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Multiple subduction cycles in the Alpine orogeny, as recorded in single zircon crystals (Rhodope zone, Greece)

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ABSTRACT

High- and ultrahigh-pressure metamorphic crustal rocks in orogenic belts provide evidence for subduction into the mantle and subsequent exhumation. The timing of metamorphism(s) of complex high- and ultrahigh-pressure rocks can be registered in the robust mineral zircon, able to preserve different growth generations. Here we present sensitive high resolution ion microprobe (SHRIMP) U–Pb age and REE compositional data from zircon in migmatitic gneisses from the ultrahigh-pressure Kimi unit of the Alpine Rhodope zone (Greece). Single zircon crystals preserve one to two magmatic (one inherited and one syn-magmatic) and two to three metamorphic generations. The $^{206}Pb/^{238}U$ ages, combined with REE zircon data, mineral inclusions in metamorphic zircon, petrological data from the matrix assemblages, as well as pseudosection calculations are interpreted to reflect Permian crystallization of the protolith of the studied gneisses and subsequent repeated subductions to high pressures over the course of the Alpine orogeny (at ~158 Ma, suggested to be close to the time of ultrahigh-pressure metamorphism; at ~74 Ma, and possibly also at ~42 Ma). This inference stands in contrast to the general thinking about subduction/exhumation cycles during Alpine-type orogenesis along a single path and is in line with recent simulation results about repeated subductions. The recognition of two distinct high-pressure subduction cycles within the Alpine orogeny in a time frame of ~80 Ma (and the indication of an additional subduction cycle ~30 Ma later) in the same zircon crystal is remarkable. It provides evidence for repeated deep subductions over longer (~80 Ma) and possibly also shorter (~30 Ma) frequencies and emphasizes the view that lithospheric plate collision/subduction during the Alpine orogeny in the Rhodope zone does not have to be a continuous, protracted process. A regime of repeated subduction/exhumation events involving micro-continental fragments intervening between the European and Adriatic margins may be rather responsible for the different (U)HP age clusters in the Rhodope zone.

1. Introduction

In Alpine-type orogenic belts, part of the subducted crust can reach great depths before being exhumed to the Earth's surface. Exhumed high-pressure (HP, >ca. 40 km) and ultrahigh-pressure (UHP, >ca. 75 km to over 130 km) (Chopin, 1984; Liu et al., 2007) rocks can provide valuable information on the pressure–temperature (PT) path that they experienced adding important insight into plate tectonic mechanisms.

The whole process of subduction and exhumation is generally thought to take place within the framework of a single path involving formation of HP and possibly UHP rocks ((U)HP)[1] and metamorphic overprint during rapid or slow decompression. Recent developments, however, based on numerical simulations examining the polymetamorphic origin of (U)HP rocks question this view (e.g., Li and Gerya, 2009; Roda et al., 2010; Gerya, 2011). Simulation results and comparison with natural data suggest a direct relationship between mantle rheology and the amount of recycled crustal material, implying that crustal rocks in a hydrated mantle-wedge can be recycled more than once during a subduction cycle (e.g., Roda et al., 2010; Blanco-Quintero et al., 2011; Roda et al., 2012). Polymetamorphic HP–UHP terranes comprising tectonic units with variable ages and peak metamorphic conditions, such as the Sulu UHP terrane in eastern China were also considered in geodynamic simulations (Li and Gerya, 2009). The results indicate that there can be a series of consecutive episodes of exhumation of (U)HP rocks related to the cyclic origin of the subduction–detachment–exhumation processes of continental crust. On the other hand, natural findings on repeated high-PT subduction

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[1] Hereafter, "(U)HP" stands for "high pressure and possibly ultra-high pressure".

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cycles are described for the Sambagawa metamorphic belt (Kabir and Takasu, 2010), while 'yo-yo tectonics' with two HP events are suggested for Central Anatolia (Whitney et al., 2008) and the Sesia zone in the Central Alps (Rubatto et al., 2011).

A major issue is, therefore, whether (U)HP rocks that were subducted and exhumed along a single PT loop can be again subducted to HP or UHP depths and return to the surface within the framework of the same orogeny. And, if so, what would be the time frame between different subduction cycles? To answer this question the absolute dating of metamorphic (U)HP rocks with solid geochronological methods is fundamental.

A key mineral able to record the polymetamorphic time history of (U)HP rocks is zircon, as it is robust at high temperatures and pressures, resistant to alteration and able to develop and preserve different domains within the same crystal corresponding to different stages of formation. The sensitive high resolution ion microprobe (SHRIMP) technique can provide spatially-resolved, high quality data on the age and trace/REE composition of complexly zoned zircon crystals. U–Pb age and trace/REE data of zircon combined with petrological information (including mineral inclusions in zircon) offer a highly promising approach toward recognizing and dating multiple subduction/exhumation cycles. This holds especially true for felsic and intermediate rocks, which represent a large part of the subducted continental crust and often fail to register the HP metamorphic history in their matrix assemblages (e.g., Heinrich, 1982). Rather they provide information on the late stages of metamorphism. Detailed petrological study and microtextural information from felsic rocks, combined with pseudosection calculations can provide additional knowledge about their metamorphic evolution (e.g., Massonne, 2009; St-Onge et al., 2013). However, part of the metamorphic history of the rocks, especially the early stages, may still remain 'hidden' and the petrological inferences alone may be misleading. This missing information may be gleaned from detailed examination of zircon. Zircon is abundant in felsic rocks and has the potential of providing insight into metamorphic reactions at the time of growth through the variability in its trace element composition and REE patterns (e.g. lack of a negative Eu anomaly is indicative of prevailing high pressures; e.g., Rubatto, 2002; Hoskin and Schaltegger, 2003; Mattinson et al., 2009). Zircon is also an excellent capsule of mineral inclusions, some of which allow calculation of PT conditions (e.g. McClelland and Lapen, 2013 and references therein).

This paper presents the temporal and petrological history of migmatitic gneisses in the Kimi unit of the UHP Rhodope Zone (Fig. 1), in an attempt to unravel the complexity of subduction and possible re-subduction processes during Alpine orogenic development. For this purpose, SHRIMP U–Pb analyses of zircon were carried out at the Research School of Earth Sciences, The Australian National University, Canberra and trace element/REE analyses at the Geological Survey of Canada, Ottawa.

2. Geological overview and previous geochronology of the Rhodope zone

During the Alpine orogeny, convergence between the European and African plates, as well as intervening oceanic crust and continental fragments led to subduction and collision. The Rhodope zone, which lies tectonically between the Hellenic–Dinaric thrust belt to the WSW and the Balkanides to the north (Fig. 1), represents part of the Alpine orogen in the Eastern Mediterranean region. It comprises a series of metamorphic thrust units with HP and partly UHP metamorphic rocks, thus offering an excellent natural laboratory for the study of subduction–exhumation processes. There is an extensive nomenclature regarding the subdivision of the Rhodope in different tectonometamorphic units

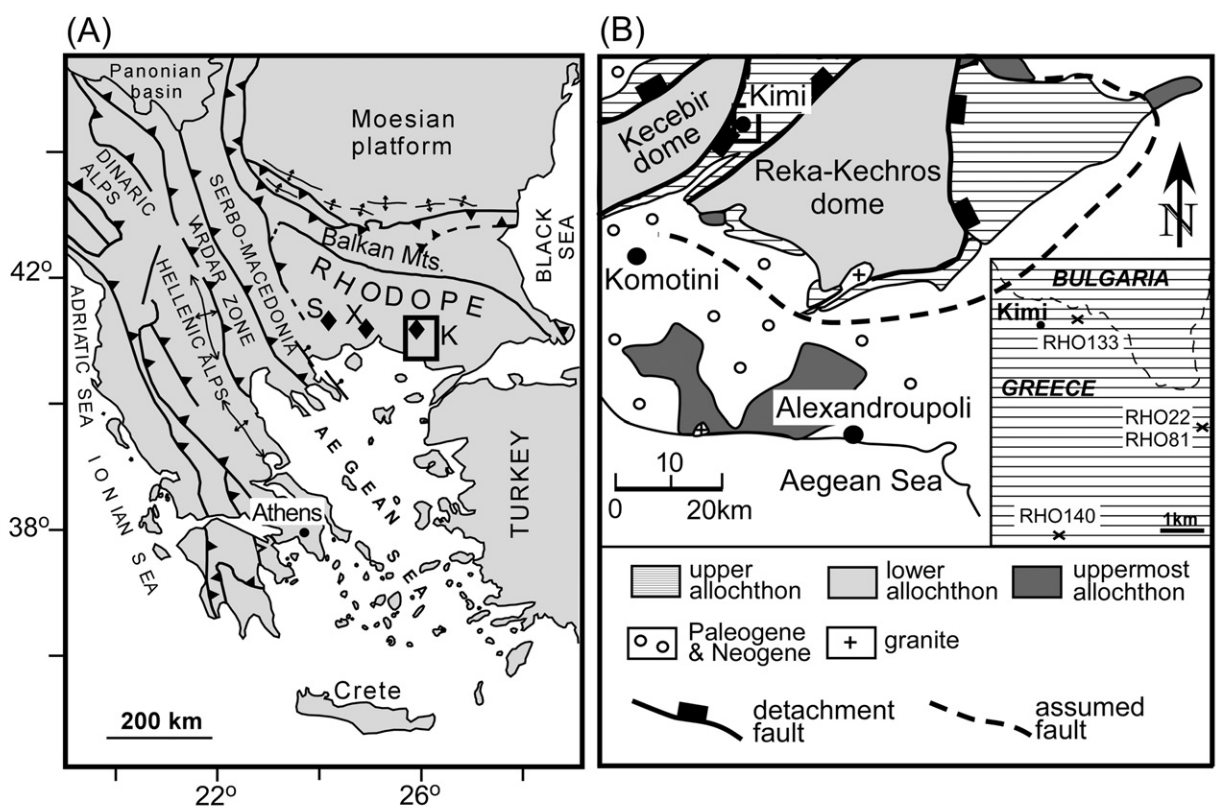

Fig. 1. (A) Location of Rhodope in the East Mediterranean region. Black diamonds denote locations of UHP metamorphism as follows: S: Sidironero area (Schmidt et al., 2010); X: Xanthi area (Mposkos and Kostopoulos, 2001); K: Kimi area (Mposkos and Kostopoulos, 2001; Liati et al., 2002; Perraki et al., 2006); (B) simplified map of the study area corresponding to the square in (A) (from Liati et al., 2011; Kirchenbaur et al., 2012). Inset sketch in (B) corresponds to the square in Kimi area and shows the geographic location of the samples referred in the text.