Combining trace-element compositions, U–Pb geochronology and Hf isotopes in zircons to unravel complex calcalkaline magma chambers in the Upper Cretaceous Srednogorie zone (Bulgaria)

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Received 18 January 2007; accepted 31 January 2008
Available online 15 February 2008

Abstract

Precise U–Pb geochronology and Hf isotope tracing of zircon is combined with whole-rock geochemical and Sr and Nd isotope data in order to unravel processes affecting mafic to felsic calcalkaline magmas prior to and during their crystallization in crustal magma chambers along the southern border of Central Srednogorie tectonic zone in Bulgaria (SE Europe). ID-TIMS U–Pb dating of single zircons from felsic and mixed/mingled dioritic to gabbroic horizons of single plutons define crystallization ages of around 86.5–86.0, 85.0–84.5 and 82 Ma. Concordia age uncertainties are generally less than 0.3 Ma (0.35%–2σ), and as good as 0.08 Ma (0.1%), when the weighted mean 206Pb/238U value is used. Such precision allows the distinction of magma replenishment processes if separated by more than 0.6–1.0 Ma and when they are marked by newly saturated zircons. We interpret zircon dates from a single sample that do not overlap to reflect new zircon growth during magma recharge in a long-lived crustal chamber. Mingling/mixing of the basaltic magma with colder granitoid mush at mid- to upper-crustal levels is proposed to explain zircon saturation and fast crystallization of U- and REE-rich zircons in the hybrid gabbro.

Major and trace-element distribution and Sr and Nd whole-rock isotope chemistry define island arc affinities for the studied plutons. Slab derived fluids and a sediment component are constrained as enrichment sources for the mantle wedge-derived magma, though Hf isotopes in zircon suggest crustal assimilation was also important. Inherited zircons, and their corresponding ε-Hf, from the hybrid gabbroic rocks trace the lower crust as possible source for enrichment of the mantle magma. These inherited zircons are about 440 Ma old with ε-Hf of −7 at 82 Ma, whereas newly saturated concordant Upper Cretaceous zircons reveal mantle ε-Hf values of +7.2 to +10.1. The upper and middle crusts contribute in the generation of the granitoid rocks. Their zircon inheritance is Lower Palaeozoic or significantly older and crustal dominated with ε-Hf values spreading from +3.9 to +7.

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Keywords: Magma mixing/mingling; Upper Cretaceous; Srednogorie; U–Pb zircon dating; ε-Hf; Nd–Sr isotopes

1. Introduction

Mantle-derived magmas in convergent tectonic zones experience a complex evolution from generation to crystallisation at shallow depths or as effusives. Magma ascent, emplacement, mingling/mixing in crustal chambers, assimilation, storage and recharge take between hours and millions of years. Volcanic studies have long made important contributions to our understanding of the time-scales and rates of magmatic
processes (see summaries of Hawkesworth et al., 2000, 2004). Such studies usually concentrate on young or active volcanic complexes, and employ two main approaches to decipher the timing of events: (i) absolute dating of different minerals (mainly zircon), using U-series isotopes (e.g. Reid et al., 1997; Bourdon et al., 2000; Miller and Wooden, 2004; Charlier et al., 2005), and (ii) relative dating, based on crystal size distribution (e.g. Cashman, 1990; Marsh, 1998), and/or major and trace-element and Sr isotope profiles in crystals (e.g. Hawkesworth et al., 2000; Knesel et al., 1999; Costa et al., 2003; Nédli and Tóth, 2003).

Volcanic rocks provide only indirect information about the magma chamber processes in convergent tectonic zones, and therefore a complimentary record of magma evolution from plutonic rocks is also necessary. Numerous detailed studies about the kinetics of magma mingling/mixing (e.g. Pitcher, 1993; Coleman et al., 1995; Castro et al., 1995; Wiebe, 1996; Wiebe and Collins, 1998; Wiebe et al., 2004) and the petrology and geochemistry of the hybrid intrusives (e.g. Didier and Barbarin, 1991; Bonin, 2004; Janoušek et al., 2004; Perugini et al., 2004; Annen et al., 2006) have contributed to our understanding of the chemical and physical changes occurring in magma chambers. However, detailed studies addressing the chemical/physical evolution of the magma within an absolute time-frame are still sparse (e.g. Griffin et al., 2002; Kemp et al., 2005), hampered mainly by the precision of the available isotope methods. Upper to middle crustal magma chambers (5–12 km deep) usually take millions of years before being exposed at the surface. Therefore, intrusive rocks are usually too old to be dated by U-series isotope methods, requiring other methods that have larger absolute uncertainties. Conventional Sm/Nd and Rb/Sr isotope methods are helpful as geochronometers only in the case of isotope homogenisation of the whole rock (e.g. Pin et al., 1990; Didier and Barbarin, 1991), which is more an exception than a rule in mixed/mingled magmas. Ar/Ar and Rb/Sr mineral dating provide information about cooling time of the magmatic complex. We chose the U–Pb single zircon ID-TIMS (Isotope Dilution — Thermal Ionization Mass Spectrometry) technique because it is the most precise method for dating plutonic rocks. When combined with Scanning Electron Microscopy-Cathodoluminescence (SEM-CL) imaging and in situ laser ablation (LA) ICP-MS analyses, it is a powerful tool to understand the chemical and thermal evolution of the long-lived magma chambers. Zircon is preferred also because its behaviour during different geological processes is well studied (see summary of Hanchar and Hoskin, 2003 and references therein). Though felsic (granitoid) rocks are usually preferred for U–Pb dating because zircon is a common accessory mineral, the present study will show that with a careful selection of the zircons, hybrid gabbros and diorites may provide suitable zircon for dating.

In subduction-related tectonic zones, the primary upper mantle magma is enriched with incompatible elements that are thought to be introduced by slab-released fluids or slab melts. This effect is largely overprinted by subsequent crustal interaction, when differing volumes of crustal materials mix with the mantle-derived magma to produce hybrid suites. The high field strength elements (HFSE), Hf, Zr, Nb, Ta, and Ti have been shown to be crucial for seeing through slab influence into the nature of the pre-subduction mantle wedge, as these elements remain largely immobile during slab dehydration reactions. The budget of HFSE and Lu is only affected during slab melting of the subducted oceanic crust (Münker et al., 2004). Of the HFSE, hafnium is unique in combining the characteristics of HFSE chemistry with a powerful isotopic tracer (Woodhead et al., 2001). Here we combine U–Pb and Hf-zircon isotope investigations linking the Hf-isotope data to magma chamber processes as dated by U–Pb zircon geochronology. Thus, we can resolve the problem of the shallow level crustal contamination, as the inherited and the newly saturated zircons are characterized by different age and Hf-zircon signature.

The present study also uses Nd and Sr whole-rock isotopes, to assess the geochemical characteristics of the different magma sources and for understanding the degree of mixing and homogenisation. Additionally the zircon geochemistry is combined with the whole-rock geochemistry to understand better how the changes in magma chemistry, temperature and H2O content affect zircon chemistry and saturation.

The region of investigation – the central parts of the Srednogorie tectonic zone in Bulgaria (Fig. 1) – was chosen because it hosts some of Europe’s biggest Cu–(Au)-porphyry and epithermal deposits, and it is well known that world class Cu–Au porphyry and epithermal type ore deposits are linked to mixed magmatic suites. The mixing can lead to magmatic volatile saturation, which can potentially trigger volcanic eruptions and/or the formation of magmatic-hydrothermal ore deposits (Keith et al., 1997; Dietrich et al., 1999; Hattori and Keith, 2001; Halter et al., 2004, 2005). In the Central Srednogorie zone, different levels of the magma chambers are exposed providing good opportunities for studying magma mixing processes, and structural and petrologic studies reveal long-lived magma chambers with time-stratigraphic record of magma replenishment (Fig. 1b, c).

2. Geological background and sampling

2.1. Geological setting and sampling

The Apuseni–Banat–Timok–Srednogorie (ABTS) belt (Fig. 1a) is part of the Alpine–Mediterranean mountain system. The belt is Europe’s most extensive belt of calcalkaline magmatism and Cu–Au mineralization and resulted from subduction and obduction of former Mesozoic ocean basins and final collision of Africa with Europe and a number of smaller continental microplates (Jankovic, 1977; Sandulescu, 1984; Mitchell, 1996; Jankovic, 1997; Berza et al., 1998; Stampfli and Mosar, 1999; Neubauer, 2002). Extensive U–Pb dating of zircons from subvolcanic intrusions and major plutons in the Central parts of the Srednogorie tectonic zone (Central Srednogorie) in Bulgaria revealed a general younging of the magmatism from ~92 Ma in the north to ~78 Ma in the south (Capitan Dimitriev in pluto, Fig. 1b) (Von Quadt et al., 2005). This age progression correlates with a north-to-south geochemical trend of
decreasing crustal input into the mantle-derived magmas (Von Quadt et al., 2005) and is explained as a consequence of slab retreat during oblique subduction (Neubauer, 2002; Lips, 2002; Handler et al., 2004; Von Quadt et al., 2005).

A chain of plutons (Plana, Gutsal, Vurshilo, Elshitsa–Boshulya and Capitan Dimitrievo) is exposed in the southern part of Central Srednogorie (Boyadjiev and Chipchakova, 1963; Boyadjiev, 1979, 1984; Dabovski, 1988) at the border with the Rhodope massif (Fig. 1b). They intrude the Pre-Upper Cretaceous basement. Structural and magnetic (accelerator mass spectrometry) studies revealed that the intrusion of the plutons was controlled by a crustal scale dextral strike-slip fault (Ivanov et al., 2001; Georgiev and Ivanov, 2003) — the Iskar–Yavoritsa shear zone (IYSZ) (Fig. 1b, c). It can be traced for a distance of 80–90 km (Fig. 1b) with a varied width of 0.4–1.0 km. Intensive ductile and rarely brittle–ductile mylonitization affects the rocks along the shear zone. Minor shear zones are developed parallel and oblique to the main IYSZ (Fig. 1b, c).
Regionally, magma emplacement was accomplished in laccolith-like chambers (Ivanov et al., 2001; Georgiev and Ivanov, 2003; Georgiev and Lazarova, 2003). The plutons reveal the characteristics of the “layered intrusions” of Wiebe (1996) and Wiebe and Collins (1998) — “interlayered mafic and granitic rocks, which preserve a stratigraphic record of magma chamber processes that were active during the crystallization of the granite intrusions”. The lower parts of the plutons consist of “crystal-rich” gabbro–diorite porphyries (Fig. 2a), diorites and granodiorites; the upper portions are “crystal-poor” granites. Between these two parts, thin sheet-like gabbro or gabbro–diorite bodies intruded. Along the bottom of the mafic sheets, chilled zones and load casts (Fig. 2b) are formed. The base of the mafic sheet is commonly perforated by flame structures and veins of leucogranite (Fig. 2c), which provide way-up indicators (Wiebe and Collins, 1998). Downward gabbroic lobes rarely form at the chilled base (Fig. 2d), whereas above the mafic sheets swarms of basic to intermediate enclaves are observed (Fig. 2e). Most mafic sheets are subhorizontal, but in the vicinity of Boshulya village they are steeply (70–80°) N–NE-dipping. Highly elongate enclaves and swarms of enclaves (Fig. 2f) have attitudes that are parallel to the mafic sheet. Mafic feeder dykes cross-cut the mafic–silicic layering. Near Velichkovo village one is subvertical, cross-cuts the

Fig. 2. Field relationships of the intrusive rocks in the southern parts of Central Srednogorie. a) crystal phase rich porphyry gabbro–diorites from Vetren quarry; b) chilled zones and load casts along the bottom of the mafic sheets; c) veins of leucogranite, perforating the base of the mafic sheet; d) lobate enclaves related to the chilled base of the gabbroic layer in the Velichkovo quarry; e) swarms of basic to intermediate enclaves; the level is cross-cut by basic feeder dyke; f) highly elongate enclaves and swarms of enclaves in the vicinity of Boshulya village.
An92 and AvQ-024 with orthocumulate texture and coarse-grained nde, clinopyroxene, K-feldspar and quartz, though in the rocks outcrops with sharp contacts between mafic and felsic sheets. These relationships give evidence for a long-lived magma chamber with magma replenishment and the sequence of deposits should provide a time record of the processes in it.

The samples for the present study are selected from different levels of the evolving magma chambers. Samples AvQ-029, 031, 032 (Elshitsa pluton and subvolcanic rocks; taken close to the village of Elshitsa; Fig. 1c) as well as ZI6 (Vurshilo pluton) represent the felsic levels. The sampled level of the Vurshilo pluton contains sparse mafic magmatic enclaves (MME) that are intermediate in composition. The most spectacular samples are taken from the mingled/mixed levels: from an outcrop north of Velichkovo village, where a sharp contact between gabbro (AvQ-018) and granodiorite (AvQ-019) is observed (Fig. 2b) and from a quarry NE of Vetren village with a quite homogenous layer in-between the basic enclave-rich levels (AvQ-023 and 024, Fig. 2a). Additionally one feeder dyke (AvQ-098) from the last outcrop (Fig. 1c) and one remobilised leucogranitoid vein (AvQ-235, Fig. 2c) from the Velichkovo quarry were sampled for analyses.

2.2. Petrological evidence for mixing and mingling

The petrology of the plutons was well characterized earlier by Boyadjiev and Chipchakova (1963) and Boyadjiev (1962, 1979), but recently Georgiev and Lazarova (2003) turned attention to some specific peculiarities of the intrusions, which are typical for mingled/mixed magmas. The gabbros and diorites both reveal signs of magma mixing, even in the outcrops with sharp contacts between mafic and felsic sheets. Their mineral composition is similar — plagioclase, hornblende, clinopyroxene, K-feldspar and quartz, though in the rocks with gabbroic composition (representative samples AvQ-023 and AvQ-024 with orthocumulate texture and coarse-grained hornblende crystals, Fig. 2a) the K-feldspar and quartz are interstitial, and plagioclase is observed in two generations — An92–88 as inclusions in hornblende and corroded cores in the second generation, and An54–32 as zoned crystals. In the hybrid gabbros to diorites (representative sample AvQ-018) the K-feldspar and quartz belong to the main mineral assemblage, whereas clinopyroxene and biotite are minor constituents (Georgiev and Lazarova, 2003). K-feldspars impregnate, replace and replace plagioclase and hornblende crystals. Plagioclase (An50–37) usually displays oscillatory zoning, marking fluctua-

3. Analytical techniques

3.1. Major and trace elements in rocks

Routine analyses of major elements in whole rocks were carried out on Li-tetraborate pellets using X-ray fluorescence (XRF) method. Trace element and REE determinations were made with Laser Ablation Inductively Coupled Plasma-Mass Spectrometry (LA-ICPMS) on the same Li-tetraborate pellets. LA-ICPMS spot analyses were done using an Excimer laser (ArF 193 nm) with a gas mixture containing 5% fluorine in Ar with small amounts of He and Ne, connected to a PE SCIEX Elan 6000 ICP-MS. For the present study we used a spot diameter of 40 μm. The reproducibility of the data during this work was estimated measuring the NIST 610 standard. For further details the reader is referred to Günther et al. (2001) and Halter et al. (2004).

3.2. Cathodoluminescence (CL) imaging

CL images were made for the studied zircons, which are imbedded in an epoxy-resin pellet and then polished to the middle of the grains. The CL images were taken from a split screen on a CamScan CS 4 scanning electron microscope (SEM) at ETH-Zurich. The SEM is equipped with an ellipsoidal mirror located close to the sample within the vacuum chamber and can be adjusted by electro-motors. The sample can be located in one focal point while the second focal point lies outside the sample chamber. Here, the CL light enters the highly sensitive photomultiplier through a quartz glass-vacuum window and a light channel. The signal of the photo multiplier
is then used to produce the CL picture via a video-amplifier. In general, weak CL emission (dark colours in the picture) means high amounts of minor and trace elements; strong CL emission (light colours in the picture) means low amounts of minor and trace elements.

3.3. Laser ablation ICPMS (LA-ICPMS) of zircon

Laser ablation ICP-MS spot analyses were done using the same Excimer laser (ArF 193 nm) and PE SCiEX Elan 6000 ICP-MS, as for the trace elements of the rock samples. The pellet with the zircons (after the CL imaging) was placed in a closed cell together with the standard material (NIST 610), from which the ablated material is carried out into the ICP-MS by the argon gas stream. We used spot diameters of 40 and 20 μm. The laser pulse repetition rate is 10 Hz. The elements have been detected with 10 ms dwell time and 3 ms quadrupole settling time. The measurement efficiency was around 70%. Backgrounds were measured for 30 s and the transient signals from the sample material to be analysed were acquired for approximately 30 s. Calibrations for the zircon analyses were carried out using NIST 610 glass as an external standard. Limits of detection are calculated as 3 times the standard deviation of the background normalised to the volume of the sample ablated (cps/μg/g). The reproducibility of the data during this work was estimated by measuring the NIST 610 standard.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Major and trace-element composition of representative samples from the southern plutons of Central Srednogorie</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AvQ-018</td>
</tr>
<tr>
<td>SiO₂</td>
<td>53.69</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.58</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>14.60</td>
</tr>
<tr>
<td>FeO</td>
<td>8.93</td>
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<tr>
<td>MnO</td>
<td>0.15</td>
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<tr>
<td>MgO</td>
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<tr>
<td>CaO</td>
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<tr>
<td>Na₂O</td>
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<tr>
<td>K₂O</td>
<td>1.84</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.12</td>
</tr>
<tr>
<td>LOI</td>
<td>1.32</td>
</tr>
<tr>
<td>Total</td>
<td>100.35</td>
</tr>
</tbody>
</table>

Abbreviations: Gb — gabbro; Gbd — gabbrodiorite; Gdr — granodiorite; Gr — granite; porph — porphyry.
3.4. U–Pb isotope analyses of zircons

High-precision “conventional” U–Pb zircon analyses were carried out on single zircon grains at the Institute of Isotope Geochemistry and Mineral Resources, ETH-Zurich, using an ion counter system (Finnigan MAT 262 thermal ionisation mass-spectrometer). Selected zircons were air-abraded to remove marginal zones with lead loss, rinsed several times with distilled water and acetone in an ultrasonic bath and washed in warm 4 N nitric acid. All single grain zircon samples were spiked with $^{235}U-^{205}Pb$ mixed tracer. Total blanks were less than 0.002 ng for Pb and U. For further details see Von Quadt et al. (2002). The PBDAT and ISOPLOT programs of Ludwig (1988, 2003) were used for calculating the uncertainties and correlations of U/Pb ratios. The calculation of the U/Pb ratios include uncertainties of the spike calibration, Pb blank measurements, common Pb correction, U and Pb fractionation and U decay constant. All uncertainties are included in the error propagation for each individual analysis. The decay constants of Steiger and Jäger (1977) were used for age calculations, and corrections for common Pb were made using the Stacey and Kramers (1975) values. The reported “Concordia age” in the figures as well as in the paper is referred to the calculation program Isoplot of Ludwig (2001, 2003); the $^{206}Pb/^{238}U$ mean age is based on the average of the selected analyses and the number of analyses is taken into account for the error calculation.

3.5. Hf-isotope analyses of zircons

Hf-isotope ratios in zircons were measured on a Nu Instruments multiple collector inductively coupled plasma mass spectrometer (MC-ICPMS; David et al., 2001) at the Institute of Isotope Geochemistry and Mineral Resources, ETH-Zurich. High amounts of Zr in the samples did not create a significant matrix effect, and this was tested by repeated analyses of Zr-doped standard solutions. Measured $^{176}Hf/^{177}Hf$ was corrected for instrumental mass fractionation using a $^{179}Hf/^{177}Hf = 0.7325$ (exponential law for mass bias correction). Repeated analysis of the JMC-475 standard solution during the measurement session yielded a $^{176}Hf/^{177}Hf$ ratio of 0.282141±0.00014 (2σ). For the calculation of the $\epsilon_{Hf}$ values the following present-day ratios of the Chondritic Uniform Reservoir (CHUR)
Fig. 4. Spider diagrams for representative samples from the southern parts of Central Srednogorie: a) Trace-element patterns normalized to N-MORB; b) Chondrite-normalized REE patterns (CI chondrite and N-MORB values after McDonough and Sun, 1995).

Fig. 5. Geochemical discrimination diagrams, Rb/30-Hf-Ta*(Harris et al., 1986) and Yb-Ta (Pearce et al., 1984). Abbreviations: WPG — within plate granites, COLG — collision granites, VAG — volcanic arc granites, ORG — ocean ridge granites.
were used: \((^{176}\text{Hf}/^{177}\text{Hf})_{\text{CH}} = 0.282769\) (Nowell et al., 1998) and \((^{176}\text{Lu}/^{177}\text{Hf})_{\text{CH}} = 0.0334\). For age correction of the Hf-isotope ratios at 82–86 Ma, a \(^{176}\text{Lu}/^{177}\text{Hf}\) ratio of 0.0050 was used for all zircons.

3.6. Rb–Sr and Sm–Nd whole-rock isotope analyses

The isotopic composition of Sr and Nd and the determination of Rb, Sr, Sm and Nd contents were performed at ETH-Zurich using ID-TIMS techniques. Nd isotopic ratios were normalized to \(^{146}\text{Nd}/^{144}\text{Nd} = 0.7219\). Analytical reproducibility was estimated by periodically measuring the La Jolla standard (Nd) as well as the NBS 987 (Sr). The mean of 12 runs during this work was \(^{143}\text{Nd}/^{144}\text{Nd} = 0.511841 \pm 0.000007\) and 10 runs of the NBS 987 standard show an \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio of 0.710235 \pm 0.000012.

4. Major and trace-element rock chemistry

Compositionally the southern plutons of Central Srednogorie zone vary from gabbros to granites with SiO\(_2\) content ranging from 50.8 to 70.4 wt.% (Table 1). The main geochemical features of the southern plutons have been reviewed by Kamenov et al. (2003a), Georgiev (2004) and Von Quadt et al. (2005). In Table 1 representative analyses mainly for the rock varieties of Elshitsa–Boshulya pluton and the nearby outcrops of Vurshilo and Gutsal plutons are shown, which are the focus of the present study. Harker’s plots (Fig. 3) display generally negative correlation of SiO\(_2\) with TiO\(_2\), FeO\(_t\), CaO and MgO and positive correlations with K\(_2\)O, Na\(_2\)O. However, the considerable variation of FeO\(_t\), CaO, MgO, K\(_2\)O, Na\(_2\)O, and Al\(_2\)O\(_3\) in the rock varieties with similar SiO\(_2\) content suggest a complex evolution of the magma (including assimilation and mixing), rather than simple fractional crystallization. There is a pronounced composition gap between SiO\(_2\) \(\approx\) 55–63%.

Although former authors described having found rocks in this missing interval (Boyadjiev, 1962; Boyadjiev and Chipchakova, 1963), the intermediate rocks are not widespread in the southern outcrops of Central Srednogorie. This could be a result of the different erosion level or the lack of full homogenization of the mixed gabbroic and granitoid magmas.

The MORB normalized trace-element patterns indicate an enrichment of LILE (large ion light elements), which is significant only in the intermediate and felsic rocks (Fig. 4). The high field strength element content (HFSE, such as Ce, Zr, P and Hf) is slightly negative compared to the MORB values, but a strong negative Nb anomaly is characteristic for all studied samples. These features are typical for subduction-related magmatic sequences.

All basic rocks reveal flat or slightly enriched (relative to chondrite) REE patterns (Fig. 4b). Intermediate and acid rocks have fractionated LREE and relatively flat HREE patterns, as typically found in subduction-related volcanic suites. The REE-distribution in the hybrid gabbro–diorite AvQ-018 and the conduit dyke AvQ-098 lie between the trends of the acid and basic rocks (Fig. 4b). The degree of enrichment of the LREE relative to HREE measured by the ratio La\(_2\)/Yb\(_n\) is 2.3–5.1 in the basic rocks and 9.5–22.2 (but mainly 10–12) in the
Table 2
U–Pb ID-TIMS zircon isotope data for representative samples from the southern plutons of Central Srednogorie

<table>
<thead>
<tr>
<th></th>
<th>Analytical Sample</th>
<th>Weight in mg</th>
<th># U ppm</th>
<th>Pb ppm</th>
<th>206Pb/204Pb error %</th>
<th>206Pb/238U error %</th>
<th>207Pb/235U error %</th>
<th>207Pb/206Pb error %</th>
<th>Rho apparent ages</th>
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<tbody>
<tr>
<td>1</td>
<td>2402</td>
<td>125 + 100</td>
<td>0.0436</td>
<td>prism.</td>
<td>988</td>
<td>14.9</td>
<td>2105.8</td>
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<tr>
<td>2</td>
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<td>125 + 100</td>
<td>0.0244</td>
<td>prism.</td>
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<td>11.4</td>
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**AbQ-215 (Vôlčihovo leucocratic vein)**

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For sample localities see Fig. 1c.

For zircon descriptions abr — abraded, prism — prismatic, transp — transparent; brw — brownish; Rho — correlation coefficient $^{208}ppb/^{206}ppb$. $^{206}ppb/^{238}ppb$.
intermediate and acid rocks. Negative Eu anomalies are not observed or are very weak, which suggests that plagioclase was not fractionated from any of the magma suites. Discrimination diagrams for Zr/TiO2 vs. Ce/P2O5 (Müller et al., 1992) are similar to those in active continental margins (continental arc — CAP field), though the basic rocks lie in the marginal field to the postcollisional (PAP) field. Discrimination diagrams of Harris et al. (1986; Fig. 5a) and Pearce et al. (1984; Fig. 5b) also support the subduction-related affinity of the studied rocks.

Additional trace-element correlation diagrams can be used to address the possible slab fluid/melt contribution. Sr/Y vs. Y (Fig. 6a, Defant et al., 1991), as well as Ba/Th vs. Th diagrams illustrate normal island arc (andesite—dacite—rhyolite, not adakitic) affinities (Münker et al., 2004) of the igneous rocks from the southern parts of Central Srednogorie. Positive correlation on the Th/Yb vs. Ba/La (Fig. 6b) and Th/Yb vs. Sr/Nd (Fig. 6c) plots give evidence for enrichment of Th, Ba and Sr of the initial magma from both slab derived fluid and sediment components (Woodhead et al., 2001). Melt derived from sedimentary rocks was not likely important, as the Th/Yb ratio is low in the basic rocks and increases only in the granitoids, where it can be easily explained by crustal contamination. Noteworthy are the low values of Ba/La and especially Th/Yb in the gabbroic rocks (filled symbols on Fig. 6b and c), which emphasize the quite primitive character of the initial magma that was slightly enriched only in elements characteristic for slab derived fluids. These data make the metasomatized mantle wedge the best candidate for the primary magma source. Somehow the remobilised granitoid vein (AvQ-235) was enriched with the same fluid-transported elements as the gabbroic rocks, which gives evidence for additional transport of these elements to the basic varieties in the upper-crustal chamber.

5. U–Pb conventional zircon dating

5.1. Dating of the felsic (granitoid) levels

Inherited zircons (rounded, beige to colourless) prevail in the sample AvQ-029 of the Elshitsa granite. Pale beige long prismatic to almost isometric zircons from the smallest size-fractions were chosen for the dating (Table 2). Four air-abraded zircons are concordant and define a mean $^{206}\text{Pb} / ^{238}\text{U}$ age of $86.62\pm0.28$ Ma, whereas the non-abraded grains have $^{206}\text{Pb} / ^{238}\text{U}$ values, corresponding to $84.3\pm8.4$ Ma (Fig. 7a). The calculated concordia age (Ludwig, 2001) of the abraded zircons indicates time of the crystallization of the granite at $86.61\pm0.31$ Ma.

Analyzed zircons from the Vurshilo pluton (ZI-6) are also pale beige and prismatic. Non-abraded grains (4 zircons) and one of the air-abraded grains spread around an age of 82 Ma (Table 2) and determine a mean $^{206}\text{Pb} / ^{238}\text{U}$ value of $84.97\pm0.39$ Ma (Fig. 7f). Colourless vitreous zircons from the small size fraction (Table 2) give an upper intercept age of $442.7\pm8.3$ Ma (Fig. 7g) and suggest the metagranitoids (?) of the metamorphic basement as the mean assimilated source material.

Transparent and muddy prismatic zircons prevail in the hybrid gabbros of the almost homogenous mixed layers (samples AvQ-023 and AvQ-024, Figs. 1c and 2a). Five out of these zircons (sample AvQ-023) yield concordant ages (Table 2), with a mean $^{206}\text{Pb} / ^{238}\text{U}$ value of $84.87\pm0.13$ Ma (concordia age of $84.81\pm0.34$ Ma, Fig. 7h). Brown overgrowths have sharp contacts with the muddy rose or milky cores (Fig. 9) and lead to negligible younging.

5.3. Dating of the leucocratic (remobilised) granodioritic vein AvQ-235

Transparent and muddy, grey–brownish prismatic zircons prevail in this granodioritic sample. As shown on Fig. 7i the first group of zircons reveal an age ~84–85.5 Ma, the second — around 82 Ma. Multiphase zircons lay in-between, whereas the error ellipses overlap the concordia curve or are very close to it.

6. Hf-isotope and geochemical zircon tracing

6.1. Hf-isotope characteristics of the zircons

Hf-isotope studies are used to provide geochemical information for the precisely dated zircons. The $\epsilon$-Hf values are corrected for the corresponding age, as determined by the U–Pb method (Table 3). The gabbroic varieties reveal the most positive and mantle dominated $\epsilon$-Hf ($\tau$) values (Fig. 8). In Velichkovo hybrid gabbro–diorite (AvQ-018) they range...
from +7.2 to +10.3, and in the Vetren hybrid gabbro (AvQ-023) from +8.0 to +8.6. Concordant zircons from the felsic rocks yield also positive ε-Hf \((t)\) and give evidence for a primary mantle source of their magma. The latter was homogenised with crustal materials prior to the zircon crystallisation, which lead to the less positive ε-Hf (Fig. 8). The other tendency in the Hf-
isotope characteristics is the increase of the mantle component with time: some of the 82 Ma old zircons of the Velitchkovo hybrid gabbro–diorite reveal $\varepsilon$-Hf ($^t$) +10. In the same sample we observe also larger scattering of the $\varepsilon$-Hf-zircon (Fig. 8), which give evidence for better homogenisation of the magma in the case of sample AvQ-023 (85 Ma ago) compared with the hybrid gabbro AvQ-018 at about 82 Ma.

6.2. BSE/CL images and trace-element distribution of the zircons

BSE and CL images of the zircons are used to reveal the internal textures of the zircons from the different rocks. The studied zircons show oscillatory and rarely sector zoning (Fig. 9). In the brown zircons of the gabbroic varieties (AvQ-018) oscillatory zoning patterns (OZPs) are usually widely spaced, which is characteristic for a low degree of zircon saturation (Vavra, 1990). Light parts in the BSE images/dark in CL (enriched in heavy elements as U and Th) are mostly in the outer parts of the crystals, but sometimes they form sectors (the pyramid one) or domains with an irregular outline. Inclusions of U/Th minerals (mainly thorite) are also found attached to the same U/Th-rich zones in zircon. The muddy/milky zircons of AvQ-018 and AvQ-023 are rich in melt or mineral inclusions of basic and acid compositions or contain very small vapour inclusions.

The acid varieties reveal typical CL/BSE images for zircons in granitoid and intermediate rocks: fine OZPs and rarely sector zoning.

All Upper Cretaceous zircons yield similar REE distributions. The intermediate and heavy rare earth elements (REE) reveal constant and typical magmatic (Hoskin and Irland, 2000; Belousova et al., 2002) patterns. Positive Ce anomalies are found in all analyzed grains. Negative Eu anomalies are weak or absent (Fig. 9), which is in agreement with the REE distributions of the host rocks and is explained with a lack of plagioclase fractionation prior to the crystallization in the middle/upper crust. Characteristic for some brown rims is the appearance of a weak negative Eu anomaly. Brown zircons of the hybrid gabbroic rocks are generally slightly richer in REE compared to the other studied zircons.

7. Sr and Nd whole-rock characteristics

Strontium and neodymium isotope characteristics of the samples (Table 4) give evidence for mixing of the enriched mantle magma with at least one type of crustal member (Fig. 10). On the ($^{87}$Sr/$^{86}$Sr) vs. the SiO$_2$ diagram (Fig. 10a) only samples AvQ-018 and ZI6 (with an age of $\sim$ 82 Ma) reveal close initial strontium ratios with increasing SiO$_2$. In the other studied rocks the initial strontium ratios spread from 0.7047 to 0.7100 in the basic/intermediate varieties and generally between 0.7052 and 0.7058 in the acid one and give evidence for mixing of mantle and crustal magma. On the SiO$_2$ vs. ($^{143}$Nd/$^{144}$Nd) diagram (Fig. 10b) two trends are observed again: the first one with an increase of SiO$_2$ and a decrease of the neodymium ratio, and the second one with quite constant ($^{143}$Nd/$^{144}$Nd) with increasing SiO$_2$ (samples AvQ-018, ZI6).

Most rock samples lie on the mantle array of the ($^{87}$Sr/$^{86}$Sr) vs. ($^{143}$Nd/$^{144}$Nd) diagram (Fig. 10c) and follow the trend to EM1 field of Zindler and Hart (1986). One sample (AvQ-023) deviates to the EM2 field. This could be due to primary source
differences (EM2 type of enriched mantle source) or to mixing with radiogenic crustal rocks at middle/upper-crustal levels.

8. Discussion of the results

8.1. Timing of magma chamber replenishment

U–Pb ID-TIMS analyses of zircons from Upper Cretaceous intrusive rocks in the southern parts of Central Srednogorie show that the method can be applied to dating replenishment processes in long-lived (more than 1 Ma) magma chambers, when the timing is combined with precise field and petrographic studies and followed by careful selection and CL/BSE imaging of zircons. The precision of the conventional ID-TIMS analyses during this study (the majority of measurements were carried out in the period 2002–2004) was usually less than 0.3 Ma (0.35% 2σ uncertainties) or better to 0.08 Ma (0.1%), when the weighted mean $^{206}\text{Pb} / ^{238}\text{U}$ value was used for age calculations. Further developments in ID-TIMS dating, such as double Pb and U spikes (Amelin and Davis, 2006; Von Quadt et al., 2007), smaller decay constant errors (Schoene et al., 2006), blank and spike calibration in combination with the improved chemical preparation of the zircons (lower laboratory blanks and chemical abrasion (Mattinson, 2005) will allow lowering the uncertainties to <0.1% and distinction of geological processes less than 0.1 Ma. Apart from analytical uncertainties a possible limitation for the accuracy of the dates, in terms of their interpretation as magma crystallization ages, can be related to the possibility that magma chamber replenishment and mixing could lead to protracted or repeated growth of zircon.

In the Elshitsa–Boshulya and Vurshilo plutons our calculated ages for concordant zircons are concentrated around 86.5–86, 85–84.5 and 82 Ma (Fig. 11). This has to be interpreted as a
series of events at a certain time, as opposed to continual zircon growth, in at least two magma chambers — one in the northern part (the region around Elshitsa), and one in the southern part (Boshulya, Velichkovo and Vurshilo, Fig. 12). Another observation is that even at about 82 Ma (AvQ-018) the field relationships (load casts, flame structures, formation of globular
Table 4

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Abbreviations: Gb — gabbro; Gdr — granodiorite; Gr — granite; subvolc — subvolcanic.

enclaves, Fig. 2) indicate interaction of the gabbroic magma with not fully solidified, but considerably colder (chilled margins, Fig. 2b) granitic mush. This observation can be explained with heat flow through the regular hot basic magma replenishment. Nevertheless, zircons in the granodiorite AvQ-019 are dated at 84.60 ± 0.32 Ma, and therefore no new zircon growth was detected. This means that the temperature of the mush was kept below the conditions that allow zirconium mobility and new zircon saturation (as overgrowths or new crystals). One exception is the leucocratic vein of remobilized granitoid material (AvQ-235, Figs. 2c and 7e), where we have new growth of zircon at about 82 Ma, contemporaneous with the intrusion of the gabbroic magma (AvQ-018, brown zircons). The main population of zircons reveal the age of the granodiorites (AvQ-019) of 84.56 ± 0.23 Ma, which we interpret as inherited from the granodiorite magma mush.

Usually isotope geochronologists have problems finding zircons in gabbroic rocks. Our studies in these mixed successions revealed hybrid gabbros and gabbro–diorites as highly suitable for dating — they contain different zircon groups that can be used for tracing of the processes during the magma ascent to the surface. One dyke sample (AvQ-098) is an exception and reveals mostly zircon inheritance. Intermediate varieties are also suitable for dating, because of the prevailing amount of newly saturated zircons and general lack of inherited grains (cores). Granitoid rocks in the southern parts of Central Srednogorie showed most complicated batch of zircons. There, most of the studied samples contain significant amounts of inherited grains or cores, and the subvolcanic varieties may lack newly saturated Upper Cretaceous crystals (an example is the granodiorite–porphyry from the Vlakyov Vrhu deposit AvQ-031, Peytcheva et al., 2003).

8.2. Zircon inheritance, saturation and growth

Placing time constraints on replenishment processes with conventional U–Pb ID-TIMS is possible when each dated magma has newly saturated zircons roughly representing its time of crystallization. The high temperature (> 1000 °C), primary chemistry and usually high water content in subduction-related magmas favour the lack of inherited zircons (Watson, 1996). Once the magma is generated, its evolution follows different scenarios. Although there are examples where mantle xenoliths are transported to the surface in hours (Nédli and Tóth, 2007), in convergent tectonic zones the magma usually travels much slower — 10–200 thousands years to >1 Ma (Hawkesworth et al., 2000; 2004; Charlier et al., 2005). Zircon inheritance and saturation are expected to respond to scenarios where after its generation in the upper mantle the magma interacts with crustal materials at different levels — on the mantle/crustal boundary (Leeman, 1983; Hildreth and Moorbath, 1988; Winter, 2001; Richards, 2003), in the lower-middle crust (Annen et al., 2006), mixing and crystallizing finally in upper-crustal chambers or being erupted as effusives. Where and when does zircon saturation start and how long does it last? Zircon saturation is most sensitive to temperature and zirconium concentration of the magma, and less sensitive to the whole-rock chemistry (specially the SiO2 concentration, or to a lesser extent in the chemistry (Watson and Harrison, 1983; Watson and Harrison, 1983; Harrison and Watson, 1983; Miller et al., 2003). In the primary magma zirconium represents an incompatible element. Its concentration is usually low (<70 ppm), and the high temperature (>1000 °C) will not allow zircon saturation neither in the metasomatized mantle wedge nor in the lower crust. Consequently zircon is expected to start crystallizing after a drastic change in the temperature or in the zirconium concentration, or to a lesser extent in the chemistry (M value) or water content. The use of the Watson and Harrison (1983) formula is previously restricted by the range of M value between 0.9 and 1.7 and later extrapolated to 1.9–2.1 (Hansmann and Oberli, 1991; Von Blankenburg, 1992; Hanchar and Watson, 2003). Granitoid rocks match this requirement, revealing usual M values ~1.3–1.5 (Watson and Harrison, 1983; Miller et al., 2003). In the southern parts of Central Srednogorie only acid intrusives are within or close to this M-value range (between 0.72 and 2.24) and a zircon saturation temperature of 710–780 °C (mainly ~730 °C) is calculated for them. These temperatures for the Central Srednogorie granitoids correspond to “cold granites” (saturation temperature < 800 °C) in the sense of Miller et al. (2003). On the other hand, according to their generation they trend to the “hot granites”, as they...
crystallize from magma with mantle origin, which was contaminated with crustal material. Therefore, either the temperature is underestimated (the case, “when natural sample and experiments did not agree”, Hanchar and Watson, 2003) because of zircon inheritance in an otherwise undersaturated magma (Miller et al., 2003), or the magma reached the zircon saturation temperature in the upper-crustal chamber after cooling and during contemporaneous crystallization with the other rock-forming minerals.

In the hybrid gabbroic samples the M values range from 3.9 to 6.0, and the FM value \((\text{Na} + \text{K} + \text{Mg} + \text{Fe} + 2^*\text{Ca})/(\text{Al}^*\text{Si})\) of Ryerson and Watson (1987) is between 10 and 23. It is clear that the Watson and Harrison (1983) saturation thermometry cannot be applied. Nevertheless zircons are abundant. Why and when did they saturate? It does not happen because the zirconium concentration was increased (it ranges between 31 and 58 ppm in the basic samples, Table 1) and we have to identify other important variables — temperature, water content and chemistry (changes in M or FM values). The M (FM) value cannot be crucial — in the gabbroic rocks it stays out of the “limits” of Harrison and Watson (1983), so that only the changes in the temperature and water content (hence the physics of magma) tend to be crucial. Mingling and limited mixing processes with colder granitoid magma/mush in middle- upper-crustal chambers favour both — the sudden and fast cooling of the gabbroic magma, as well as magma degassing. Both of them can lead to zircon saturation and will best explain the strange features of the zircons in the hybrid gabbros: high U- and REE-content; general lack of Eu-anomaly, as is characteristic for the whole rock; appearance of weak negative Eu-anomaly in some outer zircon rims, crystallizing after a significant amount of plagioclase; inclusions of potassium feldspar; presence of many small (vapour?) inclusions in the milky zircons.

Although new zircon saturation is most important for dating of the South Srednogorie plutons, the zircon inheritance can also be used to assess processes impacting mafic and felsic calc–alkaline magmas prior to and during their crystallization in crustal chambers. In the hybrid gabbros and gabbro–diorites of samples AvQ-018 and 023 the milky zircons often show brown overgrowths that suggest multiple periods of zircon growth during the magma mixing. In this case the conventional dating will result in poorly defined ages while the analysed data points spread along the concordia line. Abrasion of the rims leads to

![Fig. 10. Sr and Nd isotope data for whole-rock samples from the studied area: a) \((^{87}\text{Sr}/^{86}\text{Sr})_i\) vs. SiO₂ and (b) \((^{143}\text{Nd}/^{144}\text{Nd})_i\) vs. SiO₂ diagrams; c) \((^{87}\text{Sr}/^{86}\text{Sr})_i\) vs. \((^{143}\text{Nd}/^{144}\text{Nd})_i\) diagram. Fields of the DMM (depleted MORB mantle), HIMU (magma source having a high \(\mu -^{238}\text{U}/^{204}\text{Pb}\) ratio), EM1 and 2 (enriched mantle 1 and 2) and BSE (bulk silicate earth) are given according to Zindler and Hart (1986) and Hart and Zindler (1989) (corrected to 85 Ma). Dashed lines correspond to the Jr and Nd isotope values of the undifferentiated reservoir — identical to CHUR (DePaolo, 1988; Faure, 2001), corrected to 85 Ma.](422)

![Fig. 11. U–Pb zircon ages of the studied samples from plutons in the southern parts of Central Srednogorie. Abbreviation “b” is used for the brown/brownish zircons of sample AvQ-018 and AvQ-235, “m” for the milky zircons of sample AvQ-018.](422)
Fig. 12. Schematic model of the evolution of the magma chamber producing Boshulya, Velichkovo and Vurshilo plutons (modified after Wiebe and Collins, 1998 and Halter et al., 2005). The first portion of basic magma intrude a stratified chamber at ~ 84.9 Ma (sample AvQ-023), almost contemporary with a granodiorite AvQ-019. Mafic enclaves are formed above the sheet-like hybrid gabbroic body. Later, at ~ 82 Ma a second gabbroic magma enter the chamber (AvQ-018), using conduit dikes. The hot basaltic magma mixes with the granodiorit mush (AvQ-019). Hot deep crustal zones with hydrous basaltic magma generate intermediate and silicic igneous rocks through fractional crystallization and partial melting of pre-existing crustal rocks. Vurshilo granite (ZI6) forms above the sheet-like body of the hybrid gabbro AvQ-018.

more precise age, but unfortunately removes the younger parts. We could suppose the same phenomena for zircons, where this multiple growth is not obvious (not marked by clear differences in the U-content), for example in the zircons of ZI6.

The hybrid gabbro–diorite sample AvQ-018 contains also (sparse) inherited vitreous zircons with ~ 440 Ma age, whereas in the granodioritoids the zircon inheritance is poorly defined, or points to Proterozoic ages (Table 2). Older U–Pb multigrain age data on zircons from the basement gneisses (unfortunately with unclear sample localities) of Arnaudov et al. (1989) are difficult to interpret because of the larger uncertainties ~ 406 ± 30, 480 ± 30 and 485 ± 50 Ma. Recently Carrigan et al. (2006) measured zircon cores in a Hercynian leucosome enclosed in migmatic paragneisses with age populations at ~ 500–700, 900–1100, 1900–2200, 2350, 2550 and 2700 Ma (HR-SIMS analyses). Peytcheva and von Quadt (2004) reported preliminary protolith ages of 502.8 ± 3.2 Ma for amphibolite-facies overprinted gneiss from the northern part of Central Srednogorie and a concordant age of 443.0 ± 1.5 Ma for a low metamorphic metadiorite in the adjacent southern slopes of the Balkan. Inherited zircons and cores with mantle origin from the Medet monzodiorite (Peytcheva et al., 2004, 2006) define a discordia line with an upper intercept age of 456.5 ± 5.5 Ma. The published ages lead to the assumption that the sources for the basic/intermediate and upper crust assimilation.

Three possible magma sources for the plutons from southern parts of Central Srednogorie – slab derived LILE and LREE enriched fluids, the metasomatized mantle wedge and the continental crust – can be identified by the combination of whole-rock trace-element chemistry and Nd–Sr isotope characteristics. As mentioned above, indicative ratios such as Sr/Y, Ba/Th, Th/Yb and Ba/La in the basic (most “primitive”) rocks point to slab derived fluids as an important source for mantle wedge enrichment (Fig. 6b, c). The sediment component is negligible as we cannot relate the increased Ba/La and Sr/Nd ratios to significant crustal-sediment contamination (no change in the Th/Yb ratio, Fig. 6b, c). The intermediate and acid rock varieties reveal both the slab derived fluids and the sediment as enrichment source, but geochronological data and Hf–isotope studies of the zircons relate the sediment component to mainly crustal assimilation.

It seems that the mingling/mixing of the gabbroic magma (samples AvQ-018, 023 and 024) with the felsic one (AvQ-019 and possibly ZI-6) was either limited or occurred with fractionally crystallized magma with little crustal contamination, or both — even after mixing, the Sr and Nd characteristics and trace-element signature of the basic hybrid rocks remain quite ‘‘primitive’’.

The Lu–Hf zircon data are most reliable for tracing the processes that affected the basic and acid magma, as they are related to the dated zircons. The advantage of the isotope Hf-zircon analyses is the possibility of distinguishing between old inherited zircons (ε-Hf of ~ 28, Table 3) and newly saturated (mantle dominated), instead of the commonly used ε-Hf whole-rock analyses. The ε-Hf values of all concordant zircons from the Upper Cretaceous plutons in Central Srednogorie are positive (Fig. 8), which was also shown for the subvolcanic and volcanic varieties in the region in previous studies (Von Quadt et al., 2005). In the hybrid gabbro of Velichkovo (82 Ma), ε-Hf is slightly higher than +10 and in the monzogabbro of Capitan Dimitrievko pluton (Kamenov et al., 2003a,b), it is +9.2. These values are similar to that of the measured concordant Upper Cretaceous zircons from andesites (basaltic andesites) in the
9. Conclusions

1. The Upper Cretaceous southern plutons of Central Srednogorie were formed in long-lived magma chambers that experienced magma replenishment. Mingling and mixing processes of basic and felsic magma are inferred from field relationships and petrographic evidence for the rocks.

2. Conventional ID-TIMS U–Pb zircon geochronology is suitable for dating replenishment processes in long-lived magma chamber(s) when they are sufficiently separated in time (≥ 0.6–1.0 Myr) and marked by new zircon growth. The precision of the analyses (usually less than 0.35% 2σ uncertainties) can distinguish a series of zircon crystallization ages around 86.5–86, 85–84.5 and 82 Ma. Continuous heat flow provided by periodic gabbroic magma replenishment may account for the preservation of the granitoid mush in the chamber for long periods of time and for granitoid remelting.

3. Major and trace-element distribution, Sr and Nd isotope chemistry, as well as indicative ratios such as Sr/Y, Ba/Th, Th/Yb and Ba/La define subduction-related normal island arc affinities for the studied plutons. These trace elements are used to identify slab derived fluids as an enrichment source for mantle wedge magma, whereas a sediment component in the granitoid rocks is due to crustal contamination.

4. Zircon inheritance and the corresponding ε-Hf in the hybrid gabbroic rocks point to the lower crust as a possible source for the second enrichment of the primary mantle magma, whereas upper and middle crust contributed significantly in the generation of the granitoid varieties.

5. Hf-zircon isotope characteristics mark a slight increase of the mantle component with time: some of the 82 Ma old zircons in the hybrid gabbro reveal the highest ε-Hf (t) up to +10.3. The broad scattering of the ε-Hf-zircon within one sample could be a result of poor homogenisation of the mantle magma after the crustal contamination.

6. Abundant zircon found in the mingled/mixed successions reveals that hybrid gabbros and gabbro–diorites may be suitable for dating. Different zircon groups can be distinguished within the rocks, which can be used to trace magma sources during ascent of the magma.

7. Mingling/mixing of the mantle magma with cold crustal granitoid magma/mush at mid- to upper-crustal levels is proposed to explain the change of the physical conditions (fast cooling; magma degassing?) and to lesser extent in the magma chemistry that are necessary for zircon saturation and fast crystallization of U- and REE-rich zircons in the hybrid gabbro.

Acknowledgments

This work was supported by the Swiss National Science Foundation through project 200020-100735 and the SCOPES Joint Research Projects 7BUJP62396. The study is a contribution to the GEODE-ABCD (Geodynamics and Ore Deposits Evolution of the Alpine–Balkan–Carpathian–Dinaride province) of the European Science Foundation. Discussions with Urs Schaltegger, Peter Marchev and colleagues from IGMR, ETH-Zurich encouraged the authors to publish the data. IP appreciates the English corrections of Svetoslav Georgiev and the editing of the revised version by Blair Schoene, who made the foreigner English readable. Wendy Bohrson and an anonymous reviewer are thanked for their constructive corrections that helped to improve the manuscript.

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