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$^{40}\text{Ar}$  behaviour and exhumation dynamics in a subduction channel from multi-scale  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics in phengite

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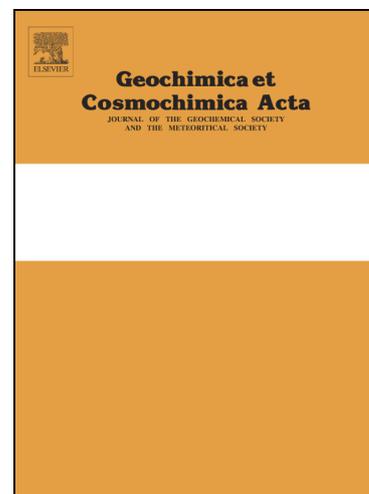
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## 18 1. Introduction

19

20 Understanding the mechanical behaviour of subduction zones and unravelling the  
21 evolution of accretionary complexes requires addressing the key question of strain distribution  
22 within high-pressure low-temperature (*HP/LT*) shear zones. The complex interplay between  
23 rheology, temperature, fluid status, and deformation influences how exhumation of *HP/LT* units  
24 is accommodated by progressive localization of deformation along major crustal-scale shear  
25 zones. In *HP/LT* accretionary wedges, such strain localization and partitioning across the  
26 brittle/ductile transition may occur at large depths and, most notably, in the critical *T*-range  
27 (300-450 °C) overlapping with the argon (Ar) retention interval of *HP/LT* micas, i.e., phengite  
28 (e.g., Scaillet et al., 1992; Warren et al., 2012a). This has endowed phengite with the status of  
29 natural  $^{40}\text{Ar}/^{39}\text{Ar}$  candidate for tracking temporal variations in shear distribution and  
30 exhumation dynamics of *HP/LT* units (Baldwin and Lister, 1998; Bröcker et al., 2004, 2013;  
31 Beltrando et al., 2013; Rogowitz et al., 2015; Fornash et al., 2016; Lister and Forster, 2016).

32 However, phengite is also known in such contexts to provide complex  $^{40}\text{Ar}$  behaviour  
33 controlled by variable Ar diffusivity, mineral composition, parental lithology (juvenile protolith  
34 vs. polycyclic basement), deformation, and fluid/rock interactions (Scaillet et al., 1992; Scaillet,  
35 1996, 1998; Giorgis et al., 2000; Di Vincenzo et al., 2006; Smye et al., 2013; Halama et al.,  
36 2014; Cossette et al. 2015; Schertl and Hammerschmidt, 2016; Fornash et al., 2016; Laurent et  
37 al., 2017). The resulting  $^{40}\text{Ar}/^{39}\text{Ar}$  ages can be highly discordant and have been interpreted  
38 either in terms of closure or resetting, assisted or not by deformation. Accordingly, the extent  
39 to which  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite ages can constrain the thermal-kinematic behaviour of exhumed  
40 *HP/LT* rocks has been questioned and investigated using different approaches involving either  
41 *in situ* dating, bulk (population) dating, single grain step-heating or single grain fusion age  
42 distributions (e.g. Wijbrans et al., 1990; Monié and Chopin, 1991; Scaillet et al., 1992; Di

43 Vincenzo et al., 2006; Warren et al., 2012a; Beltrando et al., 2013; Smye et al., 2013; Laurent  
44 et al., 2017; Uunk et al., 2018).

45 In this work, we address these issues via the  $^{40}\text{Ar}/^{39}\text{Ar}$  study of Syros and Sifnos, two  
46 key islands of the Upper Cycladic Blueschist (UCB) unit of the Aegean domain (Greece), one  
47 of the best preserved and exposed *HP/LT* subduction complexes worldwide (e.g., Hausmann,  
48 1845; Ridley, 1982; Bonneau, 1984; Dixon et al., 1987; Schliestedt and Matthews 1987; Okay,  
49 1989; Avigad and Garfunkel, 1991). Both islands record a major thermal-kinematic reworking  
50 marked by a sharp (ca.2 km–thick) metamorphic transition from eclogite and blueschist (*BS*)  
51 grade conditions to greenschist (*GS*) grade conditions. Our strategy is based on coupling  
52 thermobarometry, crystal-chemistry, and structural analysis with high-resolution *in situ* and  
53 step-heating  $^{40}\text{Ar}/^{39}\text{Ar}$  dating. A key innovation of our approach is to combine these techniques  
54 to a level of integration never attempted before. In particular, we apply extensive (regional)  
55  $^{40}\text{Ar}/^{39}\text{Ar}$  sampling across strain gradients previously recognized at all scales through this  
56 transition (e.g. Laurent et al., 2016, 2018; Roche et al., 2016), down to the petrographic/mineral  
57 scale. We further explore the behaviour of the phengite  $^{40}\text{Ar}/^{39}\text{Ar}$  system as a function of strain  
58 intensity, textural habitus, metamorphic grade, and synkinematic overprint from the regional (>  
59 10 km) down to the mineral scale (< 1 mm).

60

## 61 **2. Geological Setting**

62

### 63 2.1 Geodynamic evolution of the Cyclades

64

65 The Aegean domain (eastern Mediterranean, Fig. 1) is characterized by two main  
66 tectonic and metamorphic events (Jolivet and Brun, 2010; Ring et al., 2010). The first one  
67 involves the convergence between Africa and Eurasia during Late Cretaceous-Eocene inducing

68 the formation of the Hellenides-Taurides chain (Bonneau and Kienast, 1982). A series of  
69 oceanic and continental units were accreted by underplating and mechanical coupling to the  
70 *HP/LT* nappe stack, which started to exhume through a set of syn-orogenic shear zones. These  
71 include the top-to-the E/NE Vari Detachment (Fig. 1, Trotet et al., 2001a; Soukis and Stockli,  
72 2013; Laurent et al., 2016), the top-to-the-S thrust in Ios (Huet et al., 2009; Ring et al., 2010),  
73 and the top-to-the-E Pythagoras thrust in Samos (Roche et al., 2019). The second  
74 tectonometamorphic event corresponds to the progressive dislocation of the nappe stack as a  
75 consequence of the southward acceleration of the African slab retreat and tearing (e.g. Le  
76 Pichon and Angelier, 1981; Lister et al., 1984; Jolivet et al., 2004, 2013, 2015). The thickened  
77 crust of the Aegean domain was thus affected by post-orogenic extension, while the frontal  
78 zones were still under compression (Jolivet et al., 1994; Jolivet and Brun, 2010). In the Cyclades,  
79 detachment systems such as the top-to-the NE North Cycladic Detachment System (NCDS,  
80 Jolivet et al., 2010), the top-to-the S/SW West Cycladic Detachment System (WCDS,  
81 Grasemann et al., 2012), the top-to-the N Naxos-Paros Detachment System (NPDS, Gautier et  
82 al., 1993) and the top-to-the S Santorini Detachment (Schneider et al., 2018) accommodated  
83 back-arc extension and exhumation of the Cycladic Blueschist Unit (CBU, Fig. 1). During this  
84 phase, extensional tectonic was characterized by the development of Metamorphic Core  
85 Complexes (MCCs) on Naxos, Mykonos and Ikaria, where high-temperature parageneses  
86 overprint previous *HP/LT* parageneses at 21-17 Ma (Fig. 1, Lister et al., 1984; Wijbrans and  
87 McDougall, 1988; Urai et al., 1990; Gautier et al., 1993; Gautier and Brun, 1994; Jolivet and  
88 Patriat, 1999; Keay et al., 2001; Vanderhaeghe, 2004; Beaudoin et al., 2015; Laurent et al.,  
89 2015; Rabillard et al., 2018).

90

91 2.2 Geology of the Cycladic Blueschist Unit

92

93 The Cycladic archipelago (central Aegean domain) is mainly composed of the CBU  
94 (Fig. 1). This has been recently divided in two subunits: the Lower Cycladic Blueschist nappe  
95 (LCB) and the Upper Cycladic Blueschist nappe (UCB), which differ in lithology, geochemical  
96 record, and *P-T* conditions (Grasemann et al., 2018; Roche et al., 2018, 2019).

97 The LCB nappe is mainly observed in the southern and western parts of the Aegean  
98 domain (e.g., Serifos, Folegandros; Fig. 1). It is composed of metapelites, graphite-rich schists  
99 and marbles with minor metabasite (e.g. Grasemann et al., 2018; Roche et al., 2018). Published  
100 *P-T* data throughout this subunit indicate peak conditions of  $10 \pm 2$  kbar and 400-500 °C  
101 (Katagas, 1984; Katzir et al., 2000; Baziotis et al., 2009; Iglseider et al., 2011; Augier et al.,  
102 2015; Scheffer et al., 2016; Grasemann et al., 2018; Roche et al., 2018).

103 The UCB nappe lies in the central part of the Aegean domain (i.e., the Cycladic  
104 archipelago, Fig. 1), and is particularly well exposed on Syros and Sifnos. On Syros, the UCB  
105 stack is classically subdivided in three subunits differing in lithology and predominant  
106 metamorphic facies (Laurent et al., 2016). These are from top to bottom the Kampos, Chroussa,  
107 and Posidonia subunits (Figs. 2, 3). The Kampos Subunit consists of a *mélange* of metabasites  
108 wrapped in serpentinites and minor metasediments. Eclogite- and *BS*-facies parageneses are  
109 spectacularly preserved and mostly escaped lower-*P* retrogression. The intermediate Chroussa  
110 Subunit is a lithostratigraphic sequence of alternating micaschists, thick marble layers and  
111 lenses of metabasite. Portions of this subunit are overprinted in the *GS*-grade facies while others  
112 show well-preserved eclogite- and *BS*-facies parageneses. The lowermost Posidonia Subunit  
113 consists of the structurally lower gneiss of Komito overlain by albitic micaschists with  
114 intercalated boudins of metabasite and thin marble layers. This subunit is pervasively  
115 overprinted in the *GS*-facies and shows only few preserved *HP* parageneses.

116 The UCB on Syros was exhumed in an overall top-to-the E non-coaxial shearing from  
117 eclogite-facies through *GS*-facies conditions (Trotet et al., 2001a; Laurent et al., 2016). Strain

118 localization occurred progressively toward the base of the UCB during the *HP-GS* transition,  
119 along ductile shear zones observed at all scales (Laurent et al., 2016), preserving *HP/LT*  
120 structures in the less deformed eclogite- and *BS*-grade topmost subunits (Figs. 2, 3). Similar  
121 shear zones were described on Sifnos where, as on Syros, the topmost part of the UCB shows  
122 well-preserved *HP/LT* parageneses relative to the highly *GS*-facies overprinted lowermost part  
123 (Roche et al., 2016). Despite their variable degree of retrogression, eclogite-facies parageneses  
124 are recognized throughout the UCB subunits of Syros and Sifnos with similar peak conditions  
125 around 22-20 kbar and 550 °C (Fig. 4; Trotet et al. 2001b; Groppo et al., 2009; Dragovic et al.,  
126 2012; Ashley et al., 2014; Laurent et al., 2018; Brooks et al., 2019). Laurent et al. (2018)  
127 recently refined the *P-T* exhumation path on Syros, suggesting a multi-stage evolution  
128 involving (1) a cold syn-orogenic exhumation within the subduction channel after peak  
129 metamorphic conditions, (2) isobaric heating at ca. 12-10 kbar due to thermal re-equilibration  
130 of the lithosphere in the back-arc domain, and (3) exhumation and cooling related to post-  
131 orogenic extension. A quite similar *P-T* evolution of the UCB was also described on Tinos and  
132 Andros (Parra et al., 2002; Huet et al., 2015). The *P-T* record across the UCB is heterogeneous,  
133 the isobaric heating phase affecting to a lesser extent the topmost parts of the UCB (Kampos  
134 Subunit) than the intermediate and lowermost parts (respectively Chroussa and Posidonia  
135 Subunits, Fig. 4).

136

### 137 3. Previous geochronology

138

139 The timing of peak metamorphism in the UCB sequence has been constrained on Syros  
140 and Sifnos by U/Pb dating on zircon and Sm/Nd and Lu/Hf on garnet with ages ranging between  
141 55-49 Ma (Fig. 4, Tomaschek et al., 2003; Lagos et al., 2007; Dragovic et al., 2015). Rb/Sr and  
142  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of white mica from well-preserved *HP/LT* parageneses provided similar

143 (though more variable) ages between 55-30 Ma (e.g. Putlitz et al., 2005; Bröcker et al., 2013;  
144 Cliff et al., 2016; Lister and Forster, 2016; Laurent et al., 2017; Uunk et al., 2018).

145 Syros has been the focus of many (and especially  $^{40}\text{Ar}/^{39}\text{Ar}$ ) geochronological studies  
146 (Fig. 4), mainly in the northern part featuring spectacularly preserved *HP/LT* parageneses  
147 (Tomaschek et al., 2003; Putlitz et al., 2005; Lagos et al., 2007; Bröcker et al., 2013; Rogowitz  
148 et al., 2015; Cliff et al., 2016; Lister and Forster, 2016; Laurent et al., 2017; Uunk et al., 2018;  
149 Skelton et al., 2019). There, Rb/Sr dating constrains the timing of retrogression from 42 Ma to  
150 as young as 25-21 Ma in *BS* and *GS*-facies associated with extensional fabrics. The syn-  
151 kinematic *GS*-facies retrogression and associated age range is mostly viewed as a continuum  
152 process rather than a single discrete event (Fig. 4, Bröcker et al., 2013; Cliff et al., 2016). The  
153 question as to which extent these data can constrain the timing of the *HP* to *GS*-facies transition  
154 remains open (Bröcker et al., 2013), however, Ring et al. (2011) obtained a well defined Rb/Sr  
155 phengite isochron at  $22.8 \pm 0.2$  Ma (MSWD = 1.6) on *GS*-grade rocks of Sifnos contrasting  
156 with the scatterchron obtained on phengites from a pristine *BS*-grade sample at  $29.4 \pm 3.4$  Ma  
157 (MSWD = 46). Such disequilibrium systematics are suggested to result from partial resetting  
158 of *HP* isotopic and chemical signatures by way of deformation-induced incomplete  
159 recrystallization during the *BS-GS* transition.

160 The latest contribution to the  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of Syros (Uunk et al., 2018)  
161 revealed the existence of phengite age gradients regionally correlated with metamorphic grade  
162 and overprinting with single-grain total-fusion ages ranging from 54 to 31 Ma. To get rid of  
163 local deformation effects, that study avoided targeting complex fabrics developed in connection  
164 with local and regional strain gradients. Also, the total-fusion approach of dating isolated single  
165 grains provides no textural control on intra- and inter-grains  $^{40}\text{Ar}/^{39}\text{Ar}$  relationships. This is in  
166 contrast with our multi-scale approach that contributes *in situ* ages regionally and locally tied  
167 to deformation structures and metamorphic fabrics, allowing to substantially refine the

168 significance of local and grain-scale  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics in the context of the regional  
169 metamorphic transition.

170

#### 171 4. Methods

172

##### 173 4.1. Sampling strategy

174

175 As just stated, a major limitation of previous  $^{40}\text{Ar}/^{39}\text{Ar}$  studies of the UCB has been the  
176 lack of exhaustive sampling to permit the  $^{40}\text{Ar}$  record of *HP* phengite to be studied in connection  
177 with large-scale structures and metamorphic gradients and gaps recognized across the UCB  
178 stack. This has hampered the interpretation of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages lacking a clearly established link  
179 with (1) regional metamorphic gradients, (2) the finite strain pattern locally imposed by  
180 deformation across the eclogite/*BS-GS* grade transition, and (3) the isotope distribution at the  
181 mineral scale.

182 Our focus is on exploring the behaviour of the phengite  $^{40}\text{Ar}/^{39}\text{Ar}$  system across strain  
183 gradients and regional strain distribution patterns previously studied by our group and others  
184 (Trotet et al., 2001; Rogowitz et al., 2015; Laurent et al., 2016; Roche et al., 2016). In these  
185 studies, strain gradients were qualitatively determined via standard field practice based on  
186 strain-intensity indicators such as: (i) the development of increasingly pronounced foliation  
187 (planar fabric) and stretching (linear fabric) toward the core of the shear zones  
188 (synkinematically elongated phengite, glaucophane, epidote, etc.), (ii) the development of shear  
189 structures such as shear bands and narrow ductile shear zones and C-S shear fabrics, (iii)  
190 mineral fish and sheared porphyroblasts, (iv) in some shear zones and toward their core, the  
191 progressive synkinematic retrogression from eclogite to *BS* or from *BS* to *GS*, and (v) the

192 progressive alignment/parallelisation of folds hinges with the direction of stretching toward the  
193 core of the shear zone.

194         Based on these structural data, we applied a multi-scale  $^{40}\text{Ar}/^{39}\text{Ar}$  sampling strategy to  
195 provide, first, a regional coverage across the UCB and the overlying Vari Unit (Fig. 2) both  
196 across the island and along the southern coast of Syros where all subunits are continuously  
197 exposed and relationships between deformation and metamorphic recrystallization can be  
198 observed. We next focused on individual shear zones previously studied in detail across  
199 smaller-scale (ca. 500 m) sections (Lia shear zone, northern Syros, [Laurent et al., 2016](#); Delfini  
200 shear zone, western Syros, [Rogowitz et al., 2015](#); [Laurent et al., 2016](#); Chryssopigi shear zone,  
201 southern Sifnos, [Roche et al., 2016](#); Figs. 2, 3). These display characteristic high-strain  
202 gradients distinctly developed across the eclogite-*BS* (Lia shear zone) and the *BS-GS* (Delfini  
203 shear zone) metamorphic transitions on Syros. A further section developed entirely in the *GS*  
204 facies (Chryssopigi shear zone, Sifnos), but characterized by variable extent of deformation-  
205 assisted retrogression, was also investigated. Strain and facies variations suggest that these  
206 shear zones were not coevally active during the whole exhumation and, thus, that they  
207 potentially bear a distinct  $^{40}\text{Ar}/^{39}\text{Ar}$  signature in connection with temporal variations in the 3-  
208 D strain pattern at the scale of the UCB stack. Lastly, we applied spatially resolved (< 100  $\mu\text{m}$ )  
209 *in situ* UV-ablation on mm-scale rock sections from the targeted sections to investigate  
210  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics in connection with well-characterized microstructures and crystal  
211 chemical patterns. Integration of the data collected through all scales is a major innovation of  
212 this study that proved essential in understanding the temporal  $^{40}\text{Ar}/^{39}\text{Ar}$  pattern recorded by  
213 phengite in this part of the UCB.

214

215 4.2. EPMA analyses

216

217 Geochemical analyses of phengite crystals were performed to determine the degree of  
218 recrystallization in the studied samples, a key parameter to understand  $^{40}\text{Ar}/^{39}\text{Ar}$  ages. A  
219 CAMECA SX100 electron probe microanalyzer (EPMA) housed at ISTO (Orléans, France)  
220 was used to acquire spot analyses of phengite. Analytical conditions were 15 kV accelerating  
221 voltage and 12 nA beam current with 10 s integration times for all elements (spot mode).

222 X-ray maps were acquired to check crystal-scale compositional variations in phengite  
223 (from half a mm to a few  $\mu\text{m}$ ) and for linking geochemistry with microstructures and  $^{40}\text{Ar}/^{39}\text{Ar}$   
224 ages using a JEOL JXA-8230 instrument housed at ISTerre (University of Grenoble-Alpes,  
225 France; [de Andrade et al., 2006](#)). Mapping conditions were 15 kV accelerating voltage, 100 nA  
226 specimen current and 15 kV accelerating voltage, and 12 nA specimen current for spot analyses.  
227 Compositional mapping was carried out with dwell time of 200 ms and a step size  
228 (corresponding to the pixel size in the final image) of 2  $\mu\text{m}$ . The X-ray compositional map was  
229 processed with the program XMAPTOOLS 2.2.1 ([Lanari et al., 2014](#)). Representative microprobe  
230 analyses of phengites from the  $^{40}\text{Ar}/^{39}\text{Ar}$  analysed samples are provided in Appendix S3.

231

#### 232 4.3. $^{40}\text{Ar}/^{39}\text{Ar}$ methods

233

234 We applied  $^{40}\text{Ar}/^{39}\text{Ar}$   $\text{CO}_2$ -laser step-heating on single grains and populations  
235 handpicked from the 0.5-1.0 mm fraction (single grains) and 0.25-0.50 mm (populations)  
236 obtained by gently crushing the samples. For spatially resolved UV-laser *in situ* mapping,  
237 diagnostic microstructures were drilled out from carefully sectioned samples, then cut and  
238 polished to 1  $\mu\text{m}$  (adhesive such as superglue was not used) to obtain 0.9-1.3 mm thick  $\times$  10  
239 mm circular rock sections. Rock sections, mineral grains and separates were washed in acetone,  
240 ethanol and de-ionised water in ultrasonic bath, dried at 50  $^\circ\text{C}$  in an oven, weighed and finally  
241 microscopically analysed and photographed.

242 All samples were irradiated for 5 h at Corvallis (CLICIT in-core position, Oregon, USA)  
243 along with sanidine standard FCT ( $28.02 \pm 0.28$  Ma, [Renne et al., 1998](#)) and analysed at the  
244  $^{40}\text{Ar}/^{39}\text{Ar}$  laboratory housed at ISTO (Orléans, France). Upon return from irradiation, they were  
245 unwrapped and placed in a stainless steel sample holder and loaded in a laser port pumped to  
246 ultra-high vacuum and baked to  $195\text{ }^{\circ}\text{C}$  over 48 hours. Extracted gases were purified using two  
247 air-cooled GP50 SAES® getters during 6 minutes before admission into the mass spectrometer.  
248 Ar and Cl isotopes were sequentially measured in 20 cycles with an electron multiplier ( $^{35}\text{Cl}$ ,  
249  $^{36}\text{Ar} \pm ^1\text{H}^{35}\text{Cl}$ ,  $^{37}\text{Ar} \pm ^{37}\text{Cl}$ ,  $^{38}\text{Ar} \pm ^1\text{H}^{37}\text{Cl}$ ,  $^{39}\text{Ar}$ ,  $^{40}\text{Ar}$  isotopes) and a Faraday cup ( $^{40}\text{Ar}$  only) by  
250 peak-switching on one of the three static noble gas Helix-SFT® (Thermo Fisher Scientific,  
251 GmbH) mass-spectrometers operated at ISTO with a mass-resolution in excess of 750. Gas  
252 handling and mass-spectrometer operations are fully automated using stand-alone LabView-  
253 based software. Procedural blanks were monitored according to their evolution: every third  
254 heating step (typically the initial low- $T$  heating steps featuring little or no  $^{39}\text{Ar}$ ) to every sample  
255 gas admission (all *in situ* experiments and mid to high- $T$  extraction steps) in the same conditions  
256 as the sample. Typical values were 0.1 fA, 0.001 fA, 0.001 fA, 0.001 fA, and 0.001 fA for  $m/e$   
257 = 40, 39, 38, 37, 36, respectively. Data regression and age calculations/corrections were made  
258 following Scaillet (2000). Regressed  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic data are tabulated in the supplementary  
259 material. Individual age errors include propagation of all instrumental and procedural  
260 uncertainties. Plateau ages (PA) are calculated as integrated (inverse-variance weighted) mean  
261 ages over the corresponding steps, and total-gas ages (TGA) by individually summing the Ar  
262 isotopes of all steps (equivalent to a K-Ar age). These are quoted at  $\pm 1\sigma$ .

263 Phengites were step-heated either as single grains (size permitting), or as small  
264 populations (clusters) typically comprising 6-7 grains, rarely more (up to 30 gains). For *in situ*  
265 dating, target-matching techniques were employed whereby the section surface analysed by  
266 SEM and probed with the EPMA was uncoated (i.e., repolished to  $1\text{ }\mu\text{m}$ , then ultrasonically

267 rinsed in acetone and alcohol) to allow direct  $^{40}\text{Ar}/^{39}\text{Ar}$  targeting of mineral zones and structures  
268 previously imaged and compositionally characterized by electron microscopy. A high-  
269 resolution deep 213-UV laserprobe (Photon Machines LXG2+ model) was used to excavate  
270 100 to 50  $\mu\text{m}$ -wide square or circular-shaped ablation pits about 50-70  $\mu\text{m}$ -deep at a repetition  
271 rate of 20 Hz and 4-5 mJ/pulse. White light interferometry scanning of individual spots revealed  
272 steep-walled pits with variable bottom geometry (from nearly flat at integrated pulse counts <  
273 600, to progressively cone-shaped due to progressive defocusing and internal reflections past  
274 1000 pulses). Complete  $^{40}\text{Ar}/^{39}\text{Ar}$  data are provided in Appendix S4 and S5. Except for a few  
275 analyses,  $^{37}\text{Ar}_{\text{Ca}}$  and  $^{36}\text{Ar}_{\text{Cl}}$  isotopes were all measured close to background values. Overall,  
276 they provide no insight on geochemical-ages relationships and are not discussed further below.

277

## 278 5. Results

279

### 280 5.1. Regional gradient: Southern Syros Section

281

#### 282 5.1.1. Petrology, structure, and mineral chemistry

283

284 The most complete section across all subunits of the UCB and the Vari Unit can be  
285 studied sub-parallel to the regional E-W stretching lineation dominating across the southern  
286 part of Syros (Fig. 2, [Laurent et al., 2016](#)). This section shows strain gradients at all scales,  
287 across which 17 samples were collected for  $^{40}\text{Ar}/^{39}\text{Ar}$  dating (Figs. 2, 3). The mineralogy and  
288 structure of the analysed samples as well as the petro-textural characteristics of phengite are  
289 described below and summarized in Tables 1 and 2.

290 *Lowermost Posidonia Subunit.* Three samples (SY-14-21, SY-14-18 and SY-13-02)

291 were taken from the structurally lower felsic gneiss of Komito intercalated with boudins of

292 metabasite (Fig. 2). SY-14-21 is a chlorite micaschist partly overprinted in *GS*-facies conditions  
293 with the preservation of garnet and glaucophane. SY-14-18 is a Grt-Ep blueschist that was  
294 collected in the core of a metabasic boudin preserved from retrogression. Phengite is little  
295 deformed and compositionally homogeneous in this sample (Fig. 5). SY-13-02 is a gneissic  
296 sample, strongly foliated and showing top-to-the E shear bands. Phengite shows a spread in  
297 composition with no clear correlation with microstructures (Fig. 5). SY-16-10, SY-14-80, SY-  
298 14-76 and SY-14-77 were collected in the metapelite sequence pervasively overprinted in the  
299 *GS*-facies composing the upper parts of the Posidonia subunit (Fig. 2). SY-16-10 is a calcschist  
300 with coarse-grained primary phengite crystals. SY-14-80 is a strongly stretched and sheared  
301 *GS*-facies micaschist displaying top-to-the E kinematics with fine-grained secondary phengites  
302 set in a quartz matrix and oriented parallel to small shear bands (Fig. 5). Phengite composition  
303 is quite homogeneous and characterized by a low Si-content (Fig. 5). SY-14-76 is a weakly  
304 foliated and stretched chlorite-bearing calcschist statically overprinted in the *GS*-facies.  
305 Phengite is little deformed microscopically and is compositionally characterized by variable  
306  $X_{Mg}$  values (Fig. 5). SY-14-77 is a strongly deformed metapelite overprinted under *GS*-facies  
307 conditions. There, phengite forms interconnected layers parallel to shear bands affecting a  
308 quartz and chlorite-dominated matrix. Phengite composition displays two distinct groups  
309 characterized by different  $X_{Mg}$  values (Fig. 5).

310 *Intermediate Chroussa Subunit.* Two samples were collected in this subunit (Fig. 2).  
311 SY-16-06 is a well-preserved *BS*-facies metabasite that is foliated and sheared (Fig. 6). SY-16-  
312 15 is made up of cm-scale phengite grains that were directly collected within the extensional  
313 gap of a neck formed at the tip of an eclogite boudin (Fig. 6). The association with glaucophane  
314 in the syn-kinematic neck indicates crystallization under *BS*-facies conditions.

315 *Topmost Kampos Subunit.* Five samples displaying varying degrees of retrogression  
316 were collected below the Vari Detachment, a major tectonic structure delimiting the *HP-LT*

317 UCB rocks from the amphibolite-facies Vari Unit (e.g. Trotet et al., 2001; Ring et al., 2003;  
318 Keiter et al., 2011; Soukis and Stöckli, 2013; Laurent et al., 2016). Sample SY-14-40b is a  
319 metabasite showing a complex deformation and retrogression pattern. While the top parts of  
320 the sample (SY-14-40b<sub>2</sub>) preserves a *HP/LT* mineralogy (glaucophane and garnet) affected by  
321 both syn-*BS* top-to-the W and syn-*GS* top-to-the E shear bands, the base (SY-14-40b<sub>4</sub>) displays  
322 overprinted *HP/LT* minerals with only top-to-the E syn-*GS* shear bands (Fig. 7). This gradient  
323 is mirrored by variations in phengite composition from the top (SY-14-40b<sub>2</sub>) to the base (SY-  
324 14-40b<sub>4</sub>). While the first shows homogeneous high Si-content, the second exhibits two distinct  
325 compositional groups with a trend toward lower Si-content and  $X_{Mg}$  values from coarse-grained  
326 phengites in foliation to fine-grained phengites in shear bands (Fig. 7). SY-14-60, SY-14-63  
327 and SY-14-64 were collected from the same outcrop (Fig. 7). SY-14-60 and SY-14-64  
328 correspond to eclogite boudins preserved in a strongly foliated *BS*-facies matrix. SY-14-63 is a  
329 strongly foliated, m-long, *BS*-facies metabasic boudin. In these samples, some phengite crystals  
330 are characterized by a high-Si core and lower-Si rims with a large Si vs.  $X_{Mg}$  compositional  
331 span.

332 *Vari Unit.* Three samples were collected in the Vari gneiss (SY-14-68) and the  
333 underlying mylonitic *GS*-facies metasediments (SY-16-18 and SY-13-10). None of these  
334 displays evidence of *HP/LT* metamorphism. Phengite in SY-13-10 has a relatively  
335 homogeneous composition similar to other UCB phengite (e.g. SY-14-40b<sub>4</sub>, Fig. 7) while the  
336 Vari gneiss SY-14-68 contains significantly lower  $X_{Mg}$  phengite (Fig. 7).

337

338 5.1.2.  $^{40}Ar/^{39}Ar$  results

339

340 *Lowermost Posidonia Subunit.*  $^{40}Ar/^{39}Ar$  step-heating of the phengite population SY-  
341 14-21 yielded a complex age spectrum with apparent ages ranging from 35 Ma to 23 Ma (Fig.

342 8). The fine-grained population SY-14-18 yielded an overall flat age spectrum with a total gas  
343 age of  $28.9 \pm 0.5$  Ma. The single grain SY-13-02 yielded a flat spectrum past the first three  
344 heating steps with an age of ca. 21 Ma for 93 % of total  $^{39}\text{Ar}$  released. The paired phengite  
345 grains of SY-16-10 yielded a hump-shaped spectrum with apparent ages ranging from 26 Ma  
346 to 20 Ma (Fig. 8). The population SY-14-80 yielded a flat age spectrum with a plateau at  $18.0$   
347  $\pm 0.1$  Ma for 100 % of total  $^{39}\text{Ar}$  released. This plateau corresponds to the youngest  $^{40}\text{Ar}/^{39}\text{Ar}$   
348 age obtained on Syros. A population of nine phengite grains from SY-14-76 yielded  
349 progressively increasing apparent ages ending with a flat segment at ca. 32 Ma over the six last  
350 heating steps (64 % of total  $^{39}\text{Ar}$  released, Fig. 8). The phengite single grain SY-14-77, collected  
351 just below the contact zone delimiting the lowermost Posidonia Subunit and intermediate  
352 Chroussa Subunit (i.e. the Posidonia-Chroussa shear zone, Figs. 2, 3, [Laurent et al., 2016](#)),  
353 yields initially climbing low-T ages followed by a flat segment at ca. 20 Ma for 81 % of total  
354  $^{39}\text{Ar}$  released.

355 *Intermediate Chroussa Subunit.* The 3-grain phengite cluster SY-16-06, structurally  
356 located 10 m above the Posidonia-Chroussa shear zone, yielded three sharply increasing initial  
357 ages followed by a flat segment over the last six temperature steps around 38 Ma (67 % of total  
358  $^{39}\text{Ar}$  released, Fig. 8). The single phengite grain SY-16-15 yielded a slightly discordant age  
359 spectrum with apparent ages declining from 42 to 41 Ma. Additionally, 4 single phengite grains  
360 of different size were dated *in situ* (Fig. 9). Three crystals, SY-16-15b, SY-16-15c and SY-16-  
361 15d, yield very consistent apparent ages comprised between 45-40 Ma with broadly consistent  
362 TGA at  $43.7 \pm 0.3$  Ma,  $43.6 \pm 0.2$  Ma and  $42.0 \pm 0.2$  Ma, respectively (Fig. 9). Interestingly,  
363 SY-16-15a, the larger and heavier grain, yields consistent but significantly younger *in situ*  
364 apparent ages with 88% of the data comprised between 38-35 Ma (TGA =  $37.2 \pm 0.2$  Ma).

365 *Topmost Kampos Subunit.*  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating of single grain SY-14-40b<sub>2</sub> yielded a  
366 decreasing age spectrum with apparent ages ranging from 30 Ma to 20 Ma (Fig. 8). The

367 measured amount of released  $^{39}\text{Ar}$  for this grain is significantly lower than expected from  
368 sensitivity calculations assuming 10 wt.%  $\text{K}_2\text{O}$ , implying that this grain was not pure phengite  
369 but some interlayered phengite + paragonite  $\pm$  chlorite. The population SY-14-40b<sub>4</sub> yielded a  
370 discordant age spectrum with apparent ages ranging from 40 Ma to 33 Ma (Fig. 8). Two paired  
371 phengite grains from SY-14-60 and SY-14-63 yielded equally discordant spectra with apparent  
372 ages varying between 44 and 40 Ma. The first five heating steps of SY-14-60 define a flat  
373 segment at ca. 42 Ma and the three consecutive steps an age of ca. 44 Ma for 55% of total  $^{39}\text{Ar}$   
374 released. SY-14-63 is characterized by an initial hump climbing to 44 Ma followed by a more  
375 regular segment stabilizing around 40 Ma at the end of degassing. The age spectrum measured  
376 on the 3-grain cluster SY-14-64 is characterized by a sharp increase of apparent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages  
377 over the first three degassing steps and by a flat segment at ca. 42 Ma over the last four steps  
378 comprising 60 % of total  $^{39}\text{Ar}$  released (Fig. 8). *In situ* analyses were measured on rock-section  
379 SY-14-64 previously SEM mapped to study the relationships between composition,  
380 microstructures and  $^{40}\text{Ar}/^{39}\text{Ar}$  record (Fig. 10). A coarse phengite crystal displaying a core to  
381 rim Si decrease show core ages of 46-43 Ma indistinguishable from those obtained in the lower-  
382 Si rim (45-43 Ma). Noteworthy, younger apparent ages of 38-35 Ma were measured in  
383 phengites of intermediate and lower Si-content located at the contact with a garnet and within  
384 a pressure shadow (Fig. 10).

385 *Vari Unit* (Fig. 8). The phengite population SY-16-18b yielded an erratic pattern with  
386 apparent ages ranging from 144 to 105 Ma, all characteristically older than any other sample  
387 elsewhere on Syros. The single grain SY-14-68 is characterized by a sharp increase of apparent  
388 ages over the first 4 temperature steps followed by a general decrease from 80 to 67 Ma (Fig.  
389 8). A more consistent age pattern was obtained from the single grain SY-13-10 with a  
390 progressive increase from 42 to 59 Ma until fusion, closely mimicking a diffusive-loss profile.

391 Of particular interest, the earlier steps define the youngest ages obtained in the Vari Unit and  
392 are associated with the most deformed sample in the upper part of the Vari Detachment.

393

394 5.2. Local metamorphic and strain gradients.

395

396 5.2.1. Lia Shear Zone (Northern Syros): Eclogite to *BS* transition

397

398 *Sample description and mineral chemistry*

399

400 The northern part of Syros exposes the upper portion of the UCB (i.e. the topmost  
401 Kampos subunit), where the *HP/LT* parageneses are best preserved (Fig. 2). Increasing  
402 retrogression in the *BS*-facies is observed toward the Lia shear zone. While the less deformed  
403 samples preserve eclogitic parageneses, these are no longer recognized in the most deformed  
404 ones (Table 1), indicating strain localization early during exhumation.

405 Three samples were selected across this gradient (Fig. 2). SY-14-74 was sampled away  
406 from the shear zone (structurally 150 m below) in an undeformed eclogitic metagabbro showing  
407 no planar fabric (Figs. 11, 12). It is unaffected by the dynamic *BS* overprint, and thus serves as  
408 a local unretromorphosed reference. SY-14-71 was collected 100 m below the core of the shear  
409 zone, in an eclogite-*BS* metabasite included in serpentinite (Fig. 11). This sample is only  
410 incipiently deformed, probably recording the first steps of exhumation at the transition between  
411 eclogite and *BS*-facies conditions. Phengite is moderately deformed, compositionally  
412 homogeneous, and oriented parallel to foliation-forming glaucophane indicating growth near  
413 peak-pressure conditions. A rock section was cut across an omphacitic pressure shadow around  
414 a circular-shaped polycrystalline phengite aggregate, possibly a pseudomorph after lawsonite,  
415 embedded in a glaucophane-dominated matrix ( $\pm$  phengite, Fig. 12). This was analysed *in situ*

416 with the UV-laser probe and with the continuous-CO<sub>2</sub> laser probe on separated single grain  
417 (step-heating). SY-14-73 was collected within the Lia Shear Zone proper, where syn-BS grade  
418 deformation is extreme and marked by a strong planar fabric with top-to-the E kinematics (Figs.  
419 11, 12). One step-heating experiment (single phengite grain) was conducted. Additionally, *in*  
420 *situ* <sup>40</sup>Ar/<sup>39</sup>Ar UV-mapping was performed on a rock section drilled across a well-preserved  
421 syn-BS micro-shear band (Fig. 12).

422

423 *<sup>40</sup>Ar/<sup>39</sup>Ar results*

424

425 Twenty-eight *in situ* <sup>40</sup>Ar/<sup>39</sup>Ar ages were measured on SY-14-74 rock section  
426 (undeformed eclogitic metagabbro) with 25 analyses showing a homogeneous age distribution  
427 between 51 and 48 Ma (Fig. 12). The three oldest ages between 57-52 Ma are associated with  
428 a distinctly higher content in both <sup>36</sup>Ar and <sup>37</sup>Ar possibly indicating contribution from a shallow  
429 omphacite crystal hidden underneath the sample surface.

430 Step-heating of one single-grain of SY-14-71 (incipiently deformed eclogite/blueschist  
431 metabasite) resulted in a flat age spectrum with a total fusion age of  $47.1 \pm 0.2$  Ma (Fig. 12).  
432 Thirty-three *in situ* analyses from this sample yielded ages vary between 49 and 45 Ma in the  
433 circular-shaped pseudomorph after lawsonite (Fig. 13) and more tightly grouped ages around  
434 50-49 Ma in the eclogitic pressure shadow developed around it (four *in situ* analysis). This age  
435 range is broadly consistent with the one obtained for SY-14-74 (51-48 Ma). Less than 30% of  
436 the data are younger than 48 Ma (down to 42 Ma) and found in the main glaucophanitic matrix  
437 (Fig. 12). In stark contrast with the two previous samples, the 44 *in situ* apparent ages obtained  
438 on the strongly deformed SY-14-73 sample define a much broader range from 51 Ma  
439 (maximum age, shared with SY-14-74 and SY-14-71) to 23 Ma (Fig. 12). Of particular interest,  
440 the youngest apparent ages between 25-23 Ma are found both in little deformed coarse-grained

441 phengite away from the shear band as well as in fine-grained deformed phengite in the shear  
442 band. Note that this also holds for the older (51-45 Ma) and intermediate (45-30 Ma) apparent  
443 ages measured both within and away from the micro-shear band (Fig. 12). The companion  
444 single-grain age spectrum is characterized by a flat segment at ca. 39 Ma for 70 % of the total  
445  $^{39}\text{Ar}$  released (excluding the first and last step, Fig. 12).

446

447 5.2.2. Delfini Shear Zone (Central Syros): *BS* to *GS* transition

448

449 *Sample description and mineral chemistry*

450

451 Two *BS* to *GS*-grade shear zones cut across the Delfini peninsula on Syros (Figs. 2, 3,  
452 [Laurent et al., 2016](#)) characterized by intensely deformed rocks displaying a NE dipping  
453 foliation carrying a stretching lineation oriented E-W (Fig. 2). Asymmetric ductile deformation  
454 is characterized by top-to-the E kinematics indicated by shear bands and sigmoidal pressure  
455 shadows on garnets (Fig. 13). Six  $^{40}\text{Ar}/^{39}\text{Ar}$  samples were collected across the shear zone and  
456 analysed by step-heating (Figs. 2, 3, Table 1). SY-16-23 is a *GS*-overprinted micaschist with  
457 pronounced foliation. Phengite is fine-grained and either intensely sheared or little deformed  
458 (Fig. 13). SY-14-30 is a metabasite preserving *BS*-facies minerals. Phengite is locally deformed  
459 in *BS*-grade shear bands, but otherwise parallel in the foliation. SY-14-24 is a *BS*-facies boudin  
460 of metabasite preserved in pervasively retrogressed *GS*-facies rocks. Again, phengite is  
461 intensely deformed in local shear bands but otherwise little deformed in the foliation (Fig. 13).  
462 The different textural habitus is paralleled by a trend toward lower Si and  $X_{\text{Mg}}$  content in  
463 phengite inside the shear bands. SY-14-26 is a retrogressed micaschist preserving coarse-  
464 grained garnet. This sample is intensely sheared with top-to-the E kinematics (Fig. 13).  
465 Phengite exhibits a similar trend toward lower Si and  $X_{\text{Mg}}$  content as in sample SY-14-24 (Fig.

466 13). SY-14-28 is a tightly folded garnet and glaucophane-bearing calc schist preserving *BS*-  
467 facies parageneses with primary phengite displaying relatively homogeneous composition and  
468 less deformation than previous samples (Fig. 13). SY-14-29 is a phengite-bearing marble  
469 displaying top-to-the W kinematic shear criteria previously studied by Rogowitz et al. (2014,  
470 2015, 2016) for which they inferred extremely fast strain rates ( $10^{-10} \text{ s}^{-1}$ ) with grain-scale  
471 deformation partitioning into the weaker calcite crystals leaving phengite less deformed.

472

473 *<sup>40</sup>Ar/<sup>39</sup>Ar results*

474

475 Step-heating of the fine-grained population SY-16-23 yielded discordant apparent ages  
476 comprised between 39-33 Ma (Fig. 14). The 6-grain phengite cluster SY-14-30 is characterized  
477 by ages slightly increasing from 34 Ma to 39 Ma and a flat segment at ca. 36 Ma for 60 % of  
478 total <sup>39</sup>Ar released (Fig. 14). Single grain SY-14-24 shows an initial increase over the first  
479 temperature step then a decrease from 34 to 31 Ma over a relatively flat segment at ca. 34 Ma  
480 (65 % of total <sup>39</sup>Ar released, Fig. 14). The single grain of SY-14-26 yielded a hump-shaped age  
481 spectrum with apparent ages ranging from 34 Ma to 29 Ma (Fig. 14). SY-14-28 and SY-14-29  
482 single grains yielded two mutually consistent plateaux at  $38.5 \pm 0.2 \text{ Ma}$  and  $39.0 \pm 0.2 \text{ Ma}$  (Fig.  
483 14), broadly concordant with the step-heating ages of  $40 \pm 1.6 \text{ Ma}$  and  $37 \pm 1.3 \text{ Ma}$  obtained in  
484 these marbles by Rogowitz et al. (2016).

485

486 5.2.3. Chryssopigi Shear Zone (Sifnos): *GS*-facies deformation

487

488 *Sample description and mineral chemistry*

489

490 A strain gradient associated with pervasive retrogression in the *GS*-facies was described  
491 on Sifnos as the Chryssopigi Shear Zone (Figs. 2, 3, Roche et al., 2016). In the regional-scale  
492 tectonostratigraphic sequence of the UCB, this shear zone is located within the lateral  
493 equivalent of the lowermost Posidonia Subunit of Syros (Roche et al., 2016). Top-to-the NE  
494 shearing gradually increases toward the core of the shear zone where fold axes are deflected  
495 parallel to the stretching lineation (Roche et al., 2016). The Chryssopigi Shear Zone displays  
496 the strongest *GS*-facies finite strain gradient observed in this study.

497 Eight  $^{40}\text{Ar}/^{39}\text{Ar}$  samples were collected across the shear zone (Fig. 2). All samples are  
498 foliated and stretched, with deformation increasing toward the core of the shear zone (Fig. 15).  
499 Sample SF-14-55 is a foliated albite and epidote-bearing blueschist metabasite that was  
500 collected 300 m above the shear zone (Fig. 2). Two slightly different compositional groups are  
501 observed in phengite Si-content with no clear correlation with microstructures (Fig. 15). SF-  
502 14-52 is a *GS*-facies calcschist affected by top-to-the NE shearing. Phengite shows a trend  
503 toward lower Si-content within core-rim gradients (Fig. 15). SF-14-51 is a *GS*-facies calcschist  
504 with phengite characterized by a relatively homogeneous composition and little deformation  
505 (Fig. 15). SF-14-50 is a phengite-chlorite bearing marble overprinted under *GS*-facies  
506 conditions. Phengite is aligned in the main foliation and two distinct phengite compositions are  
507 characterized by different Si-contents with core-rim gradients (Fig. 15). SF-14-49 is a *GS*-facies  
508 calcschist showing top-to-the-NE shearing. Phengite appears either intensely sheared or little  
509 deformed with sectorial zoning toward lower Si-content, probably reflecting partial re-  
510 equilibration during exhumation (Fig. 15). SF-14-44 is a pervasively overprinted *GS*-facies  
511 micaschist sampled just above the core of the Chryssopigi Shear Zone and displaying top-to-  
512 the NE cm-scale shear bands. Phengite is relatively homogeneous with a low Si-content and  
513 slightly decreasing trend toward lower  $X_{\text{Mg}}$  values (Fig. 15). SF-14-43 and SF-14-39 are two  
514 pervasively overprinted *GS*-facies micaschists from the core of the shear zone proper (Fig. 15).

515 Phengite is intensely deformed and partially re-equilibrated (SF-14-43), with two well-defined  
516 compositional groups, or extensively recrystallized (SF-14-39), with a trend toward lower Si-  
517 content (zonal gradient and population trend, Fig. 15).

518

519 *<sup>40</sup>Ar/<sup>39</sup>Ar results*

520

521 The grain pair and 6-grain phengite cluster of SF-14-55 yielded two mutually discordant  
522 spectra, the first with a plateau age at  $21.5 \pm 0.3$  Ma distinctly younger (by about 3-6 Myr) than  
523 the companion age spectrum showing internally discordant ages between 26-22 Ma (Fig. 16).  
524 Two very similar (but internally discordant) age spectra were obtained from the single grain  
525 and 3-grain cluster of SF-14-52. Both age patterns evolve between 32 and 37 Ma and stabilize  
526 around 35 Ma near the end of the gas release. The minor internal variations occurring near the  
527 last steps of the single grain SF-14-52 may result from imprecise <sup>36</sup>Ar blank correction (Fig.  
528 16). The phengite population SF-14-51 displays a flat age spectrum with a plateau age at ca. 35  
529 Ma for 90 % of the total <sup>39</sup>Ar released. Single phengite grain SF-14-50 displays a hump-shaped  
530 age spectrum between 26-20 Ma with minor internal variations possibly reflecting imprecise  
531 <sup>36</sup>Ar blank correction after a large step again (Fig. 16). A discordant age spectrum was obtained  
532 from the 8-grain population of SF-14-49, with apparent ages wandering between 35-30 Ma with  
533 no well-defined trend. *In situ* laser ablation analyses (50 spots) of this sample are distributed  
534 between 38-22 Ma with the oldest apparent ages (38-30 Ma) found in undeformed phengites  
535 included in quartz and the youngest (30-22 Ma) in phengites located in shear bands (Fig. 17).  
536 The overall distribution is random, however, and apparently unrelated to microstructure with  
537 older ages also found in secondary shear bands. A discordant spectrum was obtained from the  
538 3-grain cluster of SF-14-44 with initial ages rising from 22 to 28 Ma, declining to 23 Ma across  
539 a flat segment spanning the last 60 % of <sup>39</sup>Ar released (Fig. 16). The 7-phengite cluster SF-14-

540 43 is broadly similar in shape and total-gas age ( $23.4 \pm 0.2$  Ma). A similar age range is  
541 reproduced by the companion 33-grain population, yet with a slightly different discordant  
542 pattern. SF-14-39 provided two mutually discordant population age spectra ( $TGA = 20.8 \pm 0.1$   
543 Ma vs.  $22.7 \pm 0.2$  Ma), the 6-grain cluster appearing more regular with a flat segment over the  
544 last 8 steps defining an age of ca. 21 Ma (90 % of the total  $^{39}\text{Ar}$  released, Fig. 16).

545

## 546 6. Discussion

547

548 We first discuss the  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics at the different scales investigated. These are  
549 then interpreted in terms of domain-scale phengite Ar record involving (prograde) growth  
550 dynamics followed by dynamic overprinting in the *BS*- then *GS*-facies. We conclude with a  
551 short discussion of the regional implications of the new  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite data.

552

### 553 6.1. $^{40}\text{Ar}/^{39}\text{Ar}$ spatio-temporal trends

554

#### 555 6.1.1. Regional $^{40}\text{Ar}/^{39}\text{Ar}$ trends across metamorphic transitions

556

557 Unlike previous geochronologic work mostly focused on the best preserved *HP-LT*  
558 occurrences in northern Syros (Bonneau, 1984; Wijbrans et al., 1990; Tomaschek et al., 2003;  
559 Putlitz et al., 2005; Lagos et al., 2007; Bröcker et al., 2013; Rogowitz et al., 2015; Cliff et al.,  
560 2016; Lister and Forster, 2016; Laurent et al., 2017; Uunk et al., 2018; Skelton et al., 2019),  
561 our  $^{40}\text{Ar}/^{39}\text{Ar}$  sampling coverage across both Syros and Sifnos allows to study in much greater  
562 detail the correlation of apparent ages with deformation and retrogression throughout the  
563 different scales investigated (Fig. 18). Despite local complexities, and taken as a whole, the  
564 data reveal a clear regional trend toward younger ages from top to bottom across the UCB (Fig.

565 18). This finding is consistent with previous (but more local and scattered) studies on Syros  
566 documenting an  $^{40}\text{Ar}/^{39}\text{Ar}$  age decrease across the UCB, from the well-preserved eclogite-facies  
567 samples at the top to the extensively developed *GS*-facies prevailing at the base (Maluski et al.,  
568 1987; Putlitz et al., 2005; Bröcker et al., 2013; Rogowitz et al., 2015; Lister and Forster 2016;  
569 Laurent et al., 2017; Uunk et al., 2018). Our oldest ages (51-48 Ma) come from *in situ* UV data  
570 from the top of the UCB stack (Kampos Subunit, Figs. 10, 12). They are consistent with (or just  
571 slightly younger than) previous Sm/Nd and Lu/Hf garnet ages and U/Pb zircon ages near 53-50  
572 Ma interpreted to date peak-metamorphic conditions in *HP*-index rock types of Syros and  
573 Sifnos (Fig. 4, Tomaschek et al., 2003; Lagos et al., 2007; Dragovic et al., 2015). *BS*-facies  
574 metabasites from the intermediate Chroussa Subunit yielded consistently younger step-heating  
575 or *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages between 41-37 Ma (Fig. 18). Samples structurally underneath in the  
576 lowermost Posidonia Subunit provided still younger ages comprised between 35-18 Ma, all  
577 together defining a coherent and progressive  $^{40}\text{Ar}/^{39}\text{Ar}$  younging toward the base of the UCB  
578 that correlates with the stronger *GS*-grade overprint of primary *HP* assemblages and the  
579 associated progressive finite strain gradient described in previous studies (Fig. 18, Laurent et  
580 al., 2016; Roche et al., 2016).

581 Similar to previous  $^{40}\text{Ar}/^{39}\text{Ar}$  studies (e.g., Reddy et al., 1996; Dunlap, 1997; Rogowitz  
582 et al., 2015) our data document a strong strain-age relationships with the youngest  $^{40}\text{Ar}/^{39}\text{Ar}$   
583 ages along the regional section corresponding to the more intensely deformed samples,  
584 particularly those involving phengite (re)crystallization (here and in the following the term  
585 (re)crystallization refers either to recrystallized phengite or to newly-formed phengites during  
586 exhumation when these processes cannot be differentiated). This is illustrated by sample SY-  
587 14-80 from the structurally deeper part of the section, which displays both the lowest average  
588 Si-content in phengite (3.24 apfu) and youngest well-defined age plateau ( $18.0 \pm 0.1$  Ma; Figs.  
589 5, 8). Except this extreme sample, there is no systematic correlation between phengite Si-

590 content and  $^{40}\text{Ar}/^{39}\text{Ar}$  age across the entire section (i.e., with younger ages associated with  
591 decreasing Si-contents, Fig. 19). The compositional-age relationships are examined in more  
592 details at the scale of single shear zones below.

593

#### 594 6.1.2. Local $^{40}\text{Ar}/^{39}\text{Ar}$ systematics across shear zones

595

596 A main result of our multi-scale approach is the observation that, across Syros, younger  
597 ages locally depart from the main regional trend close to (or within) highly deformed zones or  
598 lithologic contrast controlling strain localization and accommodation (Fig. 18). The 15 Myr gap  
599 found across the shear zone between the lowermost Posidonia and intermediate Chroussa  
600 subunits (between samples SY-16-06 and SY-14-77, Fig. 8) is one of such breaks in the regional  
601 trend. At the scale of a single shear zone, strain gradients are also mirrored by local  $^{40}\text{Ar}/^{39}\text{Ar}$   
602 age gradients (Fig. 18). The most ductilely deformed and retrogressed samples are correlated  
603 with the younger ages toward the core of all studied shear zones, including on Sifnos, with a  
604 maximum interval up to ca. 15 Myr in the Northern Lia (Syros) and Chryssopigi (Sifnos) shear  
605 zones (Fig. 18).

606 A compositional control is not apparent across these shear zones (Fig. 19). Age vs.  
607 phengite geochemistry relationships show poorly defined trends ( $R^2 = 0.08-0.15$ ), similar to  
608 what observed at the regional scale along the entire section across Syros. The Lia and Delfini  
609 shear zones show a faint correlation between phengite Si-content and apparent ages, but without  
610 a well-defined trend in Si-content against the distance to the core of the shear zone ( $R^2 = 0.01$ ,  
611 Fig. 19). Our results show that there is no first-order relationship between geochemistry and  
612 age either across the *GS*-grade Chryssopigi shear zone. Overall, while a slight  $^{40}\text{Ar}/^{39}\text{Ar}$   
613 younging is associated with (re)crystallization toward lower Si-content, the correlation is weak  
614 and the main drive for younging appears to be intracrystalline deformation rather than

615 composition. This is locally seen as a faint decrease of Si-content in phengite toward the core  
616 of the shear zone, pointing to a greater degree of recrystallization/recombination associated  
617 with increasing strain intensity and  $^{40}\text{Ar}/^{39}\text{Ar}$  younging (Fig. 19). This is illustrated by samples  
618 SF-14-39 and SF-14-44 that show the lowest average Si-content in phengite (3.40 and 3.38 apfu  
619 respectively) and youngest  $^{40}\text{Ar}/^{39}\text{Ar}$  ages obtained across the Chryssopigi shear zone (Figs. 15,  
620 16).

621 Deformation is a major controlling factor for rejuvenation that is most spectacularly  
622 illustrated by the *in situ* data collected across the Lia shear zone, north of Syros (Figs. 12 and  
623 18). Grain-scale systematics from the three *in situ* rock sections sampled across the shear zone  
624 (SY-14-71, SY-14-73, SY-14-74, Fig. 12) are discussed in the section to follow. The salient  
625 feature they document at the scale of the shear zone (Fig. 3) is a progressive broadening of the  
626 age range recorded *in situ* with the increasing synkinematic *BS*-grade overprinting (up to 23  
627 Myr for the more deformed sample SY-14-73, *cf.* spectra in Fig. 12). Remarkably, deformation  
628 at these conditions does not homogenize the  $^{40}\text{Ar}$  signature toward a well-defined younger age  
629 component. Instead, it produces mixed-scale inter-sample and within-sample age variations  
630 spanning the entire range recorded across Syros.

631

### 632 6.1.3. Sample and grain-scale $^{40}\text{Ar}/^{39}\text{Ar}$ systematics

633

634 In terms of sample-scale  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics, two fundamental observations arise  
635 from the *in situ* data, i) the absence of systematic correlation with microstructure, ii) the wide  
636 range of ages locally recorded at the scale of a single specimen. Unlike the coupled  
637 synkinematic overprinting and younging progression noted regionally, the *in situ* UV ablation  
638 data show no relationships between microstructures, chemical composition, re-equilibrations,  
639 and apparent ages at the scale of the rock sections. The most notable example is section SY-14-

640 73 across a *BS*-facies shear band that displays young ages around 25 Ma both in the core of the  
 641 shear band and in coarse, little deformed, phengite aggregates away from the shear band (Fig.  
 642 12). A faint correlation can be observed between ages and microstructures in section SF-14-49  
 643 but the evidence is tenuous and far from systematic across the section (Fig. 17). In sample SY-  
 644 14-64 (topmost Kampos subunit, southern Syros section), a compositionally zoned phengite  
 645 crystal characterised by decreasing Si-content from core to rim was dated *in situ*. Results show  
 646 undistinguishable apparent ages from core to rim (Fig. 10). Such a lack of correlation between  
 647  $^{40}\text{Ar}/^{39}\text{Ar}$  age, microstructure, and mineral composition has been noted elsewhere in the UCB  
 648 (Laurent et al., 2017), as well as in other *HP* localities worldwide (e.g., Scaillet et al., 1992; Di  
 649 Vincenzo et al., 2006; Beltrando et al., 2013; McDonald et al., 2016; Fornash et al., 2016). Note  
 650 that this is in other respects more faithfully documented here considering the better resolution  
 651 afforded by our data ( $1\sigma$  typically round  $\pm 0.5$  Ma for spots just 100-65  $\mu\text{m}$  wide). It is  
 652 remarkable that large variations do exist between grains that are otherwise characterized by  
 653 homogeneous within-grain patterns such as SY-16-15 (Fig. 9) characterized by static strain-  
 654 free growth in an extensional gash.

655 In contrast with the lack of age-textural correlation, the interval (or range  $\Delta t$ ) of *in situ*  
 656 ages recorded by each section is correlated with the finite strain intensity and degree of  
 657 retrogression recorded by each sample, much like the overall age vs. overprinting trend noted  
 658 regionally. Indeed,  $\Delta t$  extends into progressively younger ages with increasing deformation and  
 659 extent of retrogression through the sequence (Fig. 20):

- 660 (i)  $\Delta t = 3$  Myr: undeformed eclogite SY-14-74 (51-48 Ma),
- 661 (ii)  $\Delta t = 9$  Myr: slightly deformed eclogite/*BS* SY-14-71 (51-42 Ma),
- 662 (iii)  $\Delta t = 15$  Myr: slightly deformed eclogite/*BS* SY-14-64 (50-35 Ma),
- 663 (iv)  $\Delta t = 26$  Myr: intensely deformed *BS* SY-14-73 (51-25 Ma),
- 664 (v)  $\Delta t = 15$  Myr: deformed *GS*-facies sample SF-14-49 (37-22 Ma).

665 Noteworthy, the  $\Delta t$  range in Syros samples anticorrelates almost perfectly ( $R^2 = 0.997$ ) with the  
666 minimum age recorded in a given section, the trend collectively projecting to a nominal zero-  
667 spread ("undisturbed") end-member age at ca. 51 Ma (Fig. 20). This trend is tied to the  
668 remarkable preservation of a common maximum around 51-50 Ma in all these thin-sections  
669 despite their variable overprinting. Note that this trend is spatially unrelated to the sample  
670 distribution (both regionally or locally) and reflects the intrinsic degree of overprinting and the  
671 resulting heterogeneity recorded locally by the  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopes (sample-scale). Noteworthy,  
672 the sequence (i) to (v) above is broadly consistent with the age range spanned by the  
673 corresponding step-heating data in eclogite (54-49 Ma), blueschists (45-37 Ma), and  
674 greenschist-facies samples (35-18 Ma, Fig. 18), thus locally reproducing the trend seen  
675 regionally. Section SF-14-49 from Sifnos stands apart of the overall  $\Delta t$  trend essentially because  
676 it does not record any vestige of the 51 Ma *HP* age while exhibiting a modest  $\Delta t$  of only 15  
677 Myr. Compared to the nearest analogue (in terms of degree of overprinting) still preserving a  
678 record of the *HP* event on Syros (SY-14-73 with  $\Delta t = 26$  Myr), this break in trend in terms of  
679 internal heterogeneity correlates with the deeper structural position of this sample lying well  
680 within the regional *GS* grade overprint.

681 At the other end of the spectrum (i.e. lacking any *GS*-overprint) are the *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$   
682 data collected across the cleavage of the phengite flakes in the boudin neck of sample SY-16-  
683 15. These provide yet another indication of sub-homogeneous internal preservation of older  
684 ages varying from grain to grain (Fig. 9). The implications of these findings and how they may  
685 be interpreted section-wide across the UCB are discussed next.

686

687 6.2. Continuous vs. piecewise *HP* phengite growth

688

689 The coupled progression of post-*HP* deformation, phengite recrystallization, and *GS*-  
690 facies overprint down-section across the UCB involved multiple mechanisms overlapping in  
691 time and space. These include Ar diffusion, dynamic recrystallization, strain hardening and  
692 shear localization, intracrystalline deformation and fluid-assisted dissolution/precipitation.  
693 These mechanisms operated with potentially complex feedback relationships in  $P$ - $T$ - $t$ - $X_{fluid}$   
694 space, making it inherently difficult to discriminate their respective or cumulative effects on  
695 local  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics. However, close examination and quantitative evaluation of our data  
696 allows a number of critical observations to be made that bear on the significance of  $^{40}\text{Ar}/^{39}\text{Ar}$   
697 phengite ages in *HP/LT* settings.

698 The consistent preservation of a common  $^{40}\text{Ar}/^{39}\text{Ar}$  age maximum coeval with the 51  
699 Ma *HP* age derived from Sm/Nd-garnet systematics both regionally (topmost sample from well-  
700 preserved Kamos eclogite) and locally (UV *in situ* sections from the variably retrogressed Lia  
701 Shear Zone; see also *in situ* data of Putlitz et al., 2005; Laurent et al., 2017 and the single grain  
702 data of Uunk et al., 2018) indicates that this primary component is robustly recorded by  
703 phengite on Syros. The lack of remanence of this component in step-heating spectra from  
704 pristine *HP* samples dated here and elsewhere (Bröcker et al., 2013; Laurent et al., 2017; Uunk  
705 et al., 2018), suggest that this component is irregularly preserved at the sample scale. The  
706 apparent lack of such component in most step-heating data is probably genuine rather than an  
707 artifact (e.g., *in vacuo* homogenization, cf. Sletten and Onstott, 1998). It is due to the low  
708 probability of picking up fully-preserved, early-grown crystals from texturally complex *HP*  
709 assemblages exhibiting grain-scale Ar variations resolved only by *in situ* dating.

710 Wijbrans and McDougall (1986), and later Putlitz et al. (2005), emphasized that episodic  
711 or continuous *HP/LT* deformation may result in several microstructural generations in the same  
712 sample. Putlitz et al. (2005) were among the first to show that even *HP*-static mineralogies can  
713 contain grain-scale Ar disequilibrium interpretable as prograde crystallization ages during

714 protracted *HP* phengite growth. Our *in situ* data from SY-16-15 strengthen this interpretation  
715 by showing that texturally-equilibrated phengite flakes grown in a single, cm-scale, extensional  
716 gash at the tip of an eclogite boudins, record inter-grain age differences as high as 10 Myr while  
717 displaying homogeneous crystal-scale  $^{40}\text{Ar}^*$  compositions (Fig. 9). Such inter-grain isotopic  
718 disequilibrium, if interpreted as temporally distinct crystallization ages, is along with Putlitz et  
719 al. (2005) the first *in situ* evidence of protracted *HP/LT* conditions recorded by punctuated  
720 phengite growth over 10 Myr at conditions presumably unable to eradicate steady-state  
721 radiogenic build-up. Coupled with the oldest *HP* age of 51 Ma, this constrains the minimum  
722 residence time at such conditions in the interval 51-37 Ma on Syros. More generally, this  
723 implies that pristine (static or dynamic) *HP* fabrics can potentially record a mixture of  
724 crystallization phengite ages in this range.

725 Grain-scale disequilibrium has already been reported from well-preserved *HP*  
726 mineralogies from the UCB recording complex  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra varying in the range 51-  
727 37 Ma (e.g., [Wijbrans and McDougall, 1986](#); [Baldwin and Lister, 1998](#); [Bröcker et al., 2004](#),  
728 [2013](#); [Uunk et al., 2018](#); see also discussion in [Fornash et al., 2016](#)). Flat Eocene age spectra  
729 are comparatively rare. Among all *BS*-grade samples analysed by step-heating, we did not get  
730 any homogeneous (nor even near) plateau ages younger than ca. 40-38 Ma (cf. SY-14-28 and  
731 SY-14-29, Fig. 14). Coupled with the homogeneous grain-scale *in situ* ages of SY-16-15a (Fig.  
732 9), this appears to set a lower limit about 37 Ma to syn-*BS*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on Syros. Such older  
733 homogeneous ages are regarded here as time-resolved (i.e., discrete) *HP* crystallization events  
734 exceptionally preserved in the subduction channel. This bound expands significantly the time  
735 interval usually ascribed to the waning stages of the *HP* event from phengite Rb/Sr data (42-40  
736 Ma, [Bröcker et al., 1993, 2013](#)). In this connection, we note that recent phengite Rb/Sr data  
737 from Syros have been found to record ages ranging from 42 Ma down to 30 Ma in *BS* facies  
738 assemblages associated with extensional fabrics linked to exhumation ([Cliff et al., 2016](#)). This

739 suggests that extensional deformation under *BS* facies conditions possibly lasted much longer  
740 than previously thought.

741 The preservation of closure/crystallization ages throughout a complete *HP-LT-t* loop in  
742 excess of 500 °C is consistent with theoretical residence time analysis (Lister and Baldwin,  
743 1996; Baldwin and Lister, 1998; Warren et al., 2012a; Uunk et al., 2018), as well as empirical  
744 (Scaillet, 1998; Warren et al., 2011, 2012b) and more quantitative (Smye et al., 2013) fluid-  
745 rock integrated models suggesting that solid-state diffusional Ar kinetics in *HP* phengites may  
746 be strongly hindered by pressure (Harrison et al., 2009), fluid-kinetic-lithologic control  
747 (Scaillet, 1996, 1998; Giorgis et al., 2000), and compositional effects (Scaillet et al., 1992;  
748 Dahl, 1996). In a context such as the Cyclades where the intrinsic Ar-phengite retentiveness  
749 may be promoted by a steeply depressed *T/P* geotherm, our findings have far-reaching  
750 implications in terms of closed-system behaviour and crystal-growth kinetics. Using target-  
751 matching techniques (SEM + EMPA + UV laser ablation) coupled on the same rock sections  
752 (e.g., sample SY-16-15, Fig. 9), our  $^{40}\text{Ar}/^{39}\text{Ar}$ , mineral geochemistry and petrographic  
753 observations document sample-scale preservation of multiple *HP*-phengite generations, or sub-  
754 grain  $^{40}\text{Ar}/^{39}\text{Ar}$  domains. This is evidence that replacement by dissolution-precipitation ( $\pm$   
755 crystal-plastic flow) at static/dynamic *HP* conditions may be assisted by a grain-boundary fluid  
756 phase capable to drive off any Ar accumulated and released by prograde phengites  
757 recrystallized at or before near-peak conditions. This is corroborated by the single grain data  
758 from Andros by Huet et al. (2015), and the *in situ* data of Putlitz et al. (2005). On Syros as  
759 elsewhere throughout the UCB, Upper Eocene  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite ages are scanty but strikingly  
760 coeval with garnet Sm/Nd pulsatory growth ages (Dragovic et al., 2015). The narrow  $^{40}\text{Ar}/^{39}\text{Ar}$   
761 time span measured *in situ* in eclogite SY-14-74 (54-51 Ma, Fig. 12) and within the phengite  
762 flakes of SY-16-15 (37-43 Ma, Fig. 9) is commensurate with the garnet growth span determined  
763 by Sm/Nd dating on Sifnos (1-7 Myr, Dragovic et al., 2012, 2015). Such a convergence also

764 suggests extensive eradication at peak-*P* conditions of prior (prograde)  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite ages  
765 which are no longer seen due to continuous recrystallization. By analogy with the Sm/Nd  
766 record, phengite growth may be thus postulated to have been controlled by prograde, lithology-  
767 buffered, phengite forming/breakdown equilibria. As discussed elsewhere (Scaillet, 1998;  
768 Dragovic et al., 2015), these may keep the system open to continuous or pulsatory exchange  
769 phenomena as the downgoing slab was experiencing devolatilization until peak-*P* conditions.  
770 Eradication of prograde (i.e. pre-peak) features at peak-*P* conditions is qualitatively consistent  
771 with the core-to-rim decrease in Si-content seen in most compositionally zoned *HP* phengites.  
772 It is also expected from large-scale extensional deformation kinematic analysis indicating that  
773 finite *HP* strain fabric in the UCB was predominantly acquired along the exhumation path  
774 (Jolivet et al., 2003).

775

### 776 6.3. Thermal *GS*-grade resetting vs. dynamic overprinting

777 The spatial  $\Delta t$  vs. overprinting grade trend across Syros (Fig. 20) is qualitatively  
778 consistent with the similar age vs.  $\Delta t$  trend found by Uunk et al. (2018) across the upper *HP*  
779 subunit (Kampos) through the underlying (increasingly *GS*-overprinted) unit in the northern-  
780 middle part of Syros (*cf.* their Fig. 9). A major difference is that our data record a spectrum of  
781 intermediate ages at the scale of a single hand-specimen that goes well beyond the  $\Delta t$  of ca.10  
782 Myr revealed by their total fusion experiments on single grains. This is most notably shown by  
783 the wide age range recorded by SY-14-73 ( $\Delta t = 51\text{-}25$  Ma, Fig. 20) that reproduces almost the  
784 full spectrum measured at the scale of the entire UCB ( $\Delta t = 51\text{-}18$  Ma, Fig. 20). Uunk et al.  
785 (2018) focused their sampling away from local shear zones to get rid of complications due to  
786 deformation. They observed that dispersion of the ages at the outcrop scale (100 m) is correlated  
787 to grain size, suggesting thermally activated volume diffusion as a primary control on final  
788 retention ages in the absence of deformation.

789 Quantitative Ar-closure modelling of the age vs. grain size relationships documented by  
790 Uunk et al. (2018) in the middle part of the Chroussa subunit (Myttakas section) allows to  
791 calculate sample-specific cooling rates assuming that Ar loss is controlled by the physical grain  
792 size across [001]. The inferred cooling rates reveal strong temporal variations between samples  
793 only 100 m apart (Fig. 21), with a major difference in temporal phasing near 38 Ma between  
794 their samples 12SR19 and 12SR16. The first records cooling at 24 °C/Myr near 40 Ma, then 9  
795 °C/Myr at 38 Ma. The second 36 °C/Myr at 38 Ma, then 11 °C/Myr at 37 Ma, and finally 7  
796 °C/Myr at 34 Ma. These calculations show that purely diffusion-controlled closure by  
797 monotonous and wholesale cooling cannot reproduce the age trend across the grain-size of these  
798 samples, unless by invoking sharply diachronous cooling at the scale implied (100 m). Such  
799 grain-size trends rather involve partial resetting (disequilibrium diffusion) complicated by  
800 inheritance and overlapping recrystallization, with variable retention of initial  $^{40}\text{Ar}$   
801 heterogeneities that the *GS* overprinting could not completely eradicate. This again reinforces  
802 the view that the UCB rocks probably left the *HP/LT* field with already considerable sample-  
803 scale  $^{40}\text{Ar}^*$  disequilibrium prior to the *GS* overprinting.

804

#### 805 6.4. Domainal-scale Ar behaviour and the role of deformation

806

807 It is a general observation in the UCB that relict *HP* phengites yield increasingly  
808 complex (loss-like or hump-shaped)  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra with increasing retrogression and  
809 progressive younging (e.g., Naxos: [Wijbrans and McDougall, 1986](#); Tinos: [Bröcker et al., 1993](#),  
810 [2004](#); Serifos: [Schneider et al., 2011](#); Sifnos and Syros: [Wijbrans et al., 1990](#); [Bröcker et al.,](#)  
811 [2013](#); [Lister and Forster, 2016](#); Andros: [Huet et al., 2015](#)). Many of the  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating  
812 experiments in the present study provide non-ideal stepwise degassing patterns as well (Figs.  
813 8, 12, 14, 16). Likewise, and except for the pristine eclogite sample SY-14-74 and the syn-

814 blueschist-facies phengite flakes of SY-16-15, the *in situ* data are also characterized by complex  
815  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics.

816 Most of these spectra reflect mixing of heterogeneous populations or internal  $^{40}\text{Ar}$   
817 gradients as already pointed out by Wijbrans and McDougall (1986) and discussed above.  
818 Sharply defined age plateaus suggestive of simple fast cooling in the interval 35-25 Ma are the  
819 exception rather than the rule throughout the UCB. In many regional *HP-GS* transitional  
820 gradients recorded throughout the UCB,  $^{40}\text{Ar}/^{39}\text{Ar}$  spectra generally become flat again only  
821 close to - or within - the *GS*-dominated domain (i.e. downward through the pile). On Syros, a  
822 strong age polarity has been evidenced from the texturally and isotopically well-preserved 51  
823 Ma ages found atop of the pile toward the fully reset/recrystallized ages around 20-18 Ma at  
824 the base (including Sifnos). This is a characteristic feature across the UCB that brackets the  
825 transition from full retention to complete resetting, with intermediate ages in between reflecting  
826 the interplay between partial resetting/retention and full recrystallization across the *HP-GS*  
827 transition.

828 Deformation has been frequently invoked to explain such patterns in the Cyclades (e.g.,  
829 [Lister and Forster, 2016](#)), mainly on account of the presumably high-*T* Ar closure of phengites  
830 permitting the preservation of crystallization (hence deformation) ages in *HP/LT* settings. The  
831 lack of textural control on *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages demonstrated in this and previous ([Laurent et](#)  
832 [al., 2017](#)) work indicates that the situation is considerably more complex than a well-resolved  
833 sequence of texturally preserved crystallization ages. The picture is rather one of overlapping  
834 (mixed) ages cryptically preserved at the sub-crystal (lattice) scale. Physically, the interplay  
835 between partial resetting/retention and (re)crystallization can be understood in the realm of the  
836 Dodsonian formalism via the effect of grain-size reduction in progressively deformed and  
837 exhumed systems ([Goodwin and Renne, 1991](#)) and the lowered kinetic thresholds for  
838 (re)crystallization and compositional-structural recombination promoted by deformation

839 (Dunlap, 1997; Mulch and Cosca, 2004). Coupled with the enhanced retention properties of  
840 white mica at *HP*, such grain-scale processes easily explain why younger ages, out-of-sequence,  
841 or breaks in  $^{40}\text{Ar}/^{39}\text{Ar}$  regional trends occur locally next (and within) shear zones in which  
842 smaller, recrystallized and/or partly reset grains dominate (see also discussion on  $^{40}\text{Ar}/^{39}\text{Ar}$   
843 mixing systematics by Sanchez et al., 2011, and Kula and Spell, 2012). Emblematic of such a  
844 situation is sample SY-14-73 (northern Lia Shear Zone) dominated by a pristine (syn-blueschist  
845 facies) fabric but in which 50 % of *in situ* apparent ages are younger than 37 Ma (to as young  
846 as 25 Ma, Fig. 12). This is much younger than the allowed residence time of the UCB at *HP*  
847 conditions inferred above (ending probably near 37 Ma, see Section 6.2 and below). Our  
848 interpretation is that grain-scale  $^{40}\text{Ar}$  disequilibrium is preserved in this sample as a mosaic of  
849 *HP* and newly/partially (re)crystallized domains, each having a specific physical size, domain-  
850 structure, and  $^{40}\text{Ar}^*$  inventory reflecting micro-scale gradients in chemical potentials, fluid  
851 availability, partial diffusional resetting, and extent of chemical/structural recombination.

852 As a rule, mixed ages from microstructural domains remain largely unresolved by the  
853 UV laser probe (50  $\mu\text{m}$  spatial resolution). Perhaps the only exception in this study are the  
854 youngest *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages (37-35 Ma) measured on SY-14-64 (Fig. 10). The lack of  
855 compositional control on *in situ* ages noted there (see Section 6.1.3) shows that  $^{40}\text{Ar}/^{39}\text{Ar}$   
856 relationships to ongoing recrystallization processes cannot be simply inferred based on  
857 compositional grounds. But, at the same time, the 35-37 Ma ages actually happen to occur in a  
858 dilatant site formed at the interface of the garnet due to expansion of the matrix flowing away  
859 from it. Such a mechanism apparently allowed late crystal growth of *HP* phengites younger  
860 than the matrix specimens displaying ages between 42-46 Ma (above the garnet) and 40-44 Ma  
861 (along the flat lying matrix extending laterally away from the pressure shadow).

862 Aside from this case, our data show that the significance of intermediate, mixed,  
863  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on Syros and Sifnos cannot be easily extracted from micro-scale  $^{40}\text{Ar}/^{39}\text{Ar}$

864 relationships, and let alone from complex  $^{40}\text{Ar}/^{39}\text{Ar}$  spectra lacking direct relevance to textural  
865 habitus (e.g., [Lister and Forster, 2016](#)). Our results conclusively show that (1) phengite  
866 domainal-scale behaviour occurs below the spatial resolution of the UV probe (50  $\mu\text{m}$ ), and (2),  
867 single-grain step-heating data are clearly affected by such sub-grain effects as well. The parallel  
868 with the phengite Rb/Sr record is striking both in terms of age and spread ([Ring et al., 2011](#);  
869 [Bröcker et al., 2013](#); [Cliff et al., 2016](#)), suggesting much in common in terms of retention  
870 behaviour and isotope-crystal disequilibrium kinetics. At the same time, our study conclusively  
871 shows that bulk  $^{40}\text{Ar}/^{39}\text{Ar}$  patterns and large-scale variations may be used for tracking bulk  
872 temporal trends that reflect the time-averaged effect of deformation and associated Ar thermal-  
873 kinetic interaction operating across a major metamorphic transition. One major outcome of this  
874 study is that the imbrication of such widely varying spatial scales can be understood only  
875 through the combined application of large-scale sampling with *in situ* dating.

876

## 877 6.5. Regional implications

878

879 From a regional perspective, this study has implications both on the overall geometry  
880 of the *HP-LT* nappe stack and its geodynamic evolution. The lack of preservation of *HP* relicts  
881 in the Vari Unit and the stark age contrast between this (with pre-metamorphic ages largely in  
882 excess of 55 Ma, Fig. 8) and the underlying UCB (Kampos) unit argue in favour of the Vari  
883 fault being a detachment bringing shallower (cooler) rocks on top of exhumed *HP* slices as  
884 proposed previously ([Trotet et al., 2001a](#); [Soukis and Stöckli, 2013](#); [Laurent et al., 2016](#)), but  
885 disputed by some ([Philippon et al., 2011](#)). The older ages in the *HP*-free Vari Unit confirm  
886 earlier findings by [Maluski et al. \(1987\)](#) and indicate that it was exhumed much earlier than the  
887 UCB. Syn-*HP* crystallization  $^{40}\text{Ar}/^{39}\text{Ar}$  ages measured between 50 and 37 Ma (Figs. 8, 9, 10)  
888 below the detachment are consistent with  $^{40}\text{Ar}/^{39}\text{Ar}$  ages obtained elsewhere on *HP* rocks of the

889 Cycladic Islands such as Tinos and Andros (Bröcker et al., 1993; Huet et al., 2015; Laurent et  
890 al., 2017, Fig. 2). If, as discussed in section 6.2, these are indeed crystallization ages, this range  
891 constrains the timelife (in the ductile regime) of the Vari Detachment to at least this interval.

892 The Vari detachment accommodated the first steps of ductile exhumation from peak  
893 metamorphism to *BS*-facies conditions (Trotet et al., 2001; Jolivet et al., 2010; Huet et al., 2015;  
894 Laurent et al., 2016), and was later reactivated as a more localized brittle structure (Ring et al.,  
895 2003; Soukis and Stöckli, 2013). On Syros, the coupled  $^{40}\text{Ar}/^{39}\text{Ar}$  downward overprinting  
896 progression shows that deformation localized toward the base (the lowermost Posidonia  
897 Subunit) in the UCB stack until crossing the ductile-brittle transition at 20-18 Ma. This stage  
898 corresponds to a major reconfiguration at the scale of the entire CBU with strain migration and  
899 localization on major post-orogenic detachments (NCDS, WCDS, and PNDS; Fig. 1; Jolivet et  
900 al., 2010; Grasemann et al., 2012). Such a temporal progression reflects major thermo-  
901 rheological changes driving the exhumation dynamics of the UCB stack. It remains for further  
902 work to investigate how similarly aged *GS*-facies rocks across the CBU (e.g., on Sifnos, Tinos,  
903 Andros, Kea, Kithnos; Altherr et al., 1982; Wijbrans et al., 1990; Bröcker & Franz, 1998, 2006;  
904 Iglseider et al., 2011; Ring et al., 2011; Grasemann et al., 2012; Bröcker et al., 2013; Cossette  
905 et al., 2015) relate to the last increments of ductile exhumation across the ductile-brittle  
906 transition along the main NCDS and WCDS detachment systems (Fig. 1).

907

## 908 7. Conclusions and outlook

909

910 Our detailed  $^{40}\text{Ar}/^{39}\text{Ar}$ , geochemical and structural analysis of the UCB exposed across  
911 Syros and Sifnos allows the following conclusions to be reached.

912 (1) Early peak-metamorphic phengite  $^{40}\text{Ar}/^{39}\text{Ar}$  crystallization ages of ca. 51-48 Ma are  
913 preserved in pristine eclogites and blueschists formed at  $P$  ca. 22 kbar and  $550 \pm 50$  °C

914 with grain-scale homogeneous  $^{40}\text{Ar}$  patterns consistent with independent Sm/Nd garnet  
915 ages around 53-50 Ma, and inter-grain age differences locally reflecting protracted or  
916 piecewise phengite growth under sluggish  $^{40}\text{Ar}$  diffusional kinetics at  $T$  in excess of 500  
917 °C.

918 (2) During decompression and incipient overprinting at lower  $P$ , strong grain-scale  $^{40}\text{Ar}/^{39}\text{Ar}$   
919 age variations were produced as a result of domain-like Ar behaviour; this is manifested  
920 in the form of partially reset to fully preserved relicts of early *HP* clasts (or dislocated  
921 sub-grain domains) coexisting with neo-crystallized domains formed during  
922 metamorphic re-equilibration and *BS*- then *GS*-grade pervasive deformation. Such  $^{40}\text{Ar}$   
923 domains cannot be matched with clear-cut compositional or micro-textural domains at  
924 the scale resolved with the  $^{40}\text{Ar}/^{39}\text{Ar}$  UV laser probe (ca. 50  $\mu\text{m}$ ). Structural and thermal-  
925 kinetic crystallographic processes driving  $^{40}\text{Ar}$  and stoichiometric recombinations are  
926 coupled at a much more elementary level than currently accessible via the UV microprobe  
927 (i.e. possibly down the K-interlayer scale and lattice-scale nano-domains).

928 (3) A regional younging of bulk  $^{40}\text{Ar}/^{39}\text{Ar}$  ages is documented across a regionally consistent  
929 (but locally irregular) eclogite/*BS* to *GS* grade transition culminating in fully reset ( $\pm$   
930 newly crystallized) 20-18 Ma old phengites at the very base of the pile. We interpret this  
931 pattern as the progressive migration and localization of extensional deformation during  
932 exhumation through the *GS* facies. A major switch from syn-*HP* closed-system behaviour  
933 to thermal-kinetic resetting/opening occurred as the result of the progressive  
934 establishment of *GS* grade conditions around 37 Ma. Grain-scale  $^{40}\text{Ar}^*$  inheritance from  
935 the *HP* stage and the switch to domain-like diffusional Ar exchange across the transition  
936 precludes resolving discrete deformation events associated to local/regional shear zones.  
937 However, the overall younging progression allows to temporally track the bulk migration  
938 of deformation through the nappe stack.

- 939 (4) A notable feature of our  $^{40}\text{Ar}/^{39}\text{Ar}$  findings is the isotopic resilience of *HP* phengites  
940 preserving well-defined ages down to 37 Ma in pristine *BS* mineralogies (most notably  
941 our sample SY-16-15, Fig. 9); these ages reflect the ultimate stages of residence in the  
942 *HP/LT* subduction channel prior to mechanical destabilization and exhumation of the  
943 orogenic wedge. These ages are consistent with sedimentological and radiometric  
944 evidence indicating that the main stacking events lasted until the Eocene (Godfriaux and  
945 Mercier, 1965; Dubois and Bignot, 1979; Schermer, 1990, 1993; Godfriaux and Ricou,  
946 1991; Shaked et al., 2000; Cliff et al., 2016).
- 947 (5) A major outcome of this study is that it is clearly not possible to properly interpret  
948  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite ages from *HP/LT* settings without integrating the information at all  
949 scales, from the crystal proper (and below) to the regional relationships linking nappe-  
950 scale structures to time-varying thermo-kinematics. On Syros and Sifnos, the interplay  
951 between thermal-induced volume diffusion and strain localization is temporally and  
952 spatially related to the exhumation dynamics at the scale of the UCB, but these appear  
953 locally decoupled at the microscale. Such a complex behaviour is likely to be prevalent  
954 in other *HP/LT* successions exhumed elsewhere. Extensive combination of step-heating  
955 with high-resolution *in situ* dating is shown to be essential to better understand the  
956 processes governing Ar-mineral-deformation interactions at the crystal scale in such  
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967 **Research data**

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970

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- 1307

1308

1309 **Figure captions**

1310 Figure 1: Geological framework of the Aegean domain and the Cycladic archipelago. a)  
1311 Tectonic map of the Aegean domain showing the distribution of metamorphic units and the age  
1312 of magmatic intrusions highlighting southward slab retreat (Modified after Roche et al., 2019).  
1313 b) Simplified geological map of the Cycladic archipelago, localizing Syros and Sifnos islands  
1314 (after Jolivet et al., 2015). Major tectonic structures include the syn-orogenic Vari Detachment  
1315 (VD) and the post-orogenic North Cycladic Detachment System (NCDS), the West Cycladic  
1316 Detachment System (WCDS) and Naxos-Paros Detachment System (NPDS) with the local  
1317 kinematics indicated. c) Cross-sections showing the current position of the plunging slab below  
1318 Crete (after Jolivet and Brun, 2010), and the present-day structure of the Cyclades,  
1319 characterized by metamorphic domes exhumed below detachment systems (after Augier et al.,  
1320 2015). Abbreviations: AD (Alaşehir Detachment); BD (Büyük Menderes Detachment); CD  
1321 (Crete Detachment); LCB (Lower Cycladic Blueschist Nappe); MMCC (Menderes  
1322 Metamorphic Core Complex); NAF (North Anatolian Fault); SD (Simav Detachment); SDS  
1323 (Santorini Detachment System); T-C.T (Trans-Cycladic Thrust); UCB (Upper Cycladic  
1324 Blueschist Nappe).

1325

1326 Figure 2: Structural-metamorphic map of Syros with sample location. Sampling across the  
1327 Chryssopighi Shear Zone on Sifnos is also shown as well as the location of cross-sections  
1328 reported in Figure 3.

1329

1330 Figure 3:  $^{40}\text{Ar}/^{39}\text{Ar}$  ages measured in this study across strain gradients in Syros and Sifnos  
1331 islands. The cross-sections are modified after Laurent et al., 2016.

1332

1333 Figure 4: Compilation of previous geochronological data measured on Syros and Tinos and *P-*  
1334 *T* path of the UCB (after Laurent et al., 2018). All detailed ages with their references are  
1335 synthesized in Appendix S1 and S2.  $^{40}\text{Ar}/^{39}\text{Ar}$  and Rb/Sr ages are represented by a curve defined  
1336 by a normalized probability law (see Laurent et al., 2017 for more details). Maximum and  
1337 minimum ages given by hump-shaped  $^{40}\text{Ar}/^{39}\text{Ar}$  spectra are represented by orange rectangles  
1338 connected by dashed lines.

1339  
1340 Figure 5: Structural and geochemical setting of  $^{40}\text{Ar}/^{39}\text{Ar}$  samples collected in the Posidonia  
1341 Subunit. Samples are generally strongly deformed and pervasively overprinted in *GS*-facies (a),  
1342 however some samples locally preserved *HP-LT* parageneses (e.g. SY-14-18) (b). Thin sections  
1343 revealed the impact of lithology on the intensity of phengite deformation (b) and  
1344 recrystallization (c). Phengites in samples containing calcite (e.g. SY-14-76) are less intensely  
1345 deformed and recrystallized than in quartzitic samples (e.g. SY-14-80) as previously suggested  
1346 by Cossette et al. (2015) and Rogowitz et al. (2015). Geochemical data (c) represented by  
1347 squares correspond to EPMA spot analyses of phengite composition while the data represented  
1348 by small blue circles are derived from the X-Ray compositional map. Mineral abbreviations are  
1349 after Whitney and Evans (2010).

1350  
1351 Figure 6: Structural and outcrop setting of  $^{40}\text{Ar}/^{39}\text{Ar}$  samples collected in Chroussa Subunit.  
1352 The 3-D sketch shows the outcrop relationships of SY-16-06 and SY-16-15 (a). SY-16-15  
1353 sample consists of phengite crystals collected from the neck of an eclogite boudins. While the  
1354 outcrop shows a clear foliation (b) and some syn-blueschist facies shear deformation such as  
1355 shear bands (a), phengite crystals of SY-16-06 show a low deformation (c). Microscope picture  
1356 of SY-16-15 phengite grains shows relatively undeformed primary crystals (d).

1357

1358 Figure 7: Structural and geochemical setting of  $^{40}\text{Ar}/^{39}\text{Ar}$  samples collected in Kampos and Vari  
1359 Units. a) Outcrop characterization of samples from the Kampos Subunit. b) Thin-section  
1360 microphotographs of phengite textural habitus showing moderately deformed crystals. c)  
1361 Chemical composition of phengite in Si vs.  $X_{\text{Mg}}$  space. A clear partial recrystallization of  
1362 phengites is observed in sample SY-14-40b<sub>4</sub>. Phengite composition in samples from the Vari  
1363 Unit is not significantly different to composition of phengite in the UCB. Geochemical data  
1364 represented by squares correspond to EPMA spot analyses of phengite composition while the  
1365 data represented by small blue circles are derived from the X-Ray compositional map.

1366  
1367 Figure 8: Step-heating  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra of phengite single grain and population from the  
1368 southern Syros section. TGA: total gas age. Error boxes and TGA are  $\pm 1\sigma$ . The colour of the  
1369 age spectra refers to the grade of metamorphism of each sample (all shades of green:  
1370 greenschist; all shades of blue: blueschist; all shades of red: eclogite; all shades of yellow:  
1371 samples of the Vari Unit that shows no *HP* metamorphism). Note that the scale of the vertical  
1372 axis is different for samples of the Vari Unit due to a significantly older range of apparent ages  
1373 (37-145 Ma) compare to the UCB (18-45 Ma).

1374  
1375 Figure 9: Range of *in situ* phengite apparent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages measured in sample SY-16-15  
1376 showing inter-grain age differences as high as 10 Ma while displaying homogeneous crystal-  
1377 scale  $^{40}\text{Ar}^*$  compositions. Note that the larger phengite grain (SY-16-15a) yields to younger *in*  
1378 *situ* apparent ages than all the other smaller phengite grains. TGA: total gas age. Error boxes  
1379 and TGA are  $\pm 1\sigma$ .

1380  
1381 Figure 10: Distribution of *in situ* apparent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages measured in phengites from sample  
1382 SY-14-64 collected in the Kampos Subunit. a) Picture of the analysed rock-section showing the

1383 presence of garnets embedded in an omphacitic matrix. b) Results of *in situ* laser ablation  
1384 analyses. c) Correlation between measured apparent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and specific phengite  
1385 compositions highlighted on the compositional map. d) *In situ* laser ablation results represented  
1386 on BSE images. Squares (65  $\mu\text{m}$ ) and circles (50  $\mu\text{m}$ ) correspond to the geometry of the laser  
1387 ablation and numbers inside refer to the corresponding analysis (see Appendix S5). TGA: total  
1388 gas age. Error boxes and TGA are  $\pm 1\sigma$ .

1389

1390

1391 Figure 11: Structural and geochemical setting of  $^{40}\text{Ar}/^{39}\text{Ar}$  samples collected across the BS-  
1392 facies Lia Shear Zone. a) Outcrop characterization of samples from the Lia Shear Zone  
1393 including top-to the east syn-BS-facies deformation in sample SY-14-73. b) Thin-section  
1394 microphotographs of phengite textural habitus showing a clear deformation gradient from SY-  
1395 14-74 to SY-14-73. c) Chemical composition of phengite in Si vs.  $X_{\text{Mg}}$  space showing partial  
1396 recrystallization in SY-14-73.

1397

1398 Figure 12: *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  laserprobe data from the Lia Shear Zone. a) SY-14-73 rock section  
1399 analysed by the *in situ* UV-laser ablation technique and displaying a top-to-the E shear band  
1400 associated with glaucophane. b) Results of *in situ* laser ablation analyses for all three rock-  
1401 sections showing a clear trend toward younger apparent ages in the most deformed SY-14-73  
1402 sample. c) BSE close-up showing *in situ* age distribution in SY-14-73. No clear correlation  
1403 between microstructures and *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages can be seen. Squares (65  $\mu\text{m}$ ) and circles  
1404 (50  $\mu\text{m}$ ) correspond to the diameter of the laser beam with numbers indicating the  
1405 corresponding analysis (see Appendix S5). Ablation trenches are indicated by tie-lines  
1406 connecting the endpoints of the rastered area. d) BSE close-up of SY-14-71 displaying  
1407 homogenous ages around 48-50 Ma in and around phengite aggregate pseudomorph after

1408 (presumably) lawsonite. e) Step-heating  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra obtained on single phengite  
1409 grains of samples SY-14-71 and SY-14-73. TGA: total gas age. Error boxes and TGA are  $\pm 1\sigma$ .

1410  
1411 Figure 13: Structural and geochemical setting of  $^{40}\text{Ar}/^{39}\text{Ar}$  samples collected across the *BS-* to  
1412 *GS*-facies Delfini Shear Zone. a) Outcrop characterization of samples from the Delfini Shear  
1413 Zone. In general, samples are highly deformed. All analysed samples show a well-developed  
1414 foliation and stretching lineation sometimes associated with top-to-the E shear bands (e.g. SY-  
1415 14-26) and/or isoclinal folds (e.g. SY-14-28). b) Thin-section microphotographs of phengite  
1416 textural habitus showing extent of deformation, more pronounced in SY-16-23 and SY-14-26.  
1417 c) Chemical composition of phengite in Si vs.  $X_{\text{Mg}}$  space indicating partial recrystallization in  
1418 SY-14-26 and, to a lesser extent, in SY-14-24.

1419  
1420 Figure 14: Step-heating  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite age spectra on single grain and populations from  
1421 the Delfini Shear Zone. The colour of the age spectra refers to the grade of metamorphism of  
1422 each sample (green: greenschist; shades of blue: blueschist). Note apparent lack of correlation  
1423 between the degree of retrogression and apparent age (i.e., the older apparent ages are not  
1424 systematically measured in *BS*-facies samples). However, the older apparent ages have been  
1425 measured in calcite-rich samples collected at some distance of the core of the shear zone (i.e.  
1426 SY-14-28, SY-14-29). TGA: total gas age. Error boxes and TGA are  $\pm 1\sigma$ .

1427  
1428 Figure 15: Structural and geochemical setting of  $^{40}\text{Ar}/^{39}\text{Ar}$  samples collected across the *GS*-  
1429 facies Chryssopigi Shear Zone on Sifnos. a) Outcrop characterization of samples collected close  
1430 to the core of the Chryssopigi Shear Zone. Progressive alignment/parallelisation of folds hinges  
1431 with the direction of stretching lineation toward the core of the shear zone indicates increasing  
1432 of deformation (see Roche et al., 2016 for further details). b) Thin-section microphotographs of

1433 phengite textural habitus showing the increasing deformation gradient toward the core of the  
1434 shear zone (i.e. from SF-14-52 to SF-14-39). c) Chemical composition of phengite in Si vs.  $X_{Mg}$   
1435 space indicating partial recrystallization in SF-14-39 and SF-14-44 and, to a lesser extent, in  
1436 SF-14-43.

1437  
1438 Figure 16: Step-heating  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite age spectra on single grains and populations from  
1439 the Chryssopigi Shear Zone. The colour of the age spectra refers to the grade of metamorphism  
1440 of each sample (shades of green: greenschist; shades of blue: blueschist). Excluding sample SF-  
1441 14-55, the measured apparent ages are younger toward the core of the shear zone (i.e. toward  
1442 SF-14-43 and SF-14-39). TGA: total gas age. Error boxes and TGA are  $\pm 1\sigma$ .

1443  
1444 Figure 17: Distribution of *in situ* phengite apparent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages in rock section SF-14-49. a)  
1445 Picture of the analysed rock-section. b) Range of apparent *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  data ranked by age.  
1446 c) *in situ* laser ablation results located on BSE images. Squares (65  $\mu\text{m}$ ) and circles (50  $\mu\text{m}$ )  
1447 correspond to the diameter of the laser beam with numbers indicating the corresponding  
1448 analysis (see Appendix S5). Ablation trenches are indicated by tie-lines connecting the  
1449 endpoints of the rastered area. TGA: total gas age. Error boxes and TGA are  $\pm 1\sigma$ .

1450  
1451 Figure 18: Projected distribution of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages over regional- to sample-scale strain and  
1452 retrogression gradients. a) At Syros scale, increasing retrogression and finite deformation from  
1453 top to base of the UCB is associated with a trend toward younger  $^{40}\text{Ar}/^{39}\text{Ar}$  ages. b) At the scale  
1454 of a shear zone, the first-order distribution of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages is correlated with strain gradient  
1455 with younger ages in the most deformed zones. c) At the rock-section scale, *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$   
1456 ages are not correlated with deformation gradients.

1457

1458 Figure 19: Relationships between phengite geochemistry,  $^{40}\text{Ar}/^{39}\text{Ar}$  total-gas ages (TGA) and  
1459 structural position of dated samples at regional and local scales. The red line corresponds to the  
1460 trend curve calculated from the data. Error bars correspond to the range of Si-content in  
1461 phengite and the range of apparent ages measured in each sample. A general but faint trend is  
1462 observed between lower Si-content in phengite and younger apparent ages in each section.

1463  
1464 Figure 20: *In situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  delta age range *versus* the minimum age recorded in a given section.  
1465 The delta age range anticorrelates almost perfectly ( $R^2 = 0.997$ ) with the minimum age recorded  
1466 in a given section, the trend collectively projecting to a nominal zero-spread end-member age  
1467 around ca. 51 Ma.

1468  
1469 Figure 21: Cooling rate ( $^{\circ}\text{C}/\text{Myr}$ ) *vs.* apparent ages (Ma) modelled from grainsize *vs.*  $^{40}\text{Ar}/^{39}\text{Ar}$   
1470 relationships reported in the Chroussa subunit (Myttakas section) by Uunk et al. (2018). An apparent  
1471 phase-lag up to 2 Myr is revealed for these samples merely 100 m apart, indicating that the ages recorded  
1472 most probably reflect variable diffusion-driven resetting rather than true cooling ages.

1478 endpoints of the rastered area. TGA: total gas age. Error boxes and TGA are  $\pm 1\sigma$ .

1479

1480 Figure 18: Projected distribution of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages over regional- to sample-scale strain and  
1481 retrogression gradients. a) At Syros scale, increasing retrogression and finite deformation  
1482 from top to base of the UCB is associated with a trend toward younger  $^{40}\text{Ar}/^{39}\text{Ar}$  ages. b) At  
1483 the scale of a shear zone, the first-order distribution of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages is correlated with strain  
1484 gradient with younger ages in the most deformed zones. c) At the rock-section scale, *in situ*  
1485  $^{40}\text{Ar}/^{39}\text{Ar}$  ages are not correlated with deformation gradients.

1486

1487 Figure 19: Relationships between phengite geochemistry,  $^{40}\text{Ar}/^{39}\text{Ar}$  [total-gas](#) ages ([TGA](#)) and  
1488 structural position of dated samples at regional and local scales. The red line corresponds to  
1489 the trend curve calculated from the data. Error bars correspond to the range of Si-content in  
1490 phengite and the range of apparent ages measured in each sample. A general but faint trend is  
1491 observed between lower Si-content in phengite and younger apparent ages in each section.

1492

1493 Figure 20: *In situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  delta age range *versus* the minimum age recorded in a given  
1494 section. The delta age range anticorrelates almost perfectly ( $R^2 = 0.997$ ) with the minimum  
1495 age recorded in a given section, the trend collectively projecting to a nominal zero-spread  
1496 end-member age around [~ca. 51 Ma](#).

1497

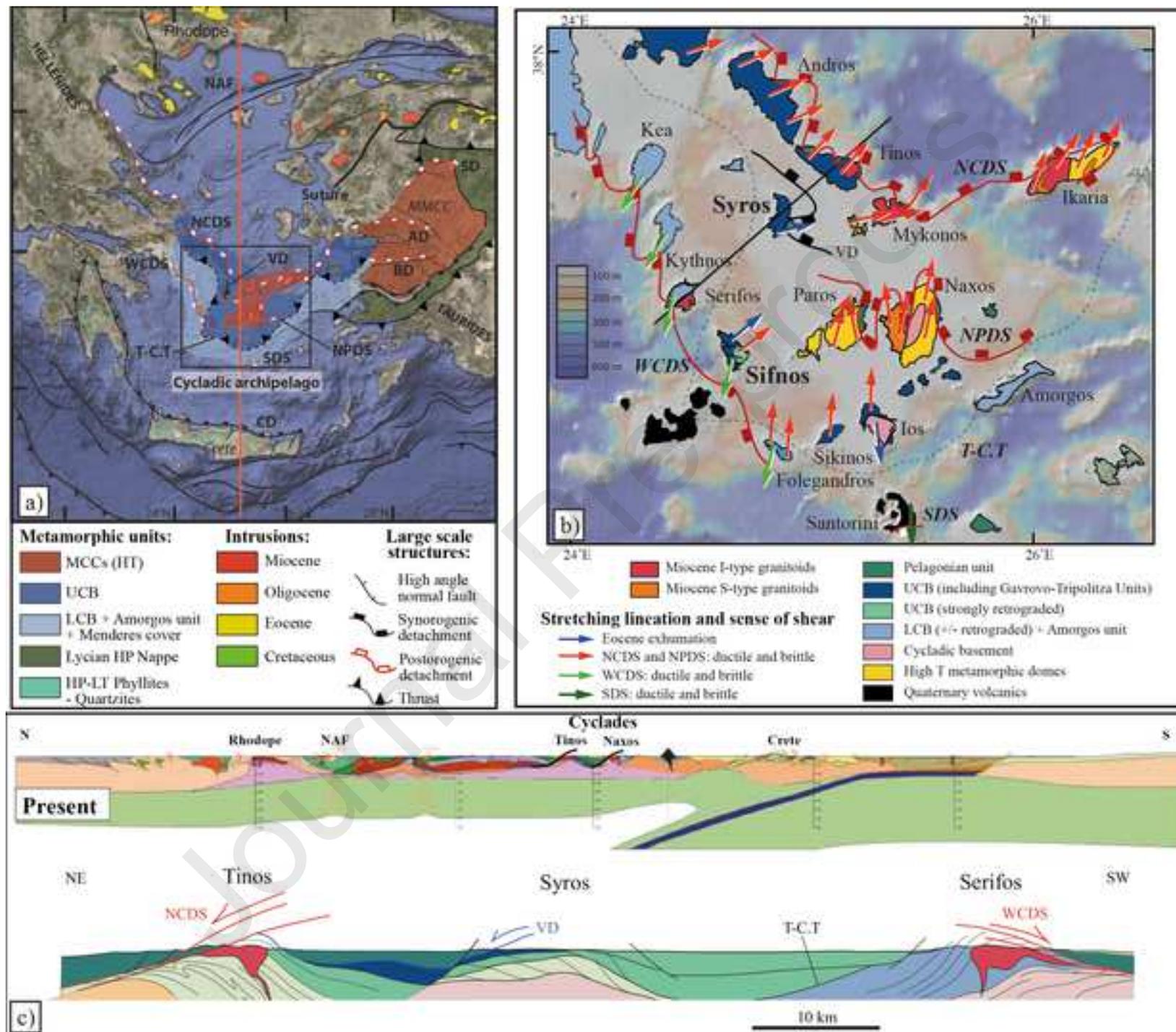
1498 Figure 21: Cooling rate ( $^{\circ}\text{C}/\text{Myr}$ ) *vs.* apparent ages (Ma) modelled from grainsize *vs.*  $^{40}\text{Ar}/^{39}\text{Ar}$   
1499 relationships reported in the Chroussa subunit (Myttakas section) by Uunk et al. (2018). An  
1500 apparent phase-lag up to 2 Myr is revealed for these samples merely 100 m apart, indicating that the  
1501 ages recorded most probably reflect variable diffusion-driven resetting rather than true cooling ages.

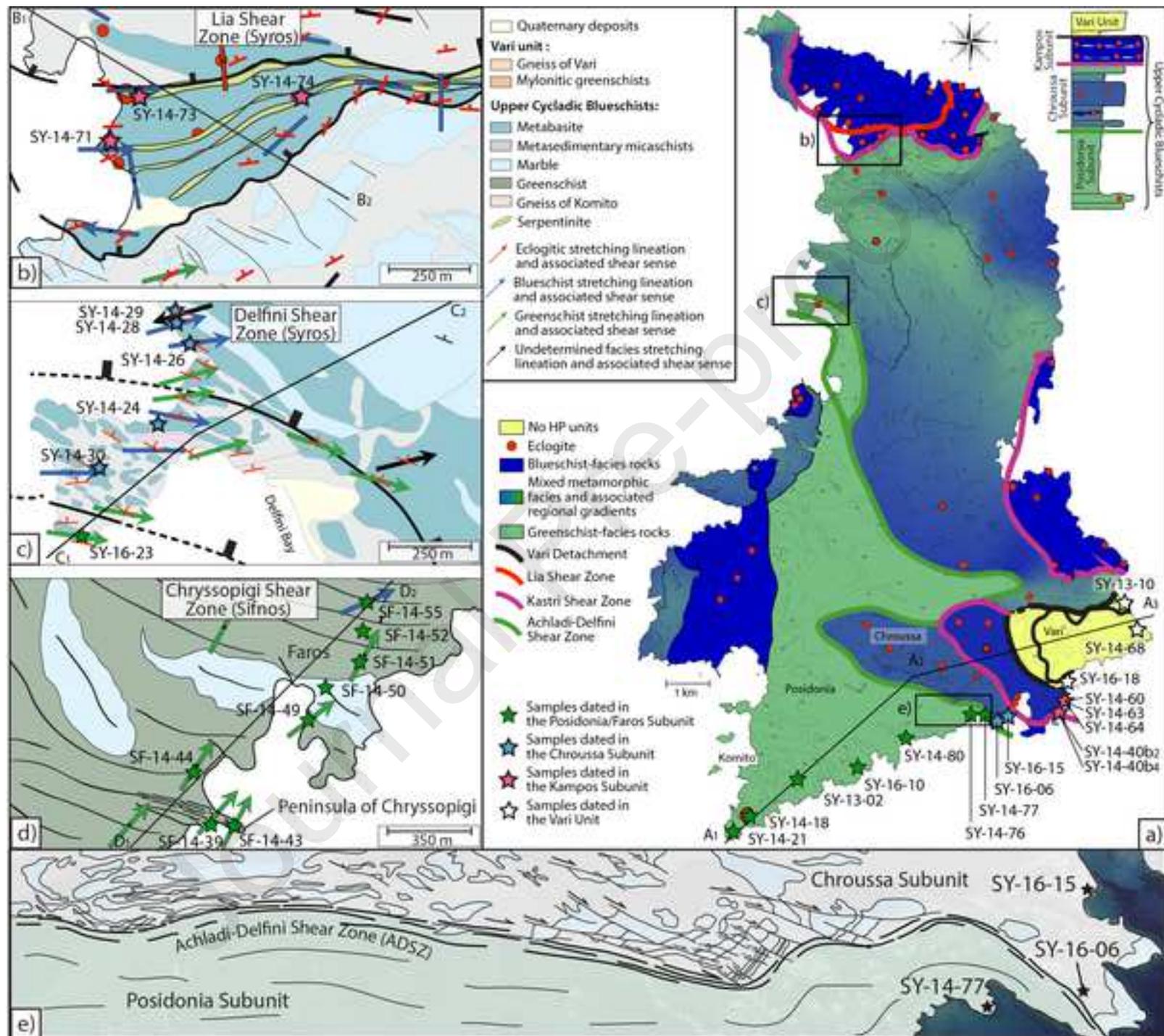
Table 1: Lithology and mineralogy of dated samples. Mineral abbreviations after Whitney and Evans (2010).

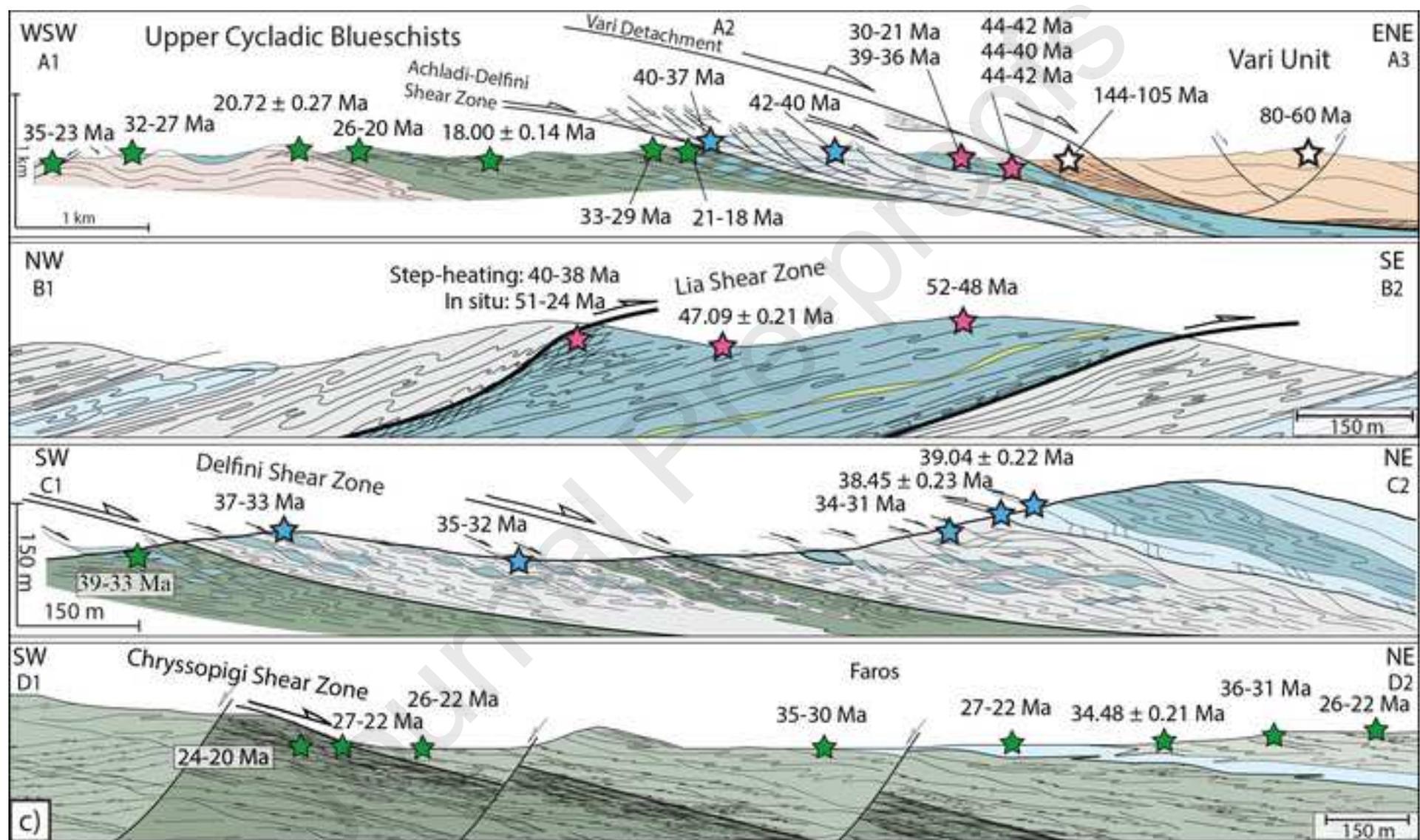
Samples	Location	Mineralogy										Lithology	GPS coordinate (WGS 84)		
		Ph	Pg	Omp	Grt	Gln	Ep	Chl	Ab	Qz	Cal		Latitude	Longitude	
SY-14-21	Posidonia	x			x	x	x	x			x	x	Chl micaschist	37.363221	24.877139
SY-14-18	Posidonia	x		x	x	x	x	x	x	x	x	x	Grt-Ep blueschist	37.370155	24.884351
SYR-13-02	Posidonia	x						x	x	x			Gneiss	37.373456	24.892570
SY-16-10	Posidonia	x	?					x		x	x		Calcschist	37.375466	24.906279
SY-14-80	Posidonia	x					x	x	x	x	x		Chl micaschist	37.381565	24.916839
SY-14-76	Posidonia	x					x	x	x	x	x		Chl calcschist	37.385748	24.931293
SY-14-77	Posidonia	x			x			x	x	x			Chl micaschist	37.385892	24.934383
SY-16-06	Chroussa	x	?			x	x	x					Grt-Ep blueschist	37.385203	24.937226
SY-16-15	Chroussa	x	?			x							Blueschist	37.388568	24.941572
SY-14-40b2	Kampos	x	x		x	x	x	x	x	x			Grt-Ep blueschist	37.386778	24.951097
SY-14-40b4	Kampos	x					x	x	x	x			Greenschist	37.386778	24.951097
SY-14-60	Kampos	x		x	x	x	x			x	x		Gln eclogite	37.389130	24.953722
SY-14-63	Kampos	x		x	x	x	x	x			x		Gln eclogite	37.389130	24.953722
SY-14-64	Kampos	x		x	x		x		x	x			Gln eclogite	37.389130	24.953722
SY-16-18	Vari Unit	x						x	x	x			Greenschist	37.392992	24.953989
SY-14-68	Vari Unit	x						x	x	x			Gneiss	37.403223	24.969233
SY-13-10	Vari Unit	x						x	x	x			Chl micaschist	37.408158	24.965869
SY-14-74	Lia SZ	x		x									Eclogite	37.492053	24.907270
SY-14-71	Lia SZ	x		x		x							Gln eclogite	37.491166	24.900779
SY-14-73	Lia SZ	x		x	x	x		x		x			Omp-Grt blueschist	37.492934	24.900877
SY-16-23	Delfini SZ	x	?				x	x	x	x			Chl micaschist	37.458322	24.890958
SY-14-30	Delfini SZ	x	?			x	x	x	x	x			Ep blueschist	37.460031	24.891500
SY-14-24	Delfini SZ	x			x	x	x	x	x	x			Grt-Ep blueschist	37.461260	24.893487
SY-14-26	Delfini SZ	x	x		x		x		x	x	x		Grt micaschist	37.463579	24.894134
SY-14-28	Delfini SZ	x			x	x	x	x		x	x		Grt-Gln calcschist	37.464079	24.893883
SY-14-29	Delfini SZ	x				x		x			x		Marble	37.464260	24.893912
SF-14-55	Chryssopigi SZ	x				x	x	x		x			Ab-Ep-Gln blueschist	36.948104	24.756036
SF-14-52	Chryssopigi SZ	x					x	x	x	x	x		Chl calcschist	36.946791	24.755715
SF-14-51	Chryssopigi SZ	x						x		x	x		Chl calcschist	36.945332	24.755298
SF-14-50	Chryssopigi SZ	x				x	x	x		x	x		Chl marble	36.943661	24.752789
SF-14-49	Chryssopigi SZ	x						x	x	x	x		Chl calcschist	36.942468	24.751587
SF-14-44	Chryssopigi SZ	x	x				x	x		x	x		Chl micaschist	36.938757	24.743623
SF-14-39	Chryssopigi SZ	x					x	x	x	x	x		Chl micaschist	36.936358	24.744940
SF-14-43	Chryssopigi SZ	x					x	x	x	x	x		Chl micaschist	36.935908	24.746873

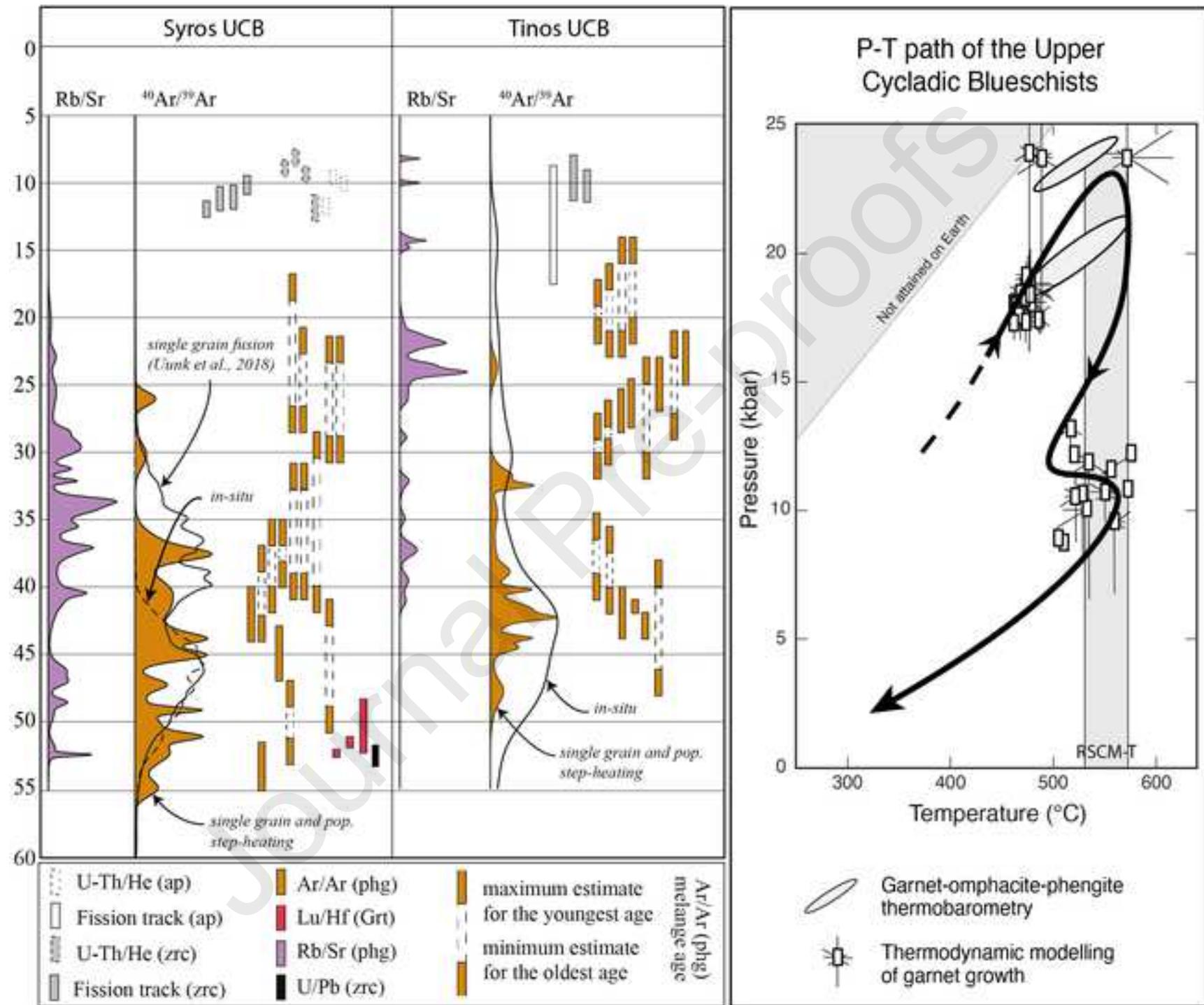
Table 2: Petro-textural description of phengite and measured  $^{40}\text{Ar}/^{39}\text{Ar}$  ages. The textural habitus of phengite was determined after pictures of grains taken before irradiation. Deformation of phengite was mainly characterised following the degree of mica alignment.

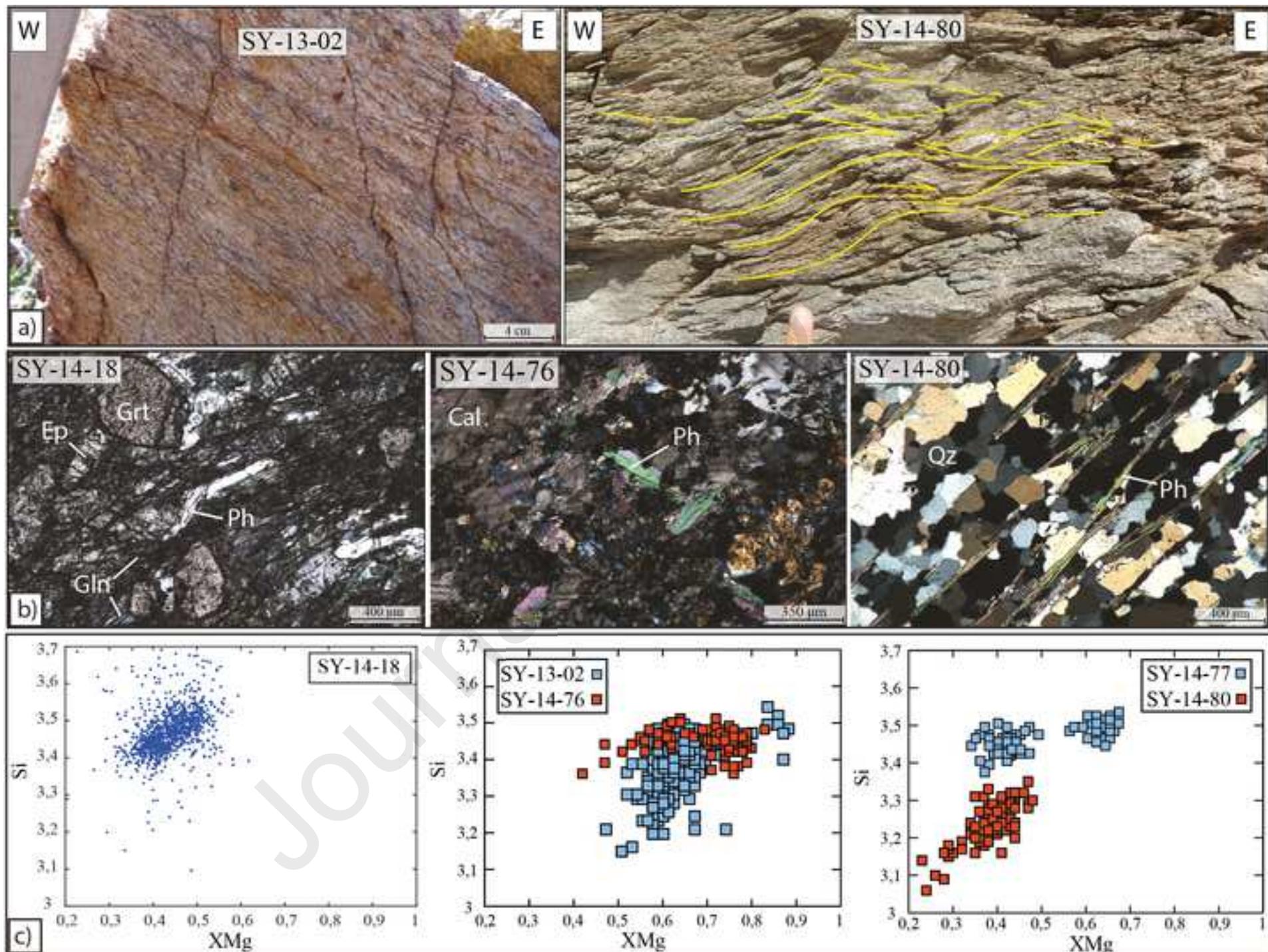
Samples	Textural habitus	Deformation	Chemical composition	Compositional zoning	Inclusion	Grain size ( $\mu\text{m}$ )	$^{40}\text{Ar}/^{39}\text{Ar}$ age (Ma)
SY-14-21	primary - partial recrystallization	moderate	-	-	rare	125-250	35-23
SY-14-18	primary	low	homogeneous	-	rare	125-250	32-27
SYR-13-02	primary to recrystallized	intense	heterogeneous	patchy	few	250-500	$20.72 \pm 0.27$
SY-16-10	primary - partial recrystallization	moderate	-	-	few	250-500	26-20
SY-14-80	recrystallized (secondary)	intense	homogeneous	-	few	125-250	$18.00 \pm 0.14$
SY-14-76	primary	low	heterogeneous	patchy	rare	125-250	33-29
SY-14-77	recrystallized (secondary)	intense	heterogeneous	sectorial	few	125-250	21-18
SY-16-06	primary	low	-	-	few	250-500	40-37
SY-16-15	primary	undeformed	-	-	rare	1000-2000	42-40
SY-14-40b2	primary - partial recrystallization	moderate	homogeneous	-	rare	500-1000	30-21
SY-14-40b4	primary to recrystallized	low to intense	heterogeneous	sectorial	rare	250-500	39-36
SY-14-60	primary - partial recrystallization	moderate	heterogeneous	concentric	frequent	500-1000	44-42
SY-14-63	primary	moderate	heterogeneous	concentric	frequent	250-500	44-40
SY-14-64	primary	moderate	heterogeneous	sectorial & concentric	frequent	250-500	44-42
SY-16-18	primary - partial recrystallization	moderate	-	-	frequent	250-500	144-105
SY-14-68	primary	moderate	homogeneous	-	frequent	1000-2000	80-60
SY-13-10	recrystallized (secondary)	Intense	homogeneous	-	frequent	500-1000	42-59
SY-14-74	primary	undeformed	-	-	rare	250-500	52-48
SY-14-71	primary	moderate	homogeneous	-	frequent	1000-2000	$47.09 \pm 0.21$
SY-14-73	primary to recrystallized	intense	heterogeneous	sectorial & concentric	frequent	250-500	51-24
SY-16-23	primary - partial recrystallization	intense	-	-	few	125-250	39-33
SY-14-30	primary	moderate	-	-	few	250-500	37-33
SY-14-24	primary - partial recrystallization	intense	heterogeneous	sectorial & concentric	few	500-1000	35-32
SY-14-26	primary - partial recrystallization	intense	heterogeneous	sectorial & concentric	rare	500-1000	34-31
SY-14-28	primary	moderate	homogeneous	-	rare	500-1000	$38.45 \pm 0.23$
SY-14-29	primary	low	-	-	rare	1000-2000	$39.04 \pm 0.22$
SF-14-55	primary	moderate	heterogeneous	patchy	rare	250-500	26-22
SF-14-52	primary - partial recrystallization	low to moderate	heterogeneous	concentric	few	250-500	36-31
SF-14-51	primary - partial recrystallization	moderate	homogeneous	-	rare	250-500	$34.48 \pm 0.2$
SF-14-50	primary	moderate	heterogeneous	concentric	rare	500-1000	27-22
SF-14-49	primary - partial recrystallization	low to intense	heterogeneous	sectorial	rare	250-500	35-30
SF-14-44	primary to recrystallized	intense	homogeneous	-	few	125-250	26-22
SF-14-39	recrystallized (secondary)	intense	homogeneous	-	few	125-250	27-22
SF-14-43	primary to recrystallized	intense	heterogeneous	sectorial & concentric	few	250-500	24-20

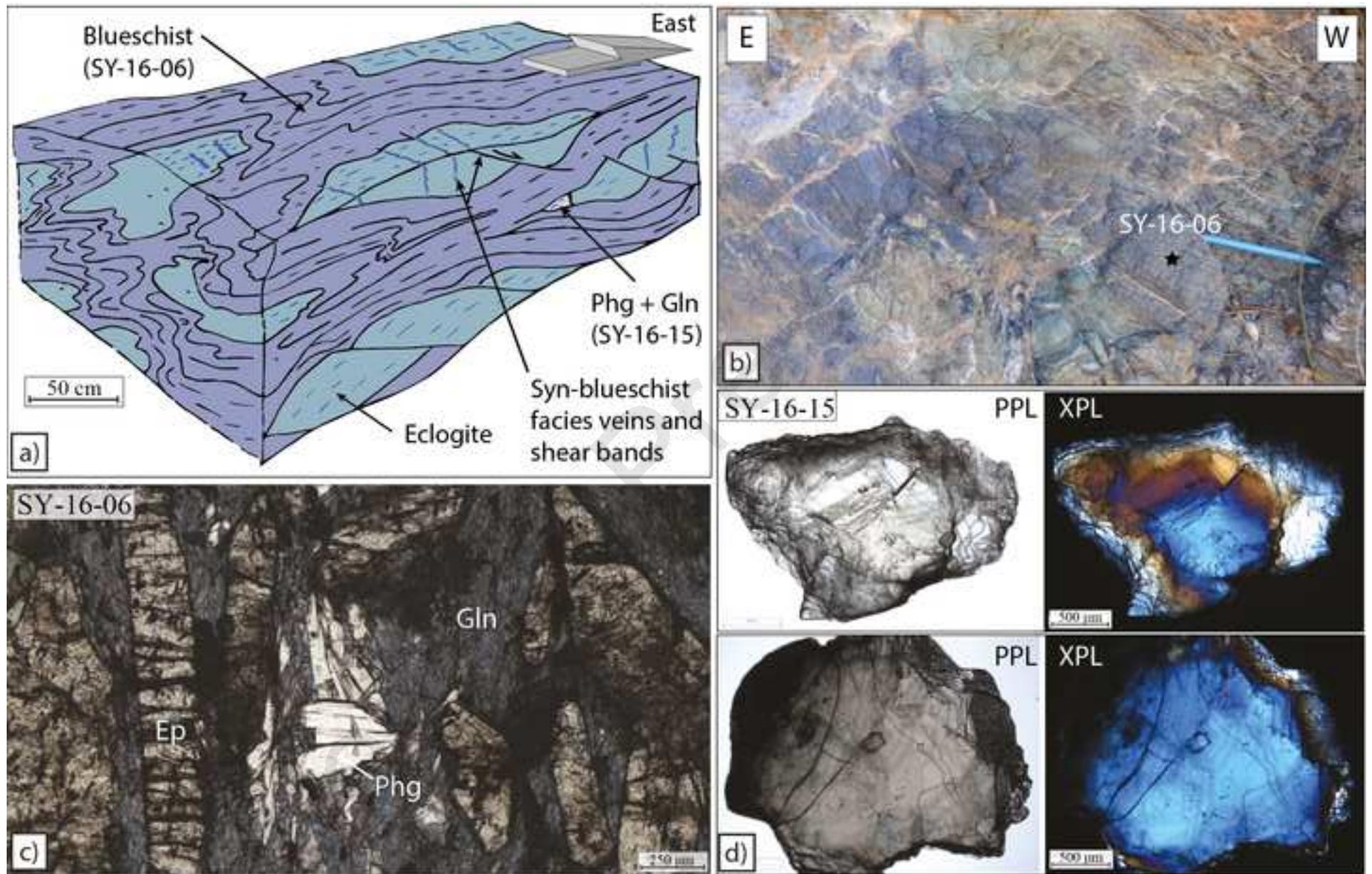


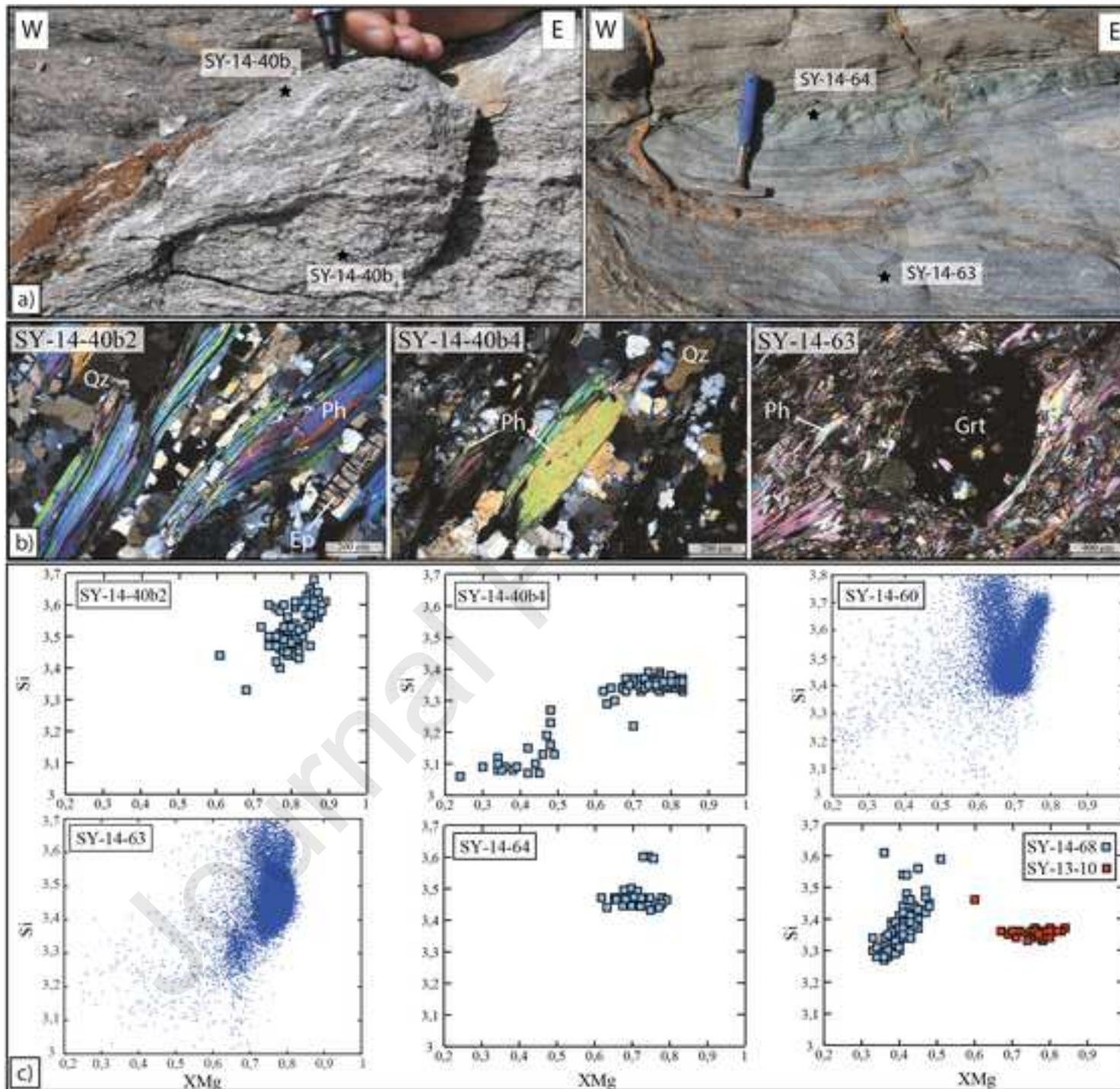


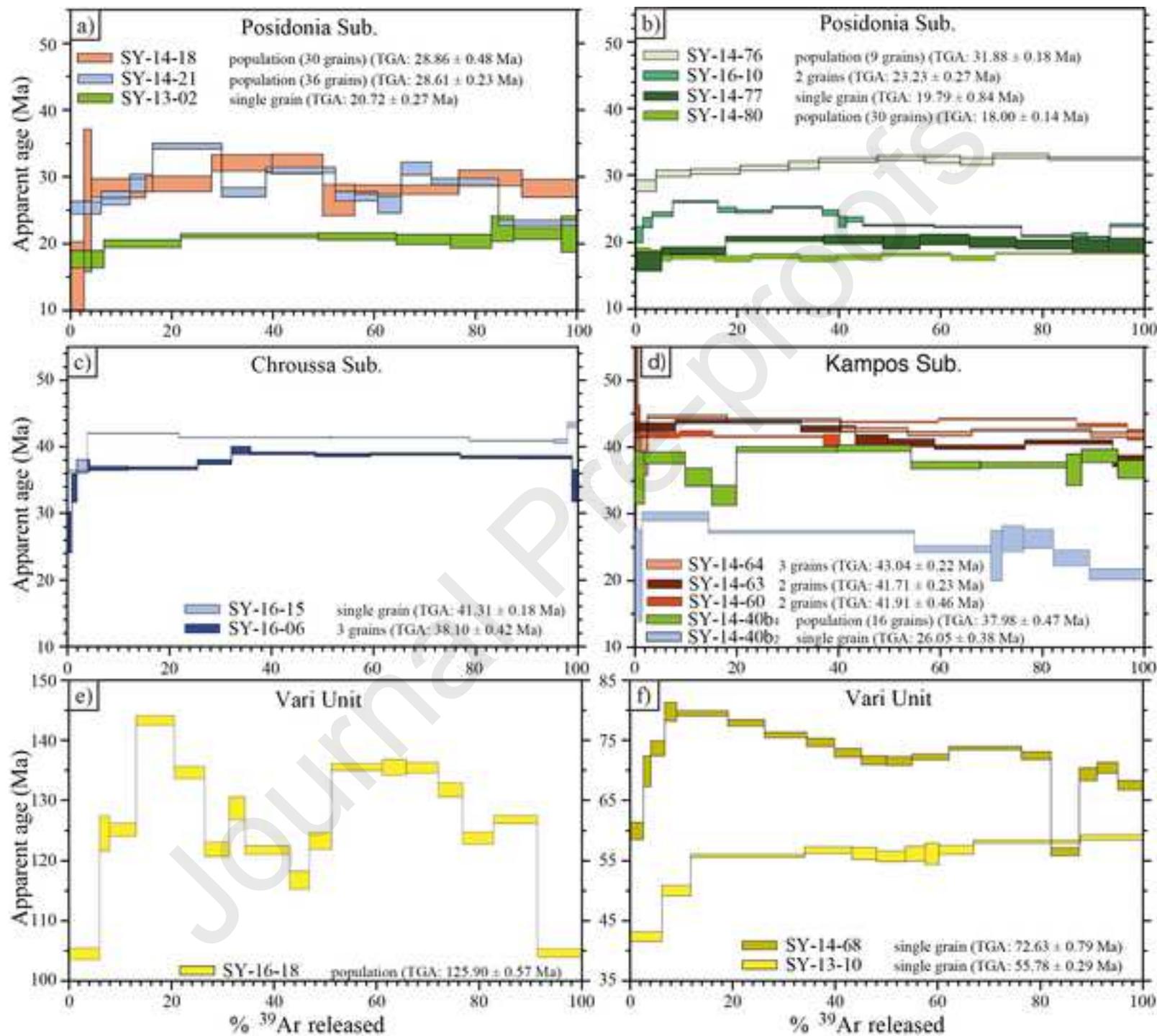


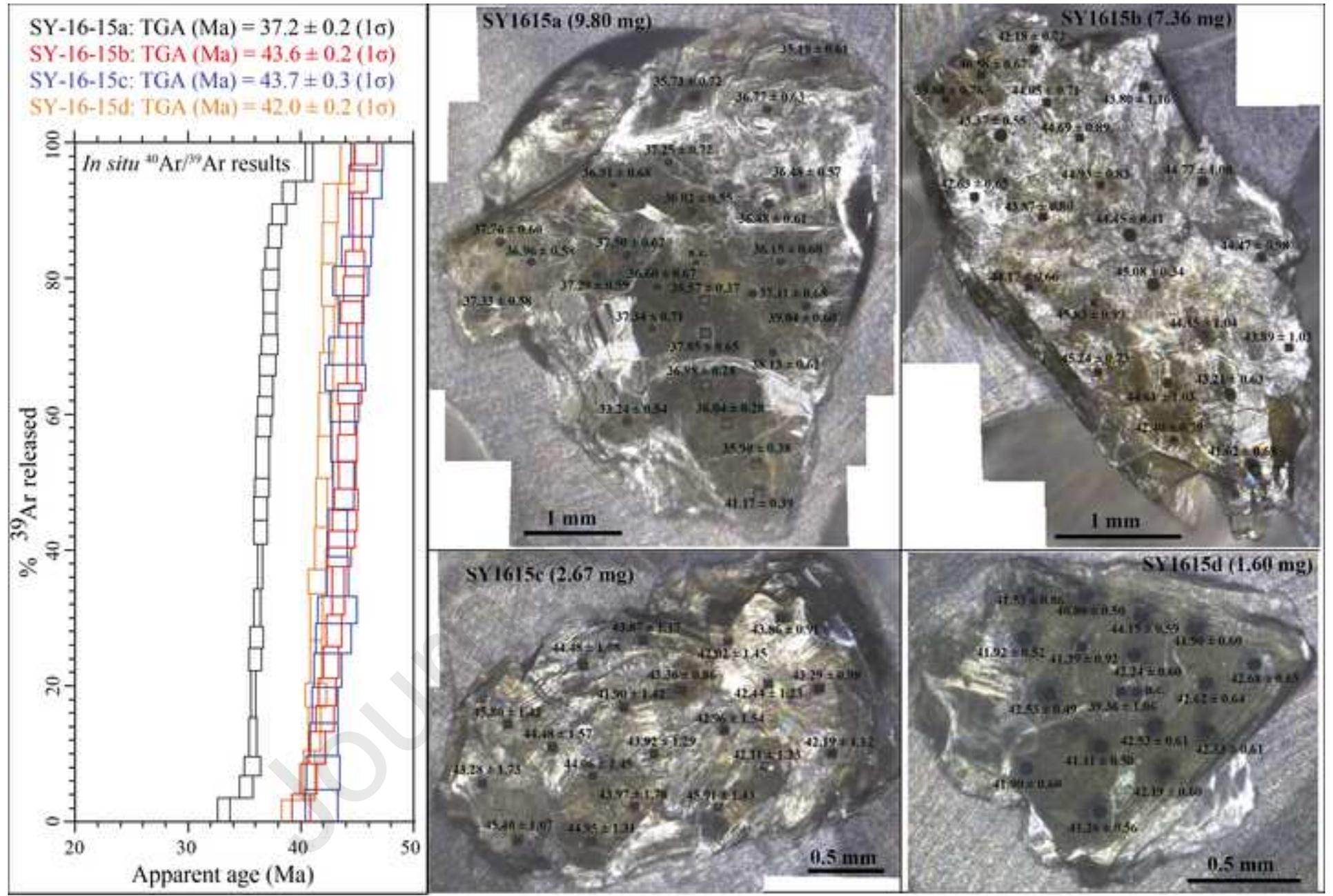


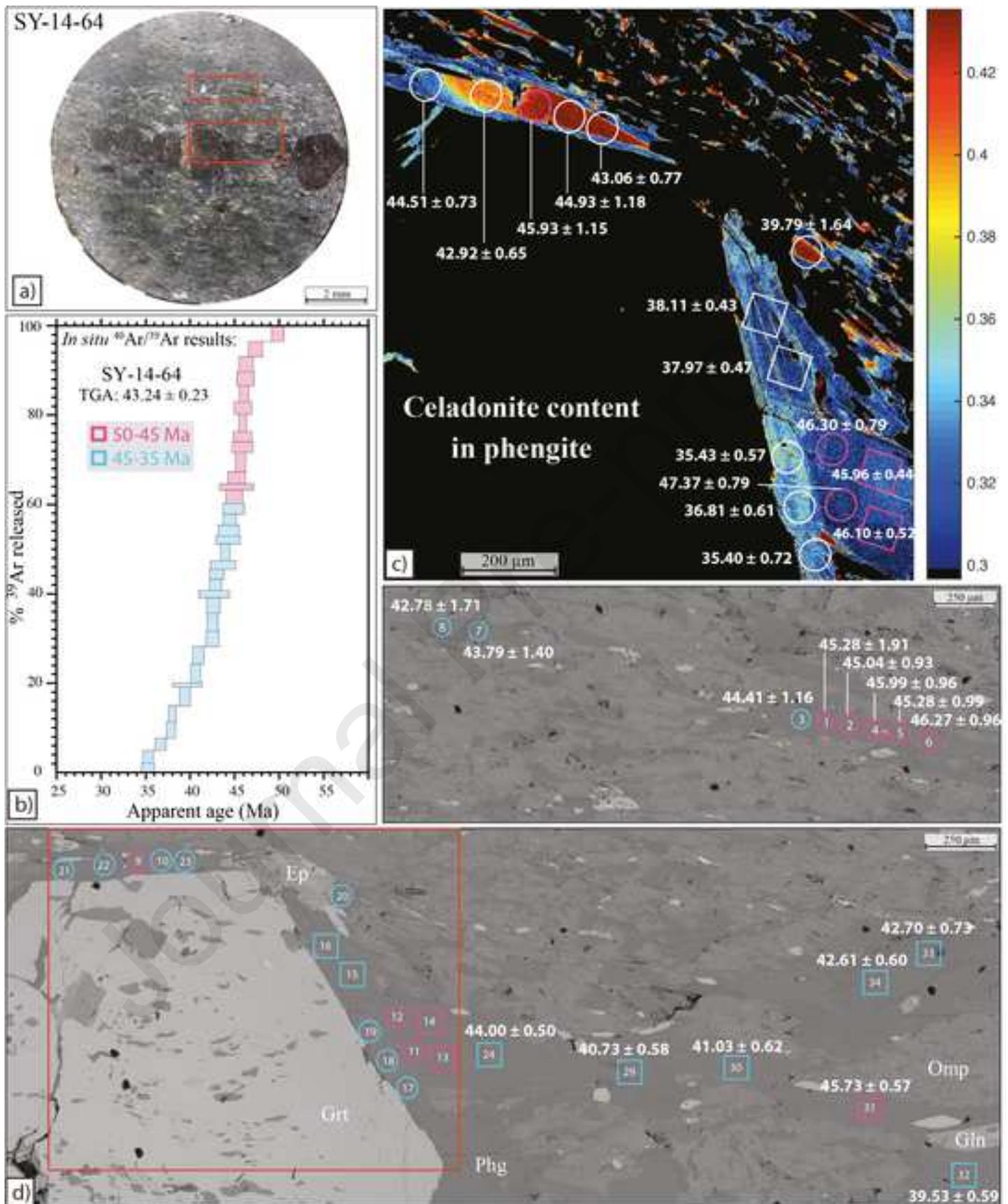


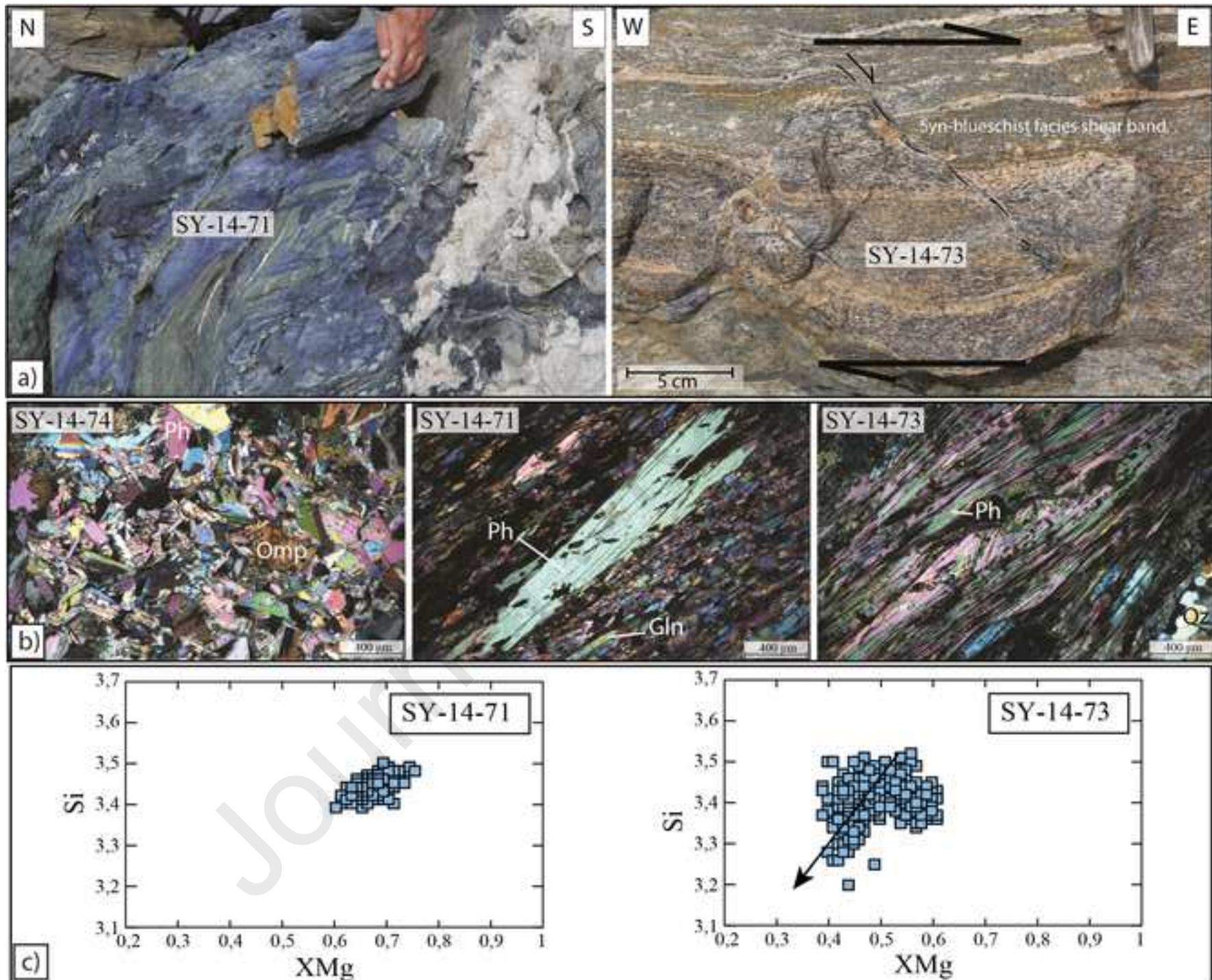


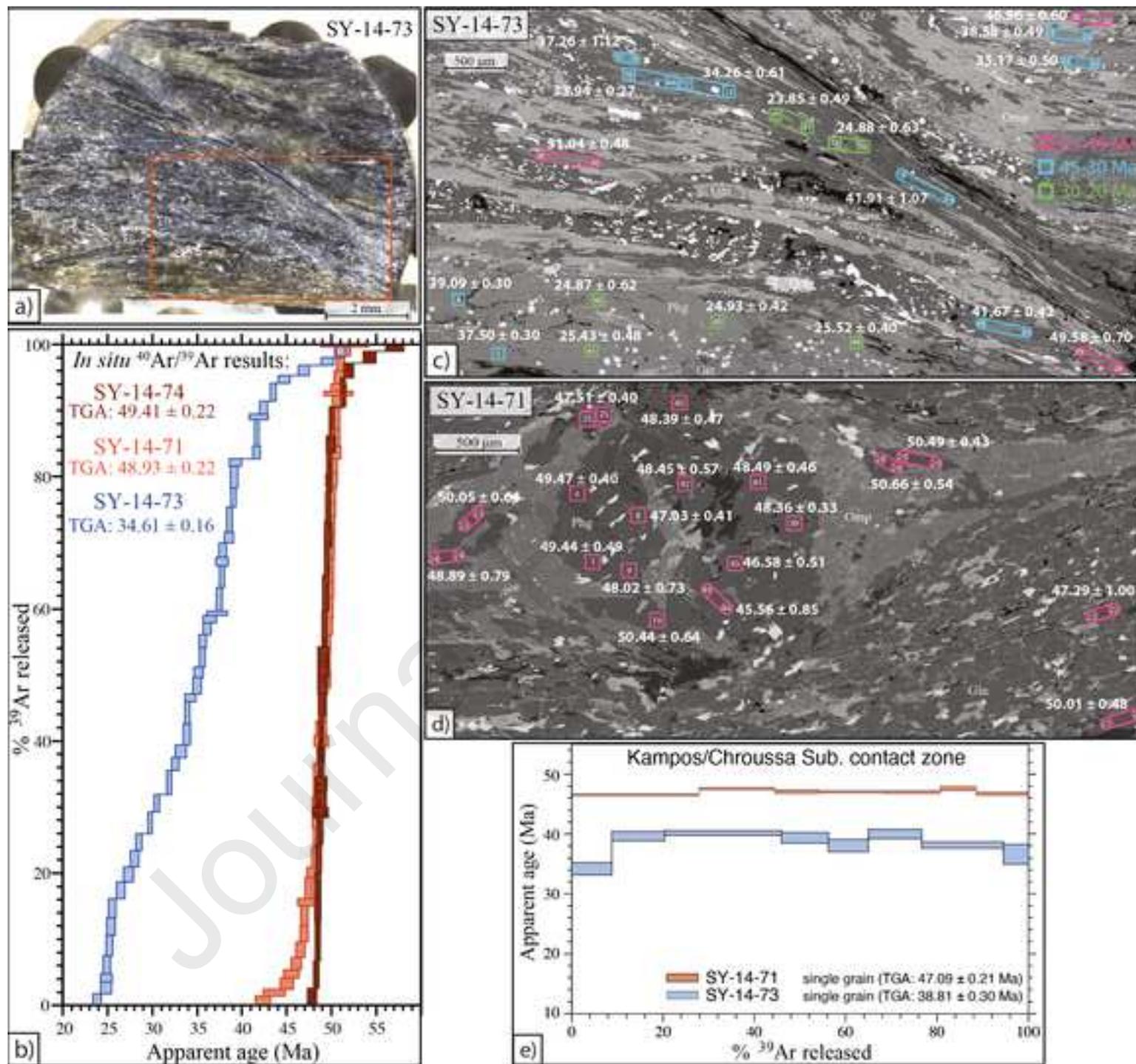


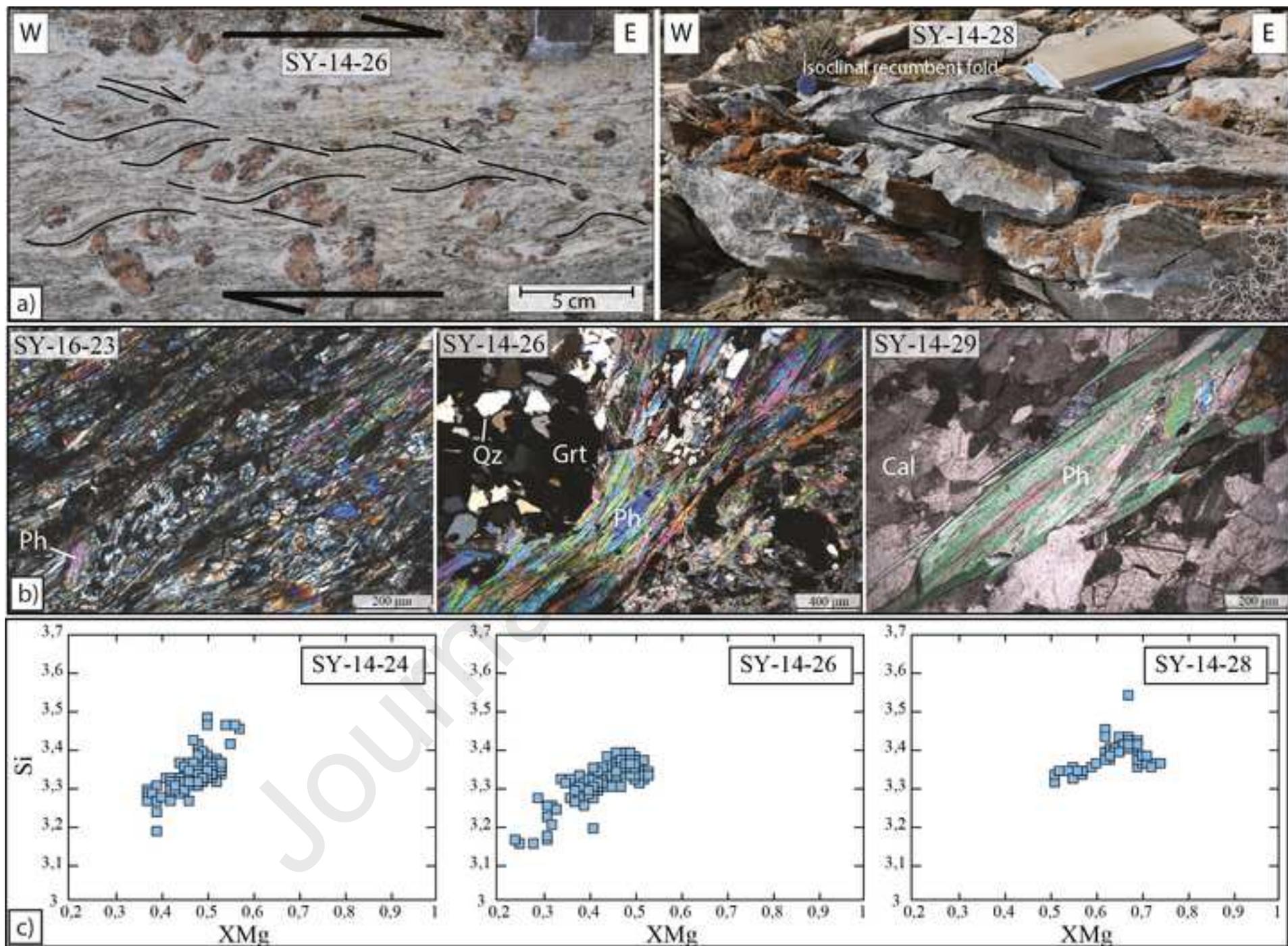


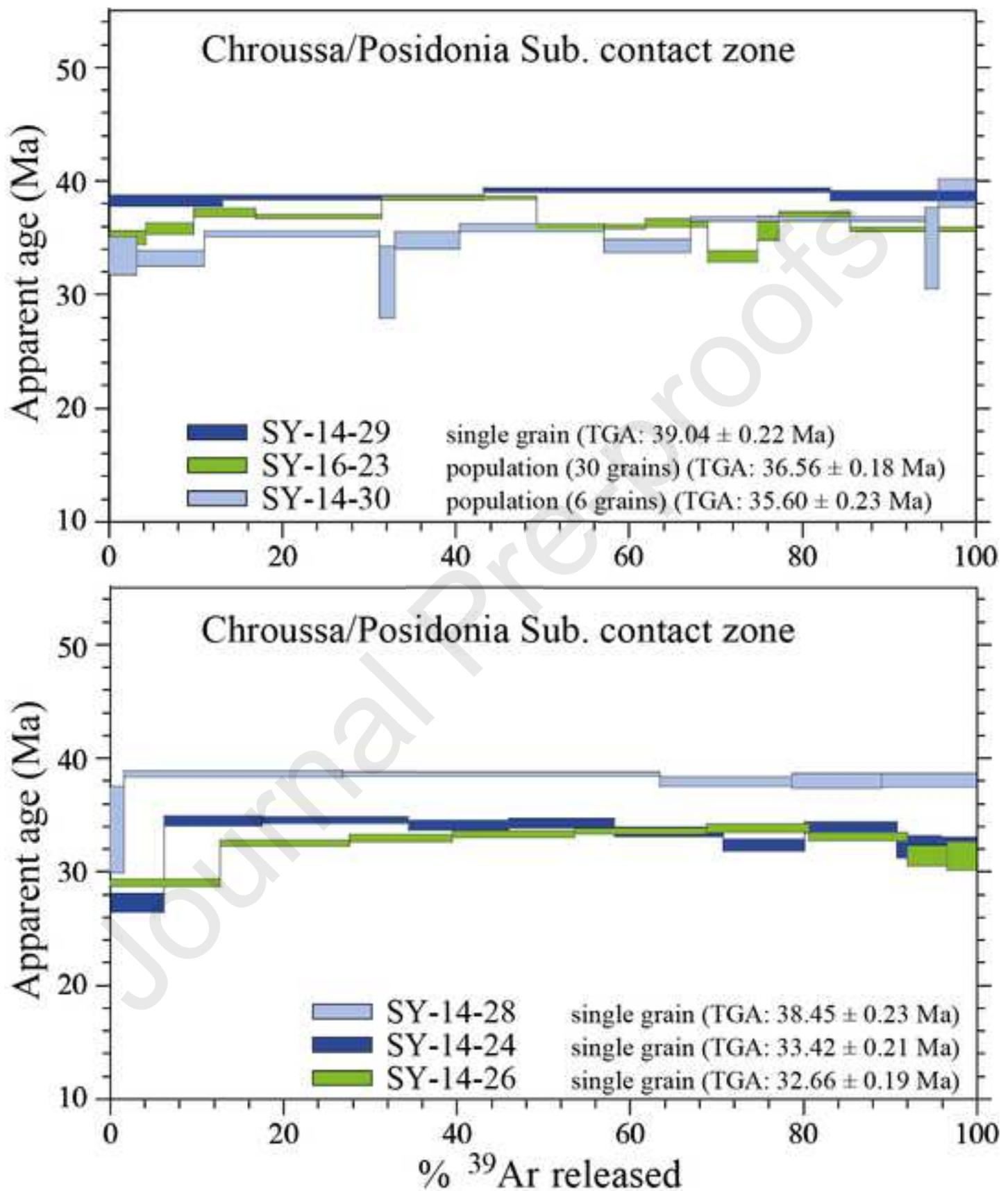


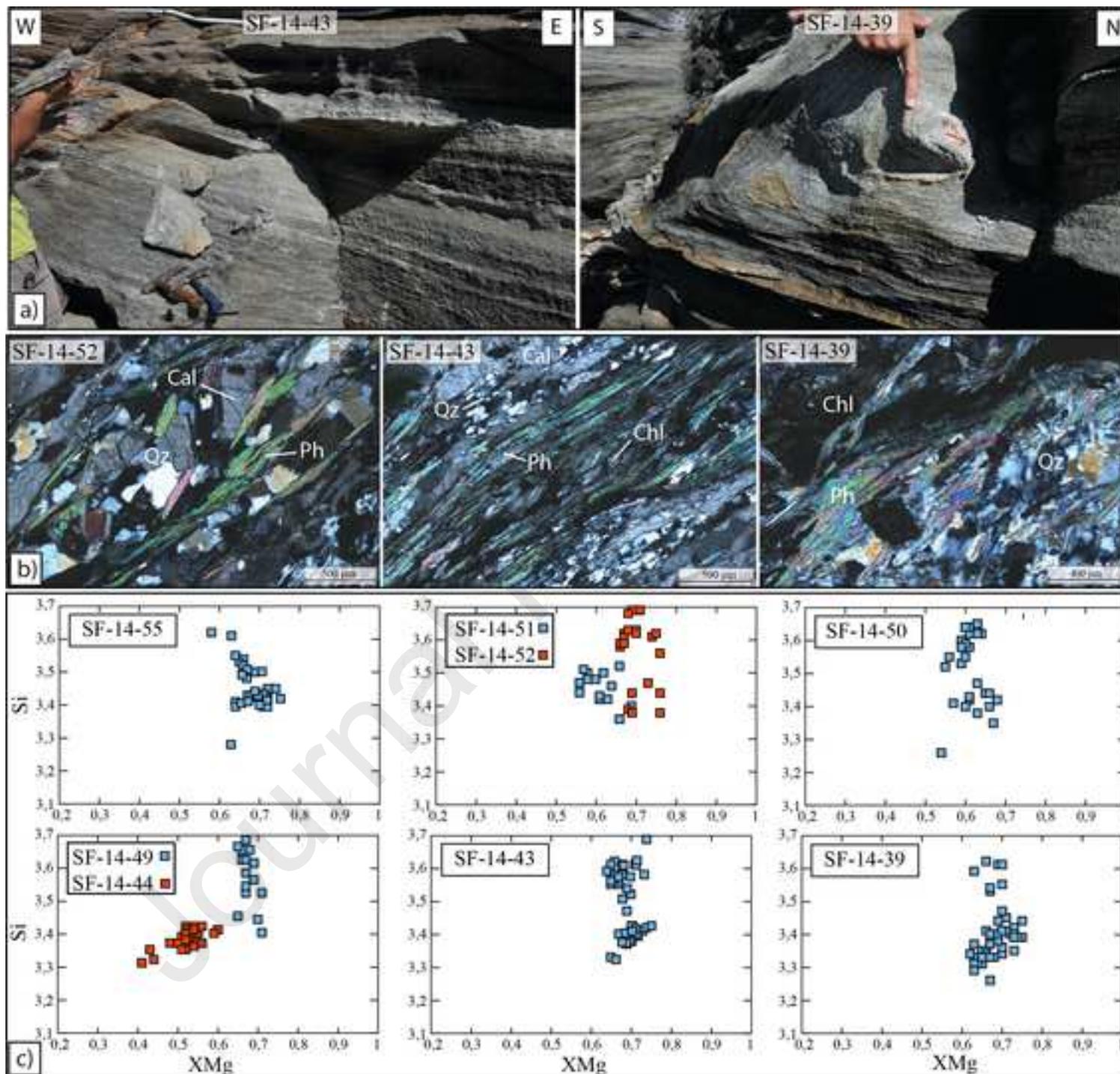


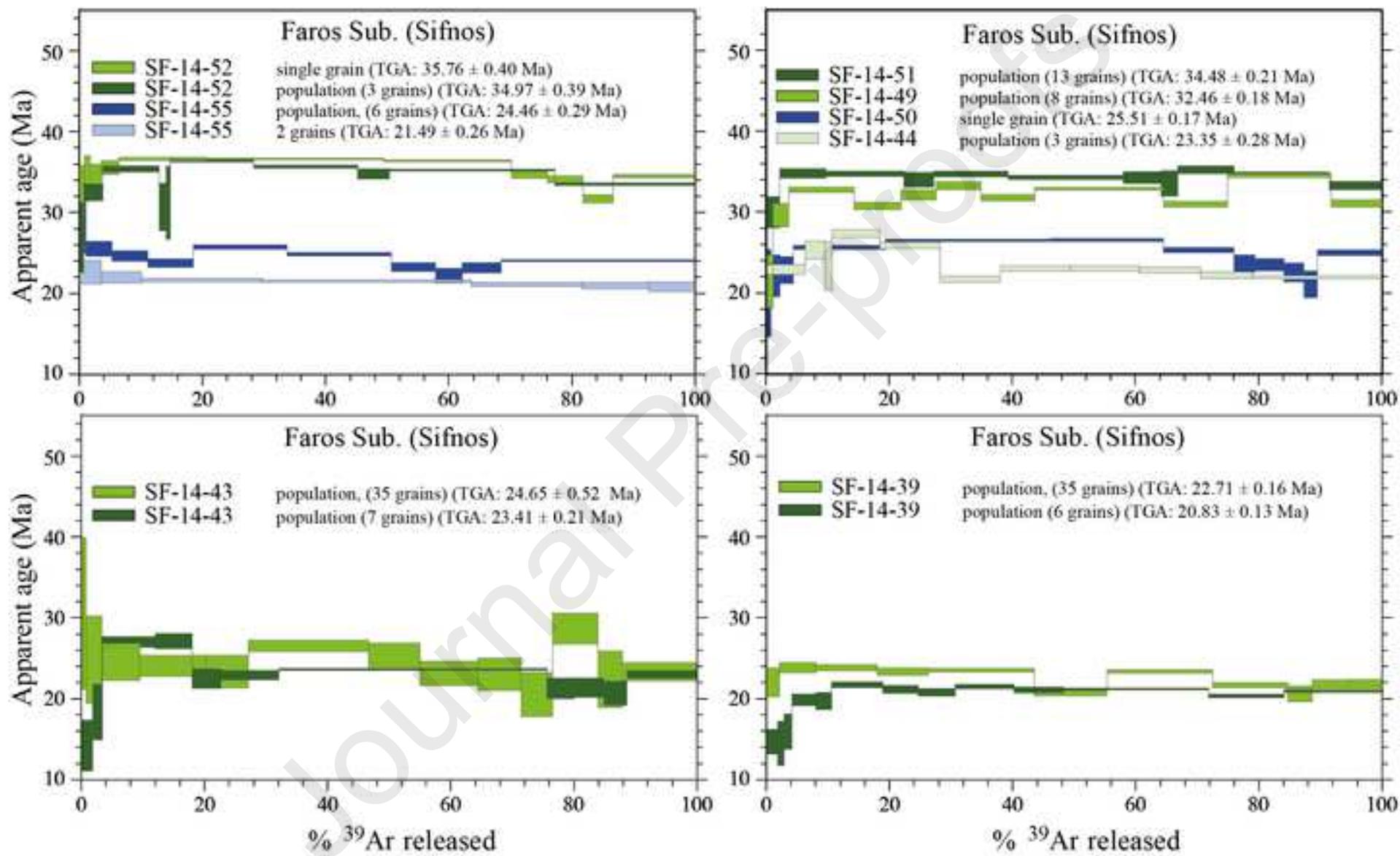


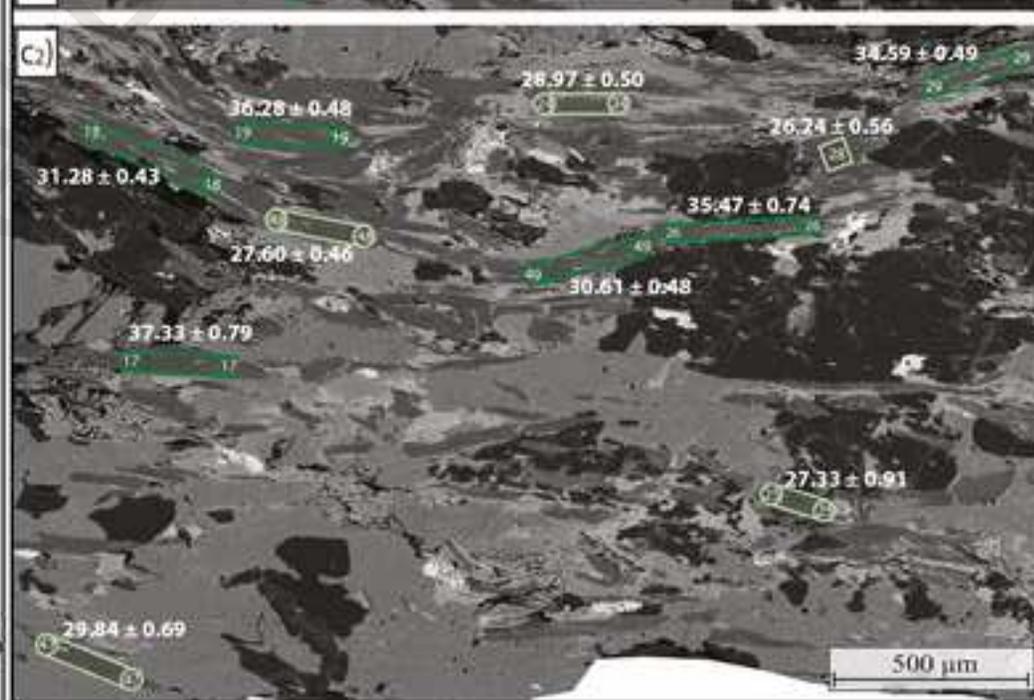
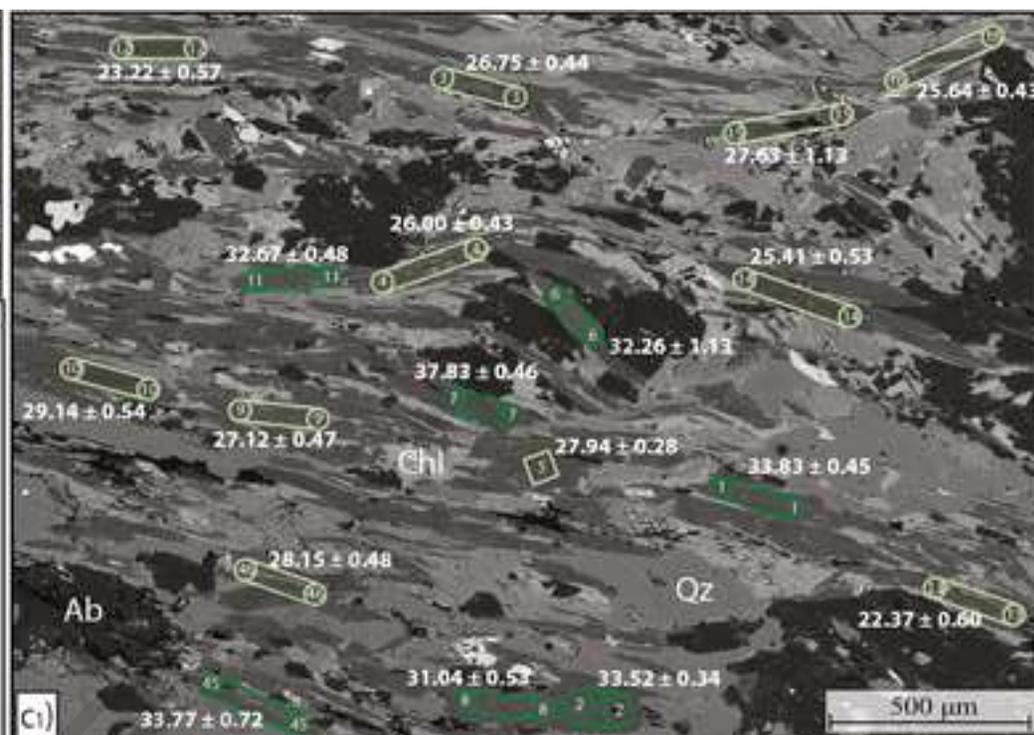
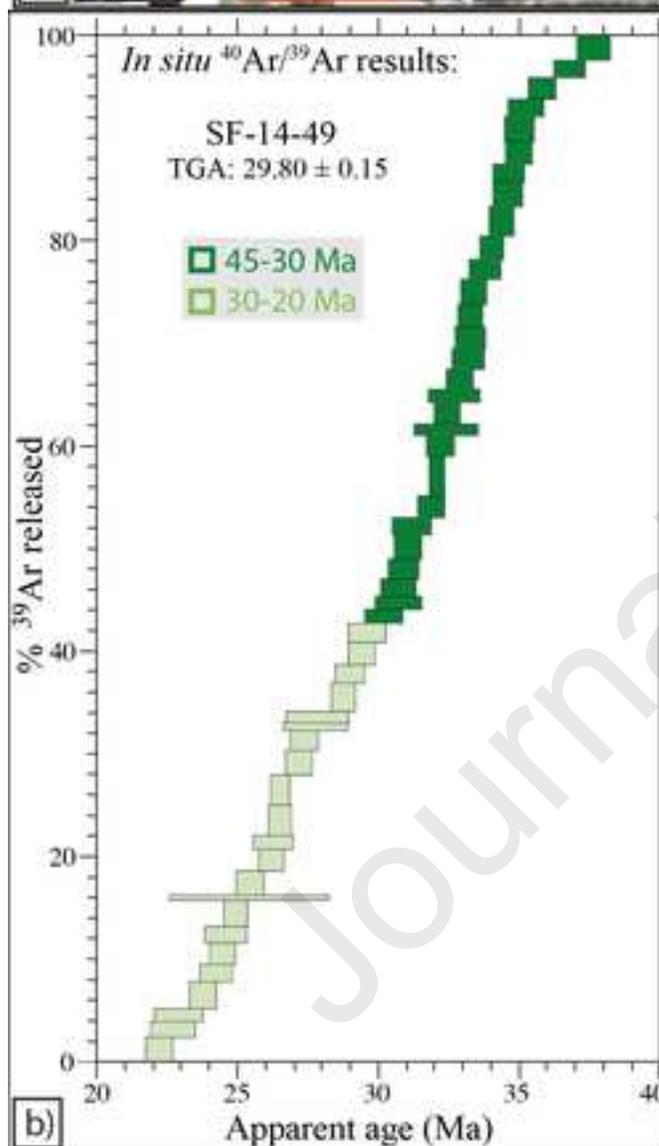












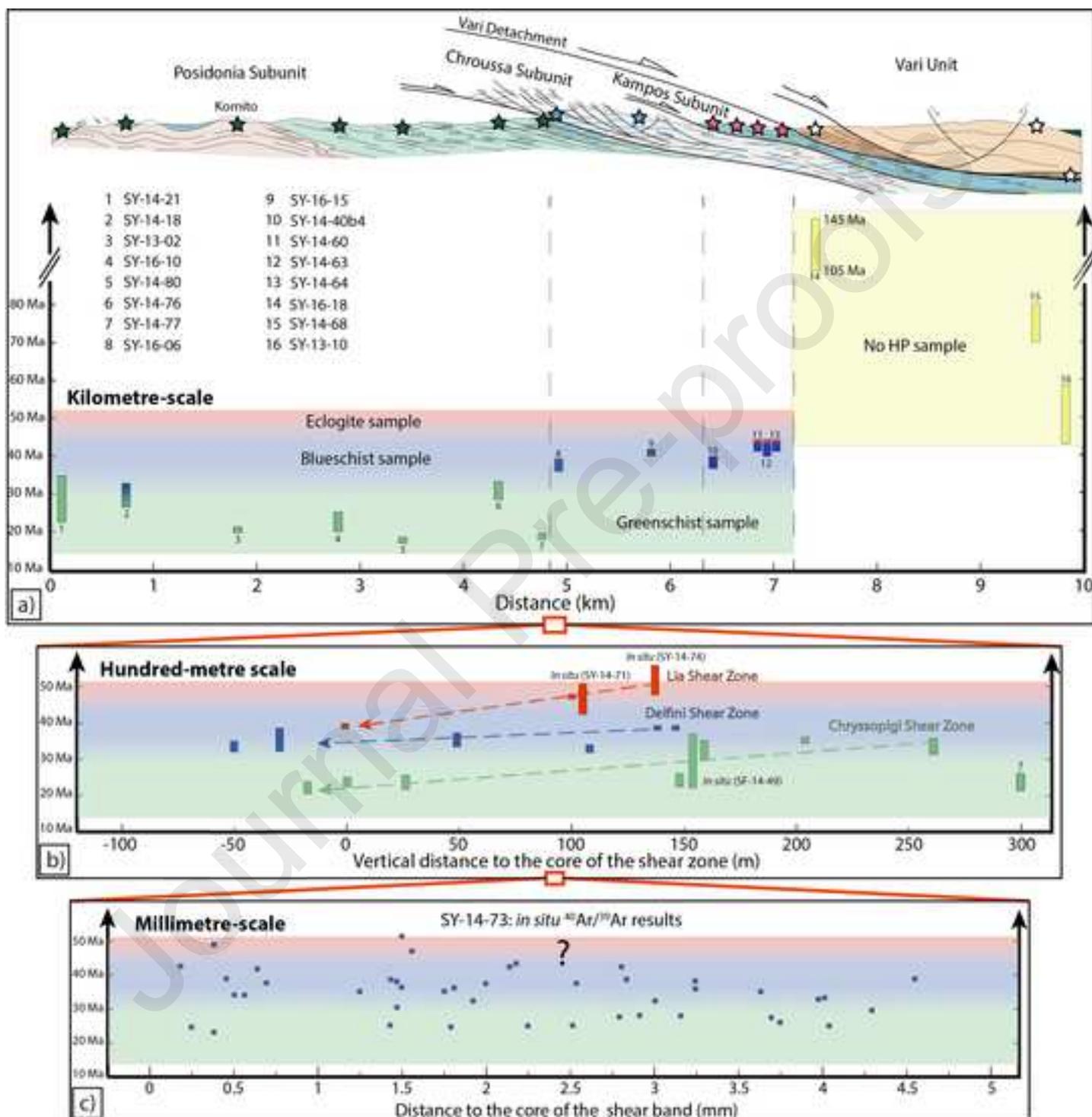
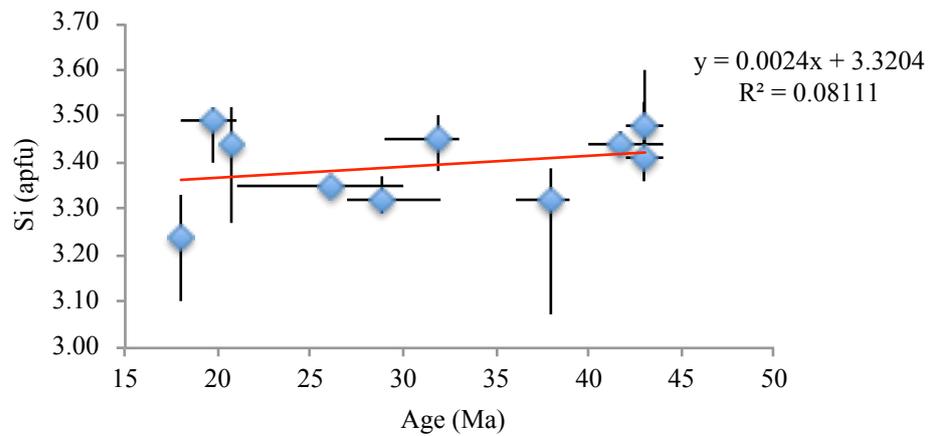


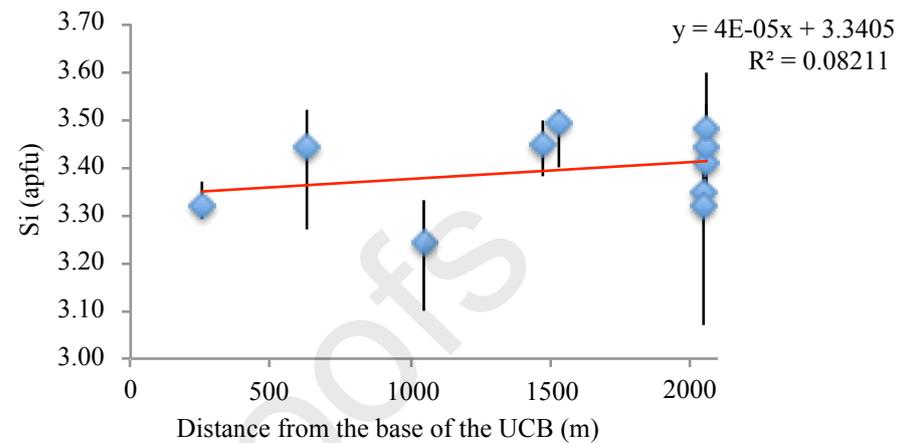
Figure 19

## Southern Syros

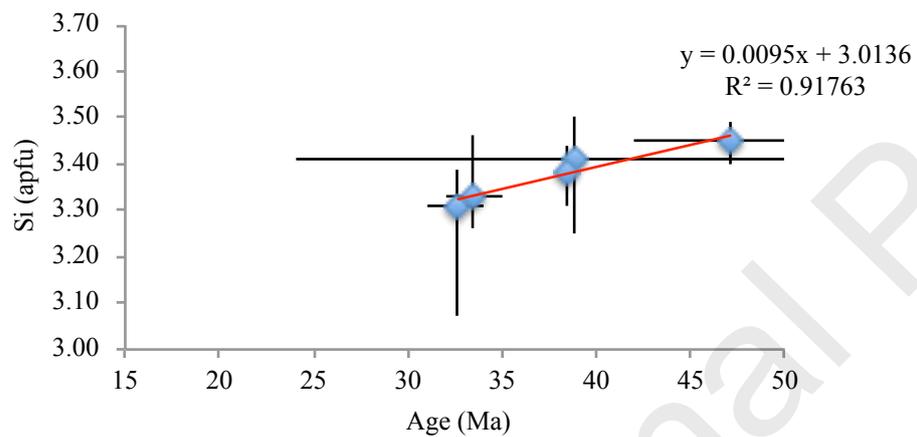


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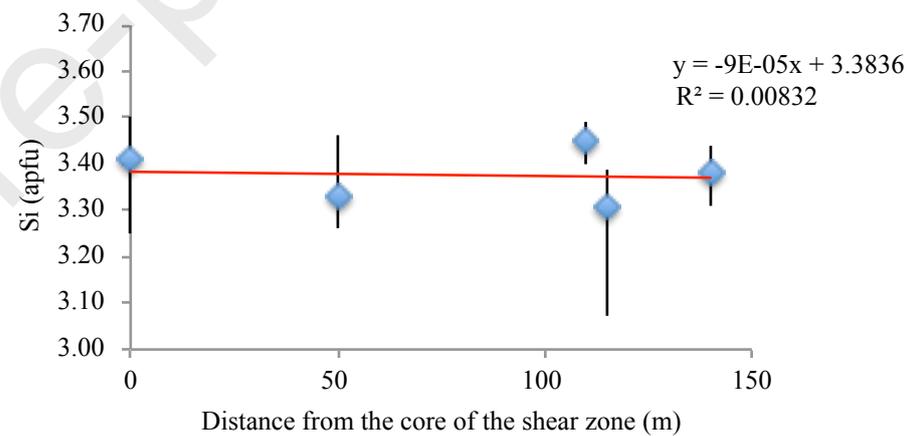
## Southern Syros



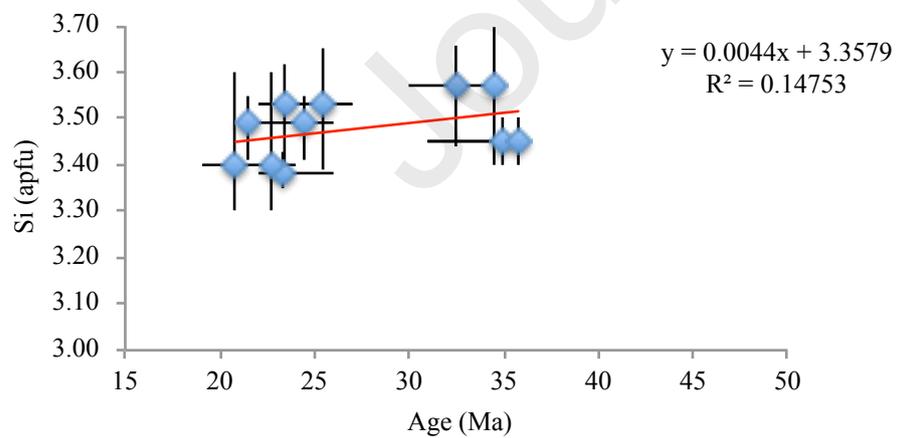
## Lia and Delfini Shear Zones



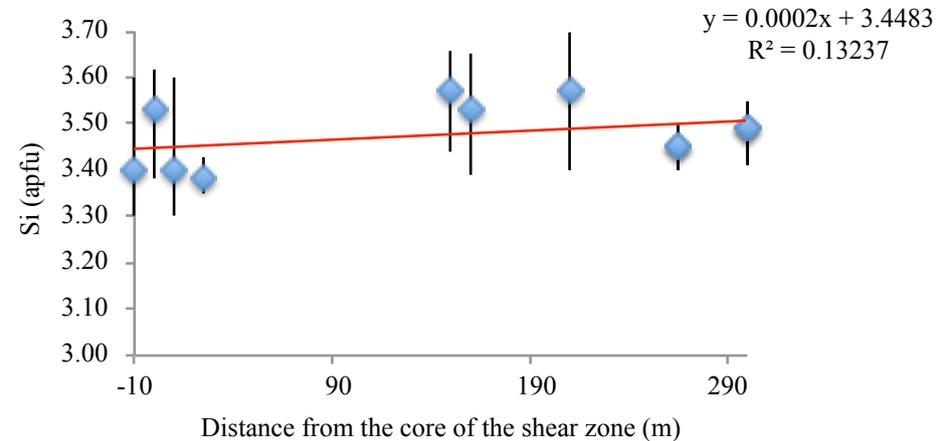
## Lia and Delfini Shear Zones

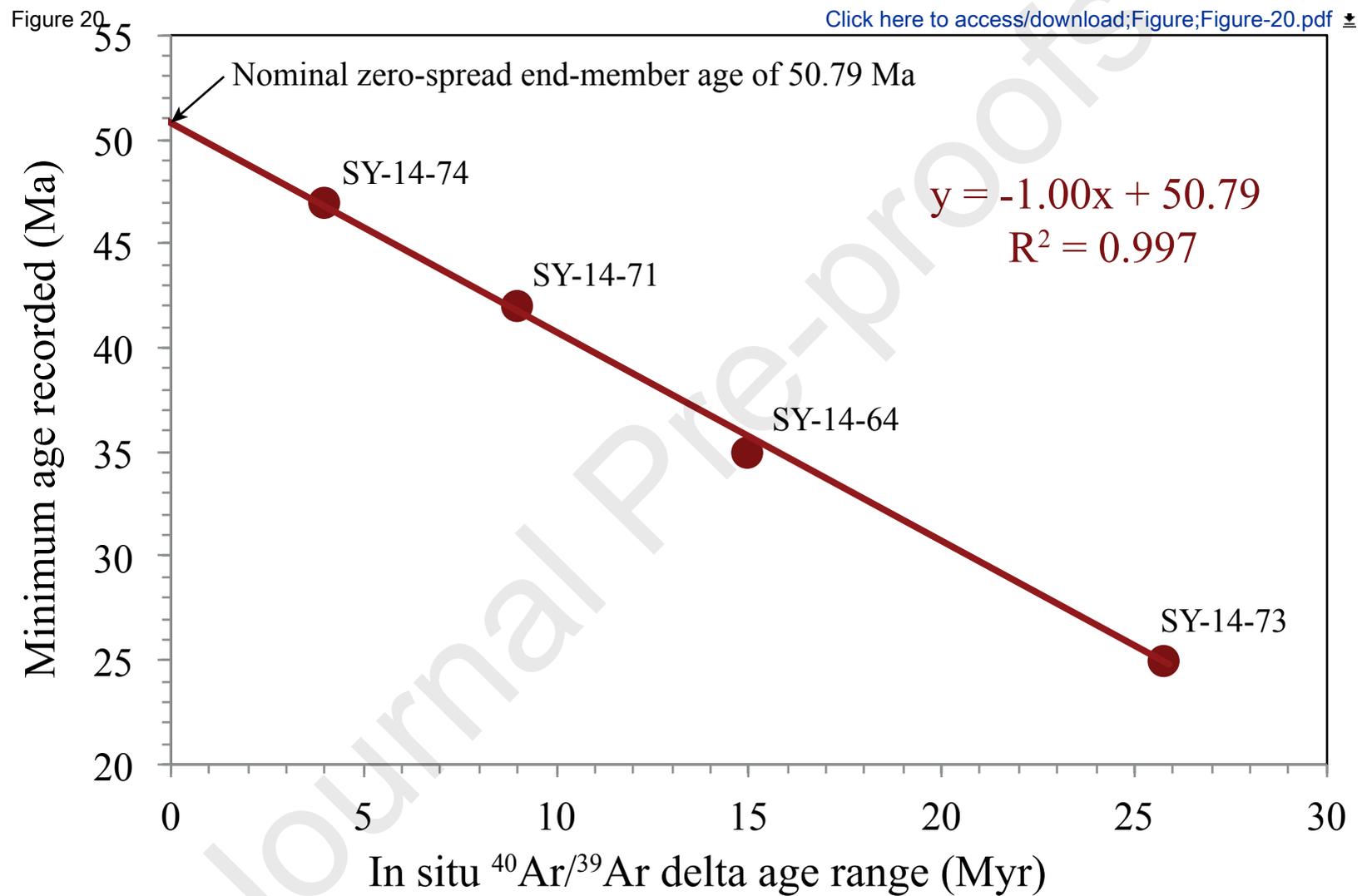


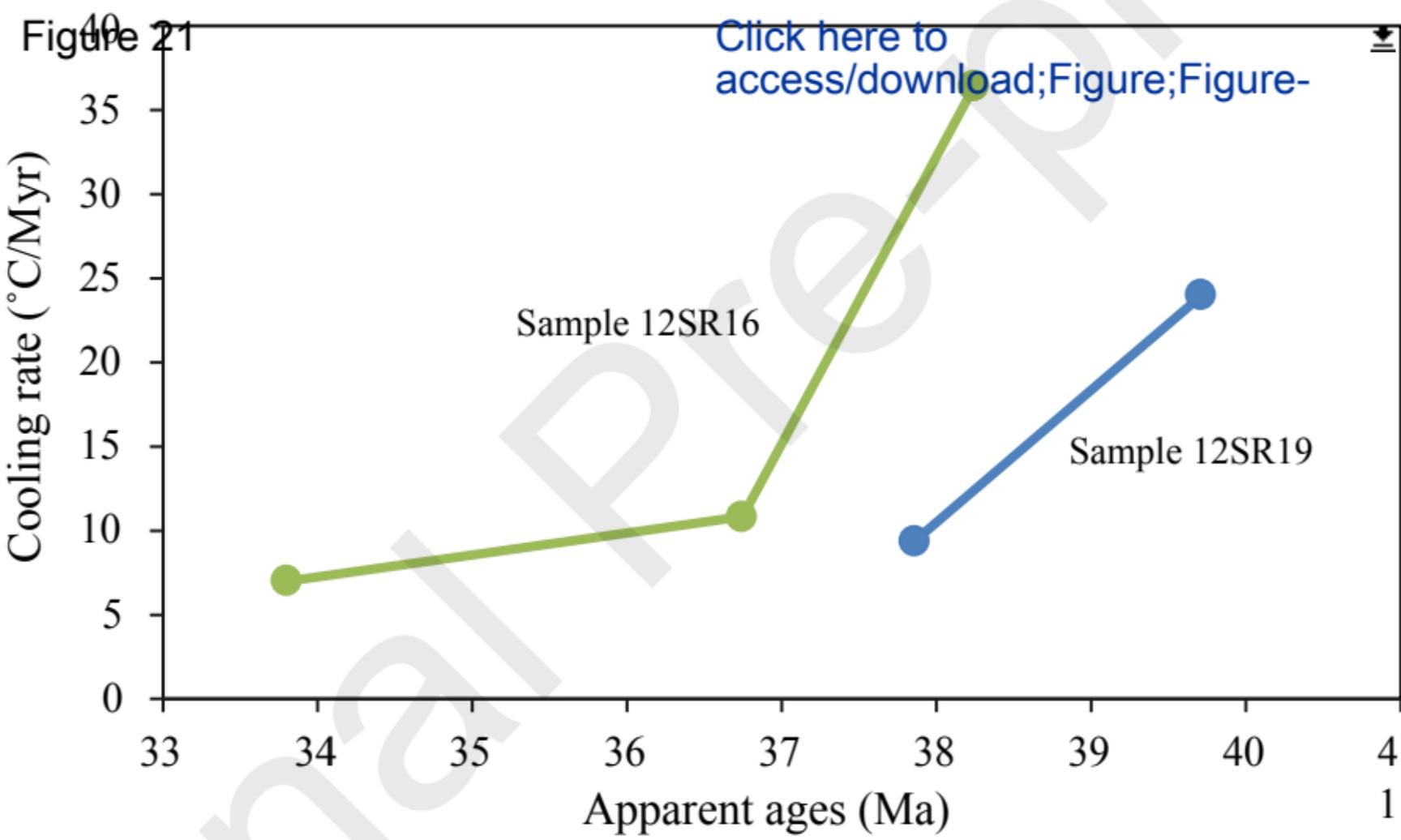
## Sifnos Shear Zone



## Sifnos Shear Zone







**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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