A Carboniferous/Permian, calc-alkaline, I-type granodiorite from the Małopolska Block, Southern Poland: implications from geochemical and U-Pb zircon age data

Andrzej ŻELAŻNIEWSICZ, Magdalena PAŃCZYK, Jerzy NAWROCKI and Mark FANNING


A granodiorite from borehole WB-102A in the Dolina Będkowska, the Małopolska Block (MB), Southern Poland, yielded a mean U-Pb zircon age of 300 ±3 Ma with SHRIMP II. No inherited older component was detected. Geochemically, it is a K-rich, I-type, calc-alkaline granodiorite with supra-subduction characteristics (negative Nb and Ti anomalies). Silicic igneous rocks are abundant at the MB margin along the Kraków–Lubliniec Fault Zone (KLFZ) across which it adjoins to the Upper Silesian Block (USB) where such rocks are scarce. Both blocks belong to the Variscan foreland. Granitic rocks cannot, however, generate at foreland settings. Thus, the hypothesis is put forward that the parent melt for the silicic rocks was derived from the thickened lower crust of the Variscan orogenic belt owing to extensional decompression melting, and transported away towards pull-apart openings developed along the crustal-scale fault zone (KLFZ) that underwent a complex strike-slip history around the Carboniferous/Permian boundary.

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Key words: Brunovistulian, Upper Silesian Block, Kraków–Lubliniec Fault Zone, SHRIMP, Variscan foreland, strike-slip.

INTRODUCTION

In Southern Poland, the NW-trending, crustal-scale Kraków–Lubliniec Fault Zone (KLFZ) separates, in the subsurface, the Upper Silesian Block (USB) of the composite Brunovistulian Block (BB) from the SW from the Małopolska Block (MB) to the NE, both concealed under Mesozoic-Cenozoic platform cover and Carpathian nappes (Fig. 1). The two blocks differ markedly in the velocity structure of the crust as shown by seismic refraction profile CEL-02 of the CELEBRATION 2000 experiment (Malinowski et al., 2005). Such seismic data is consistent with earlier interpretations of the Kraków–Lubliniec Fault Zone as a terrane boundary (Brochwicz-Lewiński et al., 1986; HaRańczyk, 1994; Dadlez, 1995; Bula et al., 1997, Nawrocki et al., 2004). Based on different lines of evidence, this prominent crustal feature is assumed to have originated in Neoproterozoic-Cambrian times and then repeatedly rejuvenated during the Palaeozoic (Dudek, 1980; Dadlez, 1995; Źelaźniewicz, 1998; Żaba, 1999; Nawrocki et al., 2004). On the pre-Mesozoic surface, the feature is confined to a ca. 500 m wide zone of intensely brittle deformation (Bula et al., 1997; Żaba, 1999) observed in Palaeozoic rocks of the MB and USB. Another conspicuous subsurface manifestation of the KLFZ is a demarcation of the Lower to Middle Cambrian shallow-water sandstone succession on the Upper Silesian Block (Bula, 2000) which does not pass across the fault (Fig. 1A). In contrast, on the MB side, unmetamorphosed to anchimetamorphosed Neoproterozoic pelites (Jachowicz, 1994; Jachowicz et al., 2002), overlain by Ordovician and Silurian carbonates and pelitic to psammitic rocks, adhere to the Kraków–Lubliniec Fault Zone (Bula, 2000). On the two blocks, Devonian carbonates are covered by Carboniferous clastic rocks. The Kraków–Lubliniec Fault Zone, which dips steeply to the NE or SW (Żaba, 1999) in its near-surface sections, likely becomes a widely distributed feature deeper in the crust (Malinowski et al., 2005).

In both walls of the Kraków–Lubliniec Fault Zone, igneous rocks are in evidence (Fig. 1). They are much less abundant on the USB side. K-rich rhyolites to dacites intruded in the form of
laccolith into Carboniferous mudstones that locally crop out WNW of Kraków in the Upper Silesian Block (Fig. 1). These were dated at 295 ±3 Ma (U-Pb zircon, Nawrocki et al., 2008).

In boreholes located along the SW margin of the Małopolska Block, granites, porphyritic dacites and rhyolites, and minor mafic rocks have been encountered for up to some 10 km from the Kraków–Lubliniec Fault Zone during extensive surveying aimed at prospecting firstly, Pb-Zn and then for Cu, Mo, and W ore mineralization (Dolina Będkowska, where the borehole WB-102A is located, Pilica, Zawiercie, Myszków and Żarki areas; Fig. 1A). The Kraków–Lubliniec Fault Zone coincides with a marked gravity gradient and magnetic anomalies owing to the mineralization of the igneous rock masses (Królkowski and Petecki, 1995; Podemski, 2001). There is an area of low gravity anomalies, stretched in a NW–SE direction between Lubliniec, Myszków and Kraków on the Małopolska Block, which reflects the extensive presence of felsic igneous rocks at upper crustal levels. As some of these rocks intruded
Devonian carbonates, their late Palaeozoic age has been long, if imprecisely, known. A few attempts of dating (K-Ar, Ar-Ar, Re-Os) yielded whole-rock or mineral ages between 312 Ma and 290 Ma (Jarmolowicz-Szulc, 1984, 1985; G. Oliver in Haranczyk, 1989; Chaffee et al., 1997; Podemski, 2001; Stein et al., 2005). This paper reports the first U-Pb SHRIMP II analyses of zircons from a granitic rock of the Dolina Będkowska area, some details of the geochemistry of this rock, and the implications of the new data.

PETROGRAPHY AND GEOCHEMISTRY

In the Dolina Będkowska area, some 30 km NNW of Kraków (Fig. 1), granodiorites were encountered in the boreholes DB-5 and WB-102A at a depth of 1198 and 1091.5 m respectively, beneath an uppermost Neoproterozoic (Ediacaran) succession of anchimetamorphosed elastic rocks (Fig. 1C). The two boreholes are 270 m apart which is the minimum size of the concealed granitic body. A core retrieved from borehole WB-102A from a depth of 1186–1188 m (Fig. 1C), is of an unfoliated, coarse-grained granitoid with virtually no fabric (Fig. 2). It is noteworthy that a lack of fabric is characteristic of all the Małopolska granitoids and related subvolcanic rocks.

The WB-102A granodiorites are greyish red to rarely greyish green, generally holocrystalline, massive, medium-grained rocks. They are characterized by porphyritic texture with medium- and even coarse-grained plagioclase and fine-grained crystals of quartz, alkali feldspar and mafic minerals represented by biotite and amphibole. Zircon, apatite and titanite are present as accessory minerals. In modal composition, rock-forming minerals occur in various proportions: plagioclase 42–55 modal per cent, quartz 24–38%, alkali feldspar 3–20%, biotite 3–9%, and amphibole (Mg-hornblende) 0.4–3.2% (Markiewicz, 2006). Subhedral or euhedral tabular crystals of plagioclase are dominant within the rock. Plagioclase with conspicuous recurrent zonation are commonly observed (Fig. 2). The cores were identified as andesine, whereas the outer rims are oligoclase and albite. Most plagioclase crystals are slightly altered (sericitisation, carbonatisation, albithisation and rarely epidotisation). Alkali feldspar forms anhedral crystals which are occasionally replaced by kaolinite. Biotites which form coarse- and medium-grained crystals (Fig. 2), very often with inclusions of zircon and apatite, are only rarely chloritised.

Based on geochemistry (Table 1), the WB-102A rock is a metasomatic, K-rich, calc-alkaline granodiorite. On the Ba-Rb-Sr plot (El Bouseily and El Sokkary, 1975), it also appears in the granodiorite field. The A/CNK index of 0.9 allows assignation to an I-type granite with a K/Rb ratio of 268 and high K2O+Na2O. Such characteristics resemble A-type granites, however the Ga/Al ratio of 2.1 as well as relatively high CaO, Ba, Sr but low Zr contents are not consistent with such an affinity (Whalen et al., 1987). Although some A-type similarity is not surprising in view of the geological position of the granodiorite in the Małopolska Block, the negative Nb and Ti anomalies strongly indicate a supra-subduction affinity, which is in line with relatively low Th contents (<10 ppm). On the Pearce et al. (1984) diagrams, the granodiorite plots persistently in the field of VAG and on the modified Rb-(Y+Nb) plot (Pearce, 1996) it also lies in the field of post-collision granites. LREE contents are 10–60 times chondrite and the REE pattern is moderately fractionated (La/Yb ratio). A lack of Eu anomaly, relatively high contents of Sr (>200 ppm) and Ba (> 800 ppm), and undepleted Rb and Cs suggest that plagioclase was not left at the source and consequently the melt could only be moderately fractionated and evolved (SiO2 <70%). The high Ba and relatively low Rb (<100 ppm) also indicate insignificant feldspar fractionation (Blevin and Chappell, 1992). Utilizing some A-type resemblance, the melt may be thought to have been of crustal derivation as suggested by Y-Nb-Ce and Y-Nb-3Ga plots (Eby, 1992). The ratio CaO/Na2O of 0.8 seems to speak in favour of partial melting of metapsammitic or granodioritic to tonalitic precursor rather than pelitic rocks (Jung and Pfänder, 2007). In the R1–R2 diagram (Batchelor and Bowden, 1985), it plots close to the border between the fields of pre-plate collision and post-collisional uplift. The lack of fabric in this rock corresponds well with the post-collisional signature and does not contradict a post-tectonic or anorogenic event in the region. However, in Zr+Nb+Ce+Y versus FeO/MgO and (K2O+Na2O)/CaO discrimination diagrams (Whalen et al., 1987), the WB-102A granodiorite plots in the field of unfractionated granites (OGT), far from the field of A-type granites.
More detailed study of the geochemistry of the felsic rocks from the Małopolska Block is beyond the scope of this paper. Geochemical correlations with felsic rocks from other occurrences in the Małopolska Block are limited, as most published analyses from this region only show limits of contents of elements except for the paper by Markiewicz (2002) which refers to major and some trace elements. Comparisons based on available data reveal that the chemistry of three granitoids from the Myszków area resembles that of the studied sample WB-102A.

<table>
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<tr>
<th>Major elements oxides [wt. %]</th>
<th>Trace elements [ppm]</th>
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<tr>
<td>( \text{SiO}_2 )</td>
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<tr>
<td>( \text{Al}_2\text{O}_3 )</td>
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<tr>
<td>( \text{Fe}_2\text{O}_3 )</td>
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<td>TiO(_2)</td>
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<tr>
<td>Total</td>
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*Table 1: Geochemistry of the granodiorite studied*

GEOCHRONOLOGY

ANALYTICAL METHODS

Zircons were separated using conventional heavy liquid and magnetic techniques. The sample was analyzed by the SHRIMP II at the Research School of Earth Sciences, Australian National University, Canberra. Zircon standard FC1 (zircon from the Duluth Gabbro) was used to correct Pb/U ratios for instrumental fractionation. All grains were imaged in cathodoluminescence (Fig. 3) and photographed in both trans-
Results of SHRIMP U-Pb analyses of zircons for the Dolina Będkowska granodiorite, sample WB-102A

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<td>21.33 ± 0.25</td>
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<td>20.76 ± 0.31</td>
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Notes:
— uncertainties given at the one level;
— error in FC1 Reference zircon calibration was 0.55% for the analytical session (not included in above errors but required when comparing data from different mounts);
— Τ206 [%] denotes the percentage of 206Pb that is common Pb;
— correction for common Pb made using the measured 206Pb/207Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).

Zircons from the sample analyzed are generally transparent, pale-coloured and euhedral with short-prismatic to normal-prismatic and less frequent long-prismatic morphology (typical elongation from 2:1 to 4:1 and 7:1). Internally, most grains have a simple structure of characteristically magmatic oscillatory zoning and a few grains have planar-banded zoning (Fig. 3). Around one third of grains have a weakly zoned or slightly differently structured euhedral to somewhat subhedral core in crystallographic continuity with euhedral overgrowth which displays more intense zoning.

**RESULTS**

The grains analysed have moderate U and Th contents with a Th/U ratio of 0.28–1.00 which is typical of zircons grown under magmatic conditions. 14 grains were analyzed in 20 spots (Table 2, Figs. 3 and 4). All 20 analyses form a single cluster around 300 Ma and a spread of ages between 311 Ma and 278 Ma, with no record of inherited old components. 10 analyses might apparently represent “older” zircons with a mean age of 304 ± 2 Ma (MSWD = 0.89) and 7 analyses would represent “younger” grains with a mean age of 294 ± 3 Ma (MSWD = 0.44). This would be in accord with the presence of euhedral to subhedral cores in some grains that might suggest two stages of zircon growth. However, there is no correlation between the core or outgrowth positions and the measured 206Pb/207U ages. The cores show a range of ages (Nos. 1, 6, 8, 9, 12, 14) between 311 to 293 Ma and do not define any distinct
independent event of zircon crystallization. Moreover, in two grains (Nos. 6 and 9), the cores appear younger than the rims (Fig. 3). Therefore, any apparent distinction within the entire group has no real significance, as confirmed by the Tera-Wasserburg concordia diagram (Fig. 4). Two analyses plot to the right of the group and are thought to possibly reflect Pb loss. Discarding these two youngest ages, 18 analyses yielded ages ranging from 311 to 293 Ma, with a mean age of 300 ± 3 Ma (Table 2, Fig. 4) which records the main zircon crystallization event in the granodioritic magma. This is taken to date magma emplacement at the Carboniferous/Permian boundary (Gradstein et al., 2004).

DISCUSSION

The time interval, 311–293 Ma, is very similar to that obtained by other methods for the Małopolska felsic rocks to the north of the Dolina Będkowska area, which is nearest to the rhyolitic laccolith area of the Upper Silesian Block (Fig. 1). The mean age of 300 ± 3 Ma of the WB-102A granodiorite overlaps within error with a mean age of 295 ± 3 Ma for the Zalas rhyolite (Nawrocki et al., 2008). It follows that the igneous intrusions in the Małopolska Block and the Upper Silesian Block of Brunovistulia were contemporaneous, straddling the Carboniferous/Permian boundary. In view of the similar timing and their present-day proximity, their derivation from the same source is likely though not certain. More isotopic studies are required to resolve this question. A striking difference lies in the absence of mineralization in the Upper Silesian rocks, which is in marked contrast to those on the Małopolska side of the Kraków–Lubliniec Fault Zone. Borehole log profiles show that the outer portions of the granodiorite body(ies) and the enveloping country rocks are mineralized (Cu-Mo-W) and include calc-alkaline porphyry copper-type deposits (Podemski, 2001). In the case of the WB-102A and DB-5 boreholes, such mineralization likely developed towards the end of the magmatic activity in the area, and the bulk of the granodiorite body having remained barren.

Localization of the igneous intrusions mainly in the NE wall of the Kraków–Lubliniec Fault Zone and a lack of any fabric in the granitoids and related subvolcanic rocks suggest some control of the crustal-scale fault zone on the distribution of the high-level magmatic bodies in the regime with nearly zero deviatoric stress. Alternatively, the felsic magmas may have intruded as a mush with a low percentage of crystals, that might have prevented them from acquiring any directionally preferred arrangement at the time of emplacement. This is in line with the nearly 15 m.y. long time interval when zircons crystallized in the granodiorite magma that must have been in a protracted molten state, allowing for dissolution of all older zircons as no inherited component survived in the new zircon population. The high temperature of the intruding magmas, although still requiring quantification, is clearly shown by wide thermal halos around the igneous bodies, and corroborated by contact metamorphism up to migmatic stage (Heflik and Piekar ski, 1992; Moryc and Heflik, 1998).

At the Carboniferous/Permian boundary, the Małopolska wall of the Kraków–Lubliniec Fault Zone was subject either to an overall extension or to wrenching that might have given room for an array of igneous intrusions, possibly emplaced in pull-apart conditions. Indeed, a complex strike-slip regime comprising dextral transtension, followed by dextral transpression and then normal faulting with a sinistral slip component is suggested to have controlled the KLFZ evolution in latest Carboniferous through Permian times (Żaba, 1999). Such conditions are very likely to have facilitated the felsic intrusions, especially the dextral transtensional event that was thought by Żaba (1999) to be the one that favoured magma rise and final emplacement of the granodiorite bodies in the Małopolska Block in late Westphalian times. Our new SHRIMP data on zircons shows the event (300 ± 3 Ma) actually
straddled the Carboniferous/Permian boundary, by reference to the GTS2004 scale (Gradstein et al., 2004).

Late- to post-collisional felsic magmatism of similar age occurred in the Variscan orogenic belt in Central Europe at ca. 310–290 Ma (Bonin, 1998; Finger and Steyer, 1990; Finger et al., 1997; Franke, 2000). However, the Malopolska intrusions occur outside the orogenic belt (Fig. 1) and granitoids are unlikely to generate in foreland settings. Therefore, we propose a hypothesis that the parent melt for the Malopolska and Upper Silesian silicic rocks was derived from the thickened lower crust of the Variscan orogenic belt owing to extensional decompressional melting near the crust/mantle boundary. The supra-subduction signatures inherited from the original setting were written in the chemical memory of the granitic melts which were derived from below the orogen that was undergoing thermal relaxation. They were likely driven by the hydraulic gradient and transported from their place of origin, in the westerly located orogenic root with remnant subduction zone, towards the not-too-distant pull-apart openings developed along the wrenched Kraków–Lubliniec Fault Zone in the relatively low velocity crust of the Malopolska Block (see Malinowski et al., 2005). The high temperature granitic magma probably traveled as a crystal mush which kept it from forming a fabric alignment or, alternatively, the magmatic flow was turbulent. Advecitive heating in the crustal zone of the Kraków–Lubliniec Fault Zone is consistent with extensive contact metamorphism in the area (including skarns developed in overlying Devonian carbonates) and subsequent extensive hydrothermal processes surrounding the Carboniferous/Permian boundary. Further geochemical and geochronological studies are necessary to test this hypothesis.

CONCLUSIONS

1. Silicic calc-alkaline magmatism occurred in the Variscan foreland parallel to the Kraków–Lubliniec Fault Zone between 310 Ma and 290 Ma, which was coeval with post-collisional granite intrusions in the Central European Variscides.

2. The magmatism was genetically connected with the Variscan orogen from which the felsic magma was likely driven by the hydraulic gradient and migrated towards the foreland.

3. Intrusions of felsic rocks were facilitated by the complex strike-slip and normal regime active along the crustal-scale Kraków–Lubliniec Fault Zone.

4. Although broadly coeval, granodiorites apparently intruded earlier than associated hypabyssal rocks in both the Malopolska Block and the Upper Silesian Block.

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