Unravelling the structural, metamorphic and strain history of the “Aegean Orogeny” Southern Greece, with a combined structural, petrological and geochronological approach

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Thesis submitted to the University of Oxford for the degree of Doctor of Philosophy in Geology and Mineralogy
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University of Oxford

Trinity, 2018

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Declaration

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Citation: Thomas Neil Lamont (2018), Unravelling the structural, metamorphic and strain history of the “Aegean Orogeny” Southern Greece, with a combined structural, petrological and geochronological approach, D.Phil. Thesis, University of Oxford, Department of Earth Sciences, Oxford, UK.

Keywords: Tectonics, Metamorphism, Cyclades, Tinos, Naxos

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Printed in the United Kingdom.
Abstract

Unravelling the structural, metamorphic and strain history of the “Aegean Orogeny” Southern Greece, with a combined structural, petrological and geochronological approach

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The Cycladic Islands in the Aegean region, southern Greece, has been indisputably under lithospheric extension throughout the last 10 Myrs but there remains a limited understanding of the regional tectono-metamorphic evolution prior to extension. In this thesis, new structural mapping, petrography, thermobarometry, phase equilibria modelling, U–Th–Pb and Lu–Hf garnet geochronology is presented from the islands of Tinos, Naxos and Delos and reveal the Cyclades have experienced a complete cycle of mountain building. The Tsiknias Ophiolite on Tinos formed at 161.9 ± 1.3 Ma and is underlaid by a metamorphic sole which displays a highly condensed and inverted temperature gradient, with partial melting directly below the ophiolite contact at P–T conditions of 8.5 kbar, 850°C. The timing of metamorphism is constrained as 74.0 ± 3.3 Ma from leucosomes and 66.6 ± 2.0 Ma from garnets in the underlying meta-sediments, and is interpreted to represent the initiation of a NE-dipping subduction zone that remained active for 20 Myrs associated with the closure of the Vardar Ocean to the NE. The arrival of the leading edge of the Cycladic continental margin caused high-pressure metamorphism (22–26 kbar, 500–570°C) at 46.4 ± 3.4 Ma on Tinos and 14.5 kbar, 470°C at 49–46 Ma on Naxos. Crustal thickening resulted in regional metamorphism and climaxed with kyanite-grade conditions (10 kbar, 670–730°C) at 18.5–16 Ma followed by sillimanite-grade anatexis (5–6 kbar, 690–730°C) at 15.5–14 Ma on Naxos. The transition from overall crustal shortening/thickening to extension is constrained to 15 Ma in the Naxos migmatite dome. I and S–type granites intruded contemporaneously between 14.6–12.2 Ma, suggesting a regional-scale partial melting event affected the deepest levels of the Cyclades, possibly associated with the onset of extension and exhumation.
Extended Abstract

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The Aegean Sea region has been considered a type locality for large-scale lithospheric extension, associated with Cordilleran-style metamorphic core complexes. Although lithospheric extension has undoubtedly occurred in the region since 15–10 Ma, the geodynamic history of the older, pre-extensional evolution is poorly understood. In this thesis, the Cyclades islands of Tinos and Naxos are studied in detail, integrating careful and detailed field mapping with petrology, whole rock and mineral chemistry, thermobarometry and equilibrium phase diagram modelling, together with U–Th–Pb allanite, monazite, zircon and rutile geochronology and Lu–Hf garnet geochronology. It is concluded that the Cyclades experienced a complete cycle of mountain building from the Late-Cretaceous to Middle Miocene, that is here termed the “Aegean Orogeny” prior to regional Aegean extension. This mountain belt formed as a result of prolonged crustal shortening associated with the closure of an ocean to the NE of the Cyclades in the present-day co-ordinates.
The Tsiknias Ophiolite exposed at the highest structural levels of Tinos Island, Greece comprises a succession of partially dismembered and structurally repeated ultramafic and mafic rocks. New field observations, an updated geological map of Tinos is, integrated with U–Pb zircon geochronology and whole-rock geochemistry from both magmatic ophiolitic and metamorphic rocks from a newly identified metamorphic sole accreted along the base of the peridotites. A plagiogranite dated at 161.9 ± 1.3 Ma, reveals the Tsiknias Ophiolite formed in a supra-subduction zone setting, comparable to the “East-Vardar Ophiolites”, and was intruded by E-MORB gabbros at 144.4 ± 5.2 Ma. In contrast, the extremely deformed underlying metamorphic sole exhibits a condensed and inverted metamorphic gradient, from partially anatectic amphibolites to lower amphibolite-greenschist-facies oceanic meta-sediments over 300 m down structural section. Thermobarometry and equilibrium phase diagram modelling using THERMOCALC reveals the sole was metamorphosed at pressure ($P$) and temperature ($T$) conditions of ca. 8.5 kbar 850–600 $^\circ$C, and represents a metamorphic field gradient of up-to 1000$^\circ$C/km. Leucodioritic leucosomes were generated in the uppermost sole amphibolite, yielding a ca. 190 Ma protolith age, and reveal the timing of high-grade metamorphism and anatexis on the major subduction thrust (Tsiknias Thrust) occurred at ca. 74.0 ± 3.3 Ma, during the initial stages of SW-directed ophiolite obduction. The Tsiknias Ophiolite was therefore obducted some ca. 90 Myrs after it formed due to the initiation of a new NE-dipping intra-oceanic subduction system to the NE of the Cyclades. To generate such elevated $P$–$T$ conditions in the sole with a 90 Myr old overlying ophiolite requires additional heat sources. It is speculated that shear heating on the Tsknias Thrust, and potentially rapid slip may supply important sources of additional heat, although this remains highly controversial. Metamorphism propagated down structural section with time as revealed by a Lu–Hf garnet age of 66.6 ± 2.0 Ma, thus supporting the metamorphic sole interpretation. Correlation with Vardar Zone rocks suggest this subduction zone was a regional feature and responsible
for Late Cretaceous ultra-high-pressure metamorphism in the Rhodope Massif.

Continued subduction during the closure of the Vardar Ocean, resulted in high-pressure metamorphism of the Adriatic (Cycladic) continental margin as it attempted to subduct some 20 Myrs later, and rocks associated with this subduction event are exposed in the Cycladic Blueschist Unit, which structurally lies below the ophiolite in the Lower Unit of Tinos. Together these rocks persevere ca. 20 Myrs of subduction zone history associated with the final closure of the Vardar Ocean is recorded over a structural thickness of less than three kilometres. The structures and petrography of these high pressure rocks on Tinos were integrated with Lu–Hf geochronology in order to constrain the $P$–$T$–$t$–$D$, M(H$_2$O) and M(O) history of eclogitic and blueschist-facies units. Equilibrium phase diagram modelling of newly discovered lawsonite-bearing garnet glaucophane schists that are exposed at the highest structural levels of the high-pressure rocks (Kionnia and Pygros Units), experienced ca. 22–27 kbar and 490–510$^\circ$C under water saturated conditions, whereas adjacent mafic aegerine-bearing eclogites obtained 20–23 kbars and 530–570 $^\circ$C under moderately oxidizing and hydrous conditions. Prograde garnets from these rocks yielded a Lu–Hf isochron age of 46.4 ± 3.4 Ma, which is interpreted as constraining the timing of peak M1 eclogite and blueschist-facies metamorphism on Tinos. Lawsonite breakdown upon the initial stages of isothermal decompression released between 3 and 6 % molar H$_2$O, facilitating growth of coarse and zoned secondary matrix glaucophanes. Water released through dehydration of lawsonite penetrated into the adjacent shear zones over a range of $P$–$T$ conditions, causing retrogression, serpentinization, and weakening which facilitated the exhumation of high-pressure rocks to ca. 13 kbar 530–550 $^\circ$C. In contrast, rocks at lower structural levels within the interior of the island record lower pressures of ca. 18.5 kbar and 480–510 $^\circ$C and are overprinted by top-to-NE shearing that occurred during ($M_1$) blueschist to ($M_2$) greenschist-facies conditions. Upon exhumation to mid-crustal conditions, these rocks attained lower amphibolite conditions of ca. 7.3
± 0.7 kbar and 536 ± 16 °C, which was related to (M₂) regional metamorphism of
the middle crust. To produce these P–T–t–D relationships, it is suggested that the
Cycladic Blueschist Unit, previously thought to be a single and coherent package of
rocks, should be differentiated into a series of tectono-metamorphic units that each
experienced different tectonic and thermal histories. These units were sequentially
buried to variable depths at slightly different times and were sequentially emplaced
during SW-directed syn-orogenic extrusion of the buoyant Cycladic continental mar-
gin. Exhumation occurred by coeval top-to-SW directed thrusting at the base and
top-to-NE normal sensed movements at the top of the extruding units. During this
extrusion stage, top-to-NE shearing was firstly highly localized on discrete passive roof
normal sensed shear zones, but became more distributed as exhumation proceeded. All
high-pressure and extrusion related features on Tinos are truncated by later normal
sensed structures related to regional extension and doming. Finally, these data reveal
that burial of the cycladic continental margin must have occurred a minimum rate of 4
mm/yr this subduction zone must have cooled rapidly following subduction initia-
at ca. 74 Ma and obduction of the overlying Tsiknias Ophiolite some ca. 20 Myrs prior
to high-pressure metamorphism. Together, these events suggest the final closure of the
Vardar Ocean, NE of the Cyclades, during the Early Eocene and was associated with
the NE–SW collision between Adria (Cyclades) and Eurasia.

Following this subduction phase, post-collisional crustal thickening resulted in
regional Barrovian metamorphism that affected the middle and lower crust levels of the
Cyclades. The geodynamic history of regional-scale (M₂ kyanite- and (M₃ sillimanite-
grade metamorphic rocks that are exposed within the core of the Naxos dome, a classic
metamorphic core complex. The pre-extensional prograde evolution of these rocks and
the relative timing of peak metamorphism in relation to the onset of extension is
poorly known. In this work new, detailed structural mapping is presented and inte-
grated with petrography, phase equilibrium modelling and U–Th–Pb geochronology of
blueschists, kyanite gneisses and anatectic sillimanite migmatites, that provide constraints on the timing and rates of metamorphism and deformation. (M2 Kyanite- M3 sillimanite-grade gneisses within the core complex record a complex history of burial and compression, and did not form under conditions of crustal extension. Deformation and metamorphism was diachronous, and propagated down-structural section with time, resulting in the juxtaposition of several distinct tectonostratigraphic nappes that experienced contrasting metamorphic histories. Attempted northeast-directed subduction of the Cycladic (Adriatic) continental margin, dated at 49–46 Ma, is very similar to the Lu–Hf age of ca. 46 Ma from eclogites and blueschists within continental margin rocks on Tinos. This high-pressure unit was subsequently extruded towards the SW and overthrust onto the more proximal continental margin. This process resulted in crustal thickening and Barrovian metamorphism dated at ca. 40–15 Ma. These rocks underwent a clockwise $P$–$T$ evolution and resulted in M2 kyanite-grade conditions of ca. 10 kbar and 600–670 °C, between 22–17 Ma. At the deepest levels, kyanite-grade, fluid-fluxed melting at ca. 8–10 kbar occurred between 18.5–17 Ma, and was followed by isothermal decompression and sillimanite-grade, fluid-absent dehydration melting (ca. 5–6 kbar and 730 °C) at 16–14 Ma (M3, facilitated by exhumation under a series of top-to-NNE passive roof normal faults. The migmatite dome formed at lower pressure conditions under horizontal constriction resulted in vertical boudinage and upright isoclinal folds, that refold the ductile shear zones.

U-Pb dating of zircons from cross-cutting leucogranite dykes, combined with young ages from sillimanite-grade gneisses constrain the timing of top-to-NNE shearing along these shear zones to 18–15.5 Ma, corresponding to an average exhumation rate of 6 km/Myr. These structures pre-date doming and are responsible for southwest-directed extrusion of gneisses and migmatites from 35 to 17.5 km depth in a compressional setting. The rocks were subsequently folded around the central migmatite dome on Naxos. North–south-oriented boudinaged leucogranite dykes and migmatites
dated at 15-13 Ma, alongside a U–Pb rutile cooling age of ca. 12.7 Ma, and published
\(^{40}\text{Ar}^{39}\text{Ar}, \text{fission track}, \text{and Rb–Sr ages, indicate that regional extension across the}
\text{Aegean began at ca. 15 Ma. This was contemporaneous with a two-fold decrease in}
\text{the convergence rate between Nubia and Eurasia that significantly accelerated cooling}
\text{rates to 60–90 °C/Myr due to the onset of upper crustal normal faulting that truncates}
\text{all earlier structures.}

During this sillimanite grade metamorphic event, muscovite dehydration melting produced S-type garnet tourmaline and biotite-muscovite leucogranites, dated at ca. 18–13 Ma on Naxos. Similar leucogranites also occur on Tinos and Delos and intrude coeval with, or immediately prior to, adjacent I-type granitoids. On Tinos, a series of intrusions bracket the timing of motion on the Tinos Shear Zone, previously interpreted as representing a low-angle normal fault. U-Pb zircon geochronology was combined with whole rock ICP-MS geochemistry on cross-cutting dacite dykes, the Tinos hornblende biotite pluton and garnet bearing leucogranite sills that cut by brittle normal faults. The leucogranites are unlikely to be derived from the same parent magma as the adjacent I-type intrusions, and therefore formed during peak sillimanite-grade metamorphism and migmatization at deeper structural levels than currently exposed on Tinos. U-Pb dating also suggests that pervasive ductile movement on the Tinos Shear Zone ended by ca. 14.6 Ma, as ductile fabrics are cut by the granites and dacite dykes. A new strain localization, at structurally higher levels around the margins of the granite resulted in steep, brittle normal faults that cut the S-type leucogranite sills and yield ages between ca. 14.8 and 14.2 Ma. Brittle deformation associated with regional extension must therefore also be younger than 14.8–14.2 Ma. These features suggest that regional scale partial melting and exhumation affected the Cyclades concomitantly with the onset of regional extension at between ca. 15 and 14 Ma. It is also suggested that because the I-type granitoids are so localized in the Cyclades and occur over such a short duration (ca. 14.8–11 Ma) coeval with, or im-
mediately post-dating, S-type leucogranites, they could represent the partially melted products of a previous arc-related protolith (i.e. the Variscan basement), rather than the volcanic arc related to the Hellenic subduction zone.

In conclusion, the data in this thesis support a model of (1) early ophiolite obduction during the Late Cretaceous, followed by (2) attempted subduction of the continental margin to eclogite and blueschist facies condition during the Eocene, followed by (3) prolonged crustal shortening, thickening and regional metamorphism in the Cyclades. These data are incompatible with a continuous southward retreating Hellenic subduction zone. Rather, the Cyclades underwent a rapid switch from overall compressional to extensional tectonics at ca. 15 Ma, associated with the ending of the sillimanite-grade event, and therefore the extension is a relatively recent feature in the region and was responsible only for the final stages of exhumation.
Acknowledgements

I am truly indebted to my supervisors Mike Searle, Dave Waters and Nick Roberts for helping devise this project and therefore allowing me to continue my academic career at Oxford. They have all invested huge amounts of time during the last four years into discussing my (sometimes crazy) ideas, providing feedback on my work, sharing invaluable geological knowledge, as well as helping me think critically and approach problems in a logical and scientific way. Mike and Dave have been incredibly supportive both during my 4th year undergrad research project, and encouraged me to peruse a D.Phil to continue working on the Aegean region, for which I am extremely grateful for. Nick has been a constant source of help and discussion and on many occasions went far beyond the call of duty. He has provided huge amounts of time to help analyse an unbelievable number of samples, greatly improved my understanding of data acquisition and processing and had to ”baby-sit” me on the SEM at the BGS whilst the Oxford Microprobe was getting set up. I like to think it was all good preparation for the birth of his first son, Joseph last year. I really could not have had three better supervisors.

Marc St-Onge was also an invaluable source of discussion and inspiration and I am truly grateful to have his advice and support on the Assynt trips and also on the Cyclades field-trip I organised during September 2017. I would also like to extend thanks to Richard Palin, Owen Weller, Andrew Smye and Dave Wallis, who have been extremely helpful with discussing various petrological, field, deformational ideas and thermodynamic modelling in THERMOCALC, and Phillip Gopon who joined me in the
field and trained me on the electron microprobe. They also provided critical feedback and acted as superb role models for me to strive to follow. I also extend thanks to Laurence Robb, Andy Parsons, Jon Wade, Philip England, Tony Watts, Bruce Level, Chris Ballhaus, Rolf Romer, Richard White and Lars Hansen for fruitful discussions, which helped crystallize my ideas.

I also acknowledge Adrian Wood for training and overseeing my sample preparation in NIGL and for the great soundtracks in the sample preparation lab, Gren Turner and Jeremy Rushmore for training me up on the Leo SEM and FEI Quanta SEM at the BGS. Ian Millar, who carried out the analysis of my garnet separates used for Lu–Hf garnet dating, and providing invaluable advice, Matt Horstwood, Simon Tappister, and Steve Noble for the valuable discussions which undoubtedly helped improve my understanding of geochronology and how to date rocks, as well as making my visits NIGL a true pleasure. I would like to extend thanks to my brother and his housemates from Nottingham University for letting me stay in their house and making me feel inclusive during my regular visits to NIGL.

I would like to thank Owen Green for thorough advise on sample preparation and training, Jon Wells for always being super helpful and making (probably 100’s) of thin-sections, and made particular exceptions if the odd ones needed to be finished quickly. I would like to thank Stanley Mertzman from the Franklin and Marshall College who ran my XRF for granite and ophiolitic samples, Ian Wyatt for carrying out the digestion of whole rock powders and finally Philip Holdship for setting up and running the mass-spectrometer to collect trace element data.

During my time as a post-grad, I have been extremely lucky to have worked closely with many MESci and D.Phil students in the Hard Rock Group. I would like to thank Eleni Wood, Robert Fox, Sam Cornish, John Henry Charles, Jacob Forshaw, Dianna Avidanii, Thomas Breithaupt, Will Mckenzie, Ethan Stammers Jones, Rellie Goddard and Brook Keats for allowing me to share ideas and have extremely useful
and stimulating discussions about their work and my own, commonly during the Hard Rock Group Lunches, which I will extremely miss. Greatest thanks go to my fellow post-grads and best friends Tyler Ambrose, who was a constant source of humour and banter, particularly on field trips such as Assynt, Shetland, and in Oman and the UAE, and taught me how to wash my clothes in a bedet. Joshua Combs, who was my housemate at 39 Stanley Road and has always been there for support, discussion and good old rowing chat. Brendan Dyck who has always made time to discuss various topics and helped teach me petrological modelling during my final undergrad year and has been a great role model. I also thank Anna Bidgood and William Nash who joined me in the field. It has been a pleasure to work alongside my office mates Serjocha Evers, Gemma Bevenento, Mimi Harrison, David Ford and Sarah Lucas, even if my rock collection might have got in the way sometimes.

Outside of my studies, I would like to thank everyone at OUCCC for making my time in Oxford thoroughly enjoyable, through training, racing and socializing. Particular thanks go to club coach Kyle Bennet who helped me during my final year come back stronger than ever from glandular fever which resulted in me getting selected to run for Cheshire in the inter-counties XC in March 2018. I would also like to thank my good friends Callum Higgins, Bhavik Lodehia who have supported me throughout my work on the Aegean and were on my first visit to Naxos 6 years ago. I would like to thank my training buddies Alex Bampton, Joseph Woods and also Rahil Sachak-Patwa, for letting me stay at 31 Walton Well Road during the last month of writing up, as well as many many others for the good times during my studies at Oxford.

I would like to thank University College for the travel grants to pursue field-work and the Natural Environment Research Council (Grant No. NE/L0021612/1) for providing the opportunity for me to carry out this work and the NERC Isotope Geosciences Laboratory for hosting me throughout the last 4 years which was funded by NIGFSC grant IP-1597-1115.
Finally, it has been a privilege to have been a student at Oxford and the last four years in Oxford have provided the best and also the most challenging experiences of my life to date. I could not have completed the D.Phil without the continual backing from my mum, dad, brother and close family. They have always believed in me and supported my passion for geology, put up with plenty of my geological conversations about Naxos and Tinos and even visited me in the field. This work is dedicated to them.