Geological Quarterly, 2010, **54** (3): 289–300

^{40}Ar-^{39}Ar ages of selected rocks and minerals from the Kraków–Lubliniec Fault Zone, and their relation to the Paleozoic structural evolution of the Małopolska and Brunovistulian terranes (S Poland)

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Nawrocki J., Krzemiński L. and Pańczyk M. (2010) – ^{40}Ar-^{39}Ar ages of selected rocks and minerals from the Kraków–Lubliniec Fault Zone, and their relation to the Paleozoic structural evolution of the Małopolska and Brunovistulian terranes (S Poland). Geol. Quart., **54** (3): 289–300. Warszawa.

New ^{40}Ar-^{39}Ar isotope ages of mafic and felsic rocks from the contact zone of the Małopolska and Brunovistulian terranes are presented and discussed. A ^{40}Ar-^{39}Ar age estimation of detrital muscovite from a Lower Devonian "old red" type sandstone drilled on the Małopolska side of this zone was also done. Our studies reveal that three events of Paleozoic magmatic activity took place in the study area. The oldest, late Emsian episode is recorded by a diorite from the core part of an intrusion penetrated by the Sosnowiec IG 1 borehole. A younger, Visean event is documented by a diabase cored in the borehole WB-137. Diabases from Niedźwiedzia Góra and from borehole PZ-10, and a rhyodacite from borehole 16-WB gave early Permian (Artinskian–early Sakmarian) ages. The youngest, middle Sakmarian age was obtained for a diabase forming the external parts of the Sosnowiec IG 1 polycyclic intrusion. A diorite penetrated by the Sosnowiec IG 1 borehole was emplaced during the late Emsian extension that preceded the Lochkovian–Pragian? transpression related to the final docking and amalgamation of the Brunovistulian Terrane.

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(received: June 24, 2010; accepted: September 17, 2010).

Key words: S Poland, late Paleozoic, palaeogeography, Ar-Ar geochronology.

INTRODUCTION

The NW-trending, crustal-scale Kraków–Lubliniec Fault Zone (KLFZ) separates the Brunovistulian (BVT) and Małopolska (MT) terranes of Southern Poland (Fig. 1; Brochwicz-Lewiński *et al.*, 1986; Buła *et al.*, 1997; Żaba, 1999; Nawrocki *et al.*, 2004; Malinowski *et al.*, 2005; Żelaźniewicz *et al.*, 2009). This zone was formed during the Proterozoic. The structure, lithology and ages of the lower Paleozoic sequences composing the marginal parts of both of these terranes are different. Lithostratigraphical-structural complexes, common to both tectonostratigraphic units, appeared only during the Early Devonian (Żaba, 1999; Buła, 2000). However, to date there has been no reliable evidence showing the exact time of final amalgamation of the BVT. The Early Devonian cover of "old red" type deposits, common to both the units, may indicate that this process took place sometime between the Silurian and the Devonian (see Nawrocki and Poprawa, 2006). Paleozoic rocks of the KLFZ were disturbed by strike-slip motions, which were most active during two periods: at the end of the Silurian (sinistral transpression) and during the late Carboniferous (dextral transpression and transtension) (Bogacz and Krokowski, 1981; Żaba, 1999). The results of recent palaeomagnetic studies of early Permian volcanic rocks from the Krzeszowice region of the KLFZ indicate that shortly after emplacement of these rocks, tectonic movements induced by sinistral transtension were initiated (Nawrocki *et al.*, 2008).

Several magmatic bodies were penetrated by the boreholes located along the KLFZ, among them granites, porphyritic dacites and rhyolites, and minor mafic rocks. Mafic intrusions were also drilled by the deep boreholes of Goczałkowice IG 1 and Sosnowiec IG 1, located about 50 km from the KLFZ, in the area of the Upper Silesian Block (part of the Brunovistulian complex Terrane, see Żelaźniewicz *et al.*, 2009). Their outcrops occur in the Krzeszowice region, west of Kraków. The best known is the diabase sill exposed in the Niedźwiedzia Góra quarry. Diabases of the KLFZ and the Upper Silesian Block cut rocks of different ages, from Precambrian to

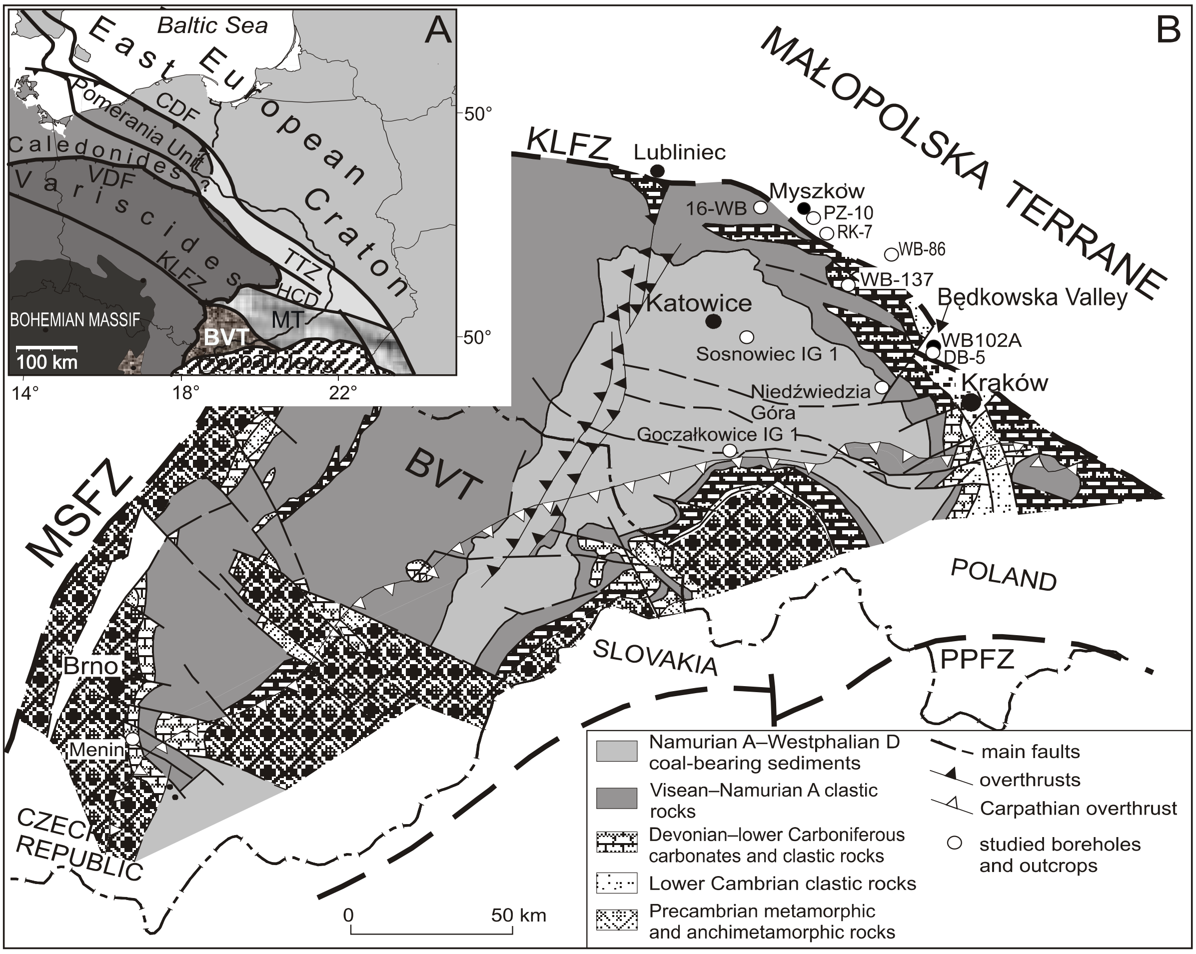

Fig. 1A – Location of the Brunovistulian terrane on a tectonic sketch map of Central Europe (after Winchester and the PACE TMR Network Team 2002, modified); B – simplified geological sketch map of the Brunovistulian Terrane without Mesozoic and Ceinozoic cover rocks (after Buła and Habryn, 2008, simplified)

A – TTZ – Teysseire-Tornquist Zone, CDF – Caledonian Deformation Front, HCD – Holy Cross Dislocation, KLFZ – Kraków–Lubliniec Fault Zone, MT – Małopolska Terrane, BVT – Brunovistulian Terrane; **B** – sites of ^{40}Ar/^{39}Ar age estimations are marked with open circles; MSFZ – Moravo-Silesian Fault Zone, PPFZ – Peri-Pieniny Fault Zone

Westphalian A. The age of the mafic rocks has been widely disputed and most of them are regarded as Variscan, but usually older than felsic rocks of that area (Bukowy and Cebulak, 1964; Żaba, 1999). According to some authors, some of the mafic intrusions, especially from the Myszków and Będkowska Valley areas, are significantly older, most probably late Silurian (Bukowy and Cebulak, 1964; Ekiert, 1971; Harańczyk, 1985). Silurian basaltic (Přichystal, 1999) and Variscan lamprophyric dykes (Šmejkal, 1964) are known in the Moravian part of the BVT (Metabazite Zone, see Leichmann and Hőck, 2008).

K-Ar, Ar-Ar and Re-Os dating of the felsic igneous rocks of the KLFZ yielded whole-rock and mineral ages between 312 and 290 Ma (Jarmołowicz-Szulc, 1985; G. Oliver in Harańczyk, 1989; Podemski 2001; Stein *et al*., 2005). A granodiorite from borehole WB102A in the Będkowska Valley, Małopolska Terrane, yielded a mean U-Pb zircon age of 300 ±3 Ma with SHRIMP II (Żelaźniewicz *et al*., 2008). K-rich ryolites to dacites, forming the Zalas laccolith, Krzeszowice region, were dated at 294 ±3 Ma with SHRIMP I (U-Pb zircon; Nawrocki *et al*., 2008). Amphiboles from a complex dyke in Dubie yielded a K-Ar age of 291.3 ±6.4 Ma (Lewandowska *et al*., 2007).

The aim of this paper is to present and discuss new ^{40}Ar-^{39}Ar isotope ages of mafic and felsic rocks from the KLFZ and from the area located further inside the BVT. ^{40}Ar-^{39}Ar age estimation of muscovite from a Lower Devonian "old red" type sandstone drilled on the Małopolska side of the KLFZ was also carried out. The isotope data obtained are discussed within a context of models of the tectonic evolution and palaeogeography of this part of Europe.

SAMPLED ROCKS

Samples were collected from massive and little-altered parts of the rocks. Most of them are diabases. The sampled boreholes PZ-10, WB-86, DB-5 and RK-7 are located in the

Małopolska Terrane. Three diabase samples were derived from the PZ-10 borehole at depths of 284, 287 and 289 m (Fig. 2A). The diabases are characterized by medium-grained, subophitic to ophitic texture. The rocks contain plagioclase laths and altered amphibole crystals with traces of chloritization and carbonatization. The diabase from borehole WB-86 (samples from 404.5 m and 458.2 m; Fig. 2B) is characterized by medium- and fine-grained, subophitic to ophitic texture (Fig. 3A). The main mineral components are plagioclase (andesine) and clinopyroxene (augite). Ilmenite and magnetite are accessory minerals. The next sample was taken from a thin trachyandesite dyke (~2.3 m thick, depth 1217.7 m; Fig 2C) penetrated by borehole DB-5. This rock is evidently altered and characterized by a fine-grained, pilotaxitic texture. The groundmass comprises plagioclase laths, pseudomorphs after mafic minerals, rare quartz crystals, opaque minerals, biotite and secondary chlorite and calcite (Fig. 3B). Plagioclase phenocrysts were also found. Detrital muscovite grains for isotope studies were separated from the Devonian clastic rocks drilled in the RK-7 borehole (depth 384 m; Fig. 2D).

The next sampling localities: the Goczałkowice IG 1, Sosnowiec IG 1, WB-137 and 16-WB boreholes and

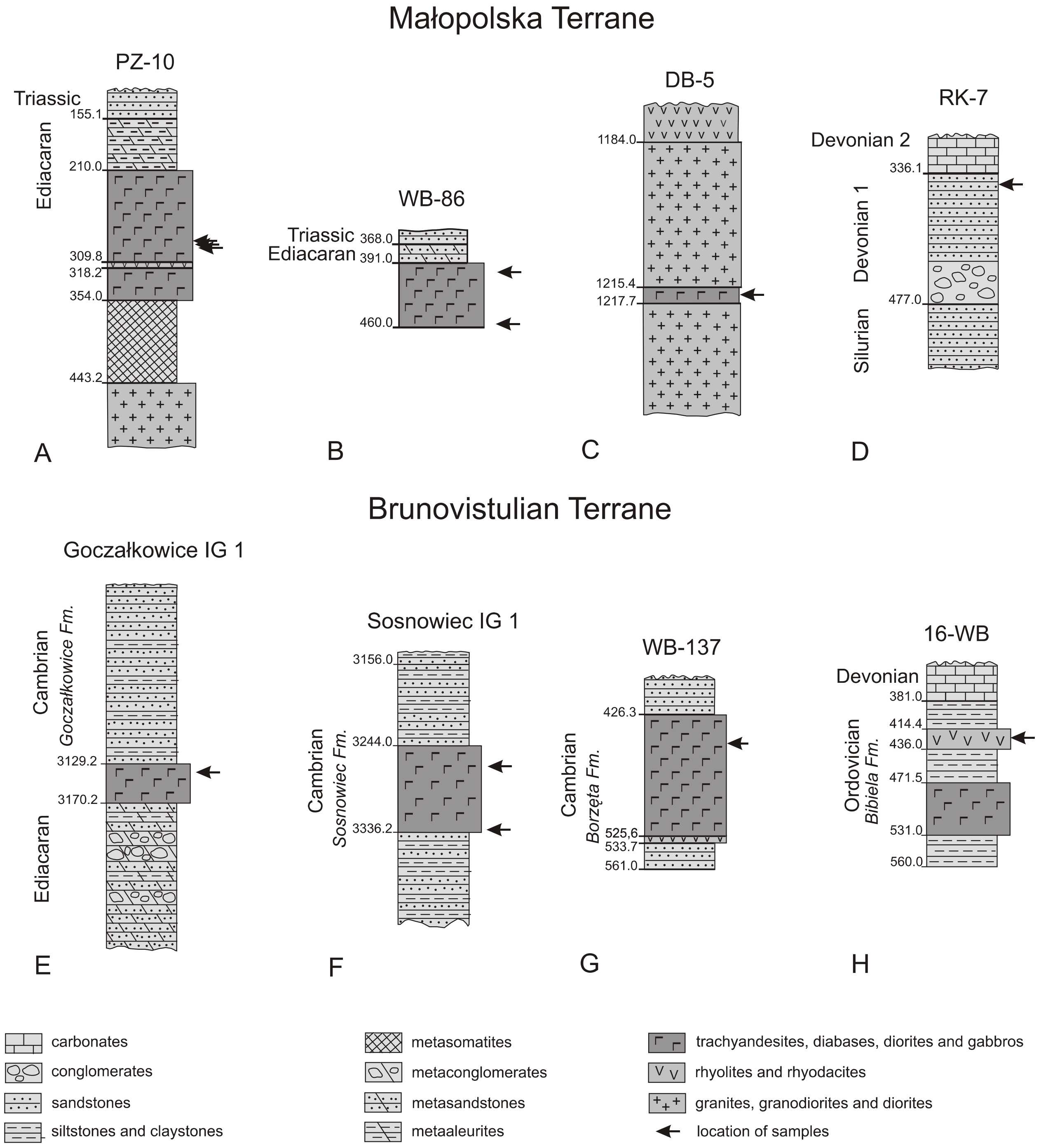

Fig. 2. Sampling sites for ^{40}Ar-^{39}Ar age determinations and simplified lithological logs of the cores analysed

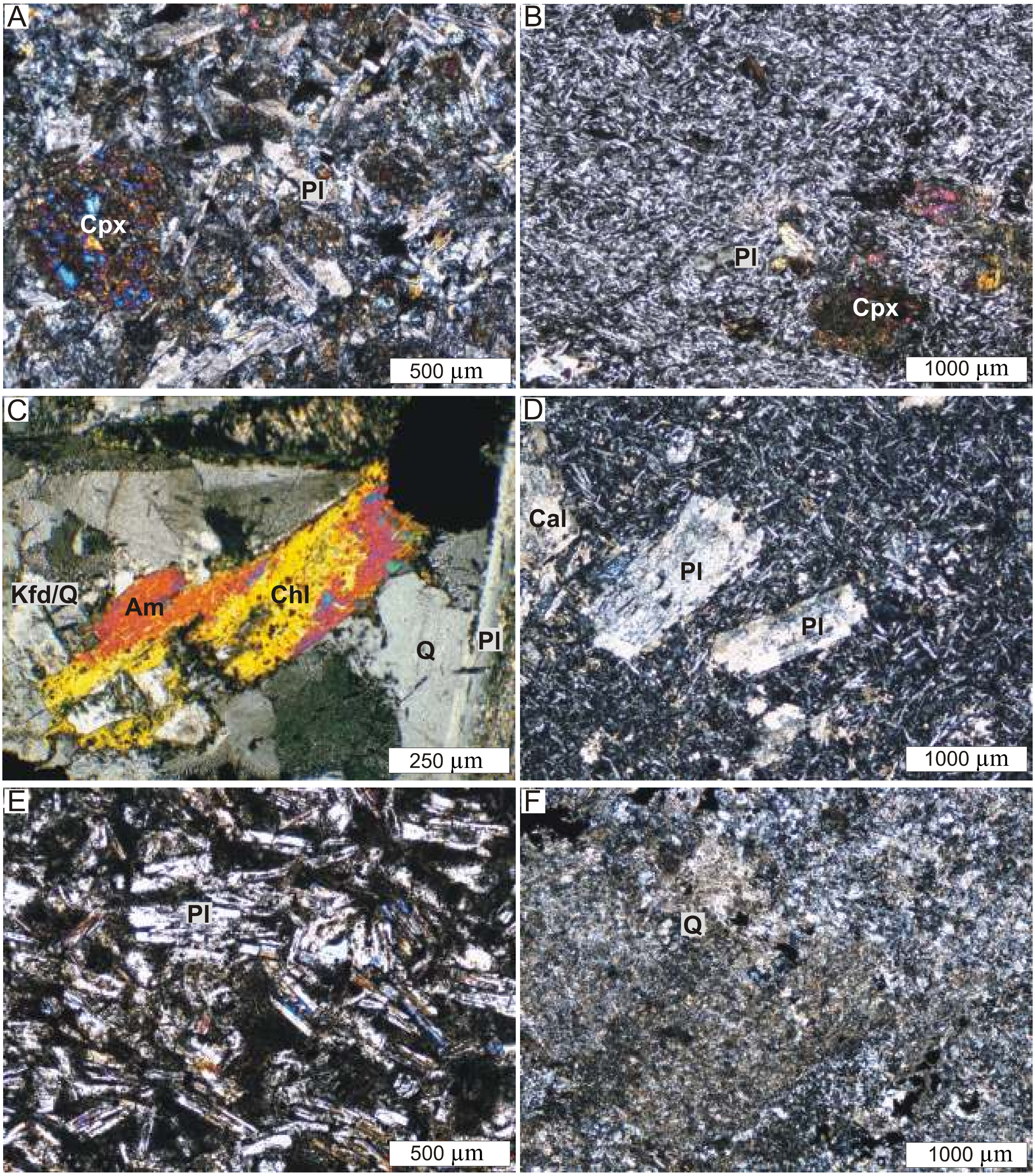

Fig. 3. Photomicrographs of selected samples prepared for ^{40}Ar-^{39}Ar age determinations

A – diabase (borehole WB-86, depth 404.5 m) – typical subophitic texture with plagioclase laths and altered clinopyroxene grains, crossed polars; **B** – trachyandesite (borehole DB-5, depth 1217.7 m) – porphyritic, fine-grained texture, the groundmass comprises plagioclase, pseudomorphs after mafic minerals, quartz grains, opaque minerals and secondary chlorite and calcite, crossed polars; **C** – diorite (Sosnowiec IG 1 borehole, 3260.3 m) – massive, granophyiric texture with altered plagioclases and amphiboles, crossed polars; **D** – diabase (borehole WB-137, depth 436.0 m) – porphyritic, fine-grained texture, the groundmass comprises laths of plagioclase and altered mafic minerals, crossed polars; **E** – diabase (Niedźwiedzia Góra quarry) – fine-grained, pilotaxitic texture, comprises plagioclase laths, clinopyroxene crystals, opaque minerals and relics of strongly altered glass, crossed polars; **F** – rhyodacite (borehole 16-WB, depth 424.0 m) – porphyritic, massive texture, strongly altered rocks (calcite and sericite), crossed polars; mineral symbols after Kretz (1983): Am – amphibol, Cal – calcite, Chl – chlorite, Cpx – clinopyroxene, Kfd – K-feldspar, Pl – plagioclase, Q – quartz

Niedźwiedzia Góra quarry are located in the Brunovistulian Terrane. Diabase samples were derived from the Goczałkowice IG 1, WB-137 and Sosnowiec IG 1 boreholes and from Niedźwiedzia Góra, whereas rhyodacite samples came from the borehole 16-WB. Additionally, diorites from the core part of the intrusion drilled by the Sosnowiec IG 1 borehole were analysed.

A diabase from the Goczałkowice IG 1 borehole (3129.5 m; Fig. 2E) is characterized by medium-grained, subophitic to ophitic textures with a plagioclase and clinopyroxene assemblage (Krzemiński, 2004). Rare oval pseudomorphs (mixture of smectite and iron oxides), most probably after olivine, were also found. Two samples were taken from the Sosnowiec IG 1 borehole. This borehole penetrated diorite-diabase intrusions. A fine-grained diabase from the upper part of the intrusions (3259.5 m) contains plagioclase laths and altered mafic minerals or former glass (altered by carbonatization and chloritization). The other sample was collected from a massive, granophiric diorite (3335.7 m; Fig. 2F), which comprises mostly altered plagioclases and amphiboles (affected by chloritization; Fig. 3C) (Krzemiński, 2004). A porphyritic, more fine-grained diabase was found in boreholes WB-137 (Fig. 2G). The groundmass contains plagioclase (andesine-labradorite) laths and clinopyroxene (augite) crystals. Single plagioclase crystals are found as subhedral phenocrysts showing relicts of chemical zoning (Fig. 3D). Apatite, epidote and Fe and Ti oxides are accessory minerals in the diabase.

A diabase from the Niedźwiedzia Góra quarry (Fig. 3E) is characterized by fine-grained, porphyritic, pilotaxitic texture. The groundmass comprises plagioclase laths, fine-grained quartz, clinopyroxenes, microlith of opaque minerals and relicts of strongly altered glass. Plagioclase and clinopyroxene phenocrysts are also found. A strongly altered rhyodacite from the borehole 16-WB (424.0 m; Fig. 2H) contains relics of plagioclase phenocrysts and pseudomorphs after mafic minerals. The groundmass comprises altered plagioclase, relics of mafic minerals and secondary calcite and chlorite (Fig. 3F). A relative high content of potassium in the basaltic trachyandesites of Krzeszowice region was noted as a primary feature of these rocks (Rospondek *et al*., 2004).

^{40}Ar-^{39}Ar GEOCHRONOLOGY

ANALYTICAL METHODS

Four amphibole and one muscovite separates and eight whole-rock samples were dated by the furnace incremental-heating ^{40}Ar-^{39}Ar method using a heating schedule that comprises eight or ten steps in the range from 650–950 to 1260–1350°C, with an average 75°C per heating step. Complete isotopic results are given in Table 1 and all of the age spectra are presented in Figure 3. A plateau age is obtained when the apparent ages of at least three consecutive steps, comprising a minimum of 50% of the ^{39}Ar$_K$ (product of K neutronic interference, see Table 1) released, agree within 2σ error with the integrated age of the plateau segment (Fleck *et al*., 1977). A so-called pseudoplateau follows the requirements of a plateau age, but has a ^{39}Ar$_K$ percentage that can be lower than 50%. The total gas age provides a weighted mean age of all of the individual heating steps.

Geochronological investigations were performed in the Central European Ar-Laboratory (CEAL) at the Geological Institute of Slovak Academy of Science, Bratislava. Mineral concentrates were enclosed in high purity quartz vials and irradiated for 4–6 h at the *9MW ASTRA* reactor at the Austrian Research centre, Seibersdorf. After a cooling down period of at least 3 weeks, the samples were filled in small, annealed (low-blank) cylindrical tantalum capsules. Two Ar-extraction lines were used during this study: a manually operated and a fully automated extraction and purification line. They are made mainly of glass and fitted with a radio frequency (RF)-induction furnace made of quartz glass. The hot portion of the extraction furnace is double-walled and continuously pumped to avoid diffusion of Ar from ambient air during the high temperature steps. Argon was released at progressively higher temperatures ranging between 650–950°C and 1260–1350°C, with, on average, 75°C intervals. During the analysis, only one tantalum capsule was in the heating position. Due to the geometry of the cylindrical capsules, which always have a horizontal position within the RF-induction coil, a uniform temperature distribution in the sample is guaranteed. Temperatures were monitored by a calibrated pyrometer, with the energy output of the RF generator being governed by the pyrometer reading. The stability at the preset diffusion temperature is within 1°C. The temperature rise was rapid and practically no overheating took place. The heating time for the low temperature steps was typically 10 min and was continuously lowered to 3 min for the high temperature steps.

Cleaning of the gas was done by a combination of cold traps, Ti-sponge- and SAE-getters. A collection of Ar with a cold trap before the sample inlet was not performed. Two-thirds of the gas was introduced into a *VG-5400* gas mass spectrometer. The rest of the gas was pumped away from the extraction line. Isotopic ratios were determined for a measuring period of 10 min, with the local ratios having been extrapolated back to the time of the sample inlet to determine the original isotopic composition. Ages were calculated after corrections for mass discrimination and radioactive decay, especially of ^{37}Ar, using the formulas given by McDougall and Harrison (1988). The specific production ratios of the interfering Ar isotopes at the *ASTRA* reactor of Seibersdorf are: ^{36}Ar/^{37}Ar(Ca) = 0.0003, ^{39}Ar/^{37}Ar(Ca) = 0.00065, ^{40}Ar/^{39}Ar(K) = 0.025. The K/Ca ratio is determined from the ^{39}Ar/^{37}Ar ratio (calculated for the end of irradiation) using a conversion factor of 0.538 based on the K$_2$O and CaO contents reported in Samson and Alexander (1987). Ages recorded by three or more contiguous gas fractions with similar apparent K/Ca ratios each representing >4% of the total ^{39}Ar evolved, and together constituting >50% of the total quantity of ^{39}Ar evolved, are mutually similar within a ±1% uncertainty. The ^{40}Ar line blank at 1000°C is $2 - 5 \times 10 -$ $- 10$ cm^3 STP and the ^{40}Ar/^{36}Ar ratio of the line blank is close to the air composition. Determination of the background, blank corrections and careful checking of the peak positions were routinely performed. J-values were determined with internal laboratory standards, calibrated by international standards including muscovite Bern 4M (Burghele, 1987), amphibole

Table 1

$^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ analytical data from step-heating experiments

Sample Step #	Temp [°C]	$^{37}\mathrm{Ar}_{Ca}/^{39}\mathrm{Ar}_{K}$	K/Ca	$^{40}\mathrm{Ar}^{*}/^{39}\mathrm{Ar}$	±1σ [%]	$^{40}\mathrm{Ar}^{*}$ [%]	$^{39}\mathrm{Ar}$ [%]	Age [Ma]	Error [Ma]
DB-5-1217.7, whole rock (trachyandesite), weight 114.7 mg, Lab# = 4786						J = 0.016950 ±0.2%			
1	700	0.348	1.55	10.36	1.0	87.1	27.8	291.8	2.7
2	780	0.157	3.44	10.16	1.1	96.0	13.9	286.6	3.0
3	850	0.209	2.58	10.07	0.8	95.5	10.2	284.2	2.2
4	920	0.317	1.70	10.05	0.8	94.8	12.8	283.8	2.0
5	1000	0.309	1.74	9.90	0.8	93.8	17.0	279.8	2.1
6	1060	0.424	1.27	9.68	0.7	91.9	9.1	274.0	1.9
7	1220	1.195	0.45	9.72	1.0	90.6	6.9	275.1	2.6
8	1300	1.034	0.52	9.49	1.8	87.5	2.3	268.9	4.5
Total gas age			1.66					283.9	5.1
S-3335.7, whole rock (diabase), weight 107.8 mg, Lab# = 4785						J = 0.016950 ±0.2%			
1	700	0.732	0.735	11.17	0.8	98.2	4.9	312.9	2.3
2	780	1.255	0.429	10.76	0.5	99.4	9.3	302.3	1.5
3	850	0.883	0.610	10.40	0.6	99.6	18.8	293.0	1.6
4	920	0.781	0.689	10.30	0.6	99.5	22.6	290.3	1.5
5	1000	0.640	0.840	10.24	0.4	99.4	21.6	288.8	1.2
6	1060	0.612	0.880	10.19	0.8	99.0	11.5	287.5	2.1
7	1230	4.525	0.119	10.15	0.9	98.7	9.1	286.4	2.3
8	1350	3.717	0.145	10.14	1.5	96.4	2.2	286.0	3.9
Total gas age			0.556					291.9	5.7
Plateau age		MSWD = 0.43	0.803			steps 4–6	55.7	289.1	1.8
16-WB-424, whole rock (rhyodacite), weight 80.2 mg, Lab# = 4787						J = 0.016950 ±0.2%			
1	700	0.333	1.61	10.48	0.4	98.0	41.8	295.1	1.0
2	780	0.027	19.91	10.42	0.7	99.4	17.5	293.5	1.9
3	850	0.024	22.60	10.42	0.7	99.2	11.5	293.3	2.0
4	920	0.027	19.91	10.38	0.6	98.8	9.5	292.5	1.5
5	1000	0.037	14.53	10.14	0.6	97.8	8.7	286.2	1.6
6	1060	0.071	7.53	10.01	1.5	96.2	6.2	282.8	4.0
7	1220	0.167	3.23	10.19	0.7	93.5	4.2	287.4	1.8
8	1300	0.250	2.15	10.00	2.6	90.1	0.5	282.5	6.9
Total gas age			11.43					292.4	2.9
Plateau age		MSWD = 0.50	14.71			steps 1–3	70.8	294.4	1.6
WB-86-458.2, whole rock (diabase), weight 98.6 mg, Lab# = 4789						J = 0.016950 ±0.2%			
1	700	3.049	0.176	10.25	1.0	73.8	12.5	289.0	2.7
2	780	0.841	0.640	10.28	1.6	68.2	5.5	289.8	4.4
3	850	0.504	1.067	11.46	1.6	82.5	5.5	294.5	4.3
4	920	0.323	1.665	10.70	0.9	90.3	11.7	300.6	2.5
5	1000	0.350	1.539	10.07	0.9	90.2	12.5	284.3	2.3
6	1060	0.432	1.245	9.84	1.0	90.5	10.6	278.3	2.6
7	1220	0.978	0.550	10.43	0.6	91.8	39.2	293.7	1.7
8	1350	2.755	0.195	10.75	2.0	85.8	2.5	302.1	5.6
Total gas age			0.885					291.2	5.4
WB-86-404.5, whole rock (diabase), weight 80.0 mg, Lab# = 4788						J = 0.016950 ±0.2%			
1	700	1.379	0.390	10.12	1.4	76.3	9.9	285.5	3.6
2	780	0.547	0.983	10.35	1.4	83.3	6.4	291.5	3.7
3	850	0.307	1.752	11.05	1.2	92.5	7.6	309.8	3.3
4	920	0.262	2.049	10.98	0.9	93.1	12.8	307.8	2.7
5	1000	0.231	2.331	10.32	0.7	90.6	16.6	290.7	1.9
6	1060	0.631	0.852	10.08	0.9	89.3	12.7	284.7	2.4
7	1220	2.398	0.224	10.55	0.6	84.2	32.8	296.9	1.8
8	1350	3.289	0.164	10.16	2.6	69.6	1.3	286.5	7.0
Total gas age			1.093					295.1	6.2

Tab. 1 cont.

Sample Step #	Temp [°C]	^{37}Ar$_{Ca}$/^{39}Ar$_{K}$	K/Ca	^{40}Ar*/^{39}Ar	±1σ [%]	^{40}Ar* [%]	^{39}Ar [%]	Age [Ma]	Error [Ma]
PZ-10-287, amphibole, weight 81.6 mg, Lab# = 4793						J = 0.017155 ±0.2%			
1	800	0.683	0.788	10.43	0.5	91.7	14.1	297.0	1.5
2	880	0.800	0.672	10.42	0.7	96.8	12.6	296.6	1.9
3	950	4.184	0.129	10.53	0.7	96.9	18.3	299.7	1.9
4	980	4.504	0.119	10.32	0.6	96.9	13.2	294.1	1.6
5	1000	3.968	0.136	10.21	0.8	97.1	8.2	291.2	2.1
6	1015	3.268	0.165	10.24	0.9	96.9	5.7	292.0	2.3
7	1045	2.445	0.220	10.29	1.0	97.5	6.7	293.2	2.7
8	1095	2.976	0.181	10.31	0.9	97.2	6.1	293.9	2.5
9	1160	2.597	0.207	10.24	0.9	97.0	8.7	292.0	2.5
10	1300	5.076	0.106	10.19	0.9	93.8	6.4	290.7	2.4
Total gas age			0.272					295.0	1.9
Plateau age		MSWD = 0.40	0.162			steps 4–10	55.0	292.6	1.3
PZ-10-289, amphibole, weight 103.4 mg, Lab# = 4794						J = 0.017155 ±0.2%			
1	750	0.376	1.433	11.02	0.3	95.3	12.5	312.3	1.0
2	820	0.394	1.365	10.97	0.5	97.6	7.9	311.0	1.3
3	880	1.718	0.313	10.92	0.6	97.5	11.2	309.7	1.8
4	950	5.710	0.094	10.65	0.7	97.3	21.8	302.7	2.0
5	990	4.950	0.109	10.35	0.4	97.7	18.4	294.9	1.2
6	1015	3.906	0.138	10.42	0.7	96.6	7.5	296.8	1.9
7	1045	3.484	0.154	10.36	0.7	96.6	4.1	295.2	2.0
8	1095	3.106	0.173	10.39	0.9	97.1	5.2	295.8	2.5
9	1160	4.016	0.134	10.32	0.9	96.1	7.1	294.1	2.5
10	1300	7.194	0.075	10.32	0.8	95.7	4.3	293.9	2.1
Total gas age			0.399					301.8	5.4
Pseudoplateau age		MSWD = 0.28	0.131			steps 5–10	46.6	295.1	1.0
NG-1, whole rock (diabase), weight 87.5 mg, Lab# = 4783						J = 0.016950 ±0.2%			
1	700	7.576	0.071	10.62	0.9	85.8	15.7	298.7	2.4
2	780	1.776	0.303	11.60	1.2	94.7	11.2	323.8	3.6
3	850	0.989	0.544	11.98	0.6	97.9	13.6	333.5	1.8
4	920	0.951	0.566	11.61	0.8	98.1	13.6	324.0	2.3
5	1000	0.890	0.605	10.59	0.8	97.6	12.3	297.9	2.1
6	1060	1.245	0.432	10.50	1.0	97.1	10.5	295.4	2.9
7	1230	1.661	0.324	10.54	0.5	97.0	22.4	296.5	1.2
8	1350	1.290	0.417	10.39	4.4	86.2	0.7	292.6	11.9
Total gas age			0.408					308.7	11.6
Pseudoplateau age		MSWD = 0.22	0.445			steps 5–8	45.9	296.6	1.5
PZ-10-284, amphibole, weight 82.1 mg, Lab# = 4792						J = 0.016950 ±0.2%			
1	950	2.976	0.181	10.80	0.8	97.4	29.3	303.2	2.2
2	980	3.584	0.150	10.65	0.8	97.6	19.4	299.3	2.1
3	1000	2.004	0.268	10.60	1.0	98.2	15.4	298.2	2.7
4	1015	1.140	0.472	10.64	0.9	98.2	9.7	299.2	2.5
5	1045	0.853	0.630	10.62	0.6	98.5	8.6	298.6	1.6
6	1095	1.011	0.532	10.61	0.8	98.5	7.7	298.3	2.2
7	1160	1.309	0.411	10.59	1.0	97.0	6.1	297.8	2.6
8	1300	2.695	0.200	10.48	1.3	94.8	3.8	295.0	3.5
Total gas age			0.356					299.9	1.7
Plateau age		MSWD = 0.06	0.411			steps 2–7	66.9	298.7	0.9
WB-137-436, whole rock (diabase), weight 81.4 mg, Lab# = 4790						J = 0.016950 ±0.2%			
1		2.128	0.253	12.52	1.5	60.8	9.3	347.3	4.8
2		2.907	0.185	13.03	1.9	58.2	7.1	360.1	6.3
3		1.253	0.429	12.04	1.3	78.9	10.8	335.0	4.1
4		0.911	0.591	11.84	0.8	92.2	22.6	329.9	2.4
5		1.562	0.344	11.87	1.0	92.3	14.4	330.8	3.1
6		3.610	0.149	12.06	1.2	87.5	7.6	335.6	3.5
7		9.804	0.055	12.22	1.0	80.0	25.3	339.6	3.0
8		3.817	0.141	12.21	1.4	83.9	3.0	339.2	4.4
Total gas age			0.268					337.5	5.5
Pseudoplateau age		MSWD = 0.39	0.455			steps 3–5	47.8	331.3	3.6

Tab. 1 cont.

Sample Step #	Temp [°C]	$^{37}Ar_{Ca}/^{39}Ar_K$	K/Ca	$^{40}Ar^*/^{39}Ar$	±1σ [%]	$^{40}Ar^*$ [%]	^{39}Ar [%]	Age [Ma]	Error [Ma]
G-3129.5, whole rock (diabase), weight 90.2 mg, Lab# = 4780						J = 0.016073 ±0.2%			
1	650	37.037	0.014	18.23	0.8	82.0	9.9	463.6	3.4
2	700	15.625	0.034	15.46	1.6	91.4	8.8	400.3	5.6
3	780	11.364	0.047	12.89	0.8	95.7	10.4	339.8	2.4
4	850	5.952	0.090	11.56	1.3	94.6	13.1	307.6	3.8
5	920	5.076	0.106	12.56	0.6	92.5	17.6	331.6	1.9
6	1000	6.410	0.084	12.66	1.5	86.7	12.1	334.2	4.6
7	1060	9.346	0.058	13.65	1.7	84.0	5.0	357.7	5.5
8	1220	35.714	0.015	17.30	1.6	91.8	11.5	442.5	6.4
9	1280	45.454	0.012	13.96	2.3	79.6	6.7	365.2	7.5
10	1350	24.390	0.022	13.94	2.8	63.8	4.8	364.8	9.2
Total gas age			0.048					366.7	24.6
S-3259.5, amphibole, weight 179.4 mg, Lab# = 4779						J = 0.016073 ±0.2%			
1	800	7.752	0.069	14.90	1.2	90.4	19.5	387.3	4.3
2	880	6.369	0.084	15.04	1.1	98.5	13.7	390.6	3.8
3	950	6.993	0.077	15.21	0.9	99.2	7.3	394.5	3.1
4	980	7.519	0.072	15.34	0.9	98.1	5.5	397.7	3.2
5	1000	8.064	0.067	15.42	1.5	98.2	4.9	399.5	5.4
6	1015	7.194	0.075	15.46	1.6	98.9	4.6	400.5	5.9
7	1045	9.434	0.057	15.36	1.1	99.0	6.4	397.9	3.9
8	1096	10.309	0.052	15.42	0.6	98.1	12.9	399.3	2.2
9	1160	9.174	0.059	15.44	0.8	99.2	19.1	399.9	2.7
10	1330	7.143	0.075	15.54	1.0	96.7	6.0	402.1	3.8
Total gas age			0.069					395.6	2.9
Plateau age		MSWD = 0.09	0.063			steps 4–9	53.4	399.3	1.4
RK-7-384, muscovite, weight 28.0 mg, Lab# = 4791						J = 0.016950 ±0.2%			
1	750	0.500	1.08	13.67	0.6	97.3	24.9	376.0	1.9
2	790	0.018	29.05	15.79	0.9	97.8	7.4	427.9	3.5
3	810	0.021	25.82	16.07	0.9	97.9	5.6	434.5	3.5
4	845	0.007	79.09	16.01	1.2	98.1	7.4	433.1	4.6
5	890	0.007	79.62	16.16	0.6	98.7	10.0	436.8	2.4
6	940	0.006	83.93	16.24	0.7	98.2	10.6	438.7	2.6
7	990	0.008	62.95	16.04	0.6	98.2	10.5	434.0	2.4
8	1060	0.013	42.50	16.06	0.5	97.8	10.7	434.2	2.1
9	1120	0.014	39.27	15.89	0.7	96.9	9.0	430.3	2.7
10	1260	0.024	22.06	16.01	0.8	92.5	4.0	433.2	3.0
Total gas age			46.54					419.5	15.5
Weighted mean age		MSWD = 0.90	54.40			steps 3–10	67.8	434.6	1.9

* – Radiogenic. Decay constants and isotopic abundances after Steiger and Jäger (1977). Errors in age quoted for individual runs are 1σ analytical uncertainty. Total gas and plateau ages calculated by weighting individual steps by the fraction of ^{39}Ar released. Errors in age weighted means are 2σ weighted standard deviation calculated according to the formula of Samson and Alexander (1987) excluding errors in the neutron irradiation flux parameter J. Apparent K/Ca molar ratios were calculated from $^{39}Ar/^{37}Ar$ using a factor of 0.538 based on the K_2O and CaO content reported in Samson and Alexander (1987). MSWD (mean square weighted deviate) are calculated for n-1 degrees of freedom. $^{37}Ar_{Ca}$ = product of Ca neutronic interference, $^{39}Ar_K$ = product of K neutronic interference

MM1hb (Samson and Alexander, 1987) and Fish Canyon sanidine (Renne *et al.*, 1994). The errors of the calculated ages for the individual steps are given as 1σ, and the error of the plateau ages or total gas ages includes an additional error of ±0.4% on the J-value. The age data obtained are reproducible with the same analytical equipment within this error. Interlaboratory reproducibility can be expected within 1–1.5%. The gas from the monitors was measured in two fractions and the value was accepted when both results differed by <0.4%.

RESULTS

Five samples, 3 amphibole concentrates – PZ-10-284 (PZ-10 borehole, 284 m of depth), PZ-10-287, S-3259.5 (Sosnowiec IG 1 borehole, 3259.5 m of depth), rhyodacite 16-WB-424 and diabase S-3335.7 – gave age spectra with well-defined plateau ages ranging between 289.1 ±1.8 and 399.3 ±1.4 Ma (Fig. 4 and Table 1). Their mean square weighted deviates (MSWD) values for plateaux data range from 0.06 to 0.50 and the corresponding *p* values from 0.998 to 0.61 (*p* = probability of occurrence based on Chi Square Tables). Pseudoplateaux representing more than 45% of the released ^{39}Ar were achieved for three other analysed specimens: one amphibole concentrate (PZ-10-289) and two diabase whole-rock samples (NG-1, WB-137-436). Their MSWD ≤0.39 and *p* ≥0.68 are fully acceptable on statistical grounds. Some of these age spectra show only a slight decrease of apparent age from the low temperature steps towards age minima in the high or intermediate temperature steps (S-601, 16-WB-424,

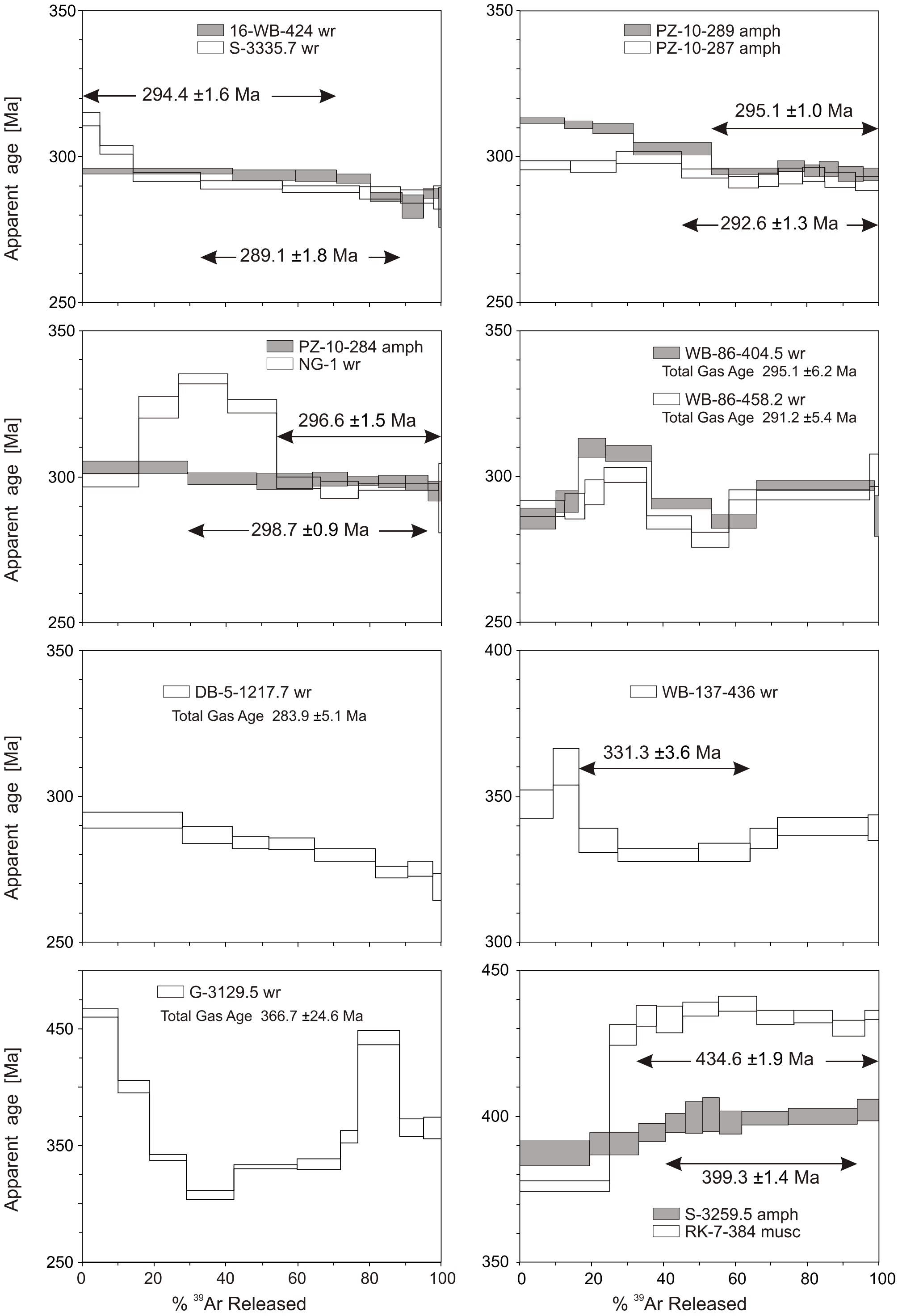

Fig. 4. ^{40}Ar/^{39}Ar age spectra of whole-rock (wr) and mineral concentrates (amph = amphibole, musc = muscovite) of mafic, felsic and sedimentary rocks from the contact zone of the Małopolska and Brunovistulian terranes

Error bars of step apparent ages are drawn at 1σ analytical uncertainties plateau and pseudoplateau ages (±2σ error) are given where applicable

PZ-10-296.7). Instead, the amphibole S-3259.5 age spectrum displays a slightly age-increasing shape.

The pseudoplateau age of the diabase WB-137-436 that constitutes the base of a relatively flat saddle (331.3 ±3.6 Ma, 47.8% of the released ^{39}Ar) and the well-defined plateau age of the S-3259.5 sample (399.3 ±1.4 Ma) are notably older than the remaining six plateau or pseudoplateau ages. The subtle saddle-shaped age spectrum from the sample WB-137-436 indicates that the rock probably contains little excess argon.

Four of the analysed specimens i.e. three diabase and one trachyandesite whole-rock samples, gave no plateau or pseudoplateau ages. The total gas age spectra of the diabase samples: WB-86-404.5, WB-86-458.2 and G-3129.5 (Goczałkowice IG 1 borehole, 3129.5 m of depth) display strongly disturbed shapes with ups and downs. They probably illustrate mixing between phases with distinct compositions (in terms of K/Ca ratios; see Table 1) and with possible distinct ages. Sample G-3129.5 shows an age spectrum with apparent ages that vary greatly between 308 and 465 Ma. The presence of higher step ages at low- and high-temperature intervals in its age spectrum most probably reflects excess ^{40}Ar. Two samples from borehole WB-86 have apparent ages in the range of 278–310 Ma. Analysis of the trachyandesite DB-5-1217.7, with a total gas age of 283.9 ±5.1 Ma, has a descending-staircase spectrum which suggests that the crystallization age is below any of the step ages, i.e. ~270 Ma.

The detrital muscovite sample RK-7-384 yields a convex-upwards age spectrum displaying a slight staircase shape at the summit of the hump, which did not define precisely a plateau age, since two of the eight steps did not agree within 2σ error with the weighted mean age of the intermediate- to high-temperature segment. Nevertheless, this eight-step weighted mean age (434.6 ±1.9 Ma) yields a statistically acceptable MSWD value of 0.90 and a corresponding *p* value of 0.51.

DISCUSSION

The results of ^{40}Ar-^{39}Ar dating reveal the presence of three events of magmatic activity in the study area (Fig. 5). The oldest one, Emsian, is documented by diorite from the core part of the intrusion penetrated by the Sosnowiec IG 1 borehole. This intrusion slightly postdates the postulated time of final tectonic transport and accretion of the Brunovistulian Terrane. According to Belka *et al.* (2002) and Nawrocki *et al.* (2007), the tectonic transport of the BVT towards the MT took place after the Ludlovian, but before the sedimentation of Lower Devonian sandstones of "old red" type. The Ludlow deposits from Małopolska were not derived from the BVT but from an island arc (Kozłowski *et al.*, 2004) located west of Małopolska, in the place occupied now by the BVT (Nawrocki *et al.*, 2007). The proximity of the BVT and the MT since the Emsian can be inferred from the distribution of boundaries

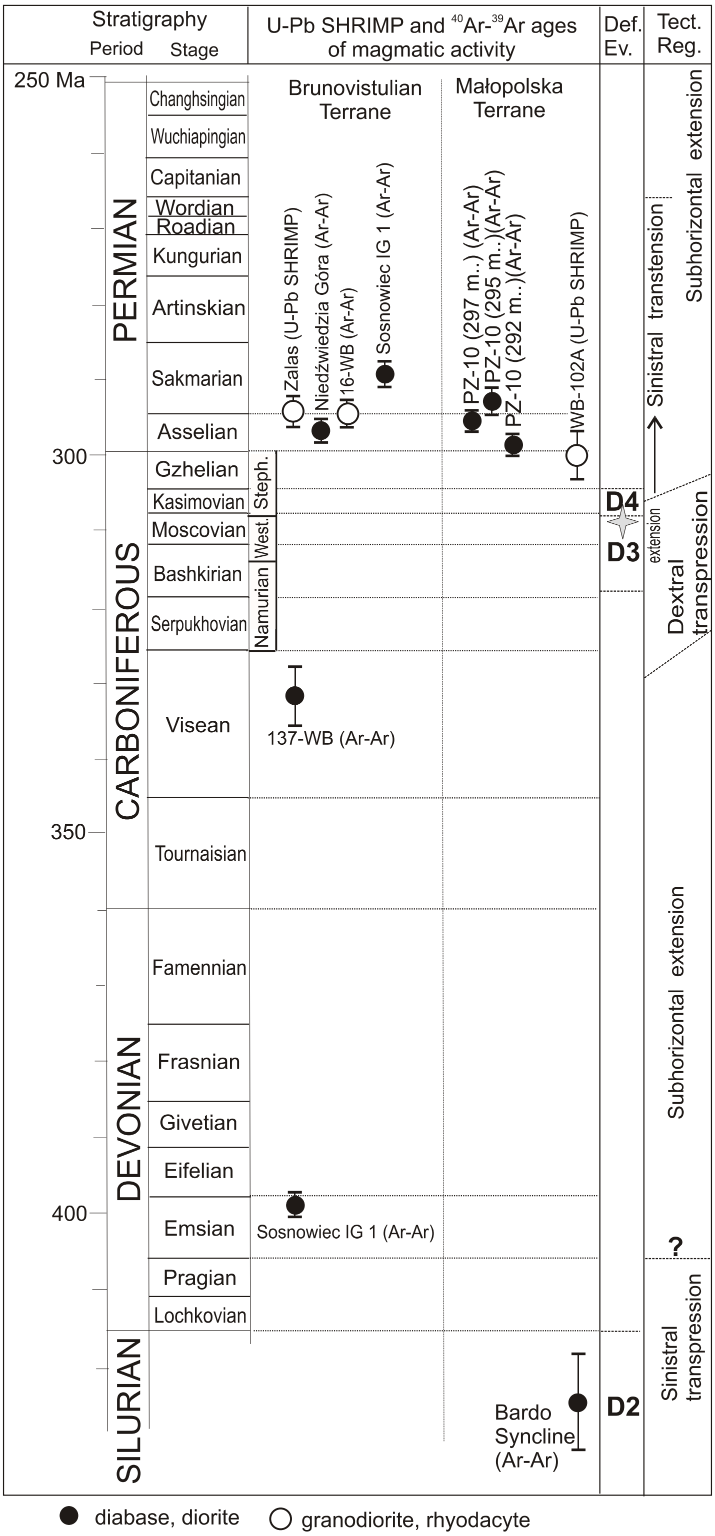

Fig. 5. U-Pb and ^{40}Ar/^{39}Ar ages of selected magmatic intrusions from the Brunovistulian and Małopolska terranes *versus* a stratigraphic chart (after Gradstein *et al.*, 2004)

Deformation events D2, D3 and D4 with time of emplacement of granitic bodies (asterisk) are listed according to Żaba (1999); changes of tectonic regime in the KLFZ from late Silurian to late Permian are also shown (for discussion see text) of particular "old red" facies (Pajchlowa and Miłaczewski, 1974). These boundaries cut the Kraków–Lubliniec Fault Zone that separates both the units. Żaba (1999) postulates an even earlier common tectonic development of both of the sides of the KLFZ, where, in the late Silurian up to the Silurian/Devonian boundary, sinistral transpression predominated and positive flower structures developed in relation to this tectonic regime. However, there is no direct evidence that these structures were developed before the Devonian. The Bardo diabase intrusion that cuts the MT was emplaced about 420 Ma ago (Nawrocki *et al*., 2007). It is about 20 Ma older than the intrusion drilled by the Sosnowiec IG 1 borehole. Thus, the extensional processes that opened the path ways for the magma in the MT and BVT were not coeval. This is not surprising because the geochemical signature of both the intrusions are also different (Krzemiński, 2004). Therefore, the late Silurian sinistral transpression could not have been a common feature for the BVT and MT. At that time, the Bardo intrusion developed in an extensional regime. Most probably, common tectonic transpression affected the BVT and MT border zone slightly later, in the Early Devonian, but before deposition of the Emsian "old red" type strata. The diorite from the Sosnowiec IG 1 borehole was associated with the late Emsian post-compressional extension. The ^{40}Ar-^{39}Ar age of white detrital mica from the Emsian sandstones drilled by borehole RK-7 is typical of the sources activated during the Ordovician/Silurian collision of Avalonia and Baltica (Torsvik *et al*., 1996; Belka *et al*., 2002). This means that after the Silurian the KLFZ was not significantly uplifted because the local detrital material should be rather of Cadomian age (see Belka *et al*., 2002).

The diabase penetrated by borehole WB-137 crystallized during the Visean extension that preceded the late Carboniferous dextral transpression (Żaba, 1999). This event of magmatic activity is most probably coeval with emplacement of diabases in the Lublin area, at the SW edge of the East European Craton (Depciuch, 1974; Grocholski and Ryka, 1995). Devonian to early Carboniferous magmatism has been described by some authors for that area as an effect of migration of the Baltic plate under the hot spot of a mantle plume (see Narkiewicz, 2007).

The early Permian whole rock ^{40}Ar-^{39}Ar age of the rhyodacite from borehole 16-WB is the same as the U-Pb SHRIMP age of the rhyodacite from the Zalas laccolith (Nawrocki *et al*., 2008). The diabases from Niedźwiedzia Góra and from borehole PZ-10 revealed that the ^{40}Ar-^{39}Ar ages were comparable within the limit of errors with the ages defined for the above-mentioned acid rocks from borehole 16-WB and from the Zalas intrusion. The youngest age (Sakmarian) was defined for the diabase from the external parts of the Sosnowiec IG 1 intrusion. Thus, the diorite from the core part of this polycyclic dyke is about 100 Ma older.

Our data and the results of SHRIMP U-Pb dating of granodiorite from borehole WB-102A (Żelaźniewicz *et al*., 2008) indicate that emplacement of granitic and granodioritic rocks of the KLFZ cannot be age-constrained to the late Westphalian only, as was suggested by Żaba (1999). The extensional stage of tectonic evolution of the KLFZ also dominated close to the Carboniferous/Permian boundary. During the early Permian, this tectonic regime changed into one of sinistral transtension (Nawrocki *et al*., 2008) that later was modified to pure subhorizontal extension (Żaba, 1999).

CONCLUSIONS

1. ^{40}Ar-^{39}Ar studies of selected magmatic rocks from the border zone of the Małopolska and Brunovistulian terranes reveal the presence of three events of Paleozoic magmatic activity. The oldest, late Emsian episode is recorded by a diorite from the core part of an intrusion drilled by Sosnowiec IG 1 borehole. A younger Visean event is documented by the diabase drilled by borehole WB-137. The diabases from Niedźwiedzia Góra and from borehole PZ-10, and the rhyodacite from borehole 16-WB were interpreted as early Permian (Artinskian–early Sakmarian). The youngest, middle Sakmarian age was yielded by the diabase forming the external part of the Sosnowiec IG 1 polycyclic intrusion.

2. The diorite from the Sosnowiec IG 1 borehole was emplaced during the late Emsian postcompressional extension. It preceded the Lochkovian–Pragian? transpression that accompanied the final docking and amalgamation of the Brunovistulian Terrane. Emplacement of more acid magmatic rocks (granodiorites, rhyodacites) marks the extensional stage of tectonic evolution of the KLFZ close to the Carboniferous/Permian boundary. During the early Permian, it changed into sinistral transtension.

Acknowledgements. This research was supported by the Ministry of the Environment (project 192/2005/Wn-07/FG-bp-tx/D). We thank A. Lewandowska and J. Leichmann for comments and suggestions that helped to improve the manuscript.

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