Evidence for the Late Cretaceous Asteroussia event in the Gondwanan Ios basement terranes

Sonia Yeung[1], Marnie Forster[1], Emmanuel Skourtsos[2], Gordon Lister[1]

Authors' responses to the reviews including a list of all relevant changes made in the resubmitted manuscript. Authors' responses are identified as blue text

Overall comment

The manuscript is not concise and explicit

The manuscript is reviewed prior to resubmission with attention to its brevity and ensuring concise and explicit links to relevant material. Rearrangements of sentence and content are made to address this issue and facilitate logical flow of the manuscript.

The manuscript has incomplete and/or illegible figures

Figures are enlarged in the resubmitted manuscript to address this comment. We note that the resubmitted version had no problems in respect to incomplete or illegible figures.

The manuscript has incomplete figure captions

Figure captions in the resubmitted manuscript are reviewed and edited with attention to this aspect.

Tables in the manuscript are improperly formatted

Tables are reformatted in the resubmitted manuscript.

The separation between original and recycled data is not clear.

Previously published data was explicitly identified in the resubmitted manuscript. The resubmitted manuscript had new figures based on the analysis of these data and are identified both intext and in the supplementary material.

The manuscript does not provide tectonic background

The Introduction of the resubmitted manuscript is restructured to explicitly draw attention to the tectonic background.

The manuscript does not differentiate deformation events (D1, D2, etc.)

As this paper tried not to get entangled in the consequences of the numbering scheme failing to document the complex tectonic evolution of the Cyclades, the D1, D2, D3 classification is not used. Instead, a new figure (figure 4) is included to illustrate this and report field observation on deformation events in the resubmitted manuscript.

The manuscript does not assign the different mineral generations (wm1, wm2, etc.) to D1, D2, etc.) events.

The paper uses Tectonic Sequence Diagrams (TSDs) instead of the numbering method mentioned in the reviewer's comment for the reason above. The TSDs focus on reporting observational data as there is no reason that an episode of metamorphic mineral growth should a priori be linked to a deformation event. A new figure (figure 4) is included to illustrate this and report field observation on deformation events in the resubmitted manuscript.

A proper structural map or cross section is missing.

The structural map and cross-section are published in Forster et al. 2009. The resubmitted manuscript draw attention to this reference.

In many paragraphs the headings are misleading and do not fit to the text.
We have reviewed and reformatted the manuscript with attention to this aspect.

Abstract

The abstract is not explicit enough and in parts speculative.
All authors are consulted, the abstract was slightly modified in the resubmitted version in response to this comment.

The phrase "Ar geochronology...demonstrates...metamorphic event" in the abstract is misleading, metamorphic events are determined by petrology and these events might be dated by geochronology.
The sentence was revised in the resubmitted manuscript.

Section 1

The introduction does not introduce the main problem and ongoing discussion in literature adequately.
The introduction was restructured with the following details in the resubmitted manuscript:

(1) The significant knowledge gap that exists in understanding old events in the Ios basement terrane prior to Alpine deformation events.
(2) The consequences of accreting this Gondwanan terrane to the Alpine terrane stack such as the extreme crustal extension after accretion, followed by magmatic event in Oligocene-Miocene period lack proper explanation.
(3) Until this work, it is largely assumed that the Ios basement is not affected by pre-Alpine deformation since ~300 Ma (hence referred as the Hercynian basement).
(4) Previous data did not recognize high-pressure rocks in the Ios basement and its tectonic history is much more complicated than a single M_0 event can define.
(5) Referring all older events as M_0 (pre-HP metamorphic event) results in little to no attention on older events prior to accretion in the evolution of the European terrane stacks
(6) Recognition of the exhumed Asteroussia terrane across the terrane stack in this study enabled us to identify a subduction jump that is impossible without a tectonic mode switch.
(7) Our proposed model on the subduction jump is able to capture and explain the extreme extension after accretion, formation of Cycladic metamorphic core complexes and the later Oligocene-Miocene magmatic event

The introduction does not introduce the controversy in interpreting Ar-data of HP rocks.
The introduction was revised with special concern in this aspect in the resubmitted manuscript.

The introduction does not introduce what plates/ terranes are involved while some information are provided in figure 2 only.
The text and figure 2 (including figure caption) are reformulated in the resubmitted manuscript in response to this comment.

Reformulate the statement “southwards of the surface outcrop of the sub- duction megathrust” in line 16.
This sentence is reformulated in the revised manuscript.

The introduction does not explain clearly why rocks mentioned in line 20 are considered the (pre-Alpine) Ios basement.
The introduction is restructured in the resubmitted manuscript, with special note to this comment.

The "Late Cretaceous metamorphic event" is not clear in the introduction (line 22).
The sentence is restructured in the resubmitted manuscript, with added details to explain the idea clearly.

No explanation on why changes mentioned in line 36 is a significant modification.
The sentence was reformulated and is part of the restructured introduction in the resubmitted manuscript.

Section 2

The idea of "the same metamorphic age" outcropped in various Cycladic islands is unspecified (line 58)
This particular sentence was revised in the resubmitted manuscript with elaborations on the idea of "the same (Late Cretaceous) metamorphic age" reported across the Cycladic islands.

The published Rb-Sr dates mentioned does not include details to its interpretation (line 61).
The revised sentence added details to the Rb-Sr dates such as the lithology analysed and its location in the Cyclades.

The reviewer suggests replacing "low-pressure" by "retrograde" in line 65.
We found "overprinted by low-pressure greenschist facies" better to describing the occurrence of a younger deformation event with different property instead of saying that the rock experienced "retrograde" metamorphism due to the complexity of deformation and mineral growths associated. Hence this sentence is not revised as suggested in the resubmitted version.

The reviewer suggests reformatting section 2.2 (which include the main research hypothesis/question) to link it with the Introduction and integrate research methodology in this section.
The resubmitted manuscript provides a better linkage between the introduction, section 2.2 and section 3. Details to the research methodology is included the supplementary material with linkage provided in the result section (section 3 and 4).

The reviewer suggests adding references in line 77-78.
References has been added to this particular sentence.

Section 2.2 failed to present the field results demonstrating different deformation events
The revised manuscript include details to explicitly draw attention to structural results on the various deformation events, this includes the structural maps provided in the supplementary material and the new figure 4.

EPMA data is missing in the manuscript in addition to BSE images to distinct complex microfabrics dated.
The EPMA analysis and BSE images are included in the supplementary materials of the resubmitted manuscript.

Tables of quantitative white mica data is missing in this section
See response above.

Many statements about mineral chemistry remain unproven or not documented.
Results from EPMA analysis are provided in the supplementary material, with in text notification pointing to the supplementary material.

Analytical errors are not shown in the mineral chemistry graphs.
Analytical errors are not placed in the mineral chemistry graphs for clearer identification of data points in the cluster. Exact values measured are presented in the supplementary material.

Reviewer suggests considering analysis on garnets for P-T calculation.
We acknowledge that there is potential of extracting further information on fabric within the garnets for P-T calculation. But this cannot be done for this paper.

P-T conditions for the Late Cretaceous Asteroussia event is generalized, detailed information on how this is derived is needed.
We included the literature used and logic used to derive our presented pressure and temperature extracted from phengite silica content in the resubmitted manuscript.

Distinction of the various white mica generations needs to be more detail, with information on how to identify them in the argon data.
We revisited how this procedure is presented in the text and added details on the figures to show how different white mica generations can be recognised. Additional information on recognition of different white mica generations using the Arrhenius plot and the York plot are presented in the supplementary material.

The methodology is poorly described in terms of sample preparation, sample size, cleaning and measuring procedure (e.g., blank values and standard age values are not reported).
We have reviewed the manuscript with attention to this aspect. To ensure the storyline of the paper, detailed description of the methodology is included in the supplementary material with the manuscript explicitly drawing attention to this supplementary material.

Some detailed structural aspect is not clear in figure 2a, b, hence causes confusion.
An enlarged figure is added to figure 2 for clear illustration of details in the resubmitted manuscript.

Sentence in line 91-92 needs to show reference to figure 3
This sentence is reformulated as suggested.

Tectonic unit "the Port Beach tectonic slice" mentioned in line 105 is not shown explicitly in figure 3.
The sentence and details in figure are revised in the revised manuscript.

Show location of the South Cyclades Shear Zone in figure 3 as mentioned in the text.
The South Cyclades Shear Zone overprints the entire field area with some places affected by the overprinting, narrow north-directed shear zone. This observation is added to the figure caption to ensure clear understanding.

"metemorphosed" is spell incorrectly in figure 3b map legend.
Map legend corrected in the revised manuscript.

Shear senses of various stages of deformation needed to be shown in figure 3b.
Showing shear senses of various stages in the lower detailed map is difficult as the entire field area is affected by the broad, large scale shear zone. We achieved this by including a new figure (figure 4 in the resubmitted manuscript) summarizing field analysis with tectonic sequence diagrams (TSDs) and compared with the traditional structural geology numbering method.

Section 3

Field evidence of the multiple alternating deformation events mentioned in line 111-112 is missing.

A new figure (figure 4) is added in the revised manuscript to provide field evidence requested. Structural maps revised from Yeung, 2019 Master's thesis are included in the supplementary material.

Sample number and labelling is unclear in figure 4a.

Corrections and modifications have been made to be clear and concise.

Figure 5 requires more information on the microstructures identified and analysed.

Corrections and modifications have been made which include further information, both in text and in the supplementary material in the revised manuscript.

The statement "The prominent structural contact between the garnet-mica schist and the augengneiss is defined by a late-developed intense north-sense shear zone" in line 128-129 is unclear.

This particular sentence is reformulated in the revised manuscript.

Calculations and deduction to the P-T conditions reported in line 143-144 is unclear.

The resubmitted manuscript included the literature used and logic used to derive our presented pressure and temperature extracted from phengite silica content in the resubmitted manuscript.

No explanation as to why the garnet rim is black in line 158.

The resubmitted manuscript added further detail to this observation. We do not know the cause of the black garnet rim and present in text that this might be due to a chemical composition change during the second mineral growth event. Analytical data will be included in the supplementary material.

No compositional data on white mica inclusions within garnet is provided in line 159-160.

The grains are too small for this type of probe analysis. The garnet crystals are small in size (1-2 mm diameter), hence the inclusion will be even finer and compositional analysis unreasonable.

No explanation why "non-end member garnets" is used in line 171.

This particular sentence is restructured with additional information.

No composition data of the white mica inclusions in garnet in line 175.

Please see response to reviewer's comment on line 159-160

Presence tense is needed in line 181-182

This is corrected in the revised manuscript.

Method of the P-T conditions estimate is unclear and missing in line 179-181.

The resubmitted manuscript includes these details with reference to previous literature.

A large portion of this paragraph should be shifted into the former section to describe and introduce the deformation zones and deformation phases.

Section 2.2 (The Asteroussia event on Ios) is reformatted in the resubmitted manuscript to create a better linkage to the introduction with the following structure:

(1) Introduction of the four terrane slices in Ios. This will include a summary of the literature review and controversies on the structure of the terrane stack outcropped in Ios
(2) Deformation zones and events recorded in this study will be presented
(3) The section will conclude why the identification of the Asteroussia event on Ios will provide a significant knowledge advancement in the tectonic architecture in Ios and the Cyclades, hence this paper.

Quantitative data should be given in tables, e.g. in supplements
The revised manuscript include text in this section explicitly drawing attention to the supplementary material with quantitative data and its methodology.

The reviewer suggests shifting the sentence in line 100-103 to the introduction.
This is changed accordingly in the resubmitted manuscript.

The reviewer suggests shifting the sentence in line 104-106 to section 2 – the Asteroussia nappe.
This is changed accordingly in the resubmitted manuscript.

The reviewer suggests enlarging the text in figure 3.
The figure is enlarged in the resubmitted manuscript.

The reviewer suggests shifting the sentence in line 111-112 to section 2 – the Asteroussia nappe. The reviewer also suggests providing field evidences to this sentence.
This change is made with the addition of a new figure (figure 4) in the resubmitted manuscript.

The reviewer suggests specifying the term "both tectonic silvers" in line 113-114.
Details that specify this term are added in the resubmitted manuscript.

Mineralogy of each sample should be added in table 1
Table 1 is revised accordingly in the resubmitted manuscript.

The reviewer suggests re-organising table 1 to be more space efficient.
Table 1 is changed accordingly in the resubmitted manuscript.

The reviewer suggests introducing all metamorphic events (including the "Δ_{1D} event" in Forster et al. (2020)) in the introduction.
The comment is accepted in the revised manuscript in the new figure (figure 4 in resubmitted manuscript).

The reviewer suggests specifying the deformation event associated to the described deformation in line 124-125.
This is changed accordingly in the resubmitted manuscript.

The reviewer suggests providing structural description in terms of a map and cross section(s) to illustrate the deformation event associated to the described deformation in line 125-127.
This sentence is adjusted and correlated to supplementary materials accordingly.

The two white mica generations need to be clearer in figure 4 with added sample details.
Further details to the observation in figure 4 (now figure 5) is provided in the resubmitted manuscript.

Figure 4c need more statistical information.
Data presented in this chart is the exact value calculated from experimental data, analytical data (EPMA data) used to calculate the figure 4c is included in the resubmitted supplementary material.

Differentiation of the different white mica generations is not concise in line 140-142.
Observations in this particular sentence can be referred to figure 5b and the figure caption in the resubmitted manuscript.

The concluding sentence in line 145-146 need evidence.
The sentence is restructured in the resubmitted manuscript with added details to the P-T estimation such as literatures used to calculate the estimated values.

Sample number is needed in Figure 5 caption.
This is corrected in the revised manuscript.

Further specification is needed in describing the “non-end member” garnet in line 154-155.
This sentence is restructured in the revised manuscript, further information is provided in the supplementary material.

Further specification is needed in differentiate between two iron ions in composition calculation in line 155-156, and data is to be supplied.
The sentence is reformatted to avoid confusion in the resubmitted manuscript.

Words that are ‘interpretations’ should be corrected to words that ‘present’ the result in line 156-157.
The sentence is corrected accordingly in the revised manuscript.

Replace “shear zone operation” by “shearing” in line 161-162.
This is corrected in the revised manuscript.

Rephrase line 162-163 to include argument for more intense deformation mentioned in text.
The sentence is rephrased.

Data presented in figure 6c needs further specification on statistical details
The error bars are initially omitted in the figure to avoid confusion as some data points cluster tightly together. This figure remains as it is in the resubmitted manuscript but raw data collected from the EPMA analysis is included in the supplementary material.

A change of line spacing in line 170
This is corrected in the revised manuscript.

The reviewer think it is unnecessary to highlight the idea of “non-endmember garnet” in line 171-172 as most garnets are mixed crystals.
This is corrected in the revised manuscript.

The reviewer thinks the differentiation between these two groups is not convincing in line 180-181. And ask for reference to the barometer used.
We acknowledge the reviewer’s suggestion. The sentence is re-structured in the resubmitted manuscript. References of the used barometer are added so the equations used for calculating the result can be traced back to the literature.

The structural unit and sample name of the sample is missing in figure 7
The suggested details are added to the figure caption.

Line 190-192 should be shifted to section 2 to describe observation in a more systematic way.
The sentence is restructured in the revised manuscript.

The phrase “Thin-section parallel to the stretching lineation” in line 194 needs clarification and should be added to the figure caption of figure 7.

The sentence is revised in the revised manuscript.

The reviewer suggests the connection of “quartz filled cracks created by crustal stretching” in line 196 is an interpretation that should go into the discussion.
This suggestion is considered when reformulating the resubmitted manuscript accordingly.

Section 4

Reviewer suggests checking the validity of the apparent Late Cretaceous Ar/Ar ages by the isotope inversion.
This has been done and the process and logic involve is presented along with the York plots in the supplementary material of the resubmitted manuscript.

Correct a typo in figure 7(a).
This is corrected in the revised manuscript.

The reviewer suggests referring line 209-210 to the supplement with Analytical details for 40Ar/39Ar dating.
Such linkage has been made in the resubmitted manuscript.

The reviewer suggests reformatting line 210-211 to be more explicit.
The sentence is revised in the resubmitted manuscript.

The reviewer suggests adding details on sample preparation as artificial small grains might be resulted when reducing a rock sample to grains in line 220.
The sentence is revised in the resubmitted manuscript. More details and reasoning in methodology selection is provided in the supplementary material.

Description of argon geochronology result in line 223- 224 needs to be similar to what described in the microstructure analysis.
Argon geochronology result producing different age clusters are linked to various observed microstructures in the resubmitted manuscript.

The reviewer suggests referring line 227-229 to the corresponding figure.
The corresponding figure to the data presented in line 227-229 is presented in the supplementary material. Connection is made between the text and the supplementary material in the resubmitted manuscript.

No explanation on “N.A” in Table 2.
This is corrected in the revised manuscript.

A word is missing in line 234-235.
This is corrected in the revised manuscript.

The reviewer suggests mention that the spectra in figure 9 are from a previous paper (Forster and Lister, 2009).
This is corrected in the revised manuscript.

Correct “ourtcrops” in line 253.
This is corrected in the revised manuscript.

The reviewer suggests reformulating "potassium feldspar was replaced by metamorphic and/or metasomatic events at those times" in line 274-275.
The sentence is modified in the revised manuscript.

Section 5

The reviewer suggests replacing "K-feldspar concentrate" in line 283 with "K- feldspar grain sample"
This is corrected in the revised manuscript.

A reference for the Gondwanan affinity is missing in line 300-301.
The sentence is revised in the revised manuscript.

The reviewer commented that: Most data are rather low-pressure, meaning T-dominated metamorphism' to lines 301-307.
Additional information is added to ensure clear presentation in this part of the resubmitted manuscript.

Title of table 2 is misleading.
The table title is revised with respect to this comment.

Reference is missing in line 326-328
This is corrected in the revised manuscript

Change "Tripoliz" to "Tripolitza" in line 362.
This is corrected in the revised manuscript

The reviewer suggests revising line 364 as there is no formal Middle Oligocene in the International Stratigraphic Chart.
This is corrected in the revised manuscript.

The reviewer thinks the relation to eastern Alps as presented in line 365 is unlikely.
As this statement is listed as unresolved issues in this paper. We think it is worth noting such correlation when one is looking at the tectonic setting of this region (e.g., the extent of the Asteroussia terrane as reconstructed by Van Hinsbergen et al., 2020). The nature of the late Cretaceous event in the Eastern Alps is not discussed in that Greater Adria reconstruction paper. Yet, the idea has been presented and we therefore include it in the "unresolved issues" section in the resubmitted manuscript.

References and supplementary material

Incomplete referencing in line 488-489, line 535
This is corrected in the revised manuscript.

Omit "IF" in line 547
This is corrected in the revised manuscript.

Reference to the Flux monitor GA1550 (Spell & Mc-Dougall, 2003) is missing in the supplementary material.
This is corrected in the revised manuscript.

The reviewer cannot open data tables in the Supplementary Material.
The data tables are included and accessible in the supplementary material.

Evidence for and significance of the Late Cretaceous Asteroussia event in the Gondwanan Ios basement terranes

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Abstract. The Late Cretaceous Asteroussia event as recorded in the Cyclades is a potential key to the tectonic evolution of Western Tethys. Microstructural analysis and $^{40}Ar/^{39}Ar$ geochronology on garnet-mica schists and the underlying granitoid basement terrane on the island of Ios demonstrates evidence of a Late Cretaceous high pressure, medium temperature (HP–MT) metamorphic event. This suggests that the Asteroussia crystalline nappe on Crete extended northward to include these Gondwanan tectonic slices. In this case, the northern part of the Asteroussia nappe (on Ios) is overlain by the terrane stack defined by the individual slices of the Cycladic Eclogite-Blueschist Unit, whereas in the south (in Crete) the Asteroussia slices are near the top of a nappe stack defined by the individual tectonic units of the external Hellenides. This geometry implies that accretion of the Ios basement terrane involved a significant leap of the subduction megathrust (250-300 km) southward. Accretion needs to have commenced at or about ~38 Ma, when the already partially exhumed slices of the Cycladic Eclogite-Blueschist Unit began to thrust over the Ios basement. By ~35-34 Ma, the subduction jump had been accomplished, and renewed rollback began the extreme extension that led to the exhumation of the Ios metamorphic core complex.

1 Introduction

A terrane stack accreted on the northern edge of the Tethys Ocean during the episodic closure of this ocean basin. Several of these tectonic slices now outcrop on the island of Ios, in the Cyclades, Greece (e.g., Durr et al., 1978; Andriessen et al., 1986; Forster & Lister, 1999a, b; Ring et al., 2007; Forster & Lister, 2009). Tectonic slices in the Cycladic Blueschist Unit were subject to high pressure metamorphism, and later juxtaposed against tectonic slices of Hercynian continental basement. How this juxtaposition occurred remains controversial (Ring et al., 2007; Huet et al., 2009; Forster and Lister, 2009, and references

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therein). One of the competing hypotheses is that a succession of tectonic mode switches took place, with episodes of crustal shortening prior to each of a succession of accretion events. Each accretion event appears to have been followed by an episode of crustal extension (Forster and Lister 2009). Extension following the accretion events that occurred later in this history caused core complex formation, including the formation of the first-recognised Aegean metamorphic core complexes (Lister et al. 1984). The hypothesis that is the main contender as an opposing point of view is that this did not occur, and the Cycladic Blueschist Unit continually extruded during the long history of Alpine convergence (in the so-called orogenic phase, Huet et al., 2009). However, Forster and Lister (2009) unequivocally demonstrate that a discrete succession of exhumation events juxtaposed the Hercynian granitoid basement (identified as the Ios basement terrane in this paper) against the overlying Cycladic eclogite-blueschist slices, so this hypothesis (at least in its present form) is not tenable. Either, the Cycladic Blueschist Unit must have been earlier over-thrust (at ~38 Ma, Forster and Lister, 2009), and largely eroded: or, alternatively, at about ~38 Ma, the Ios basement terranes must have begun to subduct beneath an already largely-exhumed Cycladic Blueschist Unit. In this case, subduction must have continued until these Gondwanan terranes were accreted at ~35 Ma. Their subsequent crustal extension involved a succession of extensional ductile shear zones and later-formed detachment faults.

Dispute arises in part because insufficient information is available as to the details of the timing and thermal evolution of individual rock units, in particular those in the Ios basement terranes that are the focus of this paper. In the extrusion model the Ios basement terranes are over-ridden as the result of thrust-induced extrusion, with deep crustal materials extruded above thrust faults that operated under continuous plate convergence, with little to no horizontal stretching (Ring et al., 2007; Huet et al., 2009). In the tectonic mode switching model, a tectonic shuffle zone must have been created in the upper levels of the Ios basement terranes, and this must have been later truncated during detachment faulting. Multiple shuffling events are implied by the several switches between horizontal shortening and horizontal stretching triggered by roll back (Lister et al., 2001; Forster and Lister, 2009; Forster et al., 2020). The marked contrast in the detail required by these competing hypotheses makes it evident that a significant knowledge gap exists in understanding the succession of discrete deformation and metamorphism events in the upper structural levels of the Ios basement terranes, in particular those that occurred prior to Alpine deformation

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and separately those that occurred prior to exhumation of the Ios basement terrane (Forster and Lister, 2009; Lister and Forster 2016; Yeung, 2019; Forster et al., 2020). This research project was undertaken, in order to begin to remedy this deficiency.

Early workers assumed that, prior to Alpine time, the Ios basement was affected only by Hercynian deformation and metamorphism, based on age data from hornblende and zircon (Andriessen et al., 1987). However, white mica deformation fabrics in the Ios augengneiss core consistently yield $^{40}Ar/^{39}Ar$ ages of ~70-80 Ma (Forster and Lister, 2009). This led us to investigate the possibility that the Ios basement terrane that was made up of garnet-mica schist and augengneiss could be part of the Asteroussia nappe (c.f. Be'eri-Shlevin et al., 2009). Previous interpretation of such age data (e.g., Andriessen et al., 1987, Baldwin and Lister, 1998) considered only the effects of 'excess argon' or 'mixing' and suggested that the apparent Late Cretaceous ages were the result of the Hercynian (~ 300 Ma) argon population mixing with Cenozoic (~ 50 Ma or younger) gas population. However, if this was the case, precisely defined Frequently Measured Ages (FMAs) would not exist in age probability plots. Therefore we were led to consider that the 70–80 Ma date reported in the structurally deepest augengneiss of the Ios lower plate was in fact the characteristic age of the 'Asteroussia event'.

To progress, we need to demonstrate that the effects of such an event can be distinguished in the complex history of deformation and metamorphism (and fluid alteration) experienced by these rocks. Therefore, we re-examined outcrops in the north-west corner of the basement terranes on Ios, in an attempt to determine the significance of the previously reported 70-80 Ma ages. We combined a field study with microstructural analysis and $^{40}Ar/^{39}Ar$ geochronology to address: i) the character and location of micro-deformation structures with late Cretaceous age; and ii) the time relations between various metamorphic and deformation events. Our study identified relicts of earlier fabrics in low strain zones that 'survived' later shear zone operation. $^{40}Ar/^{39}Ar$ geochronology on these fabrics demonstrate Late Cretaceous high-pressure metamorphism, specifically with the growth of phengitic mica in the augengneiss terrane and the overlying garnet-mica schist. The high retentivity of argon in phengitic white mica (Forster and Lister, 2014) allowed these ages to survive the thermal effects of the later Alpine history.

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2 The Asteroussia Nappe

Late Cretaceous-aged metamorphic events were first reported from small klippen outcropped near the Asteroussia mountains in Crete, and later in various Cycladic islands (e.g., Be'eri-Shlevin et al., 2009; Dürr et al., 1978; Seidel et al., 1976). This unit is identified as the Asteroussia nappe, positioned near or at the top of the Aegean terrane stack (except where klippen of Cycladic blueschist occurred above the unit), and reflects the imprint of metamorphism in the time range 70–80 Ma (Bonneau, 1972; Bonneau, 1984). The newly defined terrane was to be characterised as having Cretaceous high-temperature low-pressure (HT-LP) metamorphic assemblages associated with granitoid intrusions with peak metamorphic conditions in the Late Cretaceous, at ~70 Ma (Dürr et al., 1978; Langosch et al., 2000; Patzak et al., 1994; Seidel et al., 1976). Table 2 shows data from other researchers who then reported Late Cretaceous ages in outcrops occurring as small klippen on various Cycladic islands (Tinos, Andros, Syros, Donoussa, Ikaria, Nikouria and Anafi) as well as in further outcrops on Crete (Avigad and Garfunkel, 1989; Be'eri-Shlevin et al., 2009; Bröcker and Franz, 2006; Dürr et al., 1978; Langosch et al., 2000; Patzak et al., 1994; Seidel et al., 1976). In turn this led Be'eri-Shlevin et al. (2009) to note that although published Rb-Sr dates on amphiboles from the Asteroussia nappe range from ~45–85 Ma, the dates cluster at ~70 Ma. These authors therefore extended the areal extent of the Asteroussia nappe to cover a north-south distance of ~300 km (Fig. 1).

The geometry of the Asteroussia nappe is complex, however, with notable local variations when comparing examples from Crete with examples in the northern Aegean Sea. For instance, on Crete a Late Cretaceous event was reported in metapelites which correlates in age with the complex upper unit of the terrane stack in some areas of the Cyclades (Avigad and Garfunkel, 1989; Be'eri-Shlevin et al., 2009; Bröcker and Franz, 1998; Bröcker and Franz, 2006; Pe-Piper and Photiades, 2006). However, the Asteroussia outcrops in Crete are small tectonic klippen (up to 10-15 km wide) with poor lithological and structural correlations (Dürr et al., 1978; Seidel et al., 1976; Seidel et al., 1981). In contrast, in the Cyclades, island-scale structural models involve two to four tectonic slices, and there are reasonable correlations that can be made across the entire archipelago. Nevertheless, some examples in the Cyclades involve meta-ophiolites and mélange zones that first underwent blueschist facies, and then were overprinted by retrograde greenschist facies metamorphism. In other cases, Asteroussia klippen overlie high-pressure metamorphic rocks from the Cycladic Blueschist Unit (e.g., Avigad and Garfunkel, 1989; Be'eri-Shlevin et al., 2009; Bröcker and Franz, 1998; Bröcker and Franz, 2006; Pe-Piper and Photiades, 2006; Ring et al., 2003). Ios stands out in that the Asteroussia ages have been obtained from the lowermost structural slices in the terrane stack, with clear proof that these are Gondwanan in their affinity (Keay and Lister, 1998). Hence, although we agree with Be'eri-Shlevin et al. (2009) that the different Cycladic outcrops in the north (Andros, Tinos, Syros, Ikaria) and in the south (Ikaria, Donoussa, Nikouria, Anafi) are

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part of an extensive Asteroussia nappe that once extended northward from Crete, this observation requires the Asteroussia nappe in its entirety to have been Gondwanan in its origin. Tectonic shuffling involving large horizontal relative motions is well capable of explaining the observed complexity, but only if the terrane was first accreted in its entirety while subject to out-of-sequence thrusting and then affected by extreme crustal extension.

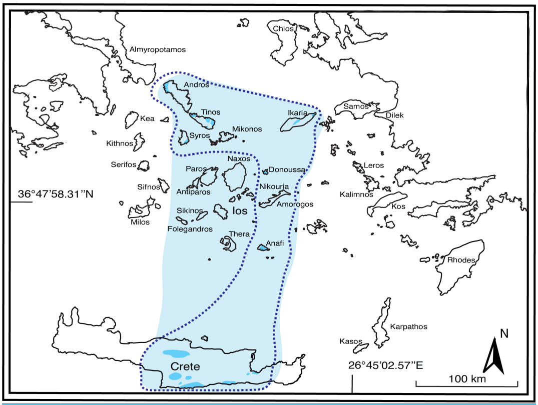

Figure 1: Map of the Cyclades and Crete, dotted line illustrates published extent of the Asteroussia nappe; area enclosed with the dashed line includes outcrop localities with late Cretaceous age (with information retrieved from Be'eri-Shlevin et al., 2009). The area shaded in light blue is the revised areal extent of the Asteroussia nappe suggested in this paper.

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Van Der Maar, 1979	Vandenberg and Lister, 1994	Forster and Lister, 2009	Correlation of TSDs developed in this study
Pre-Hercynian granite bodies intrusion	S_0 layering	TSDs for earlier events not recorded	granitoid intrusion
M_0 Pre-Alpine Hercynian amphibolite facies ~295-305 Ma	D_1 deformation event: relicts of deformation preserved as S_1 microlithons in S_2		S_s//S_{LL} S_g//S_{LL} Δgrt (large porphyroblast) Δbt (wrapping grt)
			S_{diff} (S_{cren})
			Vein qtz (//S_{LL}) Alteration Δrt Δwm Δpy Δhem
M_1 Eocene HP–MT eclogite-blueschist facies ~ 42-59 Ma	D_2 folding event (crustal shortening) formation of F_2 folds with: - S_2 axial plane cleavages - N-S oriented L_2 lineation	Δ_{1B} growth event in eclogite-blueschist unit (EBU), 52-53 Ma, omphacite + jadeite	porphyroblast growth event Δgrt (large porphyroclast)
		post Δ_{1B} SZ operation, 49-53 Ma	
		F_R (recumbent folding)	F_R S_{ps} F_U (refolding)
		Δ_{1C} porphyroblastic event in EBU, 43-45 Ma, epidote+glaucophane+garnet+mica	porphyroblast growth event Δgrt (invading foam textures in quartz aggregates)
		post Δ_{1C} SZ operation, 40-44 Ma	D_{SZ} Δwm (recrystallised fabric)
	D_3 recumbent folding event (crustal shortening)	F_R	F_U S_{ps}
M_2 Oligo–Miocene greenschist facies ~ 25-16 Ma	formation of F_3 folds which: - folded S_2 and L_2, - develops S_3 differentiation crenulation in axial zone	Δ_{1D} porphyroblastic event in EBU, 34-35 Ma, transitional blueschist-greenschist facies biotite+garnet+mica	Δgrt light core of smaller, zoned porphyroblasts Δgrt dark rim of smaller, zoned porphyroblasts
	D_4 SCSZ operation (crustal extension) forms N-S oriented S_4 lineations	post Δ_{1D} SCSZ operation, 35-30 Ma	> SZ (top-S) >> D_{SCSZ} (south-directed) R (rotation of porphyroclasts) Δwm (recrystallised fabric) (S-C' plane fabrics) Δqtz (mantle)
M_3 Late Miocene Granitoid intrusion (LP-HT contact metamorphism) ~ 22-10 Ma			$F_{reclined}$
			F_I (defined by qtz vein) F_U (fold limbs recognised as boudinage) S_{ps}
		intense North-sense SZ operation, 25-29 Ma, rapid extension ~ 25 Ma with Δ_{2A} and Δ_{2B} mineral growth event under greenschist facies	> SZ (top-N) >> D_{NCSZ} (north-directed) Δqtz (porphyroblast) Δwm (recrystallisation) R Δqtz (mantle)
	D_5 Late stage warping	fluid activities	Pegmatite intrusion
	formation of F_5 folds with S_5 axial planar fabrics	hydrothermal sericite growth over K-spar	$D_{normal\ faulting}$

Figure 2: Correlations between the results of previous work and the Tectonic Sequence Diagrams (TSDs) developed in this paper. The results imply that parts of the garnet-mica schist have been shared some parts of history of high-pressure/low-temperature metamorphism as occurred in the lowermost schist units of the Cycladic Blueschist Unit.

2.2 The Asteroussia event on Ios

The terrane stack outcropping on Ios involves thin tectonic slices separated by island-scale deformation structures such as detachment faults and/ or ductile shear zones (e.g., Forster and Lister, 2009; Forster et al., 2020). All terranes experienced Early Oligocene stretching (Fig. 2) and were variably affected by the south-directed South Cyclades Shear Zone (SCSZ, D_2 in other publications) (e.g., Forster and Lister 1999a, b; Forster and Lister, 2009; Forster et al., 2020; Huet et al., 2009; Huet et al., 2011; Ring et al., 2007). An Eocene-Oligocene high-pressure terrane (the Cycladic blueschist unit, upper plate of the Ios Detachment) overlies the Gondwanan Ios basement terrane. There are three tectonic slices in the basement, each recording slightly different metamorphic histories (refer to maps in supplementary materials). The top-most Port Beach tectonic slice contains two lithologies (garnet-mica schist above augengneiss) and lies immediately beneath the Ios detachment (Forster and Lister 1999a). Beneath this tectonic slice is the ~500-meter-thick garnet-mica schist unit (of variable thickness across the island) at mid-structural level and the structurally deepest augengneiss core of the Ios metamorphic core complex (e.g., Andriessen et al., 1987; Baldwin and Lister, 1998; Forster and Lister, 2009; Vandenberg and Lister, 1996).

Figure 1 shows the areal extent of the Asteroussia terrane based on Be'eri-Shlevin et al. (2009), with the shaded area indicating the revised extent according to what we report in this paper. Importantly, this study recognises the exhumed Asteroussia terrane north of Crete, in the Ios basement terrane across the terrane stack, which enabled the identification of a subduction jump that is impossible without a tectonic mode switch. If correct, this is a significant modification implying a widespread metamorphic event in northern Tethys during Late Cretaceous time, including most of the Cycladic islands as reported in this paper and across the Mediterranean region (Altherr et al., 1994; Be'eri-Shlevin et al., 2009; Langosch et al., 2000). Moreover, if the extent of the basement terrane is as large as indicated in Figure 1, its accretion to the modern terrane-stack in latest Eocene time implies a southward jump of the subduction zone megathrust exceeding 250–300 km (Figs. 3 and 4). Potentially these terranes were autochthonous, with their final accretion involving a period of flat slab subduction followed by the initiation of a new subduction zone (Figs. 4c-d). Subsequent rollback can then stretch the Cycladic crust, explaining the variation in crustal thickness from ~32 km thick beneath the Cyclades, to 18 km beneath the Sea of Crete, and ~ 30 km beneath Crete (based on Makris and Vees, 1976 and Makris et al., 2001). Moreover, the subduction jump is able to explain the formation of core complexes during extreme extension caused by rollback after accretion, and the later Oligocene-Miocene magmatic event that is observed across the Cyclades.

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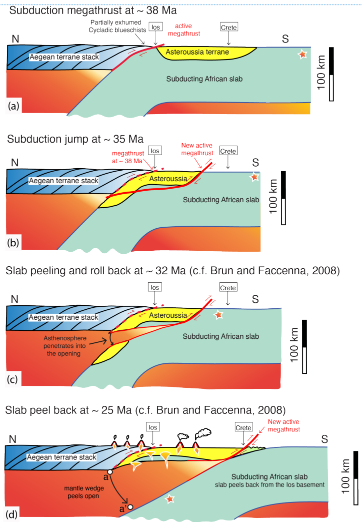

Figure 3: Schematic cross-sections illustrating the slab peel model. The orange star illustrates the relative movement of subducting material across time: (a) the Gondwanan Asteroussia terrane arrives at the subduction zone; (b) as it accretes to the terrane stack, the Asteroussia terrane underplates the youngest slice of the terrane stack; (c) the subduction megathrust jumps ~300 km southward, slicing the Asteroussia terrane from the subducting African slab, while subduction goes on and the slab continues to peel away from the 'buoyant' Asteroussia terrane. Asthenosphere penetrates to the dilating megathrust (d) while the subducting African slab continues to roll back and the break widens. Melting of the uplifting asthenosphere causes extensive magmatism.

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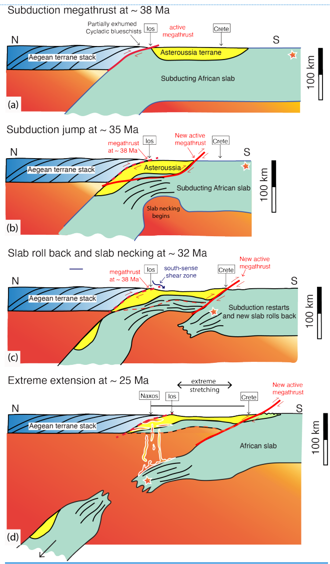

Figure 4: The slab necking-drop off model proposed in this paper: (a) the Asteroussia terrane arrives at the Aegean terrane stack; b) the subduction zone jams, so the megathrust leaps southward while the African slab begins to neck and roll back; (c) by ~ 32 Ma the subduction jump is accomplished, breaking the stretching slab; (d) a new subduction zone develops in the south, with fluids rising from the slab causing melting. Rollback of the new formed slab triggers extreme extension across the Aegean, exhuming metamorphic rocks and forming the Ios metamorphic core complex.

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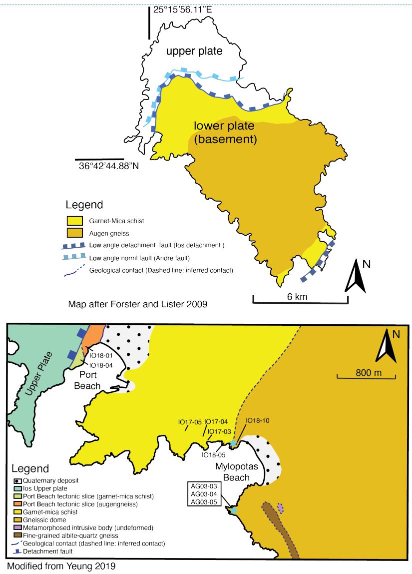

Figure 5: Top: island-scale map illustrating major lithologies. Bottom: Detailed map of study area with sample collection sites, the entire area is affected by the broad, south-directed South Cyclades Shear Zone (SCSZ). Locations observed with overprinting narrow, north-directed shear zones are indicated by blue stars, diagrams after Yeung (2019). Detailed structural maps in supplementary materials.

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3 Microstructural and mineral chemistry analyses across three tectonic slices in the Ios basement terrane

Seven samples were selected (Table 1). The augengneiss (IO18-01) was collected from the structurally shallowest Port Beach tectonic slice, which has a pervasive south-directed shear fabric, with many intensive S-directed shear bands. Four samples were collected (IO17-03, IO17-05, IO17-04, IO18-05) from the deformed garnet-mica schist that underplates the Port Beach tectonic slice, each collected from different depth of this structurally mid-level tectonic slice, which preserves different stages of the South Cyclades Shear Zone (SCSZ) operation. Two samples (AG03-03, AG03-05) were examined from the upper levels of the structurally lowest unit, the augengneiss core. Results from these samples were first reported by Forster and Lister (2009) but were re-examined to establish the association between microstructure and their Late Cretaceous ~ 70-80 Ma ages.

Previous structural studies in the Ios basement generally did not recognize the presence of high-pressure rocks in the Ios basement and its tectonic history is generally identified as the M_0 event (Vandenberg and Lister, 1996; Baldwin and Lister, 1998; Forster and Lister, 1999b, etc.). However, the history of deformation and metamorphism in these rocks is more complex than such simple notations imply. Therefore we applied the method of tectonic sequence diagrams (TSDs) presented in Forster and Lister (2008) and Forster et al. (2020) to document the effects of the succession of pre-Alpine to Oligocene metamorphic episodes that can be observed (Fig. 2). The sequence of metamorphic mineral growth and deformation events is consistent from place to place throughout the entire shear zone carapace of the exhumed Ios basement, with the order of mineral growth episodes tied to different fabrics produced during ductile shear zone operation and/or pure shear ductile stretching of the rock mass. Figure 2 compares the results of this analysis with the traditional D_1, D_2,…D_n method. The detail of relative time constraints could be accurately delineated using these TSDs.

TSDs tie metamorphic evolution to the sequence of fabric-forming events and to the processes that took place during the microstructural evolution, and are therefore critical in enabling the link between the results of $^{40}Ar/^{39}Ar$ geochronology to the detail of microstructural observations. We were able to link dates to specific deformation fabric and mineral growth events, and thus demonstrate that some of these relict fabrics preserved remnant microstructures from earlier pre-Alpine deformation

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events. The effects of a high-pressure late Cretaceous event are evident in these relict fabrics in the Ios basement, so we conclude that the pre-Alpine tectonic history prior to accretion is more complicated than a single event would allow.

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Figure 4: Comparision between conventional structural geology numbering system and the Tectonic Sequence Diagrams (TSDs) for the ability to record deformation events in detail. Usage of TSDs in documenting micro-tectonic events and structures provided a flexible framework for the addition of new observations and easy comparison to observation from another locality.¶

TABLE 1 – LIST OF SAMPLES

Sample	Rock type and mineralogy	Sample location Lat (°N)	Sample location Long (°E)	Deformation structure analysed	Ages
Port Beach tectonic slice (structurally highest in Ios lower plate)					
IO18-01	augengneiss: quartz±garnet±potassium feldspar ±hornblende± white mica±biotite	36°42.9'N	25°17.2'N	First generation (pre-shear zone operation) white mica as porphyroclasts in matrix	192 ± 1.3 Ma 188 ± 1.0 Ma 84.2 ± 2.3 Ma
				K-feldspar crystals in groundmass	592 ± 8.7 Ma 166 ± 2.8 Ma 39.8 ± 3.5 Ma
Mylopotas tectonic slice (structurally mid-level in Ios lower plate)					
IO17-03*	garnet-mica schist: Quartz±garnet±biotite±rutile ± white mica±potassium feldspar	36°42.9'N	25°17.2'E	White mica from south-directed shear zone deformation fabrics	76.9 ± 0.7 Ma 36.0 ± 0.5 Ma
IO17-04	garnet-mica schist: Quartz±garnet±hornblende±biotite ±potassium feldspar±white mica	36°42.9'N	25°17.2'E	White mica from south-directed shear zone deformation fabrics	163 ± 1.0 Ma 174 ± 1.1 Ma
IO17-05*†	garnet-mica schist: Quartz±hornblende±garnet±biotite ±potassium feldspar±white mica	36°42.9'N	25°17.2'E	White mica from south-directed shear zone deformation fabrics	81.0 ± 0.6 Ma 58.8 ± 1.5 Ma
IO18-05 †	garnet-mica schist: Quartz±garnet±biotite±rutile ± white mica±potassium feldspar	36°42.5'N	25°17.2'E	White mica from south-directed shear zone deformation fabrics, sample represents the structurally lowest level of this tectonic unit	50.7 ± 0.4 Ma 43.8 ± 1.1 Ma
Augengneiss basement (structurally lowest in Ios lower plate)					
AG03-03	Re-analysis on Ar/Ar geochronology data produced and published in Forster and Lister, 2009.	36°42.2'N	25°17.2'E	White mica from south-directed shear zone fabrics overprinted by north-directed shear zone	73.9 ± 0.6 Ma 70.4 ± 0.8 Ma
				Groundmass and porphyroclast k-feldspar grains subjected to deformation by two shear zones	84.8 ± 0.7 Ma ~ 13 ± 0.1 Ma
AG03-05	augengneiss: Quartz± biotite± hornblende± white mica±potassium feldspar	36°42.2'N	25°17.3'E	White mica from south-directed shear zone fabrics overprinted by north-directed shear zone	72 ± 0.6 Ma 68.3 ± 0.3 Ma

Samples stored in collections of the Structure Tectonics Team, Research School of Earth Sciences, Australian National University, Canberra, 2601 Australia

* Rock sample preserved evidences of eclogite facies after the first (deformation) fabric

† The younger age from the less retentive argon diffusion domain in the grain analyzed is comparable with the Δ_{1B} eclogite event in Syros

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3.1 Port Beach tectonic slice: the structurally shallowest level

The Port Beach tectonic slice just beneath the Ios detachment represents the structurally shallowest level of the Ios basement terrane and is made up of two lithological units: a thin slice of structurally above garnet-mica schist and the underplating augengneiss with quartz porphyroclasts. Both units preserved numerous recumbently folded veins, isoclinal folds and boudinage structures overprinted by the south-directed SCSZ. A section of altered, greenschist facies garnet-mica schist with chloritoid replacing garnets was observed in the garnet-mica schist tectonic slice near the tectonic contact between Ios upper and lower plate. Beneath the altered zone, garnet porphyroblasts in the garnet-mica schist overgrew a pervasive white mica fabrics, and were rotated to form and δ-type clasts during SCSZ operation (Fig. 6a, cf Passchier and Simpson, 1986).

Two generations of white mica were observed in this unit, including pre-mylonite porphyroblasts (now present as muscovite fish with dynamically recrystallised rims) and the younger, recrystallised phengite (separated into wm2 and wm3 based on their overprinting relations) that intergrew with dynamically recrystallised K-feldspar and quartz (Fig. 6b). Silicate content of the phengite deformation fabric is ~3.40–3.45 Si a.p.f.u. (Fig. 6c). This, along with the mineral assemblage of quartz ± garnet ± potassium feldspar ± hornblende ± white mica (phengite) ± biotite, suggests P-T conditions of 1.8–2.2 GPa and 500-600°C based on calculations in Massonne and Schreyer (1987), Patrick (1995) Velde (1967) and Kamzolkin et al. (2016). The small garnet blasts are preserved in low-strain zones, particularly adjacent to pull-aparts marked by quartz filled voids (Fig. 6b). Amphibolite facies may have taken place in Hercynian time, but during the Late Cretaceous it appears that the Port Beach tectonic slice was subjected to high-pressure eclogite facies conditions.

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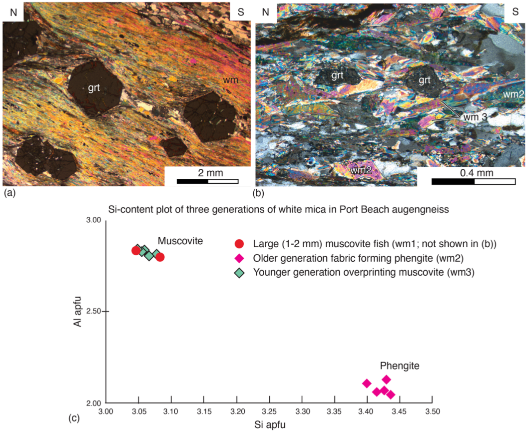

Figure 6: Microstructures analysis in the Port Beach tectonic slice. (a) garnet porphyroblasts with δ-type pressure shadows in the Port Beach garnet-mica schist (IO18-04). (b) two generations of overprinted white mica deformation fabrics, with new-grown (wm3) layer-parallel phengite overprinting the 'lens' shaped (wm2) phengite which has its mineral cleavage oblique to the fabric. (c) the plot of Si-content illustrating the presence of phengite and muscovite in the Port Beach augengneiss (IO18-01).

3.2 The structurally mid-level garnet-mica schist tectonic slice

Field observations in this garnet-mica schist slice and in the top part of the underlying augengneiss core identified evidence for multiple alternating and overprinting deformation events such as recumbent folds overprinted by extensional shear zones. The effects of the (here) N-S striking SCSZ fabric is pervasive, and most of the early fabrics recrystallised during this extensional episode. Nevertheless, relicts of earlier fabric are observed in low strain zones besides large porphyroclasts.

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Samples collected from the structurally deeper level of this tectonic slice in the north Mylopotas headland preserved the most complex mineral growth and micro-deformation history. We note that metabasite was observed sporadically in the augengneiss basement, with mineral assemblages that suggest it was subject to transitional greenschist-blueschist metamorphism during the Δ_{1D} event of Forster et al. (2020). The protolith for such metabasite pockets is likely to have been intermediate-mafic intrusive dykes that folded and deformed with the country rock (see structural maps in the supplementary material). A late-developed, intense north-sense shear zone defines the structural contact between the garnet-mica schist and the augengneiss in this locality. Fluid associated haematite nodes are found in the top three metres of an intense shear zone at the contact between the juxtaposed garnet-mica schist tectonic slices and the augengneiss core.

The four samples presented in Table 1 have garnet porphyroclasts recording multiple mineral growth events and preserved earlier fabrics as inclusions. Sample IO17-03 and IO17-04 retained the earliest formed garnets (some of which are large, exceeding 2–3 cm in diameter). Sample IO17-03, IO17-04 and IO17-05 preserved different stages of micro-tectonic events during SCSZ operation. The larger, first generation (1-2 cm diameter) garnet porphyroblasts are intact in IO17-03, fragmented during shear zone operation in IO17-04 and acting as porphyroclasts during deformation in IO17-05. Relicts of earlier fabrics are preserved in the low strain zone behind garnets in IO17-03 and IO17-04 and are microstructurally distinguishable, whereas fabrics in sample IO17-05 is almost completely reset by the SCSZ. IO18-05 is collected from a fold hinge of a recumbent fold (M_1 folding) that is overprinted by the SCSZ (D_2 crustal stretching), it represents the structurally lowest level of this tectonic slice. Haematite nucleating on the deformation fabric is observed, and relicts of earlier deformation fabrics with rutile are preserved as inclusions in the garnet porphyroblasts.

Mineral chemistries with the three generations of garnet growth recognised in sample IO17-03 are chemically similar to almandine (see supplementary material – electron microprobe analysis (EPMA)) but are iron enriched and calcium depleted with slightly higher magnesium content compared to end-member almandine. Dynamically recrystallized, south-sense white mica fabric wraps around the larger (2–3 cm diameter) garnet porphyroblasts, with second generation garnets growing over this fabric. The two younger garnet growth events are close in time, producing crystals of different size: the 2–3 mm diameter

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crystals with uniform colour and the 5–8 mm diameter garnets have a zoned mineral growth (Figs. 7a-b). Observation on the two types of crystals identify the light red (Ca-depleted, Mn-enriched) garnets as the first growth event, followed by the second growth event producing black (Mn-depleted, Ca-enriched) garnets (Fig. 7c; see supplementary material). Although the later greenschist facies is pervasive across the outcrop, with chlorite overprinting the south-directed white mica deformation fabric, traces of rutile crystals 'floating' in the relicts of earlier (pre-SCSZ) fabric in the low strain zone are preserved in IO17-03 (Fig. 7d). This also implies a higher-pressure history (potentially eclogite facies) than previously recognised.

The earliest microstructure observed was within garnet porphyroblasts, rotated during shear zone operation. This could be inferred from the oblique angle between white mica–rutile inclusions (in IO18-05) and the recrystallised groundmass (Fig. 8a, showing core of a garnet porphyroblast). As the inclusions were fine grained, energy dispersive X-ray spectroscopy (EDS) analysis was used to confirm the presence of rutile in the included fabric. Electron microprobe analysis (EPMA) identified the chemical composition the garnet porphyroblasts (5–8 mm diameter) as between almandine and grossular, nucleated on Al-rich white mica during operation of an early shear zone, and continuing to grow during deformation until they reached Al-depleted, foam-textured quartz in pressure shadows (supplementary material – EPMA analysis results). Upon reaching the foam-textured quartz, the fluids then corroded grain-boundaries, allowing the new-grown garnet to develop a skeletal structure in which the original foam texture in the incorporated quartz grains can still be recognised (Fig. 8b, bottom right corner). Late-stage (first order) grey albite grew in exsolution trails preserved across the garnet porphyroblasts, implying decompression as the garnet porphyroclast fractured during shear zone operation. (Fig. 8b, supplementary material –EPMA analysis results).

Dynamic recrystallisation of white mica (phengite) and quartz in the groundmass of IO17-03 and IO18-05 occurred synchronously during shear zone operation. The Si-content of phengite in sample IO17-03 and IO18-05 suggests that the phengite grew under P-T condition up to 450-500ºC (based on the presence of garnet and biotite) with pressure in the range 0.7–1.7 GPa based on calculations in Massonne and Schreyer (1987), Patrick (1995) Velde (1967) and Kamzolkin et al. (2016) (Fig. 8c). We therefore suggest that the structurally mid-level garnet-mica schist tectonic slice also recorded a complex history of deformation and metamorphism with evidence of high-pressure transitional amphibolite–eclogite facies metamorphism.

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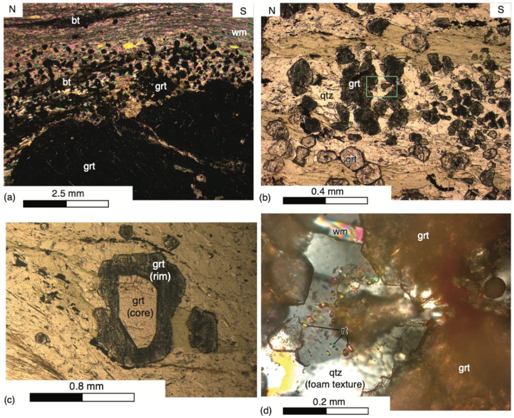

Figure 7: Microstructure analysis in the garnet-mica schist tectonic slice (sample IO17-03). (a) White mica dominated deformation fabric with minor biotite relict of early fabric surrounds large 2–3 cm diameter garnets, with younger 2–3 mm garnets grown on the deformation fabric. (b) Thin section under plane polarized light: two types small, second generation garnets with different chemical compositions are identified (see supplementary material – EPMA analysis results). (c). A slightly larger (~ 4mm diameter) second generation garnet with a zoned crystalline texture. (d) magnified view of the green box in (b), a euhedral second-generation garnet that grew into a quartz foam texture with relict rutile floating in the void space.

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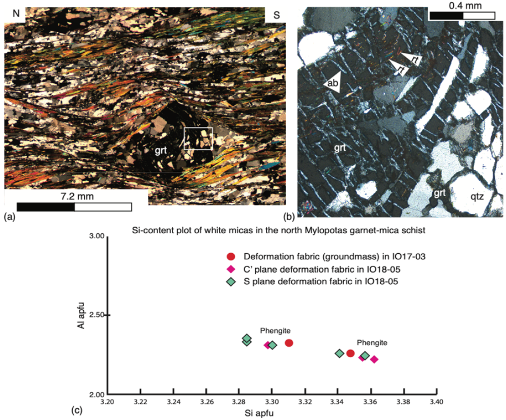

Figure 8: Sample IO18-05, garnet-mica schist collected in the fold hinge of the earliest fold (overprinted by the south-directed shear zone) in the mid-level garnet-mica schist tectonic slice. (a) a garnet porphyroblast preserving relicts of earlier deformation fabrics as inclusions and developed a skeletal structure once it reached the Al-depleted zone. (b) rutile inclusions and albite exsolution trails observed in the garnet porphyroblast. (c) a Si-content plot indicating the presence of two phengite groups in the garnet-mica schist.

3.3 The augengneiss core: the structurally lowest level

The structurally deepest augengneiss core of the Ios basement terrane is characterized by large (0.3-1.0 cm) K-feldspar xenocrysts preserved as porphyroclasts. Rocks in this locality were deformed by the south-directed South Cyclades Shear Zone (SCSZ) then variably overprinted by narrow north-directed shear zones. Occasionally, single hornblende porphyroclasts wrapped by a south-sense white-mica shear fabric could be observed (e.g., Fig. 9a, in a thin-section cut parallel to the stretching lineation). Pre-deformation hornblende was also observed in low-strain zones adjacent to these K-feldspar porphyroclasts (Fig. 9b). K-feldspar porphyroclasts surrounded by dynamically recrystallised white mica and quartz in these sample were fractured

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Three generations of garnet growth are observed in sample IO17-03 where all garnets are non-end-member minerals with chemistries similar to almandine. These non-end-member crystals are low in calcium, significantly high in iron and slightly higher magnesium when compared to end-member almandine. Dynamically recrystallized, south-sense white mica fabric wraps around the larger garnet porphyroblasts, with second generation garnets growing over this fabric. ¶
The 2–3 cm diameter garnets are formed earlier(Fig. 5a, 5b). : younger, 2–3 mm diameter crystals are light red or black (Fig. 5a, 5b). Several younger 5–8 mm diameter garnets have a zoned mineral growth in which the core is light red (Ca depleted, Mn enriched) and the rim is black (Mn depleted, Ca enriched) (Fig. 5c). It is unknown why the garnets are black, with a greenish hue, but some garnet-mica schist out crop preserve chloritoid altered garnets that is blue-green in colour yet retaining the mineral shape and structure of the original garnet in this tectonic unit and the Port Beach tectonic slice above. Dynamically recrystallized, south-sense white mica fabric wraps around the larger garnet porphyroblasts, with second generation garnets growing over this fabric. Traces of rutile crystals 'float' in the foam-textured quartz adjacent to garnet porphyroclasts (Fig. 5d). Microstructures in sample IO17-04 are similar, with first gen ... [42]

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by shearing, with recrystallisation at the edges (Fig. 9b). The youngest microstructures observed in these samples are quartz filled cracks. The augengneiss basement records evidence of recumbent folding during crustal shortening, followed by ductile stretching under a south-directed shear zone. All of this occurred before the augengneiss was juxtaposed against the garnet-mica schist slice by an intense north-directed shear zone.

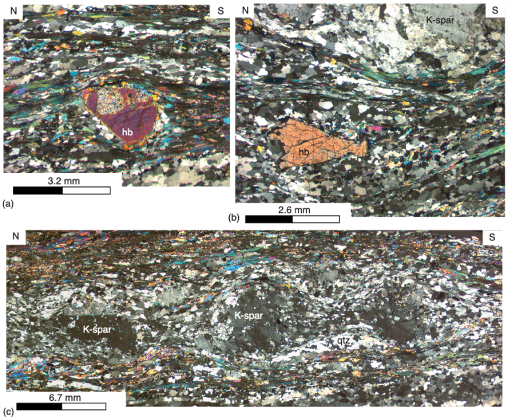

Figure 9: Microstructures analysis on the south Mylopotas headland augengneiss (AG03-03, AG03-04, AG03-05). (a) an older hornblende preserved as large porphyroclasts wrapped by younger, recrystallized white. (b) K-feldspar porphyroclasts with minor recrystallisation limited to their boundaries, and a hornblende xenocryst preserved in a low-strain zone (AG03-04). (c) K-feldspars porphyroclasts overprinted by both the earlier south-directed shear zone and the younger north-directed shear zone, forming 'micro boudinage' structures (AG03-03).

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4 Argon geochronology

To provide time constraints on mineral growth events and deformation observed across the three tectonic slices, new Ar^{40}/Ar^{39} geochronology data was collected using furnace-based step heating experiments conducted under ultra-high vacuum (UHV) conditions. These enabled new data that allowed recognition of Late Cretaceous Asteroussian ages in the garnet-mica schist mid-level unit where relicts of earlier, rutile containing fabrics are preserved. Argon geochronology was performed on white micas from deformation fabrics and on the K-feldspar porphyroclasts, with results summarised in Table 1. White micas with grain sizes ranging from 250μm to 420 μm were used as microstructural analysis identified the relicts of the earliest fabric to be of larger grain sizes compared to the dynamically recrystallised Alpine deformation fabrics (refer to supplementary material on $^{40}Ar/^{39}Ar$ analytical technique). No new analysis is performed on the two augengneiss samples AG03-03 and AG03-05 collected at the augengneiss core but the data previously published by Forster and Lister (2009) was re-examined in order to link microstructures observed with the reported Late Cretaceous dates.

The age spectra produced varied in their character depending on the structural character and rock type. For example, the morphologies of the argon spectra obtained from the garnet-mica schist are different and distinct in comparison with those obtained from the augengneiss. The phengitic white micas from the thick garnet-mica schist slice produced spectra with a characteristic 'hump-shaped' partial plateau, whereas age spectra from phengitic white mica in the underlying augengneiss generally produced spectra with a partial plateau rising to a peak in the final heating steps. The Late Cretaceous Asteroussia ages are always preserved in phengitic white mica, and since this appears to be highly retentive of radiogenic argon, these are likely to be growth ages and hence key to identifying older Asteroussian fabrics overprinted by younger Alpine events. Previous research suggested that the later-formed shear zones operated in this area operated in the Argon Partial Retention Zone (Baldwin and Lister, 1998; Forster and Lister, 2009), but this was on the basis that it had been assumed that all the white mica was muscovite, which is not correct. The complex age spectra preserve and record the effect of multiple deformation and metamorphic mineral growth events, but they are preserved only because phengitic white mica (especially under high pressure conditions) is extremely retentive of argon (Lister and Baldwin, 1996; Warren et al., 2012).

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Argon geochronology on white mica and k-feldspar grain separates from the three tectonic slices in the Ios basement terrane yielded age clusters in Early-Middle Jurassic, Late Cretaceous, Eocene–Oligocene and Oligocene–Miocene time (Table 1). However, evidence for Jurassic and Cretaceous ages is exclusively restricted to argon populations retained in phengite, or, in the case of IO18-01, to the large muscovite fish. All white mica analysed yielded Arrhenius plots that unequivocally demonstrate both phengite and muscovite components, e.g., IO17-05 in the garnet-mica schist, and AG03-03 in the augengneiss (Figs. 10-11; see corresponding figures in the supplementary material). The phengitic components produce significantly high activation energy estimates, in the range 103–115 kcal/mol (431–481 kJ/mol) compared to estimates from the muscovite domain, in the range 54–61kcal/mol (226–255 kJ/mol) (Fig. 12; see corresponding figures in the supplementary data). The estimated retentivity of the phengite implies that the ages measured are growth ages, since metamorphic temperatures were less than the inferred closure temperatures from the Arrhenius plots. Therefore, it appears that we have been successful in being able to directly date microstructures produced during the Late Cretaceous Asteroussia event.

The garnet-mica schists that produced the Late Cretaceous Asteroussia ages were collected in the northern headland of the Mylopotas Beach, Ios (Fig. 5). We have already noted that microstructural analysis of the garnet-mica schist IO17-03 and IO17-05 demonstrated multiple episodes of white mica growth. The older grains in the deformation fabric are 180 µm to 450 µm in diameter, whereas the younger grains developed during or after later shear zone operation are elongate with dimensions range 50 µm to 90 µm. Note that the older generation phengitic white micas (355-450 µm grains) were tediously hand-picked for this sample. The $^{40}Ar/^{39}Ar$ results suggest several different gas populations retained in the crystal lattice, with a younger gas population in the less retentive domain and an older gas population in the more retentive domain that dominated gas release. The older argon population accounted for 90% argon released in IO17-03 white mica and created a partial plateau ('hump') with peak minimum age of 76.9 ± 0.7 Ma in the phengitic part of the age spectrum (Fig. 10a; see corresponding figures in supplementary data). The younger gas population that accounts for the 5% of initial argon release comes from muscovite formed later in the geological history, during operation of the SCSZ. However white mica from the relicts of earlier fabrics in IO17-05 preserved an older argon population with peak minimum age of 81 ± 0.6 Ma. A younger gas population in the less

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retentive domain of the earlier white mica fabric in IO17-05 record an age of 59 ± 1.5 Ma, which is comparable with estimates for the timing of the Δ_{1A} and Δ_{1B} Alpine events (Forster et al., 2015; Huet et al., 2009).

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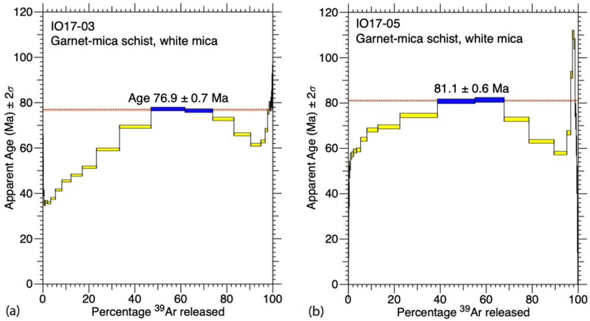

Figure 10: White mica age spectra from the structurally mid-level garnet-mica schist unit (IO17-03, IO17-05) produced Late Cretaceous ages, from mica grown during the Asteroussia event.

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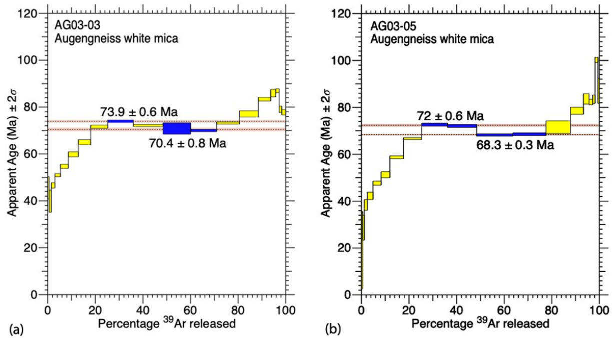

Figure 11: White mica age spectra from the structurally lowest augengneiss core (AG03-03, AG03-05). The complex age spectra are a result of multiple argon populations degassing at different temperature during the step-heating experiment. The augengneiss basement was subjected to multiple deformation events, but a significant argon population is derived from phengite with Late Cretaceous ages preserved. The argon geochronology data was published in Forster and Lister, 2009 and re-analysed in this study.

Samples AG03-03 and AG03-05 were collected from the augengneiss core, and $^{40}Ar/^{39}Ar$ geochronology on isolated white mica deformation fabrics were performed in the study reported in Forster and Lister (2009). The two rocks are microstructurally similar, fabrics underwent minor recrystallisation during south-directed then north-directed shear zone operation. We reanalyzed the diffusion experiment result in this study as white mica grain separates from the two samples produced Late Cretaceous dates (Forster and Lister, 2009). Application of the method of asymptotes and limits on the AG03-03 white mica age spectrum yielded a range of ages from 70.4–74.0 Ma (Fig. 11a) for phengitic white mica (Fig 11a, see corresponding supplementary material). White mica deformation fabrics in augengneiss AG03-05 show an upper limit at 72 ± 0.6 Ma and a lower limit at 68.3 ± 0.3 Ma in gas release of the more retentive domain, representing the minimum and maximum ages of a single Late Cretaceous event respectively (Fig. 11b). The older ages in the age spectra may represent even older relict fabrics.

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From these data it is evident that the structurally mid-level garnet-mica schist and the underlying augengneiss basement were subjected to complex deformation history with multiple events occurring from Early Cretaceous to Miocene time.

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White mica and K-feldspar differ in their $^{40}Ar/^{39}Ar$ systematics and grow and respond differently to deformation. K-feldspar grain separates were collected from all augengneiss samples in an unsuccessful attempt to pinpoint the microstructure(s) responsible for the Late Cretaceous date reported in the white mica. Forster et al. (2014) reported that K-feldspars required analysis with isothermal steps so as to recognise contamination at each temperature increase in the step heating procedure (i.e., isothermal steps being two or more heating steps at the same temperature). The first step is referred as a cleaning step and is not included in the interpretation of the spectrum. This same methodology is used on the K-feldspar analysis in this study.

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In AG03-03, Forster and Lister (2009) observed larger K-feldspars (porphyroclasts; 2000 – 6500 µm) and small K-feldspar grains (500-700 µm) interspersed between aligned white mica grains that recrystallised during later deformation. Step-heating experiments on the K-feldspar grain separates (including both porphyroclasts and small grains) from AG03-03 produced saddle-shaped apparent age spectrum with a lower limit at ~13 ± 0.1 Ma (Fig. 12a). The last argon release steps produced a peak at 84.5 ± 0.8 Ma, comparable to the date obtained from white mica from the same sample (Fig. 11a). The Arrhenius plot of K-feldspar in sample AG03-03 shows two distinct argon diffusion domains (Fig. 12b). This suggests that the K-feldspar in the south Mylopotas augengneiss also preserved complex deformation history, with the oldest (and most retentive domains) regrown during the Late Cretaceous event. The Arrhenius data (Fig. 12b) shows that these older domains were capable of retaining argon at temperatures well above those recorded by the metamorphic assemblages, implying that these are growth ages, requiring the original potassium feldspar to have been replaced during metamorphism and/or metasomatism by this time.

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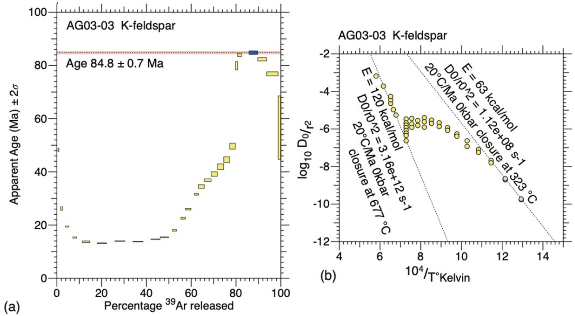

Figure 12: a) a K-feldspar age spectrum from the structurally lowest augengneiss core (with isothermal cleaning steps removed). The origin of the younger part of the age spectrum is discussed by Forster and Lister (2009). The Late Cretaceous age is preserved in the retentive core domains. (b) the corresponding Arrhenius plot shows two diffusion domains with significantly different activation energies.

5 Discussion

5.1 Evidence of the Asteroussia event in the Ios lower plate

Microstructurally, our study has conclusively identified the presence of more retentive phengite in a fabric that was later overprinted by dynamically recrystallized white mica and quartz. The earlier metamorphic fabrics formed under conditions that potentially reached eclogite facies. Our UHV ^{39}Ar diffusion experiments show that this phengite is highly retentive, allowing preservation of the growth ages of the white mica that formed during these earlier events. Thus, despite intense overprinting during Alpine deformation events, the Late Cretaceous argon populations were retained. This is consistent with the concept of an Argon Partial Retention Zone in which mineral grains undergo some partial resetting by diffusion, but where recrystallisation causes the most effects (Baldwin and Lister, 1998). However, the concept of a partial retention zone is appropriate only for systems with single diffusion domains and no variation of activation energy, which is not the case here.

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Identification of the Late Cretaceous age in the Ios lower basement has been interpreted as a result of mixing (e.g., Andriessen et al., 1987); in other words, defining these dates as “intermediate” ages due to excess radiogenic argon or simultaneous degassing of the Alpine mica and the older Hercynian micas. However, here we have shown that these ages represent a period of Late Cretaceous deformation and metamorphism. Therefore, the Ios basement may indeed be part of the Asteroussia terrane. However, pressure-temperature estimates from phengites in the Ios lower plate record high pressure conditions, contrary to what has been observed in Asteroussia klippen across the Cyclades, albeit preserved at different structural levels. This suggests that more than one set of tectonic slices may have preserved the Asteroussian ages, and we have already pointed to the role that tectonic shuffling may play in producing such variation. It is important in this aspect that the Ios data is the first report of Asteroussia ages in a terrane of unmistakeably Gondwanan affinity (Keay and Lister, 2002).

There may be an earlier Hercynian history: the earliest reported argon age in Ios is a single K/Ar hornblende date reported to be post-Hercynian (268 ± 27 Ma) by Andriessen et al. (1987) and Flansburg et al. (2019). However, based on the peak metamorphic P–T conditions documented across the Cyclades, it may be that the Asteroussian terrane slices record a variety of metamorphic pressure conditions (Table 2, and reference therein). Rocks from the basement slices on Ios suggest the occurrence of high pressure–medium temperature conditions based on the microchemistry preserved in relicts of earlier deformation fabrics.

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TABLE 2

PEAK METAMORPHIC CONDITION OF THE ASTEROUSSIA EVENT ACROSS THE CYCLADES

Island	Published studies	Sample details/ methodology	Peak metamorphic condition
Tinos	Patzak et al., 1994	Interlayered amphibolite–paragneiss	650–750 MPa
	(as cited in Be'eri-Shlevin et al., 2009)	sequence	530–610 ºC
		in Akrotiri unit	
Donoussa	Kolodner et al., 1998	P-T estimates on garnet-sillimanite-	Core of garnet
		biotite-quartz assemblage observed in	400–500 MPa
		pelitic rocks.	600–650 ºC
		Distinct chemical zoning of garnets	Rim of garnet
		allowed P-T calculation in core and rim	250–350 MPa
		respectively	550–580 ºC
Anafi	Be'eri-Shlevin 2009	EPMA analyses of garnet–biotite pairs	
		from garnet-biotite paragneiss sample	Core of garnet & biotite
		that occur as thin (1–2 m thick) layers	~720± 50–740± 50 ºC
		within the structurally intermediate	200–600 MPa
		level of the Asteroussia Unit. Garnet–	
		biotite temperatures were calculated	Rims of garnet & biotite
		using the equation of Ferry and Spear	634± 50–650± 50 ºC *
		(1978).	200–600 MPa
	Be'eri-Shlevin 2009 (cont.)	Sample collected from a massive	
		amphibolite exposure in the structurally	

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		intermediate level of the Asteroussia Unit	
		edenite–tremolite (ed–tr) reactions	677–726 ºC 200–600 MPa
		edenite–richterite (ed–ri) reactions	605–643 ºC 200–600 MPa
Crete	Seidel 1981	Peak metamorphism P-T conditions estimated from critical mineral assemblage of the outcrop of a variegated series consisting of: tholeiitic ortho-amphibolites, para-amphibolites, andalusite and sillimanite-cordierite-garnet bearing mica schists, calcsilicate rocks, and marbles.	400–500 MPa maximum temperature ~ 700 ºC
	Anderson and Smith,1995 (as cited in Langosch et al., 2000)	Al-in- hornblende barometer Granodiorites of eastern Crete	100–200 MPa Maximum temperature = 700 °C
		Granites and granodiorites of central Crete	250–400 MPa Maximum temperature = 700 °C

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Crete (cont.)	Koepke and Seidel, 1984 (as cited in Langosch et al., 2000)	Peak metamorphism P-T conditions estimated from metamorphic assemblages of quartz – plagioclase – K-feldspar – sillimanite – biotite – garnet – cordierite in pelitic paragneisses at central Crete	upper amphibolite facies: 400–600 MPa 650–700 °C
	Langosch, 1999 (As cited in Langosch et al., 2000)	Calculated by thermobarometric calibrations of Bhattacharya et al. (1988, 1992), Dwivedi et al. (1998), Koziol and Newton (1988) and Holland and Blundy (1994) Peak metamorphism P-T conditions estimated from metamorphic assemblages of (1) quartz – muscovite – chlorite – garnet – andalusite – plagioclase and	680–730 °C 500–600 MPa
		(2) quartz – muscovite – biotite – staurolite – andalusite – plagioclase observed in metapelites of Asteroussian tectonic slices	lower amphibolite facies: ~ 550 °C 300 MPa

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5.2 Tectonic implications

The nature of the tectonic processes that affected the evolution of the terranes accreted by the Hellenic subduction zone remains controversial, e.g., comparing the papers by Forster and Lister (2009), Forster et al. (2020) to that written by Huet et al. (2009) and Huet et al. (2011). However, the polemic seems misguided. The architecture of Tethyan orogenic belts, the Hellenides included, invariably involves a nappe- or a terrane-stack, and all terrane stacks are created by thrusting. However, most if not all terrane stacks are also modified by later episodes of extension (e.g., as in Forster and Lister, 2009) leading to tectonic shuffling. It is no different in the Cyclades. The Cycladic archipelago preserves the results of the destruction of an extensive terrane-stack that extended from the Hellenides in Greece to the Taurus Mountains in Turkey (Gautier and Brun, 1994a, b; Kempler and Garfunkel, 1994; McKenzie, 1977; Taymaz et al., 1991). The debate as to the nature of exhumation processes will not be resolved by a sole focus on the Cycladic eclogite-blueschist belt, as demonstrated in this paper.

The key questions surround the evolution of the terrane stack overall, rather than the details of the exhumation of an individual tectonic slice. The extrusion wedge (or forcible eduction) model suggests constant compression, resulting in the squeezing of softer material, so that it is extruded to the surface (Forster and Lister, 2008; Xypolias and Koukouvelas, 2001). The competing hypothesis, known as the tectonic mode switch or tectonic shuffle zone model, considers that thrust slices are exhumed by periods of crustal extension that take place in between episodes of crustal shortening caused by individual accretion events (Forster and Lister, 2009). Dispute arises because of the focus on the exhumation of the Cycladic eclogite-blueschist terranes, whereas the continuing nature of the orogenic process means that (without question) the subduction megathrust had to have episodically leapt southward every time a new terrane was accreted (e.g. Lister et al., 2001; Ring et al., 2007; Huet et al., 2009; Forster and Lister, 2009). As the African plate migrated northward, terranes were first subducted, then sliced from the subducting lithosphere by the advancing subduction megathrust, and thus accreted to the terrane stack (e.g., Lister et al.,2001; Lister and Forster, 2009).

For Ios, the question is how rollback of the subducting slab was able to throw the over-riding terrane-stack into horizontal extension immediately after the accretion of the Cycladic blueschist onto the Gondwanan basement from which the

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Asteroussian terranes were derived (Fig. 4), in particular given the requirement thereafter of a massive southwards leap of the outcrop of the active subduction megathrust. Previous work (e.g., Forster et al., 2020) has suggested that the Cycladic blueschist belt had already been largely exhumed before it was thrust over the Ios basement terrane in Late Eocene time (from ~38 Ma, Fig. 4a). A first period of extensional tectonism formed the Ios metamorphic core complex, and this had commenced by ~35 Ma, accelerating by the time of the Eocene–Oligocene transition. A second period of extensional tectonism then ensued, after the Oligocene–Miocene transition, with extreme lithospheric extension triggering a major magmatic event, with intrusions in and through the core of younger metamorphic core complexes across the Cyclades.

The Ios basement has been argued to be autochthonous, moving with Africa, and part of Gondwana (Flansburg et al., 2019; Keay et al., 2001; Keay and Lister, 2002). Its accretion to the terrane stack is therefore likely to have been an event with considerable tectonic significance. The magnitude of the southward leap of the subduction megathrust is thus unlikely to have been accomplished without the development of a new lithosphere-scale structure. There are two end-member options: one requiring that the slab peels free from the subduction megathrust (Fig. 3, using the slab peel hypothesis discussed by Brun and Faccenna, 2008) while the other requires a subduction jump and slab breakoff (Fig. 4, cf. von Blanckenburg and Davies, 1995). Although the slab-peel model is consistent with enhanced heat flow during crustal stretching after the accretion event, such a model requires the asthenosphere to be exhumed to such shallow levels as to require significant partial melting of the uplifting asthenosphere, which would a period of widespread basaltic volcanism, with volumes comparable to those observed in some large igneous provinces. Such effects were not observed in the Cyclades. Sizova et al. (2019) also showed the "peel off" model (Brun and Faccenna, 2008) to be unlikely in the Aegean region.

An alternative model involving slab necking (or boudinage) and break off must therefore be considered (e.g., Fig. 4). This (provisional) three-staged 'slab break off' model more accurate describes Aegean tectonics by addressing how the terrane stack was subjected to overall stretching with some evidence of melting such as plutonic intrusions in the centre of metamorphic core complexes. This model also requires significant magmatism, but in consequence of fluids rising from a devolatising slab which would lead first to crustal magmatism, such as the I-type granite of Ios, and later to the appearance of

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arc volcanoes, as on Thera. Possibly the necking and eventual break off of the subducting slab and formation of a new subduction zone (Fig. 4d) might be of sufficiently small scale to escape observation in models based on P-wave tomography.

5.3 Unresolved issues

We do not understand why the Asteroussia event is recorded in the top-most slices of the terrane stack outcropped in other Cycladic islands, but is found only in the lower slice in Ios. Such architecture implies that the Cycladic eclogite-blueschist tectonics slices are 'sandwiched' between tectonic slices affected by the Asteroussia event, whereas on Crete the Asteroussia units are juxtaposed above the Vatos unit, the Arvi unit, the Pindos unit and the Tripolitza unit (e.g., Bonneau, 1984; Flansburg et al., 2019; Kneuker et al., 2015; Langosch et al., 2000; Martha et al., 2017; Martha et al., 2016, Palamakumbura et al., 2013; Seidel et al., 1976; Zulauf et al., 2002). This must have occurred sometime between mid-Oligocene–early Miocene time. Laterally, the unit is connected to the eastern Alps in the west and the Lycian ophiolite nappes, the Menderes Massif and the Sakarya Zone in Turkey (van Hinsbergen et al., 2020). Further work is required to validate the tectonic-shuffling hypothesis which is capable of explaining these observations.

Some authors suggest that tectonic slices outcropping on islands in the northwest (Andros, Tinos, Syros) are different to those on other islands such as Anafi, Nikoria, Donoussa, Ikaria and Crete (Altherr et al., 1994; Langosch et al., 2000; Martha et al., 2016). Arguments arise due to the difference in dates obtained (despite all being Late Cretaceous) and different results for geothermobarometry across islands with different lithologies and metamorphic facies (Kolodner et al., 1998; Langosch et al., 2000; Patzak et al.,1994; Seidel et al., 1976; Seidel et al.,1981; Yeung, 2019). Research in the upper and middle tectonic units in Tinos produced dates at 90-100 Ma and a peak metamorphic P-T estimate of 120 MPa at 450-500 ^{o}C (Avigad and Garfunkel, 1989; Avigad and Garfunkel, 1991; Bröcker and Franz, 1998; Patzak et al.,1994), whereas studies on Donoussa and Crete produced younger ages at 70-80 Ma and peak metamorphic P-T conditions at 300–600 MPa and 600-730 ^{o}C (Be'eri-Shlevin et al., 2009; Keay and Lister,2002; Kolodner et al., 1998; Langosch et al., 2000; Seidel et al., 1976).

Our study reports metamorphic conditions with higher pressure, despite producing similar dates. Although the presence of phengite is wide-spread across the Ios lower plate, the highest pressures are inferred only in the garnet-mica schist unit and the

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Port Beach tectonic slice. With no evidence of higher pressures in the underlying augengneiss unit, it is possible that a more complex deformation and metamorphic history has been recorded in these intermediate slices in the Ios terrane stack. These observations also reflect on a possible distinction between European and Gondwanan terranes, with evidence mostly preserved in the Alps and in the Pelagonian zone of Greece (Pourteau et al., 2013; Porkoláb et al., 2019; Regis et al., 2014; Thöni, 2006). Brown et al. (2014) reports evidence of Late Cretaceous intracontinental shear zone deformation across Africa, thus demonstrating that the ~70-80 Ma age is not limited to northern Tethys. Detrital zircon (DZ) analysis on pre-plutonic metasedimentary rocks in Ios lower plate by Flansburg et al. (2019) pushes tectono-magmatic histories of the southern Cyclades further in time to early Cenozoic. They noted a striking resemblance between their DZ age spectra from Ios lower plate to exposures on Crete, northern and central Peloponnese, the northern Hellenides and the siliciclastic cover sequence of the Menderes massif in western Turkey (Flansburg et al., 2019). Comparing these Ios DZ age spectra to those from northeast Africa and Arabia, they confirmed that the Cycladic basement terrane (outcropped in Ios lower plate) have a distinct peri-Gondwanan affinity (Flansburg et al., 2019). This led them to propose a tectonic model where the terrane was located along the northern margin of Gondwana in early Paleozoic and experienced pluton emplacement between ~335 and ~305 Ma in an arc setting (Flansburg et al., 2019).

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Tectonic reconstructions by van Hinsbergen et al. (2020) demonstrated that major continental-scale events occurred across Eurasia and Gondwana from Late Jurassic–Late Cretaceous time. These global tectonic events involve continental-scale deformation such as the formation of the Alpine Tethys with microcontinents tearing from the south coast of Europe. In their reconstruction model, the Ios basement, along with other tectonic units in the Cycladic islands and Crete, are all part of a subducted Greater Adria continental ribbon. While our island-scale study cannot contribute to the discussion on whether Greater Adria was a single continental landmass or made up of several large islands, it is evident that Late Cretaceous deformation is wide-spread in both the European and Gondwana terranes.

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Distinguishing European versus Gondwanan terranes in the Central Aegean and greater Mediterranean area will remain difficult. One central argument is the number of oceans present in the ‘greater Tethys seaway’ between Europe, Africa and potentially Adria at Mesozoic and associated tectonic evolution (e.g., Channell and Kozur,1997; Kilias et al., 2010; Robertson et al., 2013). This argument mainly concerns the paleogeography of the Pelagonian unit outcropped in mainland Greece. It is thus of interest that evidence for Late Cretaceous ages is reported from white mica deformation fabrics isolated from the northern end of the upper Pelagonian unit (e.g., Kilias et al., 2010; Robertson et al., 2013). The Pelagonian unit may have been a continental ribbon (or micro-continent) separating two Tethyan realms: the Vardar Ocean in the northeast and the Pindos (or even Cyclades) Ocean in the southwest (e.g., Channell and Kozur,1997; Robertson et al., 2013). Such models imply high pressure metamorphism in the Pelagonian unit as the result of the attempted subduction of the continental ribbon (Robertson et al., 2013). Other reconstructions consider the Pelagonian unit as the eastern-most unit of a continental Adria terrane, adjacent to a single north-eastern oceanic basin (the Vardar Ocean) e.g., (Bortolotti et al., 2013; Ferriere et al., 2012; Kilias et al., 2010; Palamakumbura et al., 2013). These researchers disagree with the concept of a distinct Pindos Ocean both in Triassic and in Jurassic time (Kilias et al., 2010).

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6 Conclusion

Our study reports evidence of a Late Cretaceous Asteroussia event (70–80 Ma) in the originally Gondwanan lower plate of Ios. Accretion of the Asteroussia terrane is a major event in the Aegean tectonic history. This required a (250–300 km) southward jump of the subduction megathrust. Renewed rollback after the accretion event triggered Oligocene extension and facilitated the exhumation of the Asteroussia terrane within the core of the Ios metamorphic core complex.

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Data availability

$^{40}Ar/^{39}Ar$ geochronology results of two augengneiss samples (AG03-03, AG03-05) were published in Forster and Lister (2009) and re-examined in this study. All new data collected in this study and presented in this article are provided in text and in the Masters' thesis of Sonia Yeung submitted for her Masters' programme to the Research School of Earth Sciences, Australian National University.

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Author contribution

All authors contributed to the writing of the manuscript and its conceptualisation. The paper extends part of a Master's thesis by Sonia Yeung, supervised by Marnie Forster and Gordon Lister.

Disclaimer

The article includes a minor part of the Masters' Thesis of Sonia Yeung submitted for her Masters' programme to the Research School of Earth Sciences, Australian National University.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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