Application of The Titanium-In-Quartz Thermobarometer to Eclogites from The Biga Peninsula, NW Turkey

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Abstract. Eclogites crop out in the Çamlıca metamorphics and beneath the Çetmi melange as a tectonic slice in the Biga Peninsula in northwest Turkey. The Çamlıca metamorphics occur in the westernmost part of the Biga Peninsula and are tectonically separated from the Denizgören ophiolite in the west by the Ovacık fault. The Çetmi melange found on the southern part of the Biga Peninsula is mainly composed of various types of blocks within a detritic matrix. The high-P assemblages in eclogite consist of omphacite + garnet + epidote + glaucophane + quartz + phengite. Typical accessory minerals are rutile, zircon and sphene. Ti-in-quartz thermobarometer (TitanQ) was applied on eclogites from the Biga Peninsula. The P–T dependencies of Ti-in-quartz solubility can be combined with P–T dependencies of Zr-in-rutile solubility to estimate pressure and temperature of crystallization. Titanium concentrations in quartz from the Çamlıca metamorphics range from 0.26 to 0.91 ppm. Zirconium concentrations in rutile range from 26 to 64 ppm. However, Ti contents in quartz from the Çetmi melange vary from 0.47 to 2.19 ppm. Zr contents in rutile range between 50 and 150 ppm. Regional high-P metamorphism with peak conditions of 551 ± 5 °C and 21.5 ± 0.3 kbar in eclogite from the Çamlıca region and 624 ± 17 °C and 22.6 ± 1.6 kbar in eclogite from the Çetmi region. Ti-in-quartz thermobarometer gives precise and comprehensible pressure and temperature values when using the Zr-in-rutile thermobarometer, which could be an advantage over classical methods.

1. Introduction
Quartz is a common mineral in igneous, metamorphic, hydrothermal and sedimentary rocks, which attests to its stability over a wide range of P-T conditions. Quartz has been widely used to estimate temperatures of crystallization in metamorphic rocks. Trace element geochemistry of quartz has recently been used for thermobarometry purposes [1]. Recently, the solubility of Ti in quartz has been calibrated experimentally, resulting in the Ti-in-quartz (TitanQ) thermobarometer, and can be used to obtain P-T estimates of crystallization [1, 2, 3]. Ti-in-quartz solubility is strongly dependent on pressure and temperature. P–T dependencies of Ti-in-quartz solubility can be combined with P–T dependencies of Zr-in-rutile solubility [4], which can be simultaneously used to estimate a crystallization of pressure and temperature.

The pressure dependence of the Ti-in-quartz thermometer makes it potentially a powerful barometer for eclogites. The Biga Peninsula in northwest Turkey hosts exposures of high pressure –
low-temperature (HP/LT) rocks that have variable green schist-facies overprinting (Figure 1). The P-T conditions of eclogites have been estimated in a wide range [5, 6, 7]. The aim of this study is to apply the Ti-in-quartz thermobarometer for constraining pressure and temperature conditions of eclogites from the Biga Peninsula. In this paper, we present new data on P-T evolution of eclogites from localities on the western and southern part of the Biga Peninsula.

![Figure 1](image_url)

**Figure 1.** Simplified tectonic map of the Eastern Mediterranean region indicating the major geotectonic units and the bounding sutures, modified from [8, 9]

## 2. Background

### 2.1. Geological Setting

The Biga Peninsula at the western end of the Sakarya Zone is bordered to the north by the Strandja Massif and the Thrace Basin, and the Aegean Sea marks the western and southern borders (Figure 1). The Biga Peninsula in NW Turkey is characterized mostly by plutonic and associated volcanic rocks, ophiolites and amphibolite to granulite facies metamorphic rocks.

High-P metamorphic rocks crop out in the Çamlıca metamorphics and beneath the Çetmi melange as a tectonic slice (Figure 2a). The Çamlıca metamorphics occur in the westernmost part of the Biga Peninsula and are tectonically separated from the Denizgören ophiolite in the west by the Ovacık fault [5]. The Çamlıca metamorphics are subdivided into three formations, from bottom to top; the Andıktaşı formation, the Dedetepe formation and the Salihler formation. Eclogite-facies metamorphic rocks occur as tectonic lenses within schist-marble intercalations of the Dedetepe formation (Figure 2b). Rb–Sr phengite ages of eclogite-facies rocks in the Çamlıca metamorphics range from 65 to 69 Ma, which is interpreted as the age of HP/LT metamorphism [5].

The Çetmi melange found on the southern part of the Biga Peninsula is mainly composed of various types of blocks within a detritic matrix (Figure 2c). Outcrops of eclogite are seen as a tectonic slice between the Kazdağ Massif and Çetmi melange. The rocks in the Çetmi melange mainly consist of spilitized mafic volcanic rocks, blocks of Upper Triassic neritic and pelagic limestones, greywacke-shale matrix, minor radiolarian chert and serpentinite/listvenite slices [10, 11] and are unmetamorphosed. The Çetmi melange is unconformably overlain by various types of Neogene
sedimentary and volcanic rocks. Garnet-clinopyroxene Rb–Sr phengite ages from two eclogite samples in the Çetmi region gave a Lower Cretaceous age of ~100 Ma [6].

2.2. Petrography
The high-P assemblages in eclogite consist of omphacite + garnet + epidote + glaucophane + quartz + phengite (Figure 3a). Typical accessory minerals are rutile, zircon and sphene. Euhedral, relatively large (2–8 mm) porphyroblasts of garnet, are scattered through a fine-grained matrix, and contain inclusions of mainly quartz, epidote, phengite, glaucophane, Ca-amphibole and rutile (Figure 3b).

Omphacite is finely grained and forms up to 2 mm long crystals in the matrix. They are widely enclosed by rims of calcic amphibole developed during retrograde overprint. Sodic-amphibole in eclogite is glaucophane in composition, and is typically fine grained and aligned with omphacite in the matrix (Figure 3a). Glaucophane is commonly elongated with tiny sphene inclusions. Glaucophane crystals are rimmed and partially replaced by Ca-amphibole. Glaucophane inclusions in garnet also show that glaucophane was present as a matrix phase in the eclogite stage. Most rutile grains are mantled by titanite. Ca-amphibole and chlorite occur in eclogite as secondary phases that are not equilibrium with the high-P phases.
2.3. Methods

Samples were prepared for trace element as polished thin sections about 50 µm. The in situ trace element analyses of quartz and rutile were performed on prepared thick sections at the Department of Earth Sciences at the University of Gothenburg. All samples were analysed using New Wave NWR 213 laser ablation system coupled to an Agilent 8800 QQQ quadrupole ICP-MS.

Before analysing, polished thin sections have been placed into the sample holder. Trace elements of quartz were analyzed using laser beam diameter of 50 µm at laser energy of ~ 30 J/cm² and a repetition rate of 4 Hz. Signals were recorded over 50 s for each spot. The first 10 s were used for acquiring background substraction during laser warm-up. The following 30 s of dwell time were used for analysis of the sample by the ablation of quartz. The last 10 s were used for wash out. 7Li (09 ms dwell time), 23Na (11 ms dwell time), 24Mg, 27Al, 28Si, 48Ti (12 ms dwell time), 56Fe, 57Fe (13 ms dwell time) were analysed for trace element concentration in quartz. NIST SRM 610 [14] was used as primary standard. BCR-2G [15] was used as secondary standard. 28Si was used as internal standard element for all analyses. Trace elements in rutile were analysed using laser beam diameter of 12 µm at laser energy of ~ 7.7 J/cm² and a repetition rate of 5 Hz. Signals were recorded over 60 s for each spot. The first 20 s were used for acquiring background substraction during laser warm-up. The following 30 s of dwell time were used for analysis of the sample by the ablation of rutile. The last 10 s were used for wash out. 27Al, 51V, 53Cr, 57Fe, 178Hf, 181Ta, 232Th (10 ms dwell time), 49Ti, 93Nb (5 ms dwell time) and 90Zr, 238U (30 ms dwell time) were analysed for trace element concentration in rutile. Each standard block is composed of two analyses of the R10 rutile standard and two analyses of NIST SRM 610 glass standard. Titanium measured as 49Ti was used as internal standard element for all analyses. 90Zr was used to determine the Zr concentration of rutile. The glass reference material NIST SRM 610 [14] and R10 [16] rutile was used for external calibrations. The concentrations of element were determined using “GLITTER version 4.4.4” software program (On-line interactive data reduction for LA-ICPMS microprobe [17]. Ti and Si contents during data reduction was initially assumed to be 100 wt % TiO₂ and SiO₂.

3. Results and Discussions

Titanium concentrations in quartz from the Çamlıca metamorphics range from 0.26 to 0.91 ppm. Zirconium concentrations in rutile range from 26 to 64 ppm. Ti in quartz and Zr in rutile values have been plotted as isopleths on a P-T diagram (Figure 4a). The intersection of the isopleths can be used to infer average P-T conditions of around 551 ± 5° C and 21.5 ± 0.3 kbar. On the other hand, Ti contents in quartz from the Çetmi melange vary from 0.47 to 2.19 ppm. Zr contents in rutile range between 50 and 150 ppm. Figure 4b indicates a P-T diagram for eclogite samples with the range of Ti in quartz and Zr in rutile values plotted as isopleths. If it is assumed that both the quartz and the rutile crystals equilibrated at the peak of metamorphism, then the intersection of the isopleths can yield the average
P-T conditions of around 624 ± 17 °C and 22.6 ± 1.6 kbar. The P-T conditions estimated by using Ti-in-quartz thermobarometry are consistent with the previous P-T conditions. High-P metamorphism with peak conditions of 550–675 °C and 16–22 kbar in eclogite from the Çamlıca metamorphics and 575–700 °C and 17–24 kbar in eclogite from the Çetmi metamorphics [7]. These P-T conditions are constrained on a wide range. However, Ti-in-quartz thermobarometry yielded precise P-T conditions unlike previous results.

4. Conclusions
Eclogites expose on the Biga Peninsula occurring on the westernmost part of the Sakarya Zone. P-T conditions of eclogites from the Çamlıca and Çetmi region are estimated by using Ti-in-quartz thermobarometer. The most straightforward application of the Ti-in-quartz thermobarometer will be to rocks that contain rutile. Regional high-P metamorphism with peak conditions of 551 ± 5 °C and 21.5 ± 0.3 kbar in eclogite from the Çamlıca region and 624 ± 17 °C and 22.6 ± 1.6 kbar in eclogite from the Çetmi region. Ti-in-quartz thermobarometer is the best choice for P-T calculation. Ti-in-quartz thermobarometer yielded pressure-temperature estimates for eclogites consistent with previous P-T estimations.

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