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Metamorphic style and development of the blueschist- to eclogite-facies rocks, Cyclades, Greece

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Abstract. The island of Syros, Greece is part of the Attic-Cycladic blueschist belt, formed during Mesozoic Eurasia-Africa subduction. The rocks of Syros can be broadly divided into three tectono-stratigraphic units: (I) metamorphosed sedimentary and volcanic rocks (marble-schist sequence), (II) remnants of oceanic crust with fault-bounded packages of blueschist/eclogite-facies mafic rocks and serpentinite (mafic-ultramafic rocks) and (III) the Vari gneiss, which is a tectonic klippe. Low-temperature, high-pressure assemblages are found on several islands in the Cyclades. The best preserved of these rocks are on Syros and Sifnos islands. Mineral compositions and peak metamorphic assemblages are similar on both islands. Both islands are considered to share similar P-T histories with highest-pressure mineral assemblages reflecting conditions of at least 15 kbar and about 500°C.

1. Introduction

Constraining the P, T and deformation histories of Syros and Sifnos is a work in progress with many contributors who have applied traditional empirical geothermobarometry, phase equilibria and the pseudosection approach using various mineral assemblages (e.g., recently [1], [2], [3]). Many versions of P-T trajectories for Syros and Sifnos appear in the literature ([2], [4], [5], [6], [7], [8], [3], [9], 10]). Differences among these studies, some major and some minor, can be partly attributed to variation in methods and data that were used, but also to the authors' interpretation of the timing of formation of mineral assemblages, state of compositional preservation of the minerals and coexisting equilibrium assemblage. In spite of the range of published P-T estimates, we believe that a few common and widespread mineral assemblages give good limits on the P-T path that was followed during the subduction and exhumation of the interlayered marbles and schists.

For the marbles and schist on Syros, peak metamorphic conditions are limited to just under 16 kbar at about 480°C and just above 500°C at 15 kbar, which fits well with estimates (15-16 kbar and 500°C) most workers have taken as the peak of metamorphism on both Syros and Sifnos. However, some recent work suggests higher P-T conditions on both Sifnos and Syros. Maximum P-T conditions on Sifnos have been estimated at about 19 kbar and 580 °C ([1]), and [2] got similar results of about 19 kbar and 570 °C for Syros. For Syros, higher peak-metamorphic conditions for the mafic-ultramafic unit proposed by [1] are at about 19 kbar and 525°C, and [3], who applied the geothermobarometer of [11], obtained conditions as high as 19-24 kbar (± 2 kbar) at temperatures of 500-580°C (± 65°). On Syros these higher conditions are problematic, because they exceed P-T limits imposed by assemblages in the marbles. A possible scenario to reconcile these observations is that the mafic and ultramafic rocks, already metamorphosed at higher P-T eclogite-facies conditions, became juxtaposed with slices of the schist and marble units at about 15 kbar and 500°C, which are the peak metamorphic conditions seen in the schist and marble units. The fabrics of the main penetrative deformation would have formed at these condi-

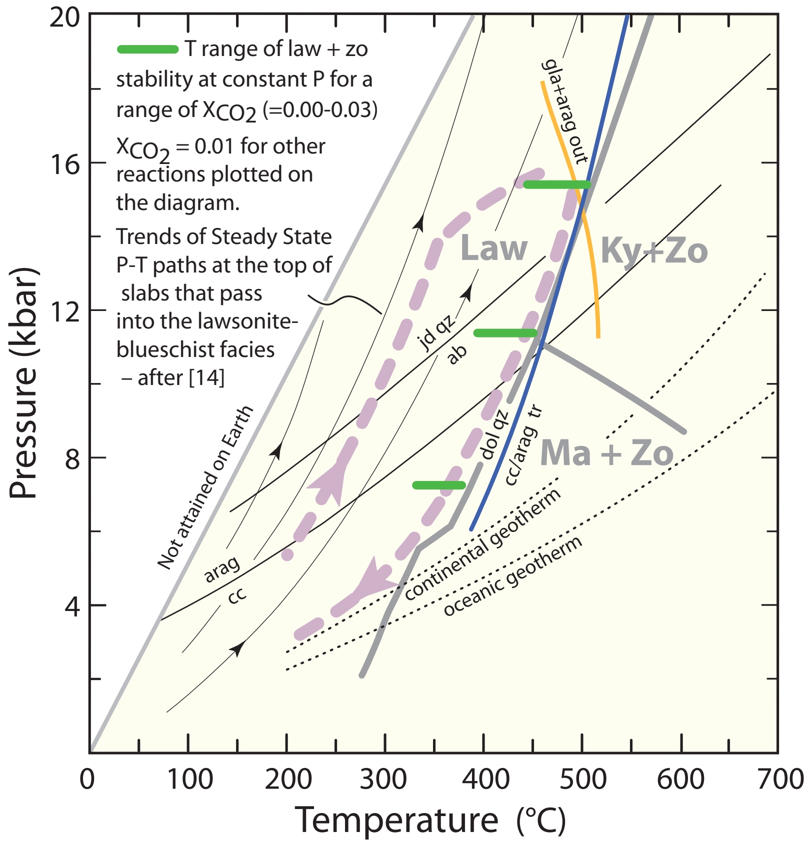

Figure 1. Pressure versus temperature diagram that illustrates the petrologic constraints on the P-T trajectory. Calculations were done with PerPlex [12] using the latest version (HP02) of the thermodynamic data of [13]. Abbreviations: aragonite (arag), albite (ab), calcite (cc), dolomite (dol), glaucophane (gl), jadeite (jd), kyanite (ky), lawsonite (law), margarite (ma), quartz (qz), tremolite (tr) and zoisite (zo).

tions. This explanation would account for the apparently contradictory estimates of peak metamorphic conditions from the marble and schist units and the mafic and ultramafic rocks as well as the observation of many workers (e.g., [8]) that the main deformation occurred at the peak metamorphic conditions.

2. Limits on P, T and grain boundary fluid composition from the schist and marble units

Mineral assemblages that are common across much of Syros provide good constraints on the maximum P-T conditions as well as on the composition of the grain boundary fluid. The assemblage glaucophane + aragonite is stable only at fluid compositions of $X_{CO2} = 0.005\text{-}0.030$. The glaucophane + aragonite/calcite assemblage also constrains the maximum pressure and temperature. The upper pressure boundary is a locus of points that form a curved, concave-downward line with a negative slope. For an $X_{CO2} = 0.01$ the maximum pressure at which glaucophane + calcite/aragonite could remain stable would be just under 16 kbar at about 480°C (figure 1, orange curve). The maximum temperature would be just above 500 °C at 15 kbar. These estimates bracket the maximum P-T conditions of the schist-marble sequence.

The assemblage dolomite + quartz is also common in many of the low-Na marbles that did not develop sodic amphibole or pyroxene. These marbles did not react to produce either tremolite or diopside, and the implication is that temperatures did not exceed the stability of dolomite + quartz. Breakdown of dolomite + quartz to tremolite ($X_{CO2} = 0.01$) has a steep P-T slope of about 9-10° per kbar that limits maximum temperature these rocks could have reached to about 475°C at 13 kbar to 560°C at 21 kbar (figure 1).

Within the schists, the preservation of lawsonite also places limits on the P-T conditions, and relict lawsonite + epidote, while difficult to find in hand sample, is relatively common in thin section. Additionally, high-temperature breakdown products of lawsonite, such as kyanite + zoisite (epidote) or margarite + zoisite (epidote), are absent. These two observations suggest that the reactions: lawsonite =

kyanite + zoisite + quartz + H_2O and lawsonite = margarite + zoisite + quartz + H_2O were never crossed and, therefore, limit the maximum T at given P for the peak metamorphism and along the retrograde P-T trajectory (figure 1, gray lines).

Like the glaucophane + aragonite/calcite assemblage in the marbles, lawsonite + epidote in the schists also indicates that water-rich fluids were present for much of the metamorphic history, since calculated T-XCO2 stability of the assemblage lawsonite + zoisite (epidote) for a range of pressures shows that these two phases can only coexist over a narrow range of temperatures and with H_2O-rich fluids (< 3% CO2). Assuming the retrograde P-T trajectory remained largely within the stability field of lawsonite + zoisite, calculations at 15, 11 and 7 kbar place limits on the retrograde P-T trajectory that returned these rocks to the surface (figure 1, green bars).

3. P-T trajectory

Very little evidence to constrain the early prograde metamorphic history of these rocks is preserved. If steady-state P-T paths are a reasonable approximation of the early subduction history of these rocks, then modeling (e.g., [14]) suggests a concave-up prograde paths (figure 1; figure 2, location 1) that pass into the lawsonite-blueschist facies. Pseudomorphs after much of the lawsonite are abundant in the glaucophane schists of Syros show that the subduction P-T trajectory must have entered the lawsonite-blueschist facies, and the rocks must have initially equilibrated there (figure 3a,b). Reaching the conditions of the epidote-blueschist facies, requires a perturbation of the modeled steady-state P-T trajectory, and the essential component is heating at a higher rate (figure 2, location 2). The conditions of the epidote-blueschist facies are marked, partly, by the end of the stability of glaucophane + lawsonite via the reaction glaucophane + lawsonite = clinozoisite + paragonite + chlorite + quartz + water [15]. These conditions are very near the maximum P-T conditions of the marble and schist units, and they mark the beginning lawsonite pseudomorph formation (figure 3a, b). The nature of the lawsonite breakdown reactions is too large a topic to cover here, but other reactions like, lawsonite + celadonite-rich phengite = zoisite + chlorite + muscovite-richer phengite + H_2O are also consistent with these peak P-T conditions and the direction of the P-T trajectory (figure 2, locations 2 & 3) and would also be consistent with some lawsonite pseudomorph formation early in the retrograde history of these rocks [16].

Maximum P-T conditions for the marble and schist units (figure 2, location 3) are based on calculated stability limits of widely-distributed, observed assemblages. The occurrence of glaucophane + $CaCO_3$ + dolomite + quartz suggests that the P-T trajectory that was followed by the rocks crossed a reaction like: albite/Na-pyroxene + dolomite + quartz => glaucophane + $CaCO_3$, but did not exceed the P-T stability of the reaction dolomite + quartz => tremolite + $CaCO_3$. The P-T locations of these reactions are sensitive to fluid composition and indicate that the attending fluid phase was water-rich with X_{CO2} constrained to be < 0.03; a value of $X_{CO2} \cong 0.01$ best fits the observed assemblages. The minerals of these assemblages form the fabric of the major penetrative deformation in the marble-schist sequence. This same fabric is found in the mafic-ultramafic rock unit, so if the mafic-ultramafic rocks follow a different early P-T trajectory, they became juxtaposed with the marble-schist sequence at or slightly before time of the main deformation (partial P-T path with question mark, figure 2). Age determinations from white micas suggest peak metamorphic ages of about 50-55 Ma [10], [17].

Limited retrograde metamorphism began almost immediately after peak temperatures were attained while the rocks were still at blueschist-facies conditions (figure 2, locations 3-4). Where fluids could infiltrate, a common reaction in the omphacite-bearing glaucophane schists was: omphacite + rutile + H_2O = glaucophane + sphene. Assemblages with stable glaucophane + albite + chlorite also form during retrograde metamorphism in the blueschist facies.

The occurrence of relict lawsonite + Al-rich epidote in schists within the marble-schist sequence also places limits on peak and retrograde metamorphic conditions. Calculations show that for pure H_2O fluids, lawsonite + zoisite are stable from about 510 to 450°C, but this range shrinks and terminates at just above 500°C as X_{CO2} approaches 0.03. The preservation of lawsonite and the lack of preservation of

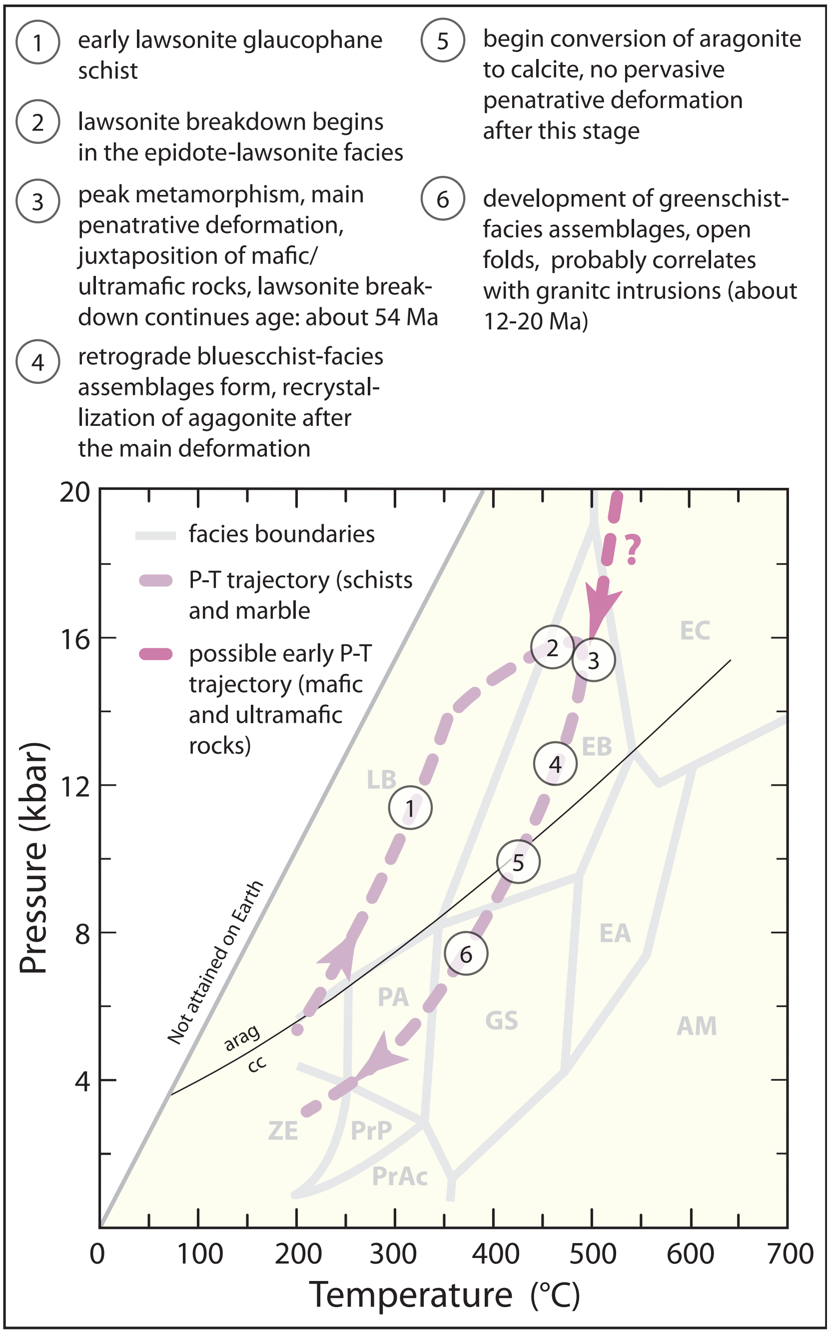

Figure 2. Pressure versus temperature diagram that shows the relative sequence of events along the P-T trajectory. Facies abbreviations: AM=amphibolite; EA= epidote-amphibolite; EB=epidote-blueschist; EC= eclogite; GS=greenschist; LB=lawsonite blueschist; LC=lawsonite-chlorite; PA=pumpellyite-actinolite; PrAc=prehnite-actinolite; PrP=prehnite-pumpellyite; ZE=zeolite [14].

any products of terminal lawsonite breakdown reactions (kyanite or margarite) indicate the P-T trajectory remained within the lawsonite stability field (figure 1, figure 2, locations 4 & 5). Additionally, since lawsonite + Al-rich epidote also have a T-X_{CO2} stability that is limited to fluids with $X_{CO2} < 0.03$, this observation combined with similar fluid compositions indicated by the glaucophane marbles suggests that the whole subduction package of schist, blueschist and marble was pervaded by an H_2O-rich fluid.

The retrograde P-T trajectory (figure 2, location 5) is estimated to have crossed the aragonite to calcite reaction boundary above 400°C, which is consistent with the observed complete conversion of aragonite to calcite, and the formation of the aragonite pseudomorphs. The shape-preferred orientation of the pseudomorphs after aragonite is typically at a high angle to the axial planes of folds (figure 3c), suggesting that aragonite continued to recrystallize after the main penetrative deformation ceased. The

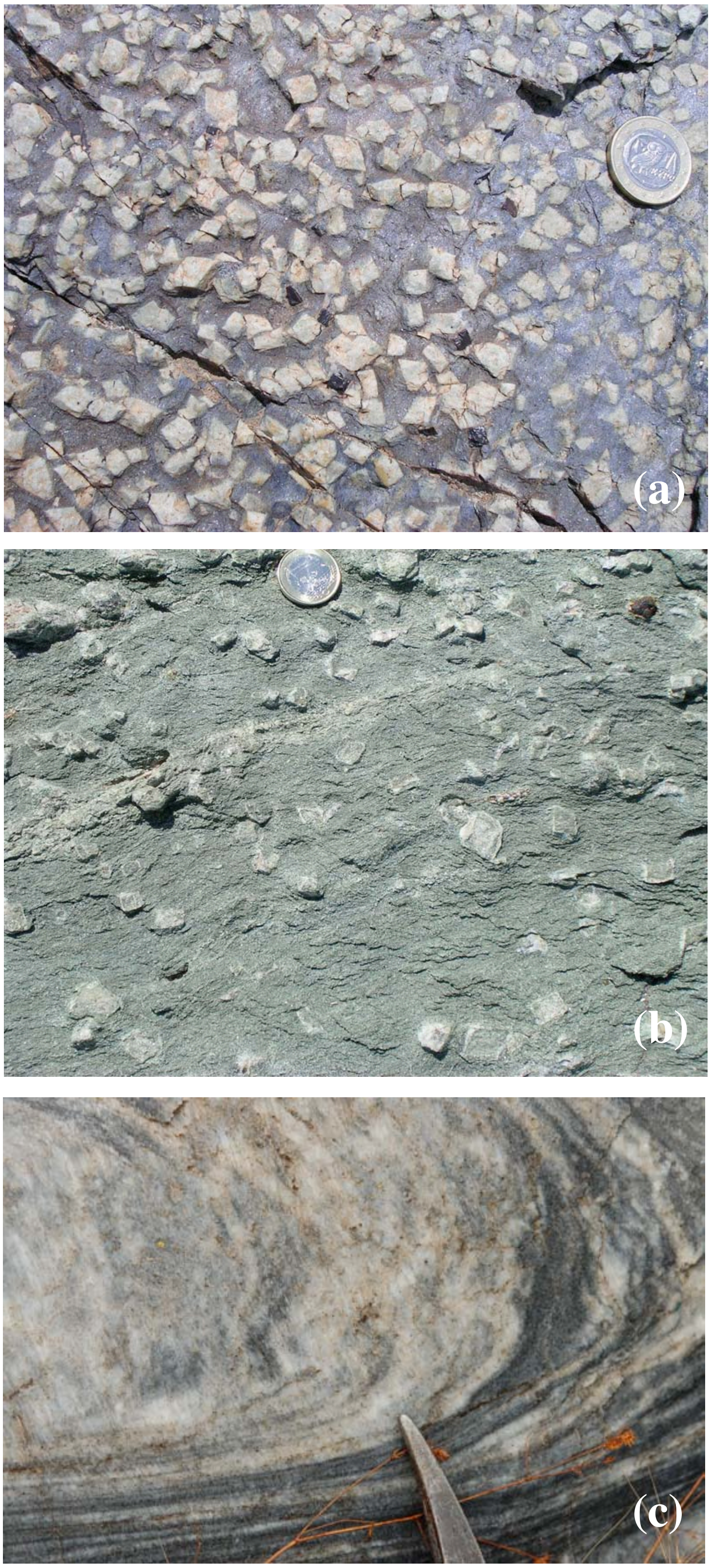

Figure 3. (a) Pseudomorphs (white) after euhedral lawsonite in glaucophane schist from near Grammata in northern Syros. Dark mineral porphyroblasts are coarse-grained rutile. The rock also contains epidote and white mica; (b) Pseudomorphs (white) after euhedral lawsonite in retrograde schist Finikas, southern Syros; (c) Aragonite pseudomorphs (aligned and acicular) showing that aragnite recrystallized after the main fabric forming event. Hammer tip is approximitely oriented parallel to the aragonite pseudomorphs. Sample is from near Vissa, southern Syros.

widespread preservation of the aragonite pseudomorph fabric on Syros indicates that no later penetrative deformation occurred while most of the rocks were within the calcite stability field, since this would have destroyed the observed aragonite pseudomorph fabric[18].

The retrograde P-T trajectory crossed into the greenschist-facies (figure 2, location 6) and much of the observed retrograde mineral growth occurred under these conditions. Elsewhere in the Cyclades greenschist-facies metamorphism is associated with the granitic intrusions (mostly about 20 -12 Ma) [19], and, if this correlation is valid, may roughly constrain the age of this phase of the retrograde metamorphism on Syros.

At low temperatures (<300°C), both the oceanic and continental geotherms converge, and it is reasonable that the P-T trajectory of the marbles and schists would also approach these geotherms near the end of exhumation, since there are no locally observed, late events on Syros that could potentially disturb the geotherm (figure 1; figure 2, location 6).

4. Conclusions

Stability of glaucophane + aragonite/calcite, dolomite + quartz and the presevation of relict lawsonite combined with the absence of minerals formed by terminal lawsonitebreakdown reactions place relatively tight constraints on the P-T conditions for the marble and schist units. Common structural elements indicate that the rocks of the marble and schist unit and the mafic-ultramafic rocks were juxtaposed at least by the time of the main deformation. Higher pressure and temperature estimates may indicate that the mafic-ultramafic rocks followed a different P-T trajectory up to the point they were combined with the marble and schist unit into a single package of rocks. The juxtaposition of this rocks would have occurred at 15-16 kbar at about 500°C, which are the peak metamorphic conditions seen in the marble and schist unit.

5. References

[1] Trotet F, Vidal O, Jolivet L 2001 *European Journal of Mineralogy* **13**, 901-920

[2] Schmädicke E, Will T M 2003 *Journal of Metamorphic Geology* **21**, 799-811

[3] Holly E A , Ross T, Cheney J T 2004 *Geological Society of America Abstr. with Prog*. **36**, A67

[4] Dixon J E, Ridley J 1987 Syros In: H C Helgeson (ed) *Chemical transport in metasomatic processes* p 489-518 D Reidel Publishing Company: Dordrecht

[5] Schliestedt, M (1986) *Journal of Petrology* **27**, 1437-1459

[6] Okrusch M, Bröcker M 1990 *European Journal of Mineralogy* **2**, 451-478

[7] Avigad D, Garfunkel Z 1991 *Tectonophysics* **188**, 357-372

[8] Rosenbaum G, Avigad D, Sanchez-Gomez M 2002 *J. Structural Geology* **24**, 1451-1462

[9] Keiter M, Piepjohn K, Ballhaus C, Bode M, Lagos M 2004 J. *Structural Geology* **26**, 1433-1445

[10] Putlitz B, Cosca M A, Schumacher J C 2005 *Chemical Geology* **214**, 79-98

[11] Ravna, E J K, Terry M P 2004 *J. of Metamorphic Geology* **22**, 579-592

[12] Connolly J A D 2005 *Earth and Planetary Science Letters* **236**, 524-541

[13] Holland, T J B, Powell, R 1998 *Journal of Metamorphic Geology* **16**, 309–343

[14] Peacock, S M 1993 *Geological Society of America Bulletin* **105**, 684-694

[15] Evans, B W 1990 *Lithos* **25**, 3-23

[16] Brady, J B, Able, L M, Cheney, J T, Sperry, A J, and Schumacher, J C 2001 *Geological Society of America Abstr. with Prog*. **33**, 250-251

[17] Bröcker M, Kreuzer H, Matthews A, Okrusch M 1993 *J. Metamorphic Geology* **11**, 223-240

[18] Brady J B, Markley M J, Schumacher J C, Cheney J T, Bianciardi G A 2004 *J. Structural Geology* **26**, 3-9

[19] Andriessen P A M, Boelrijk N A I M, Hebeda E H, Priem H N A, Verdurmen E A T, Vershure R H 1979 *Contributions to Mineralogy and Petrology* **69**, 215-225