Pseudomorphs after lawsonite as an indication of pressure-temperature evolution in blueschists from Syros, Greece

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INTRODUCTION

The high-pressure Eocene metamorphism found within the Cycladic blueschist belt is assumed to be a result of continental collision related to the northward subduction of the Apulian microplate beneath the Eurasian continent (Okrusch & Bröcker, 1990). A greenschist facies overprint related to Miocene extension destroyed evidence of the high-pressure metamorphism in many places in the Cyclades, but the island of Syros retains some of the highest grade, blueschist facies rocks in the Attic-Cycladic massif (Wijbrans et al., 1993). The thick sequences of continuous, repeated, Mesozoic marble, metabasite, and pelitic schist units of Syros are consistent with tectonic duplication of a thinner sequence of sedimentary beds, possibly in an accretionary wedge (Dixon and Ridley, 1987).

According to garnet-clinopyroxene thermometry, univariant reactions, and oxygen isotope calculations, the high-pressure metamorphism peaked at about 450-500 °C and 12-20 kbar (Okrusch & Bröcker, 1990). The mineral lawsonite is commonly found in blueschist facies assemblages such as those occurring in Syros. Previous researchers have noted the occurrence of pseudomorphs of clinozoisite + phengite/paragonite $\pm$ quartz after lawsonite in the glaucophane - epidote "glaucophanites" of Syros (Dixon, 1969; Okrusch *et al.*, 1978; cited by Okrusch & Bröcker, 1990). Fresh lawsonite also occurs in rocks on Syros. These observations suggest either a multi-stage metamorphic sequence or a bulk composition difference. This study seeks to reveal the relationship between the occurrence of lawsonite porphyroblasts and pseudomorphs after lawsonite in blueschists as well as glaucophane-free vein-like rocks of Syros.

METHODS

Although an attempt was made to sample rocks from diverse locations around the island and of a variety of types, all samples studied in detail are from the north end of the island, since the rocks from the south yielded very differently-textured pseudomorphs, which may in fact not be after lawsonite. Six samples were then selected for quantitative mineral chemistry analysis on a Zeiss Digital Scanning Electron Microscope (SEM) with a LINK Energy Dispersive Spectrometer (EDS); electron microprobe analyses are considered accurate to within $\pm$2%. The EDS was used to generate x-ray maps depicting variation in levels of certain elements across a pseudomorph. The SEM also produced photographs of mineral compositions and fine-grained textures.

RESULTS

Although the rocks studied contain epidote, clinozoisite and zoisite, the members of the epidote family will not be distinguished, and will be heretofore referred to as epidote. Epidote-phengite-albite pseudomorphs of lawsonite occur in rocks with epidote + phengite $\pm$ glaucophane, garnet, quartz, paragonite, calcite, titanite, rutile, ilmenite. In hand sample, pseudomorphs range in color from grey to pale green-yellow, in size from 0.2-1cm, and in habit from euhedral rhombs and prisms to anhedral ameboid porphyroblasts. The pseudomorphs contain epidote + albite + phengite $\pm$ paragonite, garnet, quartz, pumpellyite, rutile, ilmenite. They range in composition from white mica-rich (figure 1?) to epidote-rich (figure 2?). Some pseudomorphs retain remnant lawsonite. In some such pseudomorphs, a few original crystal faces are intact (figure 3?); in others remnant lawsonite is anhedral and patchy, but optically continuous for 1-2mm. A glaucophane-free rock with the assemblage epidote + phengite + paragonite + albite + quartz also contains lawsonite grains that are ameboid, anhedral, poikilitic, optically continuous over 8mm, and occur within a pseudomorph (figure 4?). Inclusions are quartz, phengite, and epidote. In the field this glaucophane-free rock occurred as a 30cm wide vein running through glaucophane-rich rock.

As shown in Figure 5?, the Na-amphiboles of the rocks studied plot in the glaucophane quadrant, with average XFe^{2+} values of 21.7% and XFe^{3+} average values of 20.1%. Fe^{3+} values were calculated with the assumption that the A-site is empty except for K. Phengite has silica content as high as 3.6 Si pfu, a testament to the high pressure these rocks have experienced. The Fe^{3+} content of the epidote ranges from .02-.75 Fe^{3+} pfu.

Zoning is common in the epidote. In some samples epidote has greater Fe^{3+} at the core; in others the higher Fe^{3+} epidote is found on the rims of grains. In still other samples patches of higher Fe^{3+} epidote are randomly distributed throughout grains. Garnet is composed of 52% almandine, 28% grossular, 13% spessartine, 7% pyrope component (Figure 6?). Garnet in some samples is zoned, with almandine and pyrope-rich cores (Figure 7?), whereas in other samples the garnet is homogeneous. Clinopyroxene is omphacitic with 43% jadeite, 42% diopside + hedenbergite, and 14.5% acmite (Figure 8?).

Attempts to place constraints on the temperature and pressure of the pseudomorph assemblages met with moderate success. Using garnet + clinopyroxene as a thermometer and albite + quartz + jadeite as a barometer, a temperature range of 320-350 °C and a pressure range of 7.5-9 kbar was found (Figure 9?). The pressure is low, and likely reflects the possibility either that the albite results from a retrograde mineral assemblage, or that the few quartz grains identified in the rock are not in equilibrium with the rest of the assemblage. The absence of albite would make these values minimum estimates.

One sample has a garnet with inclusions of titanite that are aligned in a pattern suggestive of a preexisting fabric (Figure 10?). The garnet itself is included within a pseudomorph with no fabric, which indicates that these rocks have undergone multiple metamorphic events. At least some of the rocks in which the lawsonite crystals originally grew must have already undergone enough stress to create a fabric, over which the garnet, and then the lawsonite grew. The complex zoning found in many of the epidotes also lends support to a multi-stage theory.

DISCUSSION

Pseudomorphs after lawsonite occur in rocks with the assemblage glaucophane + epidote + phengite. Surviving lawsonite occurs in rocks with the assemblage epidote + phengite + quartz. Because this relationship holds in most of the rocks studied, it is likely that the presence or absence of lawsonite is a result of bulk composition differences in the rocks. Figure 11 shows how the equilibrium mineral assemblages of four different bulk compositions plotted on a mineral compatibility diagram change after the non-terminal discontinuous reaction lawsonite + glaucophane <=> chlorite + paragonite + zoisite takes place. Before the reaction, rocks 2 and 4 have the assemblage glaucophane + zoisite + lawsonite. Afterwards, rock 2 has the assemblage glaucophane + zoisite + chlorite, while rock 4 has the assemblage zoisite + chlorite + lawsonite. These assemblages are similar to those of the rocks from Northern Syros.

This model works well to describe the kind of phenomena observed in the rocks studied. However, there are three problems associated with it. The first problem is the prominence of chlorite in the model's reaction in comparison to its prominence in the rocks studied. Although chlorite is present in the rocks in small amounts, it is not clear that it is part of the equilibrium mineral assemblage. The second concern is the omission of albite from the model. Albite occurs in many of the pseudomorphs, seemingly in greater quantities than chlorite. It is possible that the occurrence of albite could be the result of greenschist overprinting, but the textural relationships are ambiguous.

The final problem with this model is its simplicity. One sample studied (7A) has the reaction assemblage glaucophane + epidote + lawsonite. A possible explanation for this rock supposes that additional components such as Fe^{2+}/Fe^{3+} extend the range of pressures and temperatures over which the reaction glaucophane + lawsonite <=> chlorite + paragonite + zoisite occurs, making the reaction continuous. If this were the case, it would be possible for the reaction to occur in Fe-rich rocks while not taking place in more Mg-rich rocks. The data for sample 7A are not completely consistent with this explanation, despite the elegance of the theory.

Because the model reaction has a positive slope on a P-T diagram, the production of lawsonite pseudomorphs is consistent with prograde metamorphism during decompression (Schumacher, personal communication.). This is similar to the conclusion of Okrusch, et al., in pyroxene-bearing rocks.

REFERENCES CITED

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Dixon, J. E. & Ridley, J., 1987, Syros (filed trip excursion), *in* Helgeson, H. C., ed., Chemical transport in metasomatic processes, Nato Advanced Study Institutes Series, Series C, pp. 489-500, D, Reidel Publishing Company, Dordrecht.

Figure 1. White mica-rich pseudomorph (crossed polars)

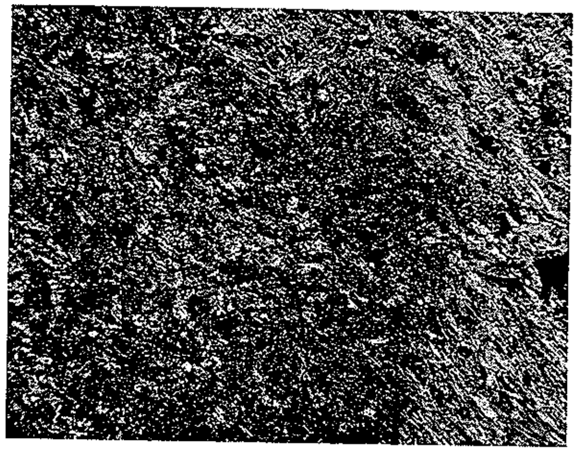

Figure 2. Epidote-rich pseudomorph (crossed polars)

Figure 3. Pseudomorph with remnant lawsonite (crossed polars)

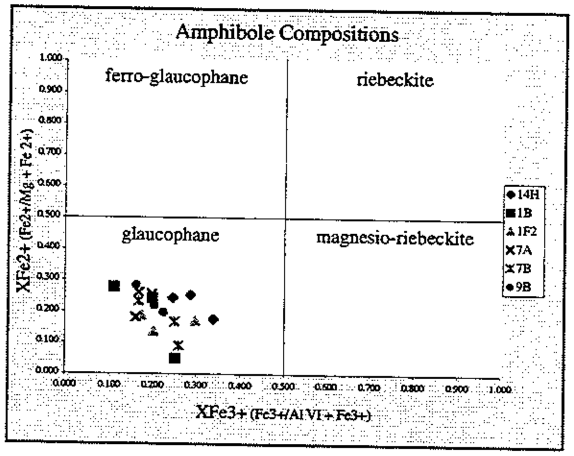

Figure 4. Na-amphiboles plot in glaucophane quadrant.

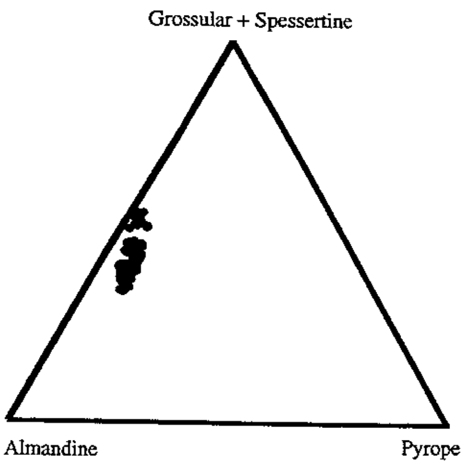

Figure 5. Garnet has little Pyrope.

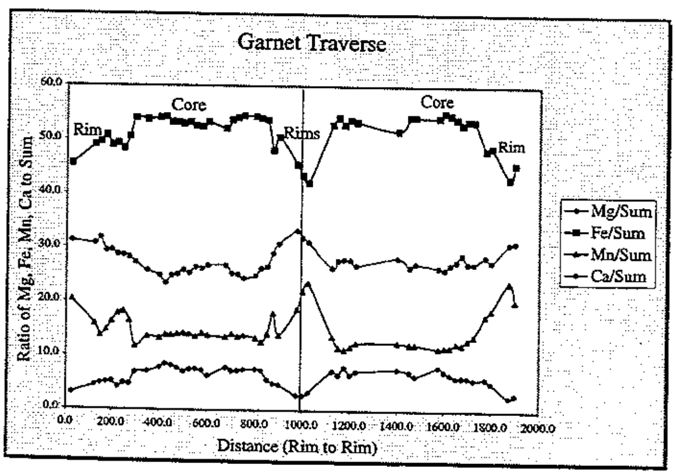

Figure 6. Garnets have higher Mg and Fe in the cores.

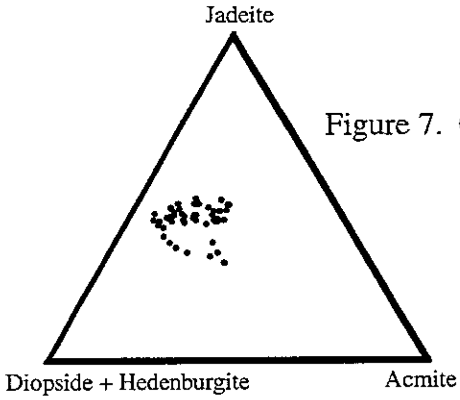

Figure 7. Clinopyroxenes are omphacitic.

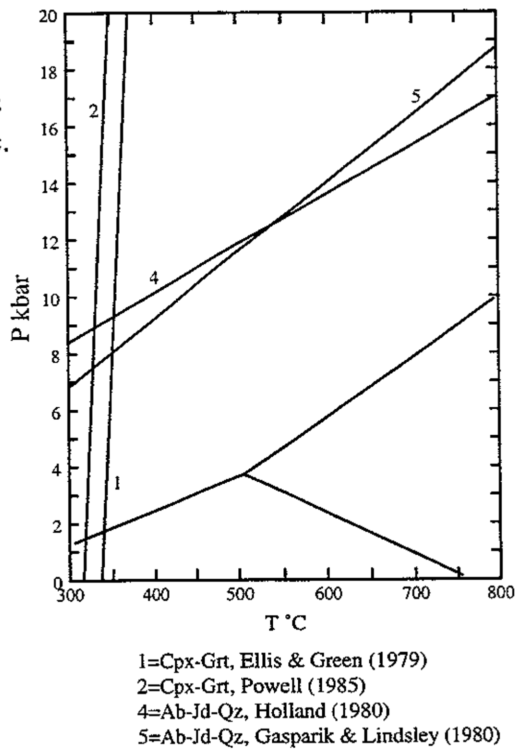

Figure 8. Geothermobarometry indicates a temperature range of 320-350 °C and a pressure range of 7.5-9 kbar for the pseudomorph assemblage.

Figure 9: Photomicrograph under crossed polars of garnet within pseudomorph that has titanite inclusions indicative of a preexisting fabric.

Figure 10. Note how the equilibrium assemblages of the starred bulk compositions numbered 1-4 change when the tie-line flips. (From Schumacher, 1999)