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Exhumation and metamorphism of an ultrahigh-grade terrane: geochronometric investigations of the Sudete Mountains (Bohemia), Poland and Czech Republic

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Abstract: The Sudete Mountains, NE Bohemian Massif (Czech Republic and Poland), preserve abundant eclogitic and granulitic centimetre- to decimetre-scale boudins enveloped in a predominantly migmatitic matrix. Published geochronometry and thermobarometry from the UHP and UHT rocks broadly constrain the crystallization and initial stage 1 exhumation history for these units; however, the timing of stage 2 metamorphism and associated unroofing is less well constrained. New *in situ* ion microprobe Th–Pb monazite results, together with complementary U–Pb zircon and electron microprobe analyser total-Pb monazite results, on 11 amphibolite-facies gneissic to migmatitic samples, place important temporal constraints on the second stage of UHP and UHT metamorphism–exhumation. The Orlica–Snieznik Dome records UHP metamorphism occurring at 375 Ma and subsequent exhumation to midcrustal levels in supra-Barrovian conditions at *c*. 345–330 Ma. In contrast, the western Góry Sowie Block preserves evidence of HP-granulite conditions at *c*. 400 Ma, and exhumation to mid-crustal levels at 380–370 Ma, revealing a *c*. 30 million years difference in exhumation events between the neighbouring terranes. The eastern Góry Sowie Block preserves ages similar to the Orlica–Sneiznik Dome, suggesting that different preserved metamorphic–cooling histories are juxtaposed across the Sudetic Marginal fault. The bounding Niemcza shear zone yields preliminary Th–Pb dates that range from 380 ± 8 Ma to 283 ± 2 Ma, preserving a protracted metamorphic record that spans the exhumation history of the region. The distinct collapsed geochronologies of both terranes probably reflect rapid vertical transport of low-viscosity crust under supra-Barrovian conditions near the mid-crustal high-strength lid during oblique (transpressional) convergence.

Keywords: Bohemian Massif, ultrahigh pressure, exhumation, monazite, geochronology.

Metamorphic terranes containing ultrahigh-temperature (UHT) and ultrahigh-pressure (UHP) assemblages exposed at the surface provide a unique opportunity to investigate the deep roots of orogenic systems. Notably, most UHT and UHP rocks are surrounded by an upper amphibolite-facies (migmatitic) rock matrix (e.g. Ernst & Liou 2000; Terry *et al*. 2000; Labrousse *et al*. 2002; Walsh & Hacker 2004), which suggests an intimate link between mid-crustal metamorphism, anatexis and exhumation. Geochronological and petrological investigations of these terranes are therefore critical not only in shedding light on the enigmatic nature of granulite and eclogite exhumation, but also in contributing to a better understanding of lithosphere geodynamics.

Recent investigations into the mechanisms driving high-grade terrane exhumation reveal a variety of models including surface processes primarily driven by erosion (e.g. Zeitler *et al*. 2001) and tectonic processes such as orogenic collapse (e.g. Vanderhaeghe *et al*. 1999) to explain how once deep-seated rocks reach the surface. Many models for UHT–UHP terranes suggest that deep-seated rocks are exhumed in two stages (e.g. Walsh & Hacker 2004). It is generally accepted that density-regulated buoyancy drives the eclogites and granulites through the lower and middle lithosphere in initial unroofing processes (Ernst *et al*. 1991; Cloos 1993; Hacker *et al*. 1995). Following this stage 1 ascent, the UHT–UHP lenses stall and re-equilibrate near the Moho as a result of diminishing body forces. In the lower crust, material exhumed during stage 1 undergoes supra-Barrovian metamorphism and partial melting that commonly overprints much of the UHT–UHP unit. Subsequently, the UHT–UHP lenses continue their ascent in stage 2 exhumation. This stage is aided by the anatexis and migmatization at the Moho, which enhances deformation of the weakened rock and promotes further ascent. Thus, the metamorphic relationship of the host rock's peak supra-Barrovian conditions coeval with a retrogressed path of the enveloped UHT–UHP units allows the second ascent stage of the eclogite and granulite to be assessed. By constraining the metamorphic history of the surrounding country rock, we are able to evaluate the ascent of eclogite and granulite through the overthickened crust.

The Sudete Mountains, northeastern Bohemian Massif (Czech Republic and Poland), are one of the few localities in the world that expose centimetre- to decimetre-scale lenses of both eclogite and granulite. The Sudetes comprise numerous Variscan fault-bounded terranes, two of which provide excellent opportunities to study the polyphase tectonic evolution of high-grade rocks (Fig. 1). The Orlica–Snieznik Dome and the Góry Sowie Block preserve primarily amphibolite-facies gneisses, migmatites, and mica schists, which locally enclose boudins of granulite and eclogite. Previous geochronometric investigations have yielded isotopic age data that indicate distinct, unresolved histories for the two terranes: for the allochthonous Góry Sowie Block, HP granulite-facies metamorphism at *c*. 400 Ma (Brueckner *et al*. 1996; O'Brien *et al*. 1997) was followed by a HT–MP metamorphic pulse at *c*. 380–370 Ma (van Breemen *et al*. 1988; Bröcker *et al*. 1998; Zahniser *et al*. 2003). In comparison, crustal thickening and coeval UHP conditions have been constrained to

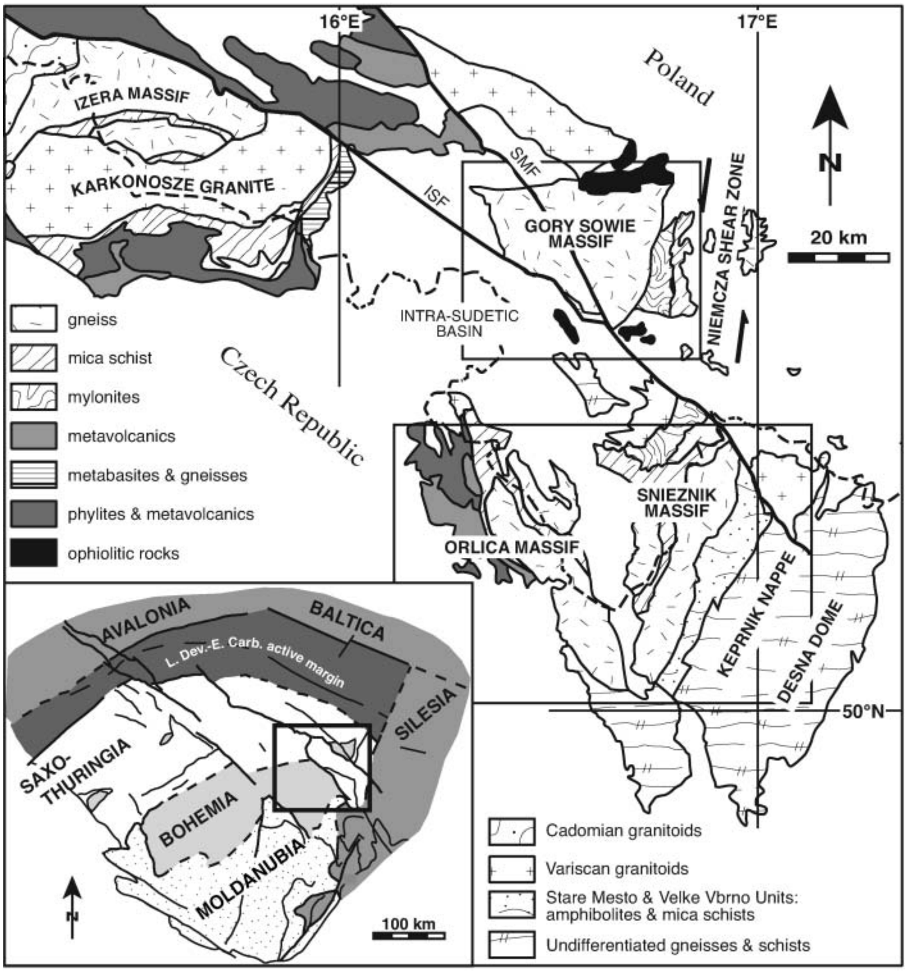

Fig. 1. Simplified geological map of the Sudete Mountains (modified after Aleksandrowski *et al*. 1997). The two boxes show the location of the study areas (Figs 2 and 3). ISF, Intra-Sudetic fault; SMF, Sudetic Marginal fault. Inset: terrane map of the Bohemian Massif and adjacent zones (after Franke & Zelazniewicz 2000). The box within the inset shows the general location of the Sudete Mountains. (Note the allochthonous nature of the Góry Sowie Block, which is separated by nearly 100 km from the rest of the Bohemian terrane.)

c. 370 Ma for the Orlica–Snieznik Dome (Bröcker *et al*. 1997). Additional geochronometric analyses for the complex have yielded evidence for a significant Variscan thermal (and cooling) event at *c*. 345–330 Ma (Brueckner *et al*. 1991; Maluski *et al*. 1995; Bröcker *et al*. 1997; Turniak *et al*. 2000; Marheine *et al*. 2002; Glascock *et al*. 2003).

In this study, primarily *in situ* ion microprobe Th–Pb monazite and complementary *in situ* electron microprobe total-Pb and ion microprobe U–Pb zircon geochronometric analyses have been performed on the amphibolite-facies gneiss and migmatite matrix from the Orlica–Snieznik Dome and the Góry Sowie Block. Published work from the Sudetes and other terranes (e.g. Zelazniewicz 1985; Guillot *et al*. 2000) has suggested a thermomechanical link between the lower crustal stage of granulite and eclogite unroofing and the amphibolite-facies metamorphism preserved in age constraints on the surrounding country rock. In addition to the Orlica–Snieznik Dome and Góry Sowie Block, this investigation reports new preliminary age constraints for amphibolite-facies units of the crustal-scale Niemcza shear zone located adjacent to the Góry Sowie Block, to ascertain its role as an accommodation structure. The geochronometric data obtained in this investigation elucidate distinct metamorphic and exhumation histories of two Variscan basement units separated by a mere *c*. 50 km.

Geological setting and previous geochronology

The Sudete Mountains, located along the NE margin of the Bohemian Massif, consist of a collage of amalgamated Neoproterozoic to Early Carboniferous terranes. Commonly interpreted as part of the European Variscan belt, the Sudetes represent the southeasternmost extent of the Saxo-Thuringia Zone and the northeastern part of Bohemia (Fig. 1; Crowley *et al*. 2002; Franke & Zelazniewicz 2002). Low- to medium-grade Proterozoic metasedimentary and metavolcanic units within the Sudetes, which preserve lenses of UHT–UHP rocks, have been intruded by two groups of granitoid bodies during a complex tectonometamorphic history (Svoboda & Chaloupsky 1966; Teisseyre 1973; Zelazniewicz 1987; Don & Zelazniewicz 1990). Geochronometric investigations within the Sudetes have provided constraints on two important early stages of tectonism prior to Variscan orogenesis: (1) a *c*. 500 Ma granitic suite intrusion; (2) Caledonian tectonics (*c*. 480–440 Ma) associated with the closure of the Iapetus–Tornquist ocean (Kröner & Hegner 1998; Turniak *et al*. 2000). Reworking of the terrane continued with closure of the Rheic ocean, Cadomian–Eo-Variscan (*c*. 400–360 Ma) tectonics, and Variscan orogenesis (*c*. 345–330 Ma), which included crustal thickening, metamorphic overprinting, and widespread contemporaneous magmatism (Turniak *et al*. 2000). Tectonic structures abut to the east against the SW margin of the East European Platform, and are truncated by the NNE-trending Moldanubian Thrust, which contains probably 400 km of dextral offset. The present spatial array of terranes in and around the corner of Bohemia reveals a disrupted orocline, dissected by dextral transpression induced through diachronous closure of the seaway. The following terrane descriptions and geochronology highlight the principal tectonothermal events of the Orlica–Snieznik Dome and Góry Sowie Block; recently summarized geochronology has also been reviewed by Marheine *et al*. (2002).

Orlica–Snieznik Dome

In the southeastern Sudetes, the Orlica–Snieznik Dome exposes a core of predominantly amphibolite-facies (garnet- to locally kyanite-zone) granitoid gneisses, mylonites, migmatites and minor mica schists (Fig. 2; Don *et al*. 1990; Lange *et al*. 2002). Eclogite and granulite assemblages are preserved as centimetre- to decimetre-scale lenses intercalated within the core migmatitic orthogneisses. Structurally, the Orlica–Snieznik Dome lacks the hallmark characteristics of a gneiss dome, but instead preserves narrow subvertical ductile deformation zones surrounded by regions of dominantly subhorizontal fabrics, all containing a gently plunging SSW stretching lineation. Notably, units containing high-grade assemblages typically have a vertical fabric (Rychleby granulite belt and Miedzygorze belt). Flanked on the western side by greenschist-facies metasedimentary and metavolcanic rocks, the Orlica–Snieznik Dome is the western 'dome' in an east–west corridor of Variscan structures that include the Orlica–Snieznik Dome and the Keprník and Desná domes, the latter two in the Jesenik Mountains. The Orlica–Snieznik Dome is separated from the Jesenik Mountains by the NNE-trending Stare Mesto belt, a highly strained complex of intercalated lower crustal and volcano-sedimentary rocks. The tectonic evolution of these structures has been attributed to extensional collapse resulting in core complexes (Steltenpohl *et al*. 1993; Cymerman 1997) and/or Variscan dextral transpression producing a stacked nappe pile (e.g. Aleksandrowski & Mazur 2002). More recent metamorphic and geochronological work has suggested that the Orlica–Snieznik Dome is possibly a result of combined vertical extrusion and lateral flow during synconvergent exhumation (Stípská *et al*. 2004).

Neoproterozoic to mid-Cambrian ages for the basement units constrain the early protolith history of the Orlica–Snieznik Dome (Borkowska *et al*. 1990). Based on Pb/Pb and U–Pb zircon ages on ortho- and paragneisses, remobilization of the crust occurred at *c*. 500 Ma through emplacement of granitoid plutons (Oliver *et al*. 1993; Kröner *et al*. 1994*a*, *b*). Throughout the Sudetes, and perhaps the Variscan belt, Early Palaeozoic granitic magmatism caused deformation, possibly on a batholithic scale (Oliver *et al*. 1993; Turniak *et al*. 2000). Additional U–Pb zircon ages from orthogneisses and an omphacite-bearing granulite constrain the timing of Eo-Variscan HT–HP metamorphism to *c*. 370–360 Ma in the Snieznik (eastern) portion of the complex (Bröcker *et al*. 1997). The HP granulite rocks reached peak metamorphic conditions within the coesite stability field at pressures of >27 kbar and temperatures of *c*. 700–800 °C and subsequently underwent near-isothermal decompression at conditions of 10 to 4 kbar and *c*. 600 °C (Bröcker & Klemd 1996; Kozlowski & Bakun-Czubarow 1997). More recent work (Stípská *et al*. 2004) revealed higher peak metamorphic temperatures of 900 °C but at shallower depths of *c*. 60 km. In contrast to the *c*. 370 Ma dates, Brueckner *et al*. (1991) reported Sm–Nd garnet–clinopyroxene–whole-rock ages between 352 and 326 Ma for mafic granulite and eclogitic lenses from the high-pressure Zlote region of the northeastern Orlica–Snieznik Dome, which they interpreted as timing the HT–HP metamorphism. The combined Sm–Nd and U–Pb data, albeit yielding a dispersed range of ages, suggest that high- to ultrahigh-grade metamorphic conditions may have locally lasted 20 Ma; some of these results may equally be interpreted as the result of partially reset or mixed dates. In any case, eclogites and granulites of similar age are preserved in the Erzgebirge and Granulitgebirge of the Saxo-Thuringian foreland

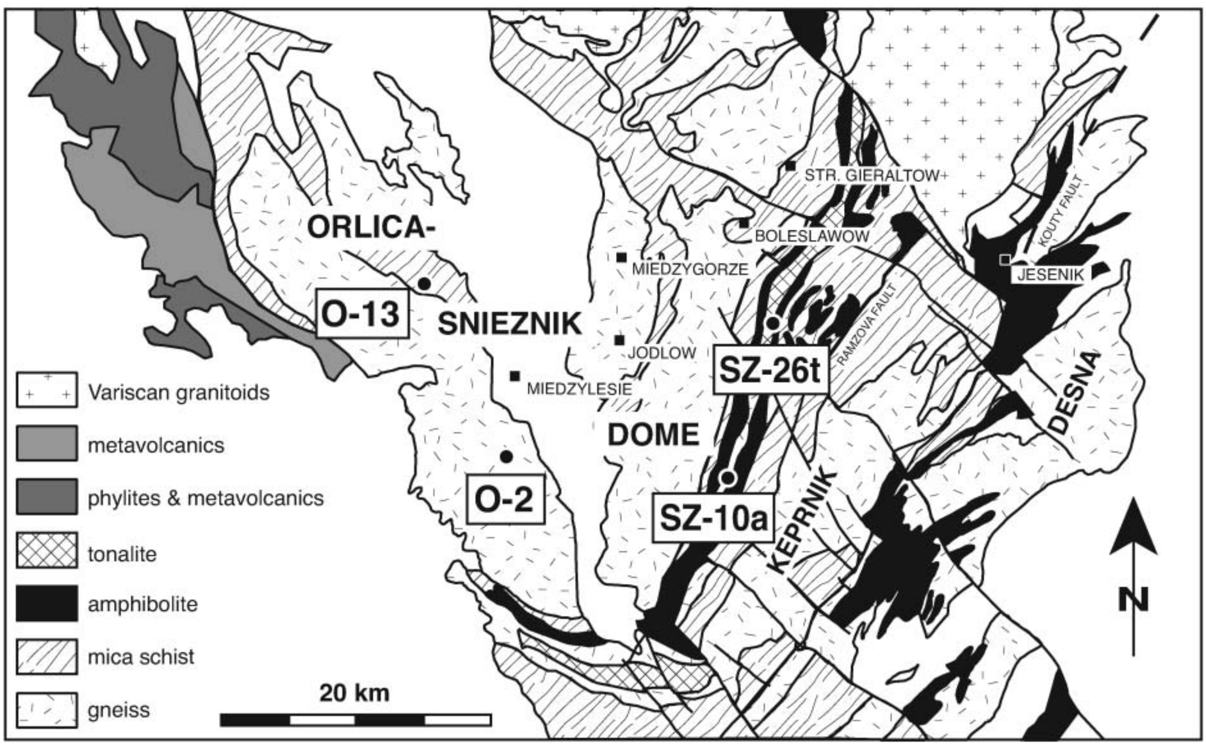

Fig. 2. Simplified geological map of the Orlica–Snieznik Dome, showing main lithological units, structural elements and sample locations (modified after Maluski *et al*. 1995).

of Germany, probably a record of subduction of continental crust (Franke & Stein 2000).

Variscan events in the Orlica–Snieznik Dome region are revealed through several Pb, Sr and Ar isotopic geochronological investigations that constrain supra-Barrovian metamorphism and subsequent cooling through the Viséan (Borkowska *et al*. 1990; Steltenpohl *et al*. 1993; Maluski *et al*. 1995; Bröcker *et al*. 1997; Turniak *et al*. 2000; Marheine *et al*. 2002; Glascock *et al*. 2003;Stípská *et al*. 2004). These dates are in marked contrast to the 310–300 Ma ^{40}Ar/^{39}Ar cooling ages reported for the Keprník and Desná domes of the Jesenik Mountains directly to the east (Maluski *et al*. 1995), which are purportedly part of the same nappe structure. Notably, no significant UHP or UHT assemblages have been identified from these eastern structures. Widespread anatexis broadly associated with Variscan tectonics resulted in the emplacement of the Karkonosze, Izera, Klodzko and Zulova plutons, significant undeformed granitoid bodies in this part of the orogen (Fig. 1). Although thermochronology records relatively rapid exhumation, and orogenic collapse has been suggested (Steltenpohl *et al*. 1993), no major normal-motion detachment structures have been identified.

Góry Sowie Block

The 650 km^2 Góry Sowie Block is a fault-bounded, triangular-shaped terrane preserving abundant migmatized gneisses and lesser amounts of serpentinites, amphibolites, and calc-silicate rocks (Fig. 3). Within this amphibolite-facies matrix, crustal-scale lenses of granulites are exposed and are usually accompanied by mantle-derived peridotites (Smulikowski & Bakun-Czubarow 1969; Bakun-Czubarow 1983; Zelazniewicz 1985). The Sudetic Marginal fault divides the Góry Sowie Block into its western and poorly exposed lowlying eastern sections. The block is flanked on its western and northern sides by two sedimentary basins containing detritus from the Góry Sowie Block: the Intra-Sudetic Depression containing Upper Carboniferous sediments, and the Swiebodzice Basin containing Famennian to Tournaisian deposits (Porebski 1981, 1990). The detritus located in these basins corresponds to the mid-Viséan clastic deposits that overstep the amphibolite-facies country rock of the Góry Sowie Block (Zakowa 1963), and places stratigraphic constraints on the surface exposure of the massif during that period (320–300 Ma). The Góry Sowie Block is also bordered by numerous ophiolitic complexes (Sleza, Nowa Ruda, Braszowice and Szklary units), which have been dated at 420 +20/−2 Ma (U–Pb zircon age on gabbro; Oliver *et al*. 1993) and 400 +4/−3 Ma (U–Pb zircon on plagiogranite; Zelazniewicz *et al*. 1998). As a result of the difference in metamorphic grade and age between the Góry Sowie Block and its flanking units, the Góry Sowie Block has been interpreted as an allochthonous block thrust over the adjacent ophiolites (Cymerman 1987; Bröcker *et al*. 1998). Other interpretations include a klippe, an 'orogenic diapir' and/or a microcontinent (e.g. Kossmat 1925, 1927; Jamrozik 1981; Behr *et al*. 1982; Cwojdzinski 1982; Oberc 1991).

For the Góry Sowie Block, Pb/Pb single zircon evaporation ages from ortho- and paragneisses reveal granitoid emplacement into the Proterozoic basement during the Early Ordovician (Kröner & Hegner 1998). Subsequent peak metamorphic conditions (900–1000 °C and 15–20+ kbar) were attained at *c*. 400 Ma, as revealed by the U–Pb and Pb/Pb zircon ages of O'Brien *et al*. (1997) of 402 ± 2 Ma and 399 ± 8 Ma for a high-pressure granulite unit. O'Brien *et al*.'s ages are similar to an Sm–Nd garnet–clinopyroxene–whole-rock age of 402 ± 3 Ma for an adjacent garnet peridotite (Brueckner *et al*. 1996). The peak pressures and temperatures were overprinted by lesser conditions of 775–910 °C and 6.5–8.5 kbar for the HP granulite rocks (O'Brien *et al*. 1997). Furthermore, the exhumation of the granulite and ultramafic sequences has been interpreted to be thermally connected and coeval with the amphibolite-facies metamorphism of the surrounding host gneisses and migmatites (Zelazniewicz 1987, 1990). A significant HT–MP (supra-Barrovian) thermal event at *c*. 380 Ma was revealed through

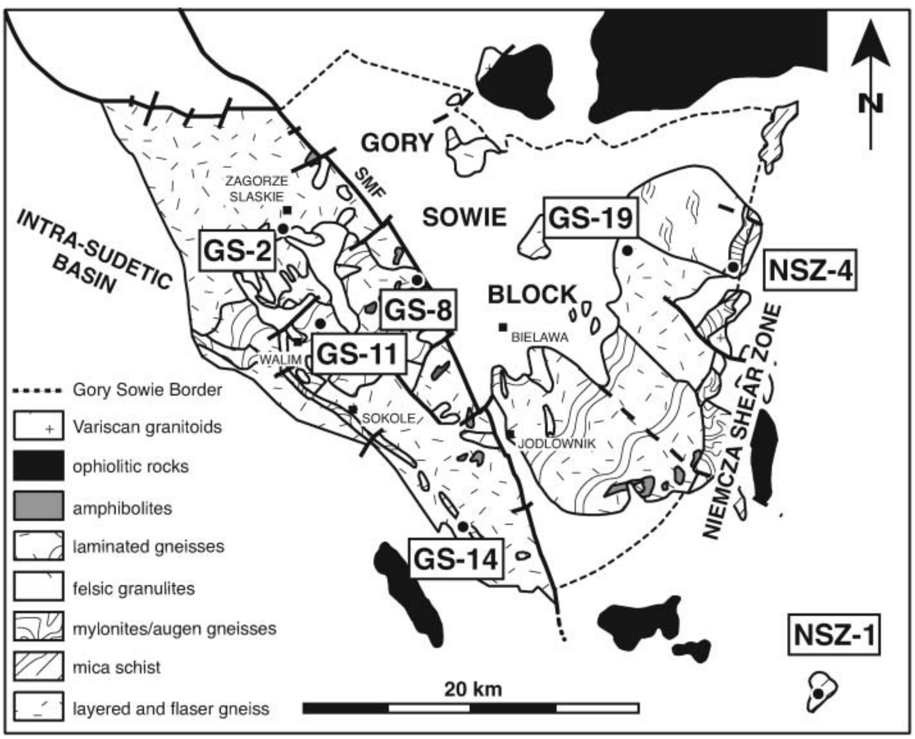

Fig. 3. Simplified geological map of the Góry Sowie Block and Niemcza shear zone. The map shows the main lithological units, structural elements and sample locations (modified after Bröcker *et al*. 1998). SMF, Sudetic Marginal fault.

conventional U–Pb monazite and xenotime ages on migmatites (van Breemen *et al*. 1988; Bröcker *et al*. 1998). Additionally, Timmermann *et al*. (2000) reported U–Pb xenotime ages of 378 ± 2 Ma and 383–370 Ma for a anatectic granite and pegmatite, respectively; prolific melting of the gneiss sequences at that time suggests either increased heat flow or, more probably, isothermal decompression melting associated with unroofing events. Cooling for the western half of the Góry Sowie Block, probably associated with unroofing, occurred from *c*. 380 to 360 Ma, based on hornblende, muscovite and biotite $^{40}Ar/^{39}Ar$ cooling ages (Marheine *et al*. 2002; Zahniser *et al*. 2003), and less robust methods (e.g. Rb–Sr; Bröcker *et al*. 1998). To the west, the southern and eastern Karkonosze–Izera massif exposes blueschist-facies rocks, as well as mid-ocean ridge basalt (MORB)-type magmatic complexes; thermochronometry reveals initial cooling at 360 Ma, which was later overprinted by a greenschist-facies event that lasted until 320 Ma (Maluski & Patocka 1997; Marheine *et al*. 2002). In comparison, the eastern side of the Góry Sowie Block yielded a $^{40}Ar/^{39}Ar$ mineral cooling age of 337 ± 0.8 Ma (Zahniser *et al*. 2003) similar to that of the Orlica–Snieznik Dome, and concordant with an age of 334 ± 2 Ma revealed through Pb/Pb zircon dating of a undeformed granodiorite sample located along the eastern block within the Niemcza shear zone (Kröner & Hegner 1998).

Truncating the eastern half of the block, the Niemcza zone is a major NNE–SSW-trending ductile shear zone. The zone consists mainly of staurolite-zone mylonitized gneisses, mica schists (quartzofeldspathic–quartzographitic–amphibolitic), marbles and minor granitoids (Dziedzicowa 1966), all enveloping smaller pods of eclogites (Józefiak 2000; Aleksandrowski & Mazur 2002). The shear zone was active until the Early Carboniferous, as revealed through U–Pb igneous zircon and Ar/Ar cooling dates (Oliver *et al*. 1993; Steltenpohl *et al*. 1993; Cymerman 1998; Kröner & Hegner 1998).

Analytical methods

To ascertain the tectonometamorphic history of the Sudetes, primarily *in situ* ion microprobe Th–Pb geochronometry and complementary electron microprobe total-Pb monazite and *in situ* ion microprobe U–Pb zircon geochronometry determinations were applied to amphibolite-facies units from the Orlica–Snieznik Dome, Góry Sowie Block and Niemcza shear zone. Monazite was principally chosen for analysis because the mineral contains large amounts of Th and U, has minor ^{204}Pb, and exhibits little elemental diffusion at high temperatures (Catlos *et al*. 2002). Furthermore, monazite is ideal for studying polyphase tectonometamorphic histories because of its high closure temperature (>850 °C; Cherniak *et al*. 2004) and ability to preserve multiple thermal events in elemental zoning patterns within the crystal (Townsend *et al*. 2000). Two of the 11 samples collected for this investigation contained small and/or few monazite grains. As a result, U–Pb analyses of zircon were also carried out, to strengthen the monazite dataset.

For eight samples, multiple-spot, single-grain Th–Pb and U–Pb ages were measured using the Cameca ims1270 ion microprobe facility at the University of California, Los Angeles, following the protocol described by Catlos *et al*. (2002). Prior to analysis, the monazite and zircon grains were located in thin sections, imaged with BSE–SEM techniques (Figs 4 and 5), drilled out, and mounted with an age-standard in an epoxy probe mount. For isotopic analyses, the primary ion beam is O^- and was focused to a 13 μm × 18 μm spot. The standard operating conditions were a primary intensity of 3–4 nA, mass resolving power of *c*. 4500 and a 50 eV energy window. The Th–Pb monazite ages were determined

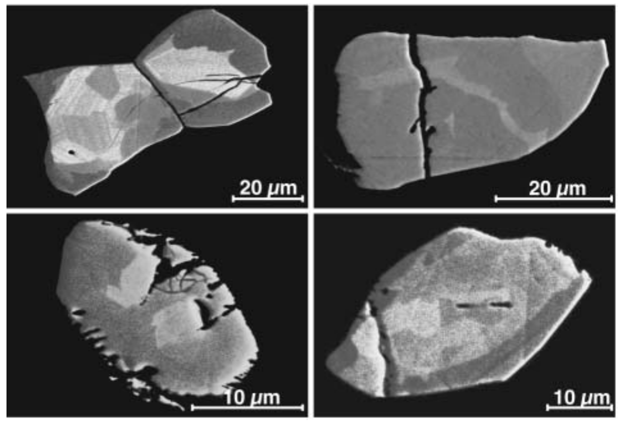

Fig. 4. *In situ* SEM images of individual monazite grains from samples GS-2 (upper left and right, lower right) and GS-14 (lower left). Grey-scale contrast has been enhanced to emphasize the elemental zonations. The monazite grain (upper left) shows a variety of internal zoning textures: patchy and convolute zoning with irregular rims. The corroded monazite (lower left) also reveals a patchy zoning texture. Upper right image shows a vein running across the crystal. Irregular rims are also revealed in the lower right monazite image, which shows faint patchy zoning. Textures are described from the nomenclature of Townsend *et al*. (2000).

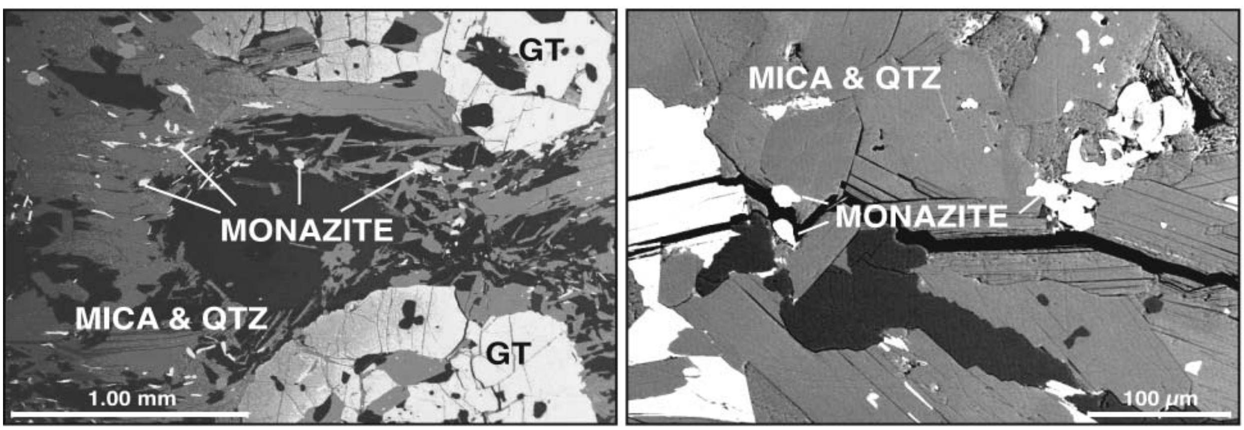

Fig. 5. SEM images of thin sections showing the location of monazite grains within the rock matrix from samples SZ-10a (left) and O-1 (right). Images reveal that the majority of monazite grains grow along the foliation planes or adjacent to major metamorphic minerals such as garnet or staurolite.

relative to the monazite standard 554 (45 ± 1 Ma; Harrison *et al*. 1999) and the U–Pb zircon ages were determined relative to the zircon age standard AS3 (1099 ± 1 Ma; Paces & Miller 1993). The precision of the method is limited not by counting statistics but by the reproducibility of the standard calibration curve, which is typically ±1% to 2% (Harrison *et al*. 1995). Uranium and thorium concentrations were estimated semiquantitatively by comparing peak heights in the unknowns with those for standards AS3 and 554. For standard AS3, the mean concentrations are *c*. 400 ppm for Th and *c*. 550 ppm for U. Because of the heterogeneity of U in standard 554, only Th, with a mean concentration of *c*. 40 000 ppm, can be utilized for the calculations.

In situ ion microprobe geochronology was determined on eight samples from the Sudete Mountains, averaging two spots per grain, although this was limited by the size and irregular shape of many crystals (Fig. 4). Accessory mineral isotopic ages and errors (±1σ) were reduced and calculated based on the methods of Harrison *et al*. (1995) and Catlos *et al*. (2002). Analytical data are available online at http://www.geolsoc.org.uk/SUP18227. A hard copy can be obtained from the Society Library. Single-spot Th–Pb dates were then plotted on relative probability diagrams using Isoplot, to assess the major populations of mineral-age domains for a given sample, shown as 'peaks' in Figure 6. Once populations were identified, Th–Pb dates were plotted on weighted average diagrams to calculate domain age and error, applying the well-established convention of maintaining a mean square weighted deviation (MSWD) below 2.5 for a given population. Analyses from the Niemcza shear zone lack any strong population, thus single-spot dates are reported only in a weighted distribution diagram. Standard concordia diagrams for U–Pb zircon results are also reported.

The *in situ* chemical U–Th–total Pb dating technique was also employed on monazite from upper amphibolite-facies rocks of the Góry Sowie Block using electron microprobe analyser (EMPA; Suzuki & Adachi 1991; Montel *et al*. 1996; Cocherie *et al*. 1998; Williams *et al*. 1999). This EMPA portion of the investigation involved two techniques: high-resolution compositional mapping to aid in the identification of intracrystalline age domains, and quantitative chemical analyses of Y, Th, U, and Pb. Analyses were carried out on a Cameca SX-50 electron microprobe at Virginia Polytechnic Institute and State University. Monazite grains were identified by manual scanning of rock thin sections noting high Ce peaks, in addition to using energy dispersive spectroscopy (EDS). Images were collected using high sample current (>200 nA) and small step sizes (*c*. 0.5 μm) while rastering the electron beam with the stage fixed (50 ms per pixel resolution of 512 × 512 pixels). Elemental maps were analysed for distinct chemical domains to determine optimal transect placement for age determinations; the analytical protocol

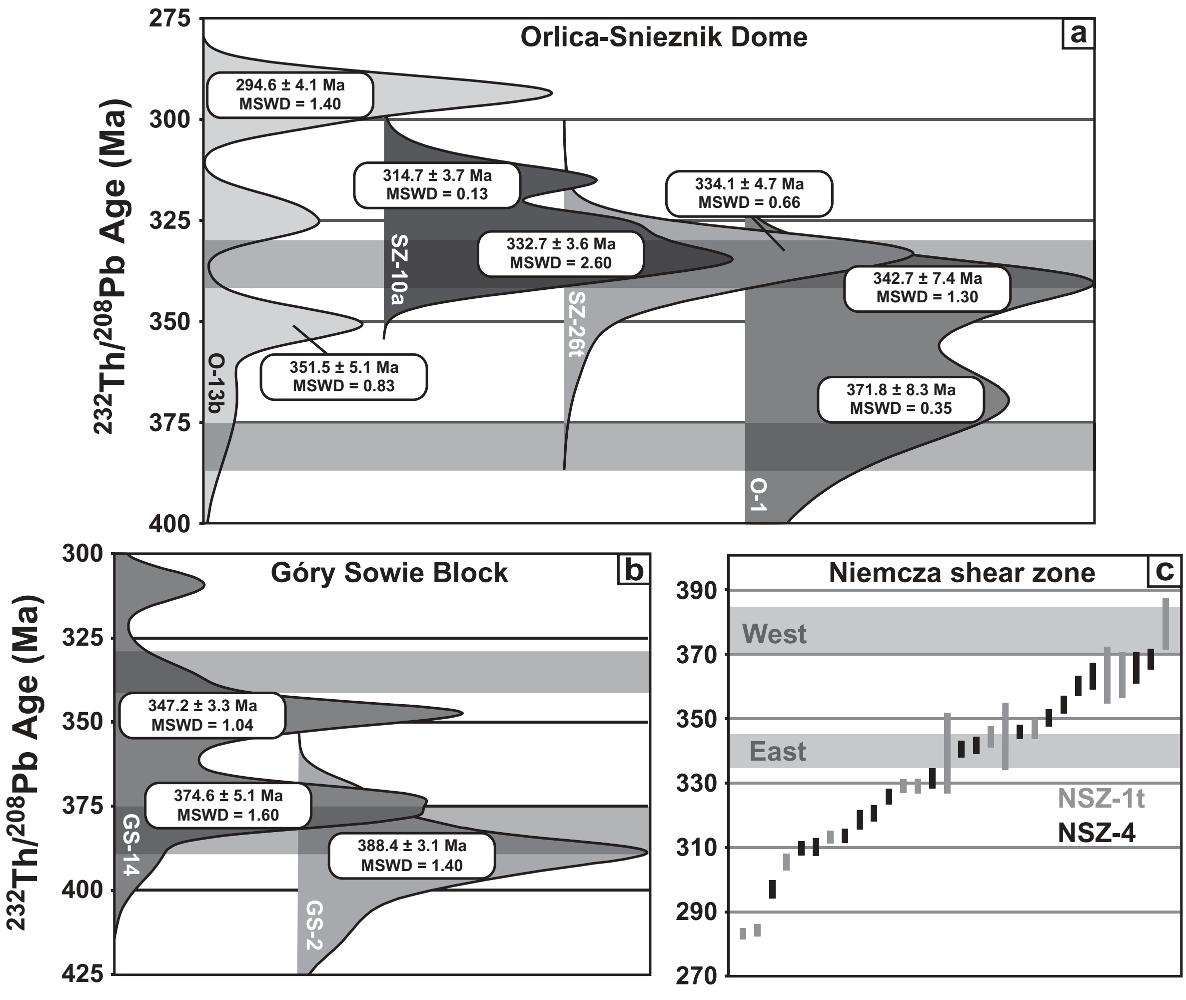

Fig. 6. Monazite Th–Pb age results from the Sudete Mountains. Cumulative probability graphs for single-spot total-Pb ages of samples from (**a**) the Orlica–Snieznik Dome and (**b**) Góry Sowie Block. 'Peak' ages calculated from weighted mean dates. (**c**) Weighted distribution of ages for both Niemcza shear zone samples, as no reliable weighted mean ages were calculated for individual samples. Horizontal grey boxes represent timing of metamorphic pulses in the Góry Sowie Block at *c*. 385–375 Ma and in the Orlica–Snieznik Dome at *c*. 340–330. (Note age scale differences for each sample.) Analytical details are available as a Supplementary Publication (see p. xxx).

followed that of Williams & Jercinovic (2002) and Schneider *et al.* (2004). Matrix corrections were made using the PAP method of Pouchou & Pichoir (1984, 1985). Quantitative trace-element analysis was carried out using a beam current of 150–200 nA at 15 kV accelerating voltage with a counting time of 700–900 s. Once concentrations of U, Th, and Pb were obtained, the age equation of Montel *et al.* (1996) was solved by iteration based on calculated Pb.

In situ EMPA was conducted on three upper amphibolite-facies samples from the Góry Sowie Block (analytical data are available as a Supplementary Publication; see p. 846); the advantage of EMPA over the ion microprobe technique is the high spatial resolution of the electron beam (<5 μm) relative to the ion beam (>15 μm). After single-spot total-Pb ages were calculated as described above, age populations were assessed using Isoplot, as outlined above for the ion microprobe data. Furthermore, dates were evaluated relative to their spot location within intracrystalline chemical zones (with the help of X-ray chemical maps) to define mineral-age domains; the K-means clustering statistical method was employed to assist in defining the age domains. Total-Pb ages and errors presented may reflect only analytical precision (analyses are grouped by identified domains) and were calculated using the equation for standard error of the mean based on the number of analyses for each domain. Weighted-mean ages were calculated using the standard error from individual analyses of similar age domains and are reported at the 2σ level.

Geochronometric results

Orlica–Snieznik Dome

Sample O-1, a medium- to coarse-grained foliated garnet–mica augen gneiss sampled from the Orlica Mountains (Fig. 3), achieved temperatures of 800 °C, as estimated by garnet–biotite thermometry (Gordon *et al*. 2003; Budzyn *et al*. 2004). The matrix of this sample consists of medium- to coarse-grained undulatory subhedral quartz, and sericitized and myrmekitic plagioclase. The monazite grains are small (<15 μm), narrow, and typically located on the edges of larger major rock-forming minerals (quartz, potassium feldspar) and where the mica matrix is fractured (probably along foliation planes). Eleven single-spot analyses on seven grains yielded two weighted average Th–Pb age domains of 372 ± 8 Ma (MSWD 0.35) and 343 ± 7 Ma (MSWD 1.30; Fig. 6).

A retrogressed biotite-rich mica schist, sample O-13b, was collected north of sample O-1 in the western half of the Orlica–Snieznik Dome (Fig. 2). The schist is composed of quartz, sericitized plagioclase, muscovite, biotite, chlorite, epidote and tourmaline with a lepido-porphyroblastic texture. The monazite grains are located along the edge of mica foliation planes, near larger accessory minerals (e.g. tourmaline). The grains are small and the majority are corroded and/or fractured. Twelve analyses on six grains using the Th–Pb monazite technique revealed two weighted mean age domains: 352 ± 5 Ma (MSWD 0.83) and 295 ± 4 Ma (MSWD 1.40; Fig. 6). This sample contained only a few monazite grains; therefore, U–Pb zircon analyses were performed to further constrain the thermal history of the sample. The zircons are 25 μm euhedral crystals that are often rimmed by xenotime. An upper intercept age of 503 +26/−22 Ma (MSWD 0.54) was found from 12 analyses on six grains (Fig. 7). Three spot analyses on a single grain, however, yielded a concordant age of *c*. 350 Ma, and the pooled near-concordant $^{206}Pb/^{238}U$ dates yielded a mean age of 326 ± 31 Ma (MSWD 2.1; Fig. 7), both of which are statistically indistinguishable from the Th–Pb age from the same sample. The high common Pb present in the analyses is probably due to mineralogical association of the zircon–xenotime pairing.

Collected from the eastern half of the Orlica–Snieznik Dome near the border with the Keprník dome (Fig. 2), sample SZ-10a is a well-foliated garnet-zone gneiss that contains minor poikilitic garnet with fractures containing pinite. Temperatures in this region are estimated to have equilibrated at 600 °C based on garnet–biotite thermometry (Gordon *et al*. 2003; Budzyn *et al*. 2004). Although monazite was not observed as inclusions in garnet, imaging shows that the majority of monazite is found along broken foliation planes between major metamorphic minerals (e.g. garnet) and the mica matrix. Furthermore, many of the imaged monazite grains reveal crystals that are apparently cracked, possibly creating conduits for fluid infiltration and Pb leaching. A total of 16 analyses on 10 monazite grains yielded two Th–Pb weighted mean domain ages of 333 ± 4 Ma (MSWD 2.60) and 315 ± 4 Ma (MSWD 0.13; Fig. 6).

To the north, a garnet-bearing mica schist, sample SZ-26t, was collected for geochronometry (Fig. 2). All monazite grains are located in the rock matrix, which consists of quartz, muscovite, biotite, epidote, chlorite, plagioclase, potassium feldspar and garnet with a granoblastic texture. Larger monazite grains show extensive corrosion producing irregular rim shapes. Six analyses

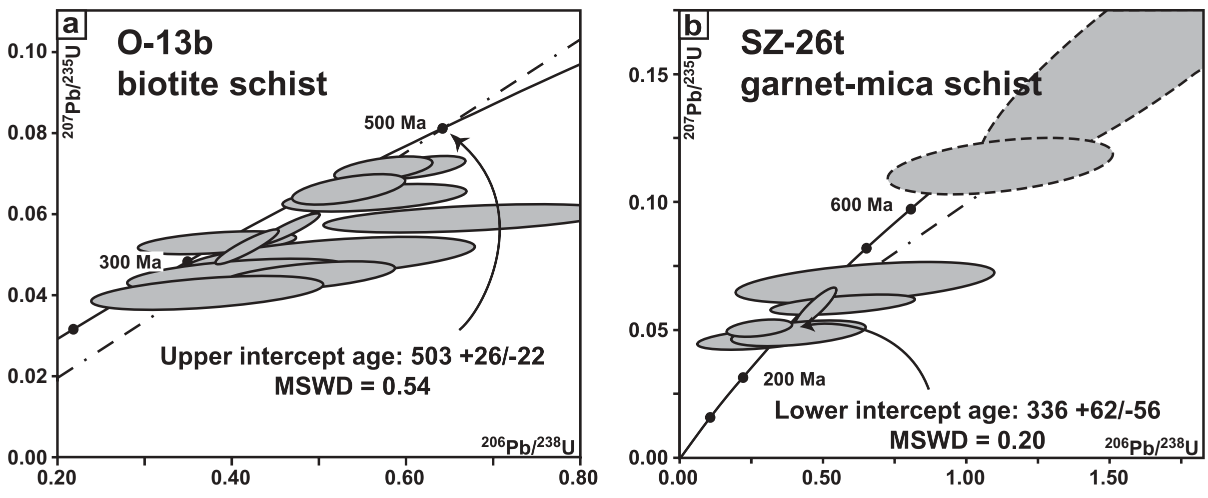

Fig. 7. Zircon U–Pb results from the Orlica–Snieznik Dome. (**a**) U–Pb concordia diagram for sample O-13b. (**b**) U–Pb concordia diagram for sample SZ-26t; dashed ellipses were removed for calculation of the intercept age. Analytical details are available as a Supplementary Publication (see p. xxx).

on three grains yielded an average mean Th–Pb age of 334 ± 5 Ma (MSWD 0.66; Fig. 6). Because of the limited amount of monazite in the sample, U–Pb zircon analyses were also performed; all zircon is located along fractures running through the sample. Isotopic analyses revealed a lower intercept age of 336 +62/−56 Ma (MSWD 0.20; Fig. 7), which, although it has large errors, complements the Early Carboniferous monazite date from the same sample. A poorly constrained upper intercept age of 1275 +44/−39 Ma is interpreted to represent protolith inheritance. Two spot analyses with large errors (dashed ellipses in Fig. 7) were not included in the intercept ages although the MSWD changed only slightly with their removal (from 0.17 to 0.20). Analysis of pooled $^{206}Pb/^{238}U$ ages revealed no reliable geochronometric information.

Góry Sowie Block

To constrain the tectonometamorphic history of the northern Sudetes, two samples were collected for geochronometry from the Góry Sowie Block and two samples from the adjacent Niemcza shear zone. Sample GS-14 is a well-foliated micaceous garnet-zone gneiss. The sample was collected from the southwestern section of the massif, where temperatures reached 600–700 °C based on garnet–biotite and muscovite–biotite thermometers (Fig. 3; Gordon *et al*. 2003; Budzyn *et al*. 2005). The sample contains leucosomal bands commonly 1–2 cm thick that are locally rich in white micas; the garnets in this sample are located near or within biotite foliation planes. Most monazite is found along the edges of major mineral phases within the rock matrix, and SEM imaging of individual grains shows that many are broken to the extent that they are apparently cracked into smaller individual crystals. Six analyses on three grains yielded a Th–Pb weighted mean age of 375 ± 5 Ma (MSWD 1.60). A subset of analyses, five spots on three grains, revealed a second Th–Pb age domain of 347 ± 3 Ma (MSWD 1.04; Fig. 6). A single grain yielded an older age of 389 ± 9 Ma.

Sample GS-2 is a granulite-facies biotite gneiss that was collected from the northwestern section of the Góry Sowie Block close to the Sudetic Marginal fault, where temperatures have been estimated at 750 °C on the basis of garnet–biotite thermometry (Fig. 3; Gordon *et al*. 2003; Budzyn *et al*. 2005). Petrographic analysis reveals that fibrous sillimanite occurs primarily as overgrowths on biotite and occasionally replaces early garnet; quartz and plagioclase exhibit a polygonal recrystallization fabric. In addition, the monazite grains in this sample are all located along the edge of larger major rock-forming minerals. A uniform Th–Pb weighted mean age of 388 ± 3 Ma (MSWD 1.40) is given by 13 analyses on 11 monazite grains (Fig. 6). Although not used to calculate the domain age, one grain yielded two younger dates of 372 ± 5 Ma and 372 ± 6 Ma, an age domain present in the Orlica–Snieznik Dome. Furthermore, two older dates, 405 ± 7 Ma and 415 ± 7 Ma, were obtained from separate grains, also not included in calculation of the 388 Ma age.

From the Kamieniec Metamorphic Complex, southern Niemcza shear zone, where temperatures reached *c*. 600 °C (Józefiak 2000), a garnet-bearing mica schist, sample NSZ-1t, was collected (Fig. 3). Under petrographic investigation, the schist was found to contain large poikiloblastic staurolite grains with a xenoblastic or lepido-granoblastic texture. The monazite grains are located along fractured mica foliation planes that run along the base of larger metamorphic minerals (i.e. staurolite and garnet). Moreover, the monazite is corroded and forms small nebulae of 15–20 μm crystals often intergrown with ilmenite; a monazite included in a garnet is not corroded but is smaller (<15 μm) than the other analysed grains. This schist revealed a range of Th–Pb dates from 380 ± 8 Ma to 283 ± 2 Ma from 13 analyses on six grains (Fig. 6). Four of the statistically indistinguishable analyses yielded an age of 345 ± 4 Ma (MSWD 0.18). Notably, the monazite inclusion in the garnet documents an older metamorphic age of *c*. 370 Ma.

Sample NSZ-4, a well-foliated garnet-bearing mylonitic gneiss, was collected from the northern Niemcza shear zone (Fig. 3). SEM imagery shows that most of the monazite is corroded and located along fractured mica foliation planes. Seventeen analyses on eight grains with multiple spots yielded a series of Th–Pb dates ranging from 368 ± 3 Ma to 297 ± 3 Ma (Fig. 6). Because of the complex age range of the analyses, and because NSZ-4 and NSZ-1t are both from the Niemcza shear zone, the results from the two datasets were plotted together in the hope of achieving a more temporally constrained history (Fig. 6). The combination of data from the shear zone samples reveals an older initial preserved history (from the garnet inclusion age and several analyses that are statistically indistinguishable at *c*. 370–360 Ma) and subsequent protracted tectonothermal activity lasting almost 100 million years.

Also for the Góry Sowie Block, three samples were chosen for analysis: a granulite from the north and two gneisses from the central massif (Fig. 3). A total of six monazite grains were examined (two per sample) with a total of 220 spot analyses. Because of the large dataset and the complexity preserved within the geochronometric record, statistical analyses were performed to determine viable age populations: K-means clustering ($\alpha = 5$) revealed four total-Pb age domains, at 359 Ma ($n = 31$), 382 Ma ($n = 59$), 403 Ma ($n = 36$) and 416 Ma ($n = 33$), consisting of 159 data points. Older domains were also revealed, although these domains are thought to represent initial protolith crystallization or emplacement rather than metamorphism.

Sample GS-19 is a kyanite-zone micaceous granulite located in the northeastern portion of the Góry Sowie Block (Fig. 3). This granulite consists of garnet, biotite, muscovite, quartz, plagioclase and cordierite. Monazite grains were typically located near, or enclosed within, biotite, with the majority of grains measuring >20 μm in diameter. Monazite GS-19-3 is a subhedral grain *c*. 75 μm × 35 μm and located along a biotite grain boundary. A total of 26 spot analyses were conducted over three transects; three distinct total-Pb age domains were determined based on overall statistics combined with cumulative probability curves (355 ± 8 Ma, 383 ± 7 Ma and 404 ± 14 Ma; Fig. 8). Elemental crystal images combined with age data reveal a well-defined older core with progressively younger domains toward the grain edges. Monazite GS-19-6, a subhedral elongate grain displaying distinct core–rim elemental zonation, is *c*. 35 μm × 65 μm in width and was also located near a biotite grain. Two transects with a total of 17 spot analyses reveal three similar total-Pb age domains (357 ± 14 Ma, 382 ± 6 Ma and 404 ± 10 Ma; Fig. 8). Chemical-age maps exhibit a small, old core near the margin of the grain with a large young zone dominating the remaining crystal. The embayed morphology of the core domains is characteristic of crystal growth via dissolution–reprecipitation processes.

Sample GS-11 is a sillimanite-zone micaceous gneiss located in the west–central Góry Sowie Block (Fig. 3). This sample's matrix is composed of primarily biotite, quartz and plagioclase, and is well foliated. Monazite grains were typically found as inclusions within biotite and the majority of these grains measured 20 μm in diameter; ideal grains were >30 μm in diameter. Monazite GS-11-17 is a subhedral crystal displaying distinct

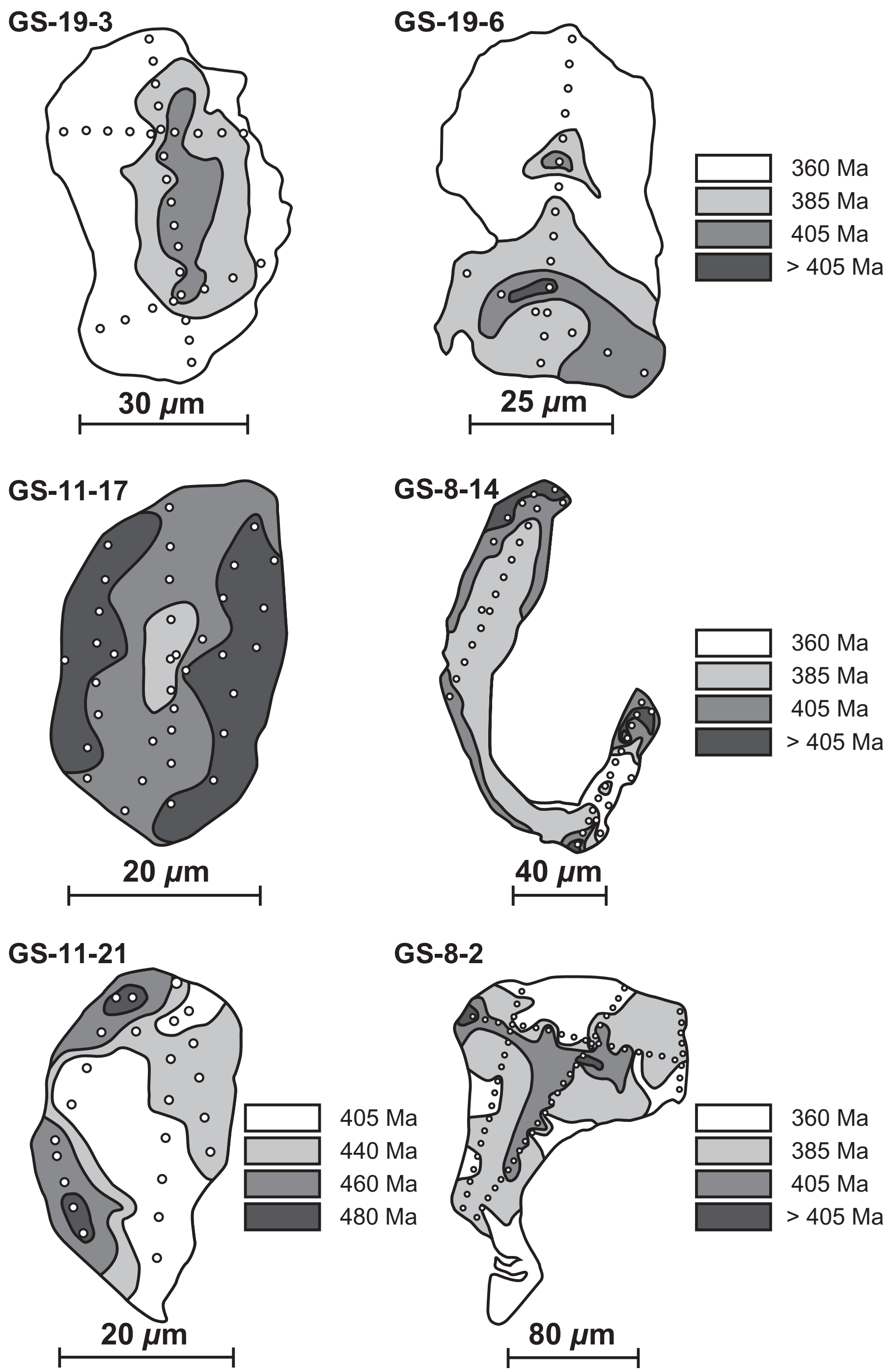

Fig. 8. Age maps of individual monazite grains from the Góry Sowie Block. Ages are based on EMPA total-Pb spot data (○) and 'chrontours' result from statistical regression of single-spot age populations and X-ray chemical maps that illustrate elemental domains.

chemical zones with a strong Y-low core, and is *c.* 40 μm × 30 μm, located along a biotite grain boundary. Statistical regression of chemical data yields total-Pb age domains of 358 ± 14 Ma, 383 ± 7 Ma and 418 ± 14 Ma (Fig. 8). Elemental maps indicate an apparent reverse age zonation pattern with the youngest domains occurring in the centre of the grain. Monazite GS-11-21, a subhedral grain, was located within biotite and demonstrates similar chemical zoning to monazite GS-11-17, including the Y-low core. This grain is *c.* 40 μm × 20 μm and data analysis revealed one total-Pb age domain coincident with monazite GS-11-17 (418 ± 8 Ma) and two more containing significantly older ages (447 ± 7 Ma and 467 ± 9 Ma; Fig. 8). Similarly, age–chemical mapping also demonstrates a reverse core–rim relationship, with the youngest ages occurring within the centre of the grain. It is important to note that core–rim relationships are often complex and the visible dimensions of the grain represent only a 2D surface of a 3D grain. It is likely that both monazites imaged from GS-11 represent the top section of the grain, and thin sectioning has not exposed the centre of the crystal when the rock was cut; the younger ages therefore represent the younger rim of the monazite, and not the true older core.

Sample GS-8, a garnet-zone gneiss, was collected from the central portion of the Góry Sowie Block. The sample is strongly foliated and consists of garnet, biotite, quartz, plagioclase and cordierite. Monazite grains were typically large (often exceeding 60 μm in diameter) and occurred almost exclusively as 'rim' overgrowths on a range of metamorphic minerals (garnet, apatite and biotite most common). Monazite GS-8-2, a sub- to anhedral grain, is *c*. 70 μm × 100 μm, located between two apatite grains. Chemical maps reveal two discrete Y-zones and cracks near the boundaries of the crystal. Regression of the data defines three total-Pb age domains (360 ± 5 Ma, 382 ± 4 Ma and 404 ± 5 Ma; Fig. 8). Elemental maps define an old core zone with successively younger zones towards the grain margins, but containing many embayments. GS-8-14 is a large grain that wraps around an apatite crystal (appearing similar to a rim growth) and measures *c*. 110 μm in length by an average of 25 μm in width. The data indicate three total-Pb age domains, which are coincident with GS-8-2 (360 ± 7 Ma, 382 ± 7 Ma and 402 ± 5 Ma; Fig. 8). Chemical mapping revealed two distinct zones with a clear overgrowth rim surrounding 80% of the grain. The unusual age zonation is probably linked to the mineralogical association of monazite and apatite during metamorphic reactions (e.g. Catlos *et al*. 2002).

Discussion

Geochronology

The monazite and zircon geochronology reported here provides temporal constraints on the metamorphic evolution of the high-grade rocks preserved in the Orlica–Snieznik Dome and Góry Sowie Block. Furthermore, the new results, although complex, reveal protracted metamorphism for the poorly constrained Niemcza shear zone.

In two of the Orlica–Snieznik Dome samples, both Th–Pb monazite and U–Pb zircon analyses were performed to constrain the thermal history of the dome; the data reveal four tectonothermal events: (1) *c*. 500 Ma; (2) *c*. 370 Ma; (3) *c*. 345–330 Ma; (4) *c*. 300 Ma. The 503 Ma U–Pb zircon age is consistent with other geochronometric Pb/Pb and U–Pb zircon dates of *c*. 500 Ma, interpreted as initial protolith ages (Oliver *et al*. 1993; Kröner *et al*. 1994*b*, 2000; Turniak *et al*. 2000). A subsequent thermal event is constrained to *c*. 372 Ma by the Th–Pb dates from the Orlica Mountains; similar ages of *c*. 373 Ma obtained from U–Pb zircon and Sm–Nd garnet–clinopyroxene–whole-rock analyses have been reported for the Snieznik Mountains (Brueckner *et al*. 1991; Bröcker *et al*. 1997). This Famennian age is also well documented in the western half of the Góry Sowie Block to the north, and within the Orlica–Snieznik Dome represents the timing of UHP conditions.

The subsequent tectonometamorphic history has remained somewhat unresolved for the Orlica–Snieznik Dome, but our Th–Pb monazite ages strengthen previous investigations that reveal supra-Barrovian metamorphism associated with Variscan orogenesis. Turniak *et al*. (2000) obtained zircon rim ages of 342 ± 6 Ma by U–Pb sensitive high-resolution ion microprobe (SHRIMP) analyses on a gneiss, consistent with our 342–332 Ma monazite age results from three gneissic samples. Brueckner *et al*. (1991) reported similar Sm–Nd ages (*c*. 350–330 Ma) on eclogites for the eastern half of the Orlica–Snieznik Dome, and Stípská *et al*. (2004) obtained 340 Ma U–Pb metamorphic zircon ages from HP granulites in the Rychleby belt. Although one of our monazite domain ages of 352 ± 5 Ma from the northern Orlica massif is consistent within error of the reported oldest age of Brueckner *et al*. (1991), we interpret the date to reflect an analytical mixed age between the older Famennian thermal event and the Viséan supra-Barrovian metamorphic episode probably related to Variscan tectonics. Cooling ages of *c*. 340–330 Ma, obtained through $^{40}Ar/^{39}Ar$ and Rb–Sr techniques, indicate rapid cooling, and possibly exhumation, synchronous with Variscan upper amphibolite-facies metamorphism (Borkowska *et al*. 1990; Steltenpohl *et al*. 1993; Bröcker *et al*. 1997; Glascock *et al*. 2003).

The monazite age domains of 315 ± 4 Ma and 295 ± 4 Ma from the Orlica–Snieznik Dome are somewhat younger dates than previously reported metamorphic ages for the region. However, a few studies document similarly young dates: Maluski *et al*. (1995) reported an $^{40}Ar/^{39}Ar$ muscovite age of 313 ± 3 Ma, interpreted as a late thermal pulse for a migmatite collected in the Snieznik Mountains. Within the northern Orlica Mountains, Glascock *et al*. (2003) Glascock (2004) also reported an $^{40}Ar/^{39}Ar$ muscovite age of 314 ± 1 Ma. Moreover, in parts of the Moldanubian zone of the southern Bohemian Massif, Svojtka *et al*. (2002) reported a concordant U–Pb zircon age of 318 ± 1 Ma, dating granite intrusions and synchronous deformation of granulite gneisses. Based on these younger ages, the 315 Ma date reported here probably results from a weak, localized heating episode and probably does not represent a significant metamorphic event. For sample O-13b, an *in situ* fragment of the thin section was selected where, under petrographic analysis, apparent fluid infiltration and recrystallization of the matrix minerals is revealed by the abundance of sericite and chlorite. This selection was made to constrain the timing of this retrogression; dated at 295 Ma, the alteration appears to be localized, as similar ages were not observed elsewhere in the Orlica–Snieznik Dome, and is probably related to hydrothermal alteration. Notably, this mineral-age domain is similar to the youngest single-spot Th–Pb ages from the Niemcza shear zone to the north.

Previous work in the Góry Sowie Block has constrained HP granulite-facies metamorphism to *c*. 400 Ma through U–Pb and Pb/Pb zircon geochronometry (Brueckner *et al*. 1996; O'Brien *et al*. 1997); our EMPA total-Pb geochronology also reveals this Early Devonian metamorphism as discrete age domains preserved within all three Góry Sowie Block samples analysed (Fig. 8), although more strongly preserved in the two western samples. The subsequent tectonometamorphic activity associated with exhumation has remained unresolved and therefore, the remaining Th–Pb and total-Pb monazite results reported here provide critical constraints on the evolution of the Góry Sowie Block, demonstrating apparently significant tectonothermal activity from *c*. 385 to 360 Ma for the western half of the Góry Sowie Block. The oldest Th–Pb age found in this study, 388 ± 3 Ma, was for a sample collected from the northern region of the block, where the deepest crustal levels and highest metamorphic grade are exposed (Zahniser 2004). Our EMPA total-Pb age domains from the two samples in the western Góry Sowie Block further document monazite growth over this time interval. These ages are broadly consistent with U–Pb monazite ages of *c*. 380 Ma on a migmatitic gneiss and diatexitic migmatite (van Breemen *et al*. 1988; Bröcker *et al*. 1998), and overlap within error with U–Pb monazite and xenotime ages of *c*. 375 Ma from the northwestern Góry Sowie Block (Timmermann *et al*. 2000). The combined geochronology indicates that the entire western half experienced a *c*. 385 Ma supra-Barrovian event. Furthermore, metamorphism was coeval with rapid cooling as indicated by $^{40}Ar/^{39}Ar$ and Rb–Sr ages of *c*. 380–375 Ma (van Breemen *et al*. 1988; Bröcker *et al*. 1998; Marheine *et al*. 2002; Zahniser *et al*. 2003;

Zahniser 2004). Marheine *et al*. (2002) reported $^{40}Ar/^{39}Ar$ muscovite ages of 360 Ma from along the margins of the massif; these, together with our 360 Ma total-Pb monazite age domain, suggest a semi-pervasive weak thermal pulse at temperatures well below the monazite closure temperature.

The youngest Th–Pb age of 347 ± 3 Ma from the monazite data presented here is the first to document localized Variscan metamorphic activity in the western half of the Góry Sowie Block, although Timmermann *et al*. (2000) reported a poorly constrained U–Pb lower intercept zircon age of 353 ± 61 Ma from an anatectic granite. In contrast, Variscan ages have been obtained from the eastern Góry Sowie Block through Pb/Pb zircon and $^{40}Ar/^{39}Ar$ hornblende and biotite analyses on ortho- and paragneisses (Kröner & Hegner 1998; Zahniser 2004). Structurally separated by the Sudetic Marginal fault from the western half (Fig. 1), the eastern half of the Góry Sowie Block mostly exhibits Variscan tectonothermal ages with little record of the older *c*. 400 or *c*. 385 Ma metamorphic events that have been revealed in the western Góry Sowie Block. Sample GS-19 from the eastern Góry Sowie Block yielded total-Pb ages of 360 Ma, some of the oldest dates from the east and supporting a massif-wide thermal episode during the Early Carboniferous.

Prior to this investigation, few geochronometric data existed for the Niemcza shear zone: Kröner & Hegner (1998) reported a Pb/Pb single zircon age of 334 ± 2 Ma on a granodiorite and Oliver *et al*. (1993) documented a U–Pb lower intercept zircon age of 338 +2/−3 Ma from the same quarry. Cooling to shallow crustal conditions is constrained to the Viséan (Zahniser *et al*. 2003; Zahniser 2004). The preliminary Th–Pb data reported here reveal a 100 million year range of dates from 380 ± 8 Ma to 283 ± 2 Ma. The oldest Niemcza shear zone dates (*c*. 380–370 Ma) were obtained through Th–Pb analyses on a monazite included in a garnet, and are similar in age to the Late Devonian metamorphic event documented throughout the Sudetes. Although it appears that the Niemcza shear zone samples preserve evidence of both the Góry Sowie Block (380–370 Ma) and Orlica–Snieznik Dome (340–330 Ma) amphibolite-facies thermal episodes, it is important to note that the complex age distribution (Fig. 6) also demonstrates the difficulty in dating rocks from shear zones: rocks located in high-strain zones appear to be easily susceptible to partial resetting of crystal isotope systems. Several workers report the effects of hydrothermal influences coupled with shearing (which reduces grain size) on U–Th–Pb isotope systematics of monazite (Teufel & Heinrich 1997). Results reveal that during deformational-induced dissolution and precipitation monazite reactions, radiogenic Pb does not become incorporated into the neocrystallized monazite but rather remains in the fluid phase, essentially resetting the isotopic clock. This coupled with other resetting mechanisms, such as Pb-loss diffusion as a result of frictional heating, can have strong isotopic effects in an active shear zone through the loss of daughter product and the resetting of the isotope system (e.g. Getty & Gromet 1992; Townsend *et al*. 2000; Cherniak *et al*. 2004). Therefore, careful interpretation is required because the ages appear younger and do not preserve clear evidence for the principal metamorphic events. Garnet's armouring effects upon the monazite inclusion, however, result in a reliable initial metamorphic date at *c*. 380–370 Ma.

Exhumation model

Our new geochronologic data reported here both complement and support prior geochronological work on the metamorphic history of the Sudetic high-grade terranes. Both blocks investigated in this study show distinct collapsed geochronologies, suggesting very rapid cooling correlated with equally rapid exhumation following isobaric supra-Barrovian conditions at mid-crustal levels (Fig. 9). The Orlica–Snieznik Dome and Góry Sowie Block reveal a similar yet diachronous two-stage metamorphic evolution, consistent with the interpretation that they are independent crustal blocks exhumed at different times during Variscan convergence. Extensional collapse via listric low-angle normal faults was not a likely exhumation mechanism given the wide temperature range over which rapid cooling occurred (Fayon *et al*. 2004) and the uniform cooling history of the rocks exposed in individual blocks. The overall metamorphic and geochronometric characteristics of the Sudetes suggest that exhumation was dominated by rapid vertical ascent (Thompson *et al*. 1997).

Exhumation models for this region must account for the apparent conundrum of rapid subvertical extrusion as indicated by the geochronology with the existence of subhorizontal foliations and lineations that trend subparallel to narrow subvertical zones (e.g. the main Orlica–Snieznik Dome fabric and the NNE-striking Stare Mesto belt to the east). Dumicz (1979) attributed the steep fabrics to lateral shortening, and the transition to flat fabrics to represent mass lateral flow as a consequence of gravitational load. More recently, Stípská *et al*. (2004) presented

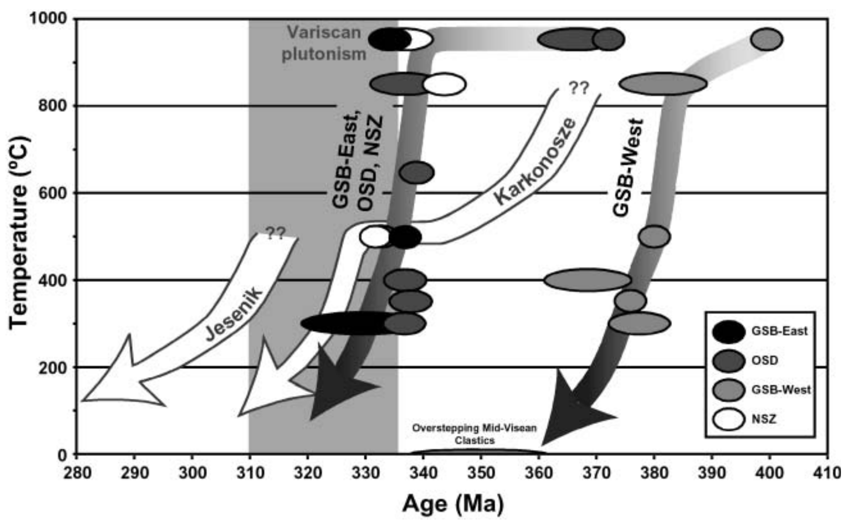

Fig. 9. Temperature–time evolution of the central Sudete Mountains based on published geochronometry and the results of this study. (See text for references and discussion of geochronometric systematics.) The coincident cooling histories for the Orlica–Snieznik Dome (OSD), Niemcza shear zone (NSZ) and eastern half of the Góry Sowie Block (GSB) relative to the older cooling path for the western half of the Góry Sowie Block should be noted.

a model for the NE Orlica–Snieznik Dome in which the UHT rocks were exhumed initially by localized buckling and subsequently by main-stage rapid vertical ductile extension with associated high cooling rates. In their model, late-stage exhumation involved deep (8–10 kbar) lateral viscous spreading and a corresponding lower cooling rate. We interpret our collective results to reveal only very high cooling rates to moderate crustal depths (<350–300 °C as indicated by concordant $^{40}Ar/^{39}Ar$ and monazite geochronology). Following stage 1 near-isothermal decompression and buoyancy-driven ascent to the Moho, we interpret stage 2 exhumation to involve further decompression of weak, low-viscosity material at supra-Barrovian conditions up to near the mechanical high-strength lid of the crust (Dewey *et al*. 1993). Cessation of rapid exhumation at this crustal level would be followed by rapid cooling to about 300 °C, the nominal closure temperature for argon diffusion in biotite.

We present here a conceptual model for the metamorphic evolution and exhumation of crustal blocks in the Sudete Mountains. Our working model draws heavily on recent advancements in our understanding of vertical coupling between rheologically distinct layers in the continental lithosphere (i.e. Grocott *et al*. 2004). Initial buoyancy-driven ascent of the UHP and HP rocks was arrested in the lower crust, probably near the Moho, where the exhumed mass of continental material underwent subsequent supra-Barrovian metamorphism and anatexis. Preservation of UHP and UHT assemblages at the surface indicates that the Bohemian rocks had to have been exhumed from the lower crust before the high-grade record could be completely erased. Migmatization during early supra-Barrovian metamorphism would have weakened the overthickened crust, allowing continued rapid subvertical ascent of a low-resistance (low-viscosity) matrix carrying small, resistant pods of eclogite, granulite and garnet peridotite. We suggest that rapid stage 2 vertical exhumation continued until the lower ductile crust became partially attached to the base of rigid upper crustal blocks, which were horizontally translating during oblique plate collision. Upon reaching the crustal high-strength lid, the ductile rocks ceased exhuming, spread laterally, and cooled quickly. In a transpressional setting, the overall final orientation of the ductile fabric would be subhorizontal (lateral spreading), but with gently plunging lineations developed subparallel to steep, strike-slip boundaries. This model may explain the widespread subhorizontal fabric and strong stretching lineation direction (S10°W) in the Orlica–Snieznik Dome (Fig. 10; Pressler *et al*. 2005). There have been fewer structural studies carried out in the Góry Sowie Block, although the existence of NNE-trending lineations on subhorizontal foliations in several locations (Cymerman 1998) appears at least consistent with their having formed in this manner.

The model invoked here serves to explain rapid cooling to *c*. 300 °C and diachronous but similar metamorphic histories across subvertical narrow zones containing high-pressure rocks. In this setting, the rocks of the western Góry Sowie Block underwent stage 2 supra-Barrovian metamorphism and exhumation at *c*. 385–370 Ma while rocks from disparate but nearby blocks were undergoing stage 1 UHP metamorphism (Orlica–Snieznik Dome and possibly the eastern Góry Sowie Block). We suggest that the Sudetic Marginal fault, which separates the Góry Sowie Block into two distinct metamorphic–age domains, may be an important structure for juxtaposing rocks of slightly(?) different structural depths and therefore with differing fossilized metamorphic–cooling ages. Ultimately, the Orlica–Snieznik Dome underwent stage 2 exhumation at *c*. 345–330 Ma. Similar diachronous metamorphic histories for other nearby blocks (Jesenik and Karkonosze blocks; Fig. 9) may also be explained by this exhumation model.

Finally, in the Western Gneiss Region of Norway, the overprinting supra-Barrovian metamorphism was synchronous across the entire area (Walsh & Hacker 2004), indicating simultaneous ponding of the exhumed UHP to HP rocks at the continental Moho. In contrast, the metamorphic history of the NE Bohemian massif suggests that blocks juxtaposed today were at dramatically different depths during the Mid- to Late Devonian. This seems to favour an exhumation process involving the rise of thin zones of UHP or HP terranes rather than large-scale diapiric rise of low-viscosity rock masses (Wallis *et al*. 2005).

Conclusions

(1) The Th–Pb monazite and U–Pb zircon analyses from high-grade Sudetic gneisses reported here, coupled with published ages, can be used to temporally constrain two discrete tectonothermal events for both the Orlica–Snieznik Dome and Góry Sowie Block, indicating a two-stage exhumation process for the UHT and UHP assemblages. Notably, these massifs

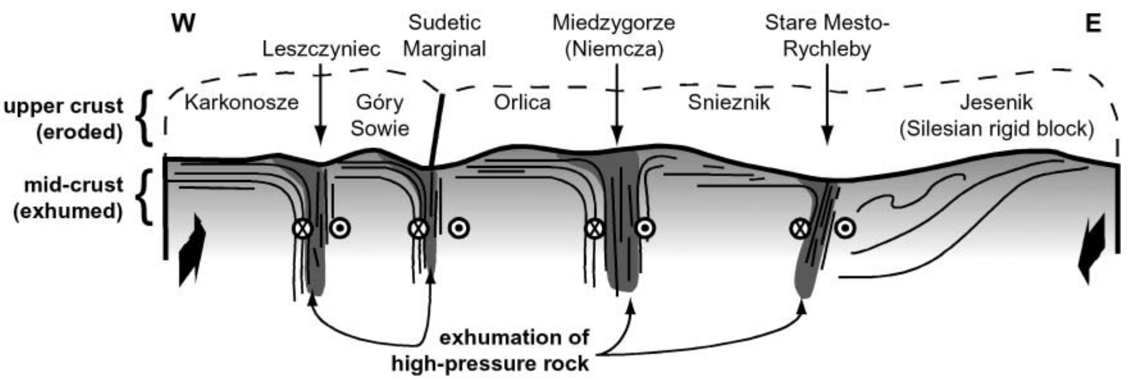

Fig. 10. Composite conceptual cross-section across the Sudetes, illustrating model for stage 2 mid-crustal exhumation of UHP and HP rocks (dark grey shaded region). Zones of vertically extruded high-pressure rocks (Leszczyniec, Miedzygorze–Niemcza, western Stare Mesto–Rychleby) spread laterally in the mid-crust below a horizontally translating high-strength lid (see Stípská *et al*. 2004). 'Gory Sowie' represents only the western part of the block; the eastern Góry Sowie Block is north of Orlica. The Sudetic Marginal fault separates halves of the Góry Sowie Block massif with differing chronologies and metamorphic grade.

differ in their metamorphic timing by *c*. 30 million years, but are <50 km apart.

(2) In the western Góry Sowie Block, HP granulite-facies metamorphism at *c*. 400 Ma was followed by upper amphibolite-facies metamorphism and exhumation to mid-crustal depths at *c*. 385–370 Ma, as constrained by metamorphic ages of surrounding migmatites.

(3) In the Orlica–Snieznik Dome, HT–HP eclogite-facies metamorphism at *c*. 375–360 Ma was followed by exhumation to mid-crustal depths at *c*. 345–330 Ma, as constrained by metamorphic ages from the enveloping migmatites.

(4) The Th–Pb monazite analyses for the Niemcza shear zone document the protracted history of the high-strain zone, and the probable effects of fluid infiltration during deformation along a crustal-scale shear zone, resulting in a *c*. 100 million year age range
(*c*. 380–280 Ma); dissolution–reprecipitation reactions within the monazite Pb systematics essentially reset the isotopic clock.

(5) The metamorphic and geochronometric signatures of the eastern Góry Sowie Block are more similar to that of the Orlica–Snieznik Dome than the western Góry Sowie Block, suggesting that the Sudetic Marginal fault juxtaposes different fossilized metamorphic–cooling histories.

(6) The northeastern Bohemian massif contains narrow zones of steep fabrics exhumed during stage 2 rapid vertical extrusion and flat mid-crustal fabrics developed during lateral (orogen-subparallel) spreading in an overall oblique compressional setting.

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