peak. A limited number of  
757 outcrops suggest that the sense of shear was toward the south during this first episode  
758 (Philippon et al., 2011). The main evidence of thrusting is that the uppermost HP-LT Kampos  
759 Subunit is mostly made of ophiolitic material, while the lowermost Posidonia Subunit is rich  
760 in metapelites that may have been deposited over a continental basement (Keiter et al., 2004;  
761 2011; Schumacher et al., 2008; Philippon et al., 2011). In a second stage, the contacts were  
762 reactivated during the retrograde evolution and exhumation, via a top-to-the east shearing  
763 deformation, localized along the main contacts or distributed within the whole Posidonia

764 Subunit. This continuum of top-to-the east shear thus encompasses two major periods of the  
765 geodynamic evolution of the Aegean: (1) The Eocene construction of the Hellenides nappe  
766 stack and HP-LT accretionary complex of the CBU; (2) the Oligocene to Miocene extension  
767 leading to crustal thinning and formation of the Aegean Sea in the back-arc region of the  
768 Hellenic subduction. The first period corresponds to exhumation of the CBU within the  
769 subduction channel (syn-orogenic exhumation, [Jolivet et al., 2003](#); [Jolivet and Brun, 2010](#)),  
770 and the second stage to the formation of metamorphic core complexes of the Cyclades (post-  
771 orogenic extension, [Huet et al., 2011](#)).

772

773 6.5) The Vari Detachment: an example of a subduction channel roof

774

775         Several studies describe the existence of the Vari Detachment on Syros, juxtaposing  
776 the Vari Unit above the CBU ([Trotet et al., 2001a](#); [Rosenbaum et al., 2002](#); [Ring et al., 2003](#);  
777 [Jolivet et al., 2010](#); [Keiter et al., 2011](#); [Soukis and Stöckli, 2013](#)). It is also suggested that this  
778 detachment reappears on the neighboring island of Tinos ([Maluski et al., 1987](#); [Patzak et al.,](#)  
779 [1994](#); [Jolivet et al., 2010](#); [Soukis and Stöckli, 2013](#)). This assumption is based on similar  
780 structural and metamorphic features of the footwall and hangingwall of the detachment  
781 outcropping in each island. On the other hand, [Philippon et al. \(2011\)](#) drastically revised the  
782 interpretation of this contact, repositioning the Vari Unit below the CBU. According to them,  
783 these rocks have to be correlated with the Cycladic Continental Basement cropping out in the  
784 southern part of the Cyclades (cf. [Huet et al., 2009](#); [Augier et al., 2015](#)). On the contrary, we  
785 demonstrated here, that clear field evidences support the original interpretation putting the  
786 Vari Unit on top of the CBU (Figs. 13a, 13b). The Vari Detachment is generally considered as  
787 responsible for the exhumation of the CBU ([Trotet et al., 2001a](#); [Jolivet et al., 2010](#); [Soukis](#)  
788 [and Stöckli, 2013](#)). [Trotet et al. \(2001a, 2001b\)](#) and [Jolivet et al. \(2010\)](#) argued that the Vari



789 Detachment has accommodated part of the exhumation since the syn-orogenic period,  
790 whereas Ring et al. (2003) conclude that this structure only allowed the final exhumation of  
791 the CBU. Ring et al. (2003) obtained different retrograde cooling paths at the footwall and at  
792 the roof of the Vari Detachment with fission-tracks data on apatite and zircon gathered on  
793 Syros (Fig. 2b) and Tinos. From their results, they derive that intra-arc distributed extension  
794 caused only the final 6-9 km of vertical exhumation, and they conclude that the Vari  
795 Detachment was characterized by fast extension but caused little exhumation. But this  
796 detailed study is based upon fission-track data, which put only T-t constraints on the final  
797 parts of exhumation. Our structural observations show that the top-to-the E/NE deformation  
798 affecting the rocks located at the footwall of the Vari Detachment started in eclogite to  
799 blueschist P-T conditions and evolved progressively toward the conditions of the greenschist-  
800 facies. Cataclastic deformation observed in the Vari Detachment testifies that this detachment  
801 has continued to operate in brittle conditions, but not that this detachment started in brittle  
802 conditions as asserted by Ring et al. (2003). Huet et al. (2009) and Jolivet et al. (2010)  
803 hypothesized that the Vari Detachment represents the Eocene roof of the subduction channel.  
804 Then, with the Oligocene to Miocene southward slab retreat, the Vari Detachment was  
805 transferred in a back-arc position in the Late Miocene as attested by its present position.

806

#### 807 6.6) Tectonometamorphic evolution of a subduction channel

808

809 Integrating the above presented and discussed new observations with the one available  
810 in literature, we propose a new tectonometamorphic evolution sequence. This scenario is  
811 divided in four steps:

812 1) From the early Paleocene (65 Ma) to the early Eocene (50 Ma):

813 From the end of the Cretaceous, the Apulian continental block subducted below the southern  
814 margin of Eurasia (Jolivet and Brun, 2010). During this N-S oriented subduction phase, the  
815 Hellenic nappe stack was progressively constructed. The Pindos oceanic domain probably  
816 started to subduct around 55 Ma (Menant et al., 2015) forming at depth the CBU (Bonneau  
817 and Kienast, 1982; Jolivet and Brun, 2010). Between 55 and 50 Ma, CBU rocks were strongly  
818 deformed, forming the observed N-S trending stretching lineation, resulting in the thrusting of  
819 subunits such as the Kampos Subunit with a resultant top-to-the S/SW sense of shear  
820 associated with prograde shear zones (Philippon et al., 2011) and large-scale open folds  
821 (Keiter et al., 2011; see also Roche et al., submitted, for Sifnos Island).

822 2) From the early Eocene (50 Ma) to the early Oligocene (35-30 Ma):

823 The CBU started to exhume, following an initial cold retrograde P-T path able to preserve  
824 HP-LT parageneses. Ductile shear zones associated with syn-blueschist top-to-the east sense  
825 of shear accommodated this exhumation below the Vari Detachment that represented the roof  
826 of the subduction channel. During this syn-orogenic phase, deformation started to localize at  
827 the interface between large lithological units, probably along former thrusts, delimiting the  
828 subunits detached from the overlying plate. During this period, a top-to-the south thrust,  
829 observed on Ios Island and located at the base of the CBU (Huet et al., 2009), was active and  
830 exhumation of the CBU was accommodated within the subduction channel of a slowly  
831 retreating subduction zone while the thrust front was propagated southward (Jolivet et al.,  
832 2003; Brun and Faccenna, 2008; Jolivet and Brun, 2010; Ring et al., 2010).

833 3) From the early Oligocene (30-35 Ma) to the early Miocene (23-19 Ma):

834 A drastic change in kinematic boundary conditions occurs at 30-35 Ma with a decrease of the  
835 absolute northward motion of Africa and the southward retreat of the subducting slab (Jolivet  
836 and Faccenna, 2000). This drastic change marks the transition from syn-orogenic exhumation  
837 to post-orogenic extension and the formation of the Aegean Sea. The post-orogenic

838 extensional regime is still characterized by top-to-the E/NE sense of shear as observed in the  
839 Achladi-Delfini Shear Zone. During exhumation, deformation progressively localized in  
840 lower structural levels of the CBU where retrogression is almost complete.

841 4) From the Early Miocene (23-19 Ma) to the present:

842 The final exhumation of the CBU is first controlled by ductile-brittle normal faults and finally  
843 by purely brittle normal faults. The Achladi-Delfini Shear Zone displays ductile-brittle  
844 deformation with top-to-the E/NE sense of shear, like some outcrops in the Chroussa Subunit.  
845 Large-scale brittle normal faults can finally affect the exhumed units such as the 4 km  
846 Finikas-Galissas Fault, which juxtaposes well-preserved eclogite- to blueschist-facies rocks  
847 with strongly retrogressed units (Figs. 3, 8b).

848

849 7) Conclusion

850

851 In this study, new geological and metamorphic maps and cross-sections of Syros have  
852 been proposed, described and discussed. Field mapping combined with structural and  
853 petrological observations allow us to subdivide the CBU into three subunits, Kampos,  
854 Chroussa and Posidonia subunits, separated by major ductile shear zones. Eclogite is found  
855 within all three subunits. This implies that, despite their entirely different degree of  
856 retrogression (from eclogite at the top to greenschist at the base), the subunits have undergone  
857 the same HP-LT metamorphic peak in eclogite-facies, pointing to important differences in P-  
858 T-time evolution during exhumation. Large-scale ductile shear zones delimiting the subunits  
859 record a multi-stage structural evolution. They may have formed during burial with the  
860 development of a currently N-S trending eclogite to blueschist stretching lineation  
861 accompanied by top-to-the S/SW sense of shear. From the P-T conditions of the metamorphic  
862 peak and during exhumation, the contacts were reactivated as top-to-the east ductile

863 extensional shear zones. New observations of the Vari Detachment, which juxtaposes the low-  
864 pressure Vari Unit onto the CBU, show consistent top-to-the-east shear sense. We infer that,  
865 after the prograde top-to-the S/SW deformation, the CBU was exhumed by an overall top-to-  
866 the east shearing all the way from the depth of the eclogite-facies to the greenschist-facies and  
867 finally, into the brittle crust. During exhumation, deformation progressively localized  
868 downward in the CBU, along several large-scale ductile shear zones, allowing preservation of  
869 earlier HP-LT structures and metamorphic parageneses.

870         This study brings new insights on the tectonometamorphic evolution of a subduction  
871 channel, showing progressive strain localization, during both the prograde and retrograde  
872 history. The rate of this progressive strain localization is however unknown, and in general,  
873 poorly known in similar geological contexts. Are all shear zones coeval, do they work at the  
874 same time or can we see a sequential development until final localization on the brittle Vari  
875 Detachment? As an open question left for further work, we can say that modeling the  
876 evolution of the CBU accretionary complex and understanding the mechanical behavior of the  
877 subduction interface requires quantifying the rate of strain localization. Acquisition of  
878 detailed time constraints along the P-T path is fundamental in determining the role and the  
879 importance of the shear zones bounding the subunits of Syros, it is a pre-requisite for further  
880 considerations on exhumation mechanisms.

881

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892

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894

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