Lithos 144–145 (2012) 88–108

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Heterogeneous extrusion and exhumation of deep-crustal Variscan assembly: Geochronology of the Western Tatra Mountains, northern Slovakia

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ARTICLE INFO

Article history:
Received 21 September 2011
Accepted 31 March 2012
Available online 6 April 2012

Keywords:
Geochronology
Thermochronology
Eclogite
Migmatite
Exhumation
Variscan

ABSTRACT

The nature and style of mid-crustal assembly and exhumation during continental collision has been investigated in the Tatra Mountains of the Western Carpathians. The pre-Alpine basement of the Western Carpathians represents the easternmost exposure of the Variscan orogen in Europe, which marks the collision of Laurasia with Gondwanian-affiliated terranes during the Palaeozoic. The Tatric crystalline unit of the Western Tatra in northern Slovakia displays an inverted metamorphic sequence where a high-grade unit comprising migmatites with relicts of eclogite has been thrust over a lower-grade mica schist unit. New geochronological and thermochronological data together with published thermobarometry illuminate the metamorphic history of the Western Tatra. The Upper Unit eclogites with occasionally preserved omphacite record near isothermal decompression from 1.6 GPa to 1.0–1.2 GPa at 750–800 °C which lead to intensive re-equilibration at high-pressure granulite facies conditions, comparable to the peak metamorphic conditions of the host migmatite. Both eclogite and migmatite shared a retrograde P–T path following the insertion of the eclogite assemblage into the migmatites. The metamorphic evolution of the Lower Unit mica schist is constrained to peak P–T conditions of 0.6–0.8 GPa and 640 and 660 °C followed by retrogression. This suggests that different rock types of the Western Tatra metamorphic core shared only their exhumation path from mid-crustal levels. ID-TIMS Sm–Nd dating of garnet from eclogite yields a whole rock-garnet isochron age of 337 ± 10 Ma, with an initial ε_{Nd} isotopic composition of +8.3. In situ U–Pb dating of monazite from a migmatite surrounding the eclogite shows one age population of c. 380 Ma whereas monazite from a migmatite away from the eclogite preserves a robust 340 ± 11 Ma age which is indistinguishable from Sm–Nd garnet age and U–Pb age of zircons in the anatectic leucosome of the migmatite (347 ± 7 Ma). A younger monazite age population from the migmatite of 300 ± 16 Ma is consistent with $^{40}Ar/^{39}Ar$ mica ages of c. 310 Ma. This argues for a contemporaneous, and likely shared, exhumation path of the assemblage pair. In situ monazite total-Pb analyses from the Lower Unit mica schists yields xenocrystic and c. 370 Ma ages, but no geochronologic evidence for peak Variscan tectonism. Exhumation of the deep crustal root occurred most probably in a two-stage process. The timing of the high-pressure, eclogite facies metamorphism before the onset of exhumation into the mid crust, was likely between c. 380 Ma and 360 Ma. Subsequent exhumation into the middle crust was coeval with migmatite generation at c. 340 Ma and garnet diffusion modeling suggest ~30 °C/Ma cooling rates. The exhumation was likely tectonically forced by the action of a rigid indentor, which prompted the weak lower crust to be heterogeneously extruded to mid-crustal levels at a time coeval with anatexis and subsequently extruded with mid-crustal material to the upper crust.

1. Introduction

Resolving the heterogeneous crustal architecture in many metamorphic terranes has proved to be a challenge in developing crustal-scale models of orogenic growth (e.g. Western Gneiss Region, Engvik and Andersen, 2000; Bohemian Massif, Schulmann et al., 2008; Grenville Province, Rivers, 2008). One oft-noted lithotectonic relationship is the occurrence of migmatized crustal-scale blocks preserving boudins of deep crustal assembly. This apparent association has led to the suggestion of an intimate link between the exhumation of the lower crust and buoyancy forces that are likely driven by widespread anatexis. In order to better understand the relationship between adjoining and disparate metamorphic blocks such as these, documenting the pressure–temperature–time (P–T–t)

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doi:10.1016/j.lithos.2012.03.025

evolution of each of the assemblages is a reliable first step in the discrimination between tectonic models.

The Tatric crystalline unit of the Western Carpathians represents the easternmost exposure of the Variscan orogen in Europe, which marks the collision of Laurasia with Gondwanian-affiliated terranes during the Palaeozoic. These rocks were uplifted and exposed from shallow depths in the Miocene during Alpine collision but their Variscan signature remains intact. Further, Alpine tectonism has allowed the 3D Variscan framework to be envisaged: the basement core of the Western Tatra Mountains displays an inverted metamorphic sequence where high-grade migmatite and orthogneiss-bearing unit is overlying lower grade mica schists (Janák, 1994; Janák et al., 1996, 1999). The migmatites enclose eclogite-bearing amphibolites, and late- to post-orogenic granites intrude the entire sequence.

Extensive work on the metamorphic evolution of the Variscan lower crustal assemblages has been carried out in previous studies (Janák, 1994; Janák et al., 1996, 1999; Moussallam, 2010), which illuminate the clockwise P–T paths followed by the crystalline rocks of the Western and High Tatra. In this contribution, our objective is to determine the timing of peak metamorphism, anatexis, and exhumation of the main lithotypes, in an attempt to resolve the timing of juxtaposition and metamorphic inversion of the core of the Western Tatra. We performed Sm–Nd garnet geochronology on an eclogite sample as well as U–Pb zircon geochronology on the migmatitic sequence surrounding the eclogite boudins. Total-Pb monazite geochronology was also conducted on the micashists of the footwall. To establish the Tatra's lower-temperature cooling history, we also carried out diffusion modeling on garnet from the migmatites and $^{40}Ar/^{39}Ar$ thermochronometry on migmatites and micashist micas of the upper and lower structural units. With the cumulative data sets, we show that investigated rocks from both tectonic units record a protracted history from c. 380 to 360 Ma but came together only at c. 340 Ma under middle crustal conditions, with attendant anatexis followed by exhumation under moderate cooling rates. These results shed light on the nature and style of mid-crustal assembly during continental collision in large hot orogens, proposed from crustal flow models (e.g. Beaumont et al., 2006).

2. Geological background

2.1. Variscan orogen in central Europe and tectonic setting of the Western Tatra

The Variscan belt of Europe, stretching from Portugal to Slovakia, was a large, hot bivergent orogen (Franke, 2000; Matte et al., 1990) that marked the collision of Laurasia with Gondwana-derived terranes during the Palaeozoic. The eastern margin of the orogen is exposed in the Bohemian Massif of central Europe (Fig. 1), which is commonly subdivided (e.g. Kossmat, 1927; Suess, 1926): i) The Rhenohercynian zone, consisting of greenschist facies Devonian and Early Carboniferous meta-sedimentary rocks, ii) The Saxo-Thuringian zone, composed of a Neoproterozoic basement of migmatites and paragneisses intruded by Cambro-Ordovician granitoids converted to orthogneisses during the Variscan orogeny (e.g. Schulmann et al., 2009), iii) The Teplá–Barrandian zone comprising Neoproterozoic basement overlain by Early Palaeozoic sediment and volcanic sequences, and iv) The Moldanubian zone composed of a high- to medium-grade metamorphic rocks intruded by Carboniferous granitic plutons, interpreted to represent a back-arc basin formed during the Siluro-Devonian (e.g. Schulmann et al., 2009). The adjacent Brunia block is defined as the western deformed margin of the Moravo-Silesian zone (Dudek, 1980). Brunian crystalline rocks are composed of granitoids, migmatites and schists originated from Pan-African orogenic events (e.g. Finger et al., 2000; Friedl et al., 2004), which are unconformably overlain by Early to Late Palaeozoic strata. Schulmann et al. (2008) hypothesized that the Brunian continental promontory acted as an indentor on the Moldanubian domain, leading to the development of a channel flow-like mid-crustal system during the Variscan orogeny.

Occupying the critical juncture between eastern Bohemia and the Brunian block are the Western Tatra Mountains. This Alpine fold-thrust belt in northern Slovakia and southern Poland is the outer portion of the Carpathian orocline, which truncates the Variscan belt. Here in the Carpathians, three major units define the lithotectonic blocks, which were juxtaposed during north-directed Cretaceous thrusting. Rocks of the Western Tatra belong to the northernmost Tatric unit, which is overlain to the south by the Veporic and the

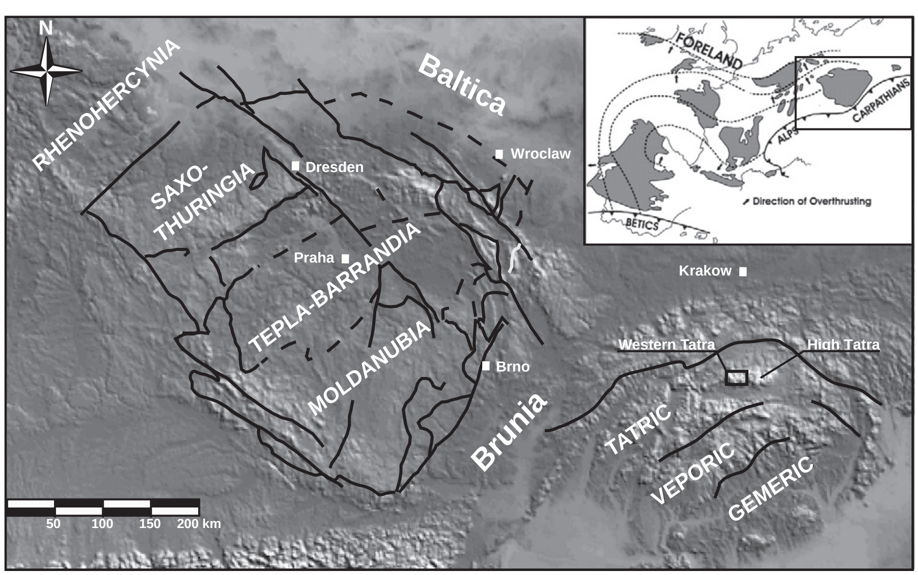

Fig. 1. Simplified terrane boundary map of the Bohemian Massif and the Carpathians. Brunia and Baltica refer to proto-continents whereas Rhenohercynia, Saxo-Thurigia, Teplá-Barrandia and Moldanubia refer to Variscan zones; Tatric, Veporic and Gemeric refer to Carpathian units. The small open box shows the location of the Western Tatra and Fig. 2. The upper right inset shows the position of the Bohemian Massif in the framework of the European Variscides.
Modified from Bromley and Holl, 1986.