

Exhumation of the high-pressure northwestern Cyclades, Aegean: New thermodynamic data from Penteli mountains

A.L. Holm¹, I. Baziotis², S. Klemme¹, J. Berndt¹

(1) University of Muenster, Muenster, Germany, a_holm04@uni-muenster.de (2) Agricultural University of Athens, Iera Odos str. 75, 11855, Athens, Greece

Introduction

The Attic-Cycladic Crystalline Belt (ACCB) is one of the well-studied regionally metamorphosed provinces (under high-pressure/low-temperature conditions) worldwide (e.g., Ring *et al.*, 2010). It is formed as a result of major extensional collapse of the Alpine orogenic belt in the Aegean that resulted from the collision between the Eurasian plate and Gondwana-derived fragments in the Cenozoic (e.g., Jolivet and Brun, 2010). The ACCB underwent high-pressure/low temperature (HP/LT) blueschist to eclogite facies metamorphism in the period ca. 50–40 Ma, and greenschist-amphibolite facies overprint in ca. 25–20 Ma (e.g., Laurent *et al.*, 2017 and references therein). The northwesternmost extension of ACCB is represented by Penteli area where two major units are exposed: the upper tectonic unit (UTU) and lower tectonic unit (LTU). In this study, we focus on metapelitic lithologies and provide new geothermobarometric data (pseudosections) that constrain peak and post-peak P-T evolution of the LTU of Penteli area in western ACCB.

Analytical Methods

We have performed detailed characterization of 10 metapelitic samples for their texture and mineral chemistry. Major element compositions on minerals were determined in polished thin sections (Fig. 1) using a JEOL JXA 8900 Superprobe EPMA equipped with four wavelength-dispersive spectrometers at the Agricultural University of Athens (Athens, Greece). All analyses were performed with an accelerating voltage of 15 kV, 15 nA, focused beam for all minerals except for beam sensitive minerals where the beam was slightly defocused (5 μ m diameter). Counting times were 20 s on peak and 10 s on background positions. Natural mineral standards used were quartz (Si), corundum (Al), diopside (Ca), jadeite (Na), olivine (Mg), fayalite (Fe), spessartine (Mn), orthoclase (K), ilmenite (Ti), chromite (Cr), apatite (P) and Ni-oxide (Ni) obtained from the Smithsonian Institute.

Whole-rock major element concentrations were determined on fused beads, using the X-ray fluorescence (XRF) wavelength spectrometer (Panalytical PW-2400) of the accredited according to EL0T EN ISO/IEC 17025:2005 biogeochemical laboratory of the Hellenic Centre for Marine Research. Major elements were determined as oxides following the procedure described in Karageorgis *et al.* (2005).

Results

The LTU schists are pervasively foliated and are divided into five types (based on the predominant matrix assemblage): calcite-chlorite-garnet (type-I), chloritoid-phengite (type-II), chlorite-phengite (type-III), paragonite-chlorite-phengite (type-IV) and paragonite-chloritoid-phengite (type-V) schists. The type-I schists and marbles are the predominant lithologies in the Penteli LTU. Mineral assemblages of type-I contain calcite + quartz + chlorite + phengite + albite + garnet \pm zircon \pm apatite \pm titanite \pm opaques. The paragonite-bearing schists (type-IV and type-V) contain aligned chlorite, phengite and chloritoid growing in the main foliation; paragonite may occur as inclusions in chloritoid, too. In type-II and V, chloritoid porphyroblasts host chlorite + phengite inclusions.

The K-rich white micas are mainly phengites with Si ranging from 3.126 to 3.526 a.p.f.u.. The celadonite component ranges from 5.9 to 36.2%, pyrophyllite from 7.1 to 34.9% and paragonite is up to 15%. The X_{Mg} [$X_{Mg}=Mg/(Mg+Fe)$] of chlorites is in the range of 0.41–0.70, and the Si content of 2.51–2.84 a.p.f.u.. The clinocllore component ranges from 34 to 62% and the daphnite from 26 to 52%. The chloritoid is rich in iron with X_{Fe} [$Fe^{2+}/(Mn + Mg + Fe^{2+})$] in the range of 0.77–0.95. The paragonite composition is relatively homogeneous, and Si content ranges from 2.928 to 3.097 a.p.f.u., while X_{Na} [$X_{Na}=Na/(Na+K)$] from 0.878 to 0.980. Detailed mineral chemistry data can be found in Baziotis *et al.* (2019).

P-T pseudosections – Modeling approach

We used the bulk-rock compositions of three different rock types (II, III and IV) as an analogue for the representative rock types in this study. Pressure-Temperature isochemical phase diagrams (pseudosections) were calculated in the system SiO_2 – TiO_2 – Al_2O_3 – MgO – MnO – FeO – Fe_2O_3 – CaO – Na_2O – K_2O – H_2O , employing Perple_X software (ver. 6.8.6; 2019, Connolly, 2005, 2009) over the P-T range 0–14 kbar and 300–600 °C. The thermodynamic database of Holland & Powell (1998, updated 2002) was used for minerals. Solid solution models are included in the latest version of Perple_X: Gt(HP) for garnet (Powell and Holland, 1998), Omph(HP) for clinopyroxene (Holland and Powell, 1996), Pheng(HP) for phengite (Powell and Holland, 1999), Bio(HP) for biotite (Powell and Holland, 1999), Chl(HP) for chlorite (Holland *et al.*, 1998), Pl(h) for plagioclase, Ep(HP) for epidote (Powell and Holland, 1998), Ctd(HP) for chloritoid (White *et al.*, 2000), Act(M) for amphibole (Massonne and Willner, 2008), Mica(M) for K white mica (Massonne and Willner, 2008), Stlp(M) for stilpnomelane (Massonne and Willner, 2008), Pu(M) for pumpellyite (Massonne and Willner, 2008), and an ideal solid-solution model IlGkPy for ilmenite. Reflecting the selected solution models, Mn is considered as incorporated in garnet and ilmenite, thus precludes the possibility of garnet over-stability. The fluid phase was assumed to be pure H_2O , initially

in excess.

A caveat required by the pseudosection computations is the choice of the bulk-rock composition. In calculations based on whole-rock analysis (XRF method), the derived phase assemblage is assumed to represent equilibrium over the scale of a hand-specimen; for fine-grained rocks like those obtained from LTU of Penteli, the XRF compositions may represent a good proxy of the effective composition. Paralyzer operated under Matlab environment was used to run the build file (v1.6. Mark Caddick). Finally, we employed the WERAMI software (in Perple_X) to compute compositional and modal isopleths for specific solid solutions as was the PyWERAMI software for projection of the calculated isopleths.

Our pseudosection approach provides a unique frame of P-T conditions for a specific bulk-rock composition, but also serves as an ideal tool to derive the peak and post-peak metamorphic evolution. The variability of the rock composition even on a very small scale (hand-specimen or smaller) as clearly seen along the intense foliation can be depicted for different stable assemblages. Further, because mineral compositions are also controlled by bulk chemistry under various P-T conditions, each isopleth corresponding to different mineral solid solutions is also uniquely determined in terms of P-T values, range, and slope. Each was calculated separately for each rock type. We should note, that even though the phase assemblages depend on the fluid phase evolution (e.g., Wei and Clarke, 2011; Baziotis *et al.*, 2017), it is not the goal of the current study and we will apply such exercise on a future paper.

In the computed pseudosections, the main reactions, represented by a few univariant reactions, several narrow divariant, and wider trivariant, quadrivariant and quinvvariant fields, delimit the stability fields of chloritoid (ctd), chlorite (chl), epidote (ep), garnet (gt), zoisite (zo), plagioclase (pl), albite (ab), stilpnomelane (stp), omphacite (omp), actinolite (act), biotite (bi) and phengite (phg). Pumpellyite (pu) was not stable. Based on both observed (thin sections) and calculated mineral assemblages, a P-T history was derived from the different pseudosections for the three rock types. Detailed pseudosection calculations will be presented at the meeting.

Discussion and Conclusions

We provide new constraints from pseudosection modelling of three rocks from the LTU of Penteli, part of the northwestern extension of the ACCB. Data gathered from mineral compositions and assemblages, textural relationships, Perplex_X calculations (P-T pseudosections, isopleths) demonstrate that these rocks underwent HP/LT metamorphism. The studied LTU rocks underwent similar high-P/low-T conditions of formation, in which a distinct post-peak history characterized by heating along a clockwise P-T path is suggested; such rocks probably recrystallized within a subduction channel environment. The post peak T history is almost identical with the path proposed for the Syros rocks (see Laurent *et al.*, 2018). Both areas (Penteli and Syros) are characterized by heating during exhumation continuously from P~12 kbar, and then by cooling from P~8 kbar and onward. In this case, then the present position may suggest either a mechanism which incorporates lateral extension of ~ 100 km or the two areas where part of the same heterogeneous (Syros reached much deeper parts; ~35–40 difference for their maximum depth recorded in the two units) subduction/exhumation system but at different places in the horizontal scale (Baziotis *et al.*, 2019).

Acknowledgements

We greatly thank Dr. A. Karageorgis for performing the XRF analyses at the Hellenic Centre for Marine Research (HCMR).

References

- Baziotis, I., Tsai, C.H., Ernst, W.G., Jahn, B.M., Iizuka, Y., 2017. New P–T constraints on the Tamayen glaucophane-bearing rocks, eastern Taiwan: Perple_X modelling results and geodynamic implications. *Journal of Metamorphic Geology* 35(1), 35–54.
- Baziotis, I., Proyer, A., Mposkos, E., Windley, B., Boukouvava, I., 2019. Exhumation of the high-pressure northwestern Cyclades, Aegean: New PT constraints, and geodynamic evolution. *Lithos* 324, 439–453.
- Connolly, J.A.D., 2005. Computation of phase equilibria by linear programming: tool for geodynamic modelling and its application to subduction zone decarbonation. *Earth and Planetary Science Letters* 236, 524–541.
- Connolly, J.A.D., 2009. The geodynamic equation of state: what and how. *Geochemistry, Geophysics, Geosystems* 10, doi: 10.1029/2009GC002540 (Q10014).
- Holland, T., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of metamorphic Geology* 16(3), 309–343.
- Jolivet, L., Brun, J.P., 2010. Cenozoic geodynamic evolution of the Aegean. *International Journal of Earth Sciences* 99, 109–138.
- Karageorgis, A.P., Anagnostou, C.L., Kaberi, H., 2005. Geochemistry and mineralogy of the NW Aegean Sea surface sediments: implications for river runoff and anthropogenic impact. *Applied Geochemistry* 20(1), 69–88.
- Laurent, V., Huet, B., Labrousse, L., Jolivet, L., Monie, P., Augier, R., 2017. Extraneous argon in high-pressure metamorphic rocks: distribution, origin and transport in the Cycladic Blueschist Unit (Greece). *Lithos* 272, 315–335.
- Massonne, H.J., Willner, A.P., 2008. Phase relations and dehydration behaviour of psammopelite and mid-ocean ridge basalt at very-low-grade to low-grade metamorphic conditions. *European Journal of Mineralogy* 20(5), 867–879.
- Powell, R., Holland, T., Worley, B., 1998. Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *Journal of metamorphic Geology* 16(4), 577–588.
- Powell, R., Holland, T., 1999. Relating formulations of the thermodynamics of mineral solid solutions; activity modeling of pyroxenes, amphiboles, and micas. *American Mineralogist* 84(1–2), 1–14.
- Ring, U., Glodny, J., Will, T., Thomson, S., 2010. The Hellenic subduction system: High pressure metamorphism, exhumation, normal faulting, and large-scale extension. *Annual Review of Earth and Planetary Sciences* 38, 45–76.
- Wei, C.J., Clarke, G.L., 2011. Calculated phase equilibria for MORB compositions: a reappraisal of the metamorphic evolution of lawsonite eclogite. *Journal of Metamorphic Geology* 29, 939–952.
- White, R.W., Powell, R., Holland, T., Worley, B.A., 2000. The effect of TiO₂ and Fe₂O₃ on metapelitic assemblages at greenschist and amphibolite facies conditions: mineral equilibria calculations in the system K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–Fe₂O₃. *Journal of Metamorphic Geology* 18(5), 497–511.