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New ^{40}Ar-^{39}Ar age constrains for magmatic and hydrothermal activity in the Holy Cross Mts. (southern Poland)

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New ^{40}Ar-^{39}Ar isotope ages of diabase intrusions from the Holy Cross Mountains (Poland) confirm the presence of at least two events of Paleozoic magmatic activity in the study area. The oldest, latest Silurian/earliest Devonian (ca. 424–416 Ma) episode is recorded by a diabase from the Bardo Syncline (Zarobiny PIG-1 borehole) in the Kielce Region. A younger, Serpukhovian (ca. 331–323 Ma) event is documented by a diabase from the Milejowice-1 borehole drilled in the Łysogóry Region. The diabase intrusion penetrated by the Wzorki-1 borehole, also located in the Łysogóry Region, is most probably of the same age. It provided, however, consistent mid-Triassic (243 Ma) ^{40}Ar-^{39}Ar isotopic age reflecting its pervasive hydrothermal alteration. The first stage of the post-Caledonian hydrothermal activity in the Holy Cross Mts. which produced polymetallic copper and iron-bearing mineralisation may be linked with the younger magmatic phase defined here. The second stage of post-Caledonian hydrothermal activity in the Holy Cross Mts., associated with the lead-zinc mineralisation, may be correlated with the Middle Triassic hydrothermal event recorded in the Wzorki diabase. Suggestions of temporal relationships between magmatic/hydrothermal activities and mineralisation events should, however, be constrained by further detailed geochemical and mineralogical studies.

Key words: Ar-Ar geochronology, diabases, mineralisation, Holy Cross Mts.

INTRODUCTION

In some places, Paleozoic sedimentary rocks of both tectono-stratigraphic units of the Holy Cross Mts. (HCM), i.e. of the Kielce and Łysogóry regions (Fig. 1A), are cut by scattered small to medium size magmatic intrusions represented by dykes and sills of basaltic composition (Fig. 1B; e.g., Czarnocki, 1919; Ryka, 1957; Kardymowicz, 1967). The ages of these mafic intrusions remain a matter of controversy. They range from Late Silurian to Carboniferous. The HCM subvolcanic rocks have a distinct signature of anorogenic magmatites, typical of continental extensional settings, and they represent tholeitic melts generated probably as a result of the thermal effect of a mantle plume on the base of the subcontinental lithosphere (Krzemiński, 2004).

The medium-grained rocks of basaltic composition of this study should, according to standard igneous rock classification, be named as microgabbros. However, due to the widespread usage of the traditional name diabase for basaltic dykes and sills from the Kielce and Łysogóry regions, we continue to use this local name.

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A possible link between hydrothermal vein mineralisation and magmatic events in the HCM has been suggested by several authors (Czarnocki, 1950; Rubinowski, 1962, 1971), on the assumption that magmatic intrusions and the Variscan epigenetic mineralisation had the same deep magmatic source (Kardymowicz, 1967; Rubinowski, 1971). A secondary hydrothermal origin was inferred for the post-Triassic lead-zinc formation (Rubinowski, 1971). The occurrence of epigenetic mineralisation containing different metals is common in the HCM. The system of crosscutting veins represents several events with different types of mineralisation, and some ore-bearing zones have been exploited for several centuries. Since the last century they have also been a focus of scientific studies (e.g., Czarnocki, 1950, 1956; Rubinowski, 1971). Three ore assemblages: iron-bearing, copper-bearing and lead-zinc-bearing, were distinguished by Rubinowski (1971) who also defined two stages of hydrothermal activity in the Holy Cross Mts. – pre-Permian and post-Triassic.

During the pre-Permian stage the polymetallic copper assemblages was formed. Apart from copper it contains nickel, cobalt, silver and gold (Rubinowski, 1971; Balcerzak et al., 1992; Muszer et al., 1995). This type of mineralisation is correlated with low to medium temperature hydrothermal activity and linked with the Variscan fault zones of the western part of the Kielce Region (Rubinowski, 1971). Relatively large occurrences of copper-bearing mineralisation are only known from two sites of long-lasting mining in Miedzianka and Miedziana Góra (Czarnocki, 1956; Rubinowski, 1971).

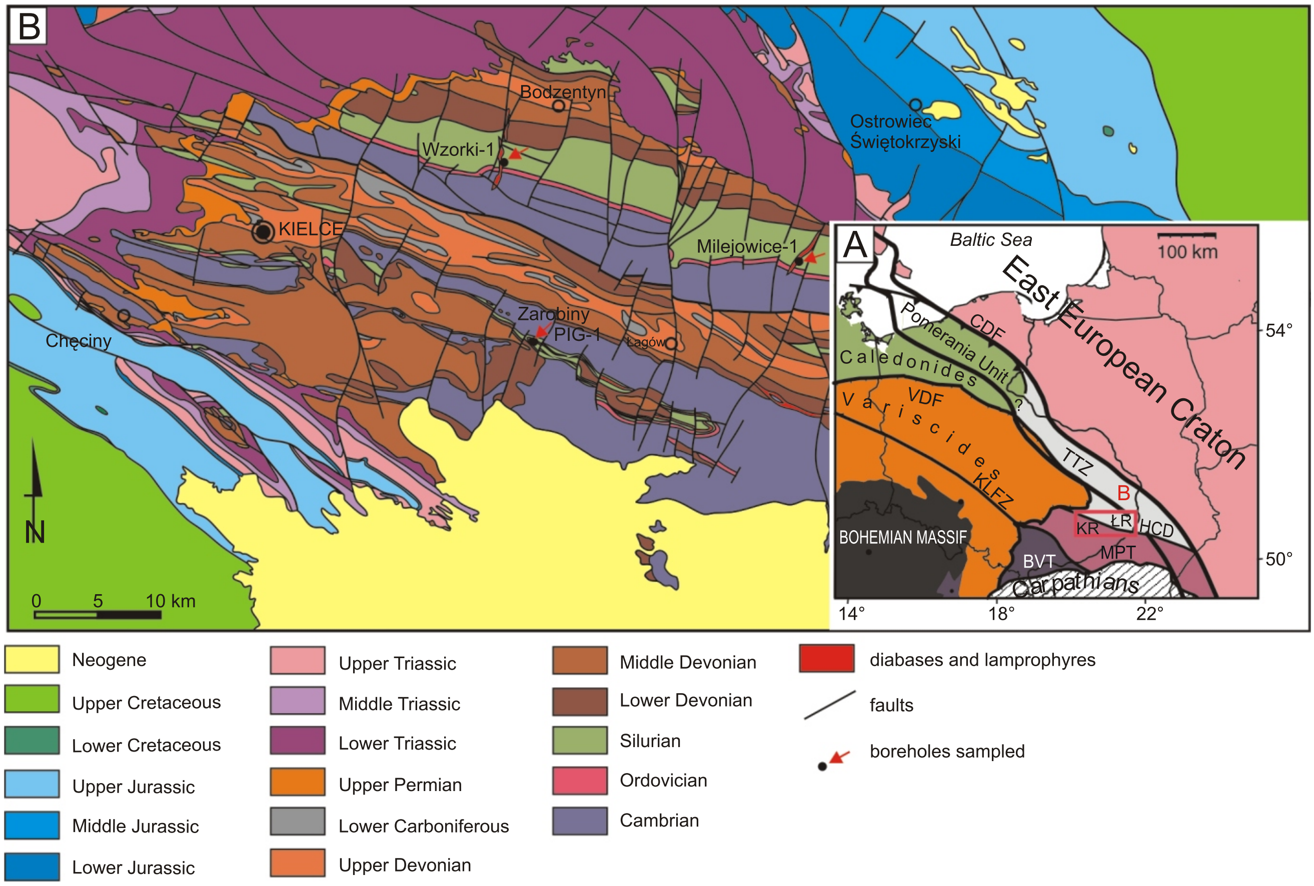


Fig. 1A – location of the Holy Cross Mountains on a tectonic sketch map of Central Europe (after Winchester and the Pace TMR Networkteam, 2002, modified); B – geological sketch map of the Holy Cross Mountains (after Filonowicz, 1981; Romanek, 1988; Kowalczewski et al., 1990) with boreholes yielding the ^{40}Ar-^{39}Ar age estimations marked

BVT – Brunovistulian Terrane, CDF – Caledonian Deformation Front, HCD – Holy Cross Dislocation, KLFZ – Kraków–Lubliniec Fault Zone, KR – Kielce Region, ŁR – Łysogóry Region, MPT – Małopolska Proximal Terrane, TTZ – Teisseyre-Tornquist Zone

The iron-bearing formation, which occurs in the Łysogóry Region only, is also regarded as Variscan. This age estimation is based on the occurrence of pyrite, hematite and siderite pebbles in local Permian conglomerates (Samsonowicz, 1934; Rubinowski, 1971). The largest ore body containing pyrite, hematite and siderite was found at Rudki and was mined until the early 1970s. Smaller occurrences of iron-bearing mineralisation were noted in Zagnańsk (Czarnocki, 1950), Łączna and Wzdół-Kamieniec (Osika and Ekiertowa, 1958). In all cases the iron-bearing mineralisation occurs as a system of veins developed along tectonic discontinuities.

Calcite veins up to tens of metres thick lacking of metal-bearing mineralisation and defined as pre-Permian occur mainly in the western and central parts of the Kielce Region (Rubinowski, 1967, 1971). A pre-Permian age for this mineralisation is inferred because pebbles of calcite veins have been found in Permian conglomerates (Rubinowski, 1971). Some authors, however, postulate a different, i.e. post-Permian age of the calcite and quartz mineralisation in the HCM. Migaszewski et al. (1996) assigned the main calcite mineralisation phase to the latest Permian and mid/late Early Triassic. Quartz occurrences, noted in the Devonian carbonate sequences of the HCM, were linked by Migaszewski et al. (1996) with the Visean/Serpukhovian phase. According to Salwa (2006), quartz mineralisation in the HCM has a polycyclic nature. Decimetre-scale quartz vein formed in pre-Devonian and pre-Permian time because pebbles derived from quartz veins have been found within the Permian and Lower Devonian conglomerates (Salwa, 2006).

Another type of vein mineralisation in the Kielce Region contains the lead-zinc association. This has been regarded as post-Triassic in age and epigenetic in origin (Rubinowski, 1970, 1971). This mineralisation fills different systems of fissures developed in Middle and Upper Devonian carbonates and impregnates the Buntsandstein strata.

Two sites with polymetallic mineralisation, and containing marcasite, pyrite, uraninite and siderite, were found at Rudki and Wzdół-Kamieniec of the Łysogóry Region (Osika and Ekiertowa, 1958, Rubinowski, 1971; Szecówka, 1987). A target of the past mining in the HCM was also the barite deposit. Several prominent barite veins have been exploited in the western part of the HCM where they cut Paleozoic to Middle Triassic strata (Czarnocki, 1936).

The aim of this study is to define precise and credible isotopic ages for selected mafic intrusions of the HCM. Precise ages of magma emplacement are important in reconstructing the Late Caledonian and Variscan tectonic regimes in that area. These data could also help in determining the sources and chronology of epigenetic mineralisation in the HCM.

INTRUSIONS STUDIED

BARDO DIABASE

The most extensive igneous intrusion of the HCM occurs in the Bardo Syncline in the central part of the Kielce Region (Fig. 1). This diabase intrusion penetrates the Silurian rocks of this syncline, close to the stratigraphic boundary between Lower Ludlow graptolite shales and Upper Ludlow greywackes. The overall thickness of the intrusion varies from 10 to 30 m. Tectonic and stratigraphic observations suggest a Late Ludlow–Siegenian age interval for the Bardo diabase (Kowalczewski and Lisik, 1974). However, preliminary isotope studies have not excluded a Variscan age (Migaszewski, 2002). A palaeomagnetic study of the Bardo diabase provides a pre-folding palaeomagnetic pole concordant with the latest Silurian segment of the apparent polar wander path for Baltica (Nawrocki, 2000). The results of the palaeomagnetic correlation are consistent with those of subsequent ^{40}Ar-Ar^{39} determinations of plagioclase grains derived from the diabase (Nawrocki et al., 2007). Both age estimations are, however, not sufficiently precise. The ^{40}Ar-Ar^{39} sample studied revealed the presence of two plateaus for the low and high temperature steps, which were 432 ± 2 Ma and 425 ± 11 Ma, respectively. On the other hand, the step size weighting indicated that the section of the age spectrum from the step-heating run, from 0.4 to 0.97, was 424 ± 6 Ma (Nawrocki et al., 2007). According to Krzemiński (2004) the Bardo diabase intrusion may record a detachment of the Małopolska Block from Baltica, and its translation along the craton margin during Late Ludlow–Emsian times up to its present-day position (see also Narkiewicz, 2002). However, this tectonic translation is not supported by any existing palaeomagnetic data (Nawrocki, 2000; Schätz et al., 2002). It should be noted that Silurian (438 ± 16Ma) magmatic activity has been also documented through K-Ar dating of a basalt vein intruding into the Brunovistulian basement (Přichystal, 1999).

A new sample for the whole rock ^{40}Ar-Ar^{39} studies was taken from the western part of the Bardo Syncline where the diabase intrusion was penetrated by the new Zarobiny PIG-1 borehole (latitude: 50°46'44.9"N, longitude: 20°55'44.7"E). A fresh piece of rock was collected from the borehole at a depth of 84.8 m (Fig. 2). The Bardo diabases are characterized by a fine-grained subophitic texture (Fig. 3A). The main mineral components are plagioclase laths of labradorite-andesine composition and clinopyroxene (augite) crystals. Individual megacrysts of plagioclase (labradorite), which exceed 2 mm in length, are also sporadically found (Fig. 3B). Ore minerals such as skeletal titanomagnetite and titanohematite crystals are common, whereas tiny crystals of pyrite and chalcopyrite are scarce (Fig. 3C). The rocks are moderately altered (secondary quartz, calcite, kaolinite; chloritization of augite) and cut by microveins filled with calcite and chlorite (Fig. 3D).

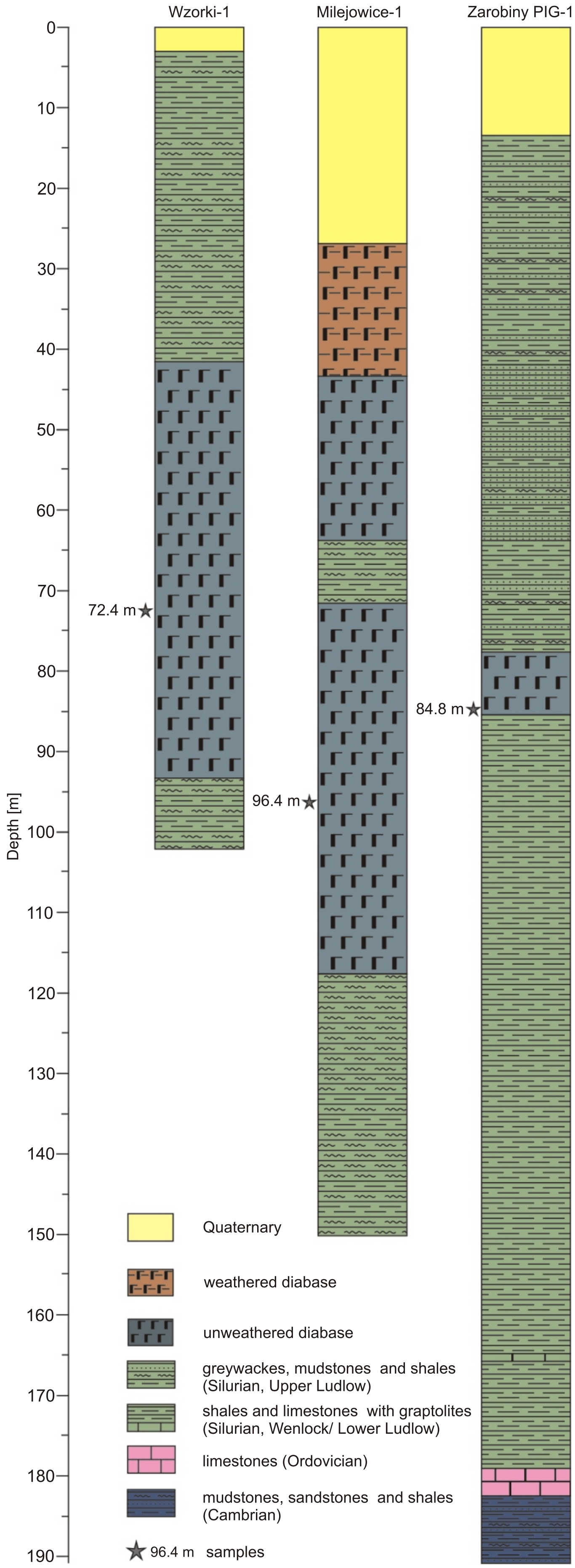
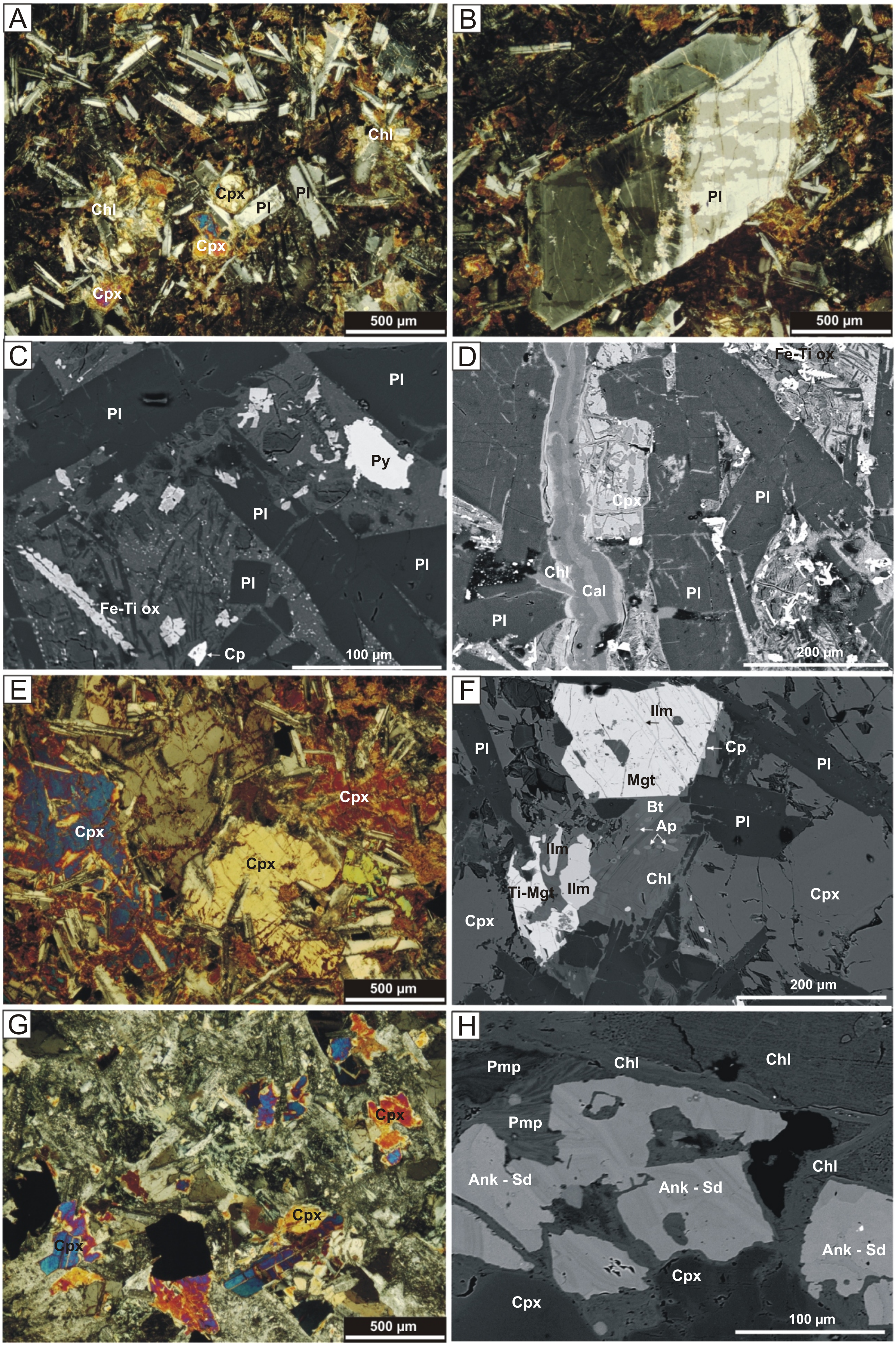


Fig. 2. Sampling sites with ^{40}Ar-^{39}Ar age determinations *vs*. simplified lithological logs of the borehole cores analysed


A
Chl
Cpx
Pl
Pl
Chl
Cpx
Cpx
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B
Pl
500 µm
C
Pl
Pl
Py
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Pl
Fe-Ti ox
Cp
100 µm
D
Fe-Ti ox
Cpx
Pl
Chl
Cal
Pl
Pl
200 µm
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Cpx
Cpx
Cpx
500 µm
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Pl
Ilm
Ti-Mgt
Ilm
Chl
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Cpx
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Cpx
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Cpx
500 µm
H
Pmp
Chl
Chl
Pmp
Chl
Ank - Sd
Ank - Sd
Ank - Sd
Cpx
Cpx
100 µm

MILEJOWICE DIABASE

The diabases analysed from the Łysogóry Unit are represented by two varieties of rock: the Milejowice diabase and the Wzorki diabase, which differ in mineral paragenesis, texture and intensity of alteration. The Milejowice diabase from the Łysogóry Region forms a narrow zone (max. 20 m wide) of long dykes cutting folded Late Ordovician to latest Silurian shales and greywackes. They were probably intruded during the late Gedinnian–early Siegenian (Kowalczewski, 2004). According to Krzemiński (2004) the Milejowice diabase can be considered as a post-tectonic magmatic event associated with the extension of the Baltica passive margin at the final, Late Silurian stage of its collision with East Avalonia.

A sample for whole rock ^{40}Ar-Ar^{39} age determinations was taken from the Milejowice-1 borehole at a depth of 96.4 m. The Milejowice-1 borehole was located at 50°50'17"N latitude and 21°13'50"E longitude. The diabases (microgabbro?) from this depth are characterised by a medium-grained subophitic texture (Fig. 3E). The rocks contain mainly clinopyroxene (augite) crystals and plagioclase laths of labradorite-andesine composition. Titanomagnetite, ilmenite and titanite are commonly observed. Ore minerals are represented also by very small crystals of chalcopyrite (Fig. 3F). Slightly chloritised biotite occurs scarcely. Additionally, accessory minerals are represented by apatite, which forms inclusions within biotite crystals. The augite as well as subordinate biotite are somewhat chloritised.

WZORKI DIABASE

Several distinct magnetic anomalies measured by Pawłowski (1947) near the village of Święta Katarzyna–Psary indicated the presence of previously unrecognized diabase intrusions in that area of the Łysogóry Region. A diabase intrusion about 50 m thick was penetrated by the Wzorki-1 borehole located at 50°54'57.8"N latitude and 20°53'10.5"E longitude. The diabase cuts across the Ludlovian shales and mudstones. A sample for the ^{40}Ar-Ar^{39} study was taken from the borehole at a depth of 72.4 m. The fine-grained subophitic Wzorki diabase is evidently altered. The rock contains strongly altered plagioclase laths (previously of labradorite-andesine composition) and chloritised clinopyroxene (augite) crystals (Fig. 3G). Titanomagnetite, ilmenite and titanite are typical ore minerals, whereas very small chalcopyrite crystals are very scarce. Relicts of clinopyroxene grains occur within a mixture of alteration products. The common secondary minerals are carbonates – ankerite and siderite as well as chlorite and kaolinite. Pumpellyite and prehnite were also identified within the Wzorki diabase (Fig. 3H) as products of intense metasomatism.

The diabases studied from both areas contain ca. 50% of SiO_2. On the total alkalis *versus* silica (TAS) classification diagram (Fig. 4A; Maitre et al., 1989), all samples fall within the basaltic field. Plotted on the classification diagram of Winchester and Floyd (1977; Fig. 4B), the composition of the mafic intrusions falls within the subalkaline basalt field.

ANALYTICAL METHOD

All the whole-rock samples for ^{40}Ar-^{39}Ar geochronology were crushed by hand or with a jaw-crusher and subsequently milled using a swing-mill. The samples were cleaned and processed into a range of grain-sizes and the 0.25–0.5 mm fraction was selected. Phenocrysts were removed from the samples and, in some cases, the fractions were separated into one magnetic and one non-magnetic part. The ^{40}Ar-^{39}Ar dating was carried out at the ^{40}Ar-^{39}Ar geochronological laboratory at the University of Lund, Sweden. The samples selected for ^{40}Ar-^{39}Ar dating were irradiated together with the TCR sanidine standard (28.34 Ma following Renne et al.,1994) for 24 hours at the Oregon State research reactor. J-values were calculated with a precision of <0.25% and are reported for each sample in the data tables. Decay constants utilized were those given in Steiger and Jäger (1977). The ^{40}Ar-^{39}Ar geochronology laboratory at the University of Lund uses a *Micromass 5400* mass spectrometer with a Faraday and an electron multiplier. A metal extraction line, which contains two *SAES C50-ST101* Zr-Al getters and a cold finger cooled to ca. –155°C by a *Polycold P100* cryogenic refrigeration unit, is also present. Whole rock separates were loaded into a copper planchette that consists of several 3 mm holes. Samples were step-heated using a defocused 50W CO_2 laser. Sample clean-up time that made use of the two hot Zr-Al SAES getters and a cold finger with a *Polycold* refrigeration unit was five minutes. The laser was rastered over the samples to provide even-heating of all grains. The entire analytical process is automated and runs on a *Macintosh-steered OS 10.2* with software modified specifically for the laboratory at the University of Lund and developed originally at the Berkeley Geochronology Center by *Al Deino*. Time zero regressions were fitted to data collected from 10 scans over the mass range of 40 to 36. Peak heights and backgrounds were corrected for mass discrimination, isotopic decay and interfering nucleogenic Ca-, K- and Cl-derived isotopes. Isotopic production values for the cadmium lined position in the OSU reactor were: ^{36}Ar-^{37}Ar(Ca) =

Fig. 3. Photomicrographs of samples analysed from the Bardo diabase (A–D) and of diabases from the Łysogóry Region (E–H)

A – fine-grained subophitic texture with plagioclase laths and clinopyroxene grains, crossed polars (Zarobiny PIG-1 borehole, depth 84.8 m); **B** – plagioclase phenocryst (labradorite composition), crossed polars (Zarobiny PIG-1 borehole, depth 84.8 m); **C** – plagioclase laths, chloritised clinopyroxene, pyrite and chalcopyrite and skeletal titanomagnetite and titanohematite crystals, back-scattered electron image (BSE; Zarobiny PIG-1 borehole, depth 84.8 m); **D** – diabase cut by microveins filled by two generations of calcite and chlorite, back-scattered electron image (outer parts of veins; Zarobiny PIG-1 borehole, depth 84.8 m); **E** – diabase (microgabbro?) with subophitic texture with fine plagioclase laths of labradorite composition partially enclosed by medium-grained clinopyroxene (augite) crystals, crossed polars (Milejowice-1 borehole, depth 96.3–96.5 m); **F** – predominant clinopyroxene accompanied by plagioclase and chloritised biotite with apatite inclusions, and ore minerals such as titanomagnetite, ilmenite, magnetite and very small chalcopyrite crystal, back-scattered electron image (BSE; Milejowice-1 borehole, depth 96.3–96.5 m); **G** – strongly metasomatised diabase with relicts of clinopyroxene crystals and groundmass composed of a mixture of secondary minerals, crossed polars (Wzorki-1 borehole, depth 72.3–72.5 m); **H** – secondary minerals: pumpellyite, carbonates and chlorite, back-scattered electron image (BSE; Wzorki-1 borehole, depth 72.3–72.5 m); mineral symbols after Kretz (1983): Ank – ankerite, Ap – apatite, Cal – calcite, Chl – chlorite, Cp – chalcopyrite, Cpx – clinopyroxene, Ilm – ilmenite, Mgt – magnetite, Pl – plagioclase, Pmp – pumpellyite, Py – pyrite, Sd – siderite, Ti-Mgt – titanomagnetite; all BSE images and mineral phase identification were performed at the Microprobe Analysis Laboratory (PIG-NRI) in Warsaw using a *Cameca SX 100* instrument

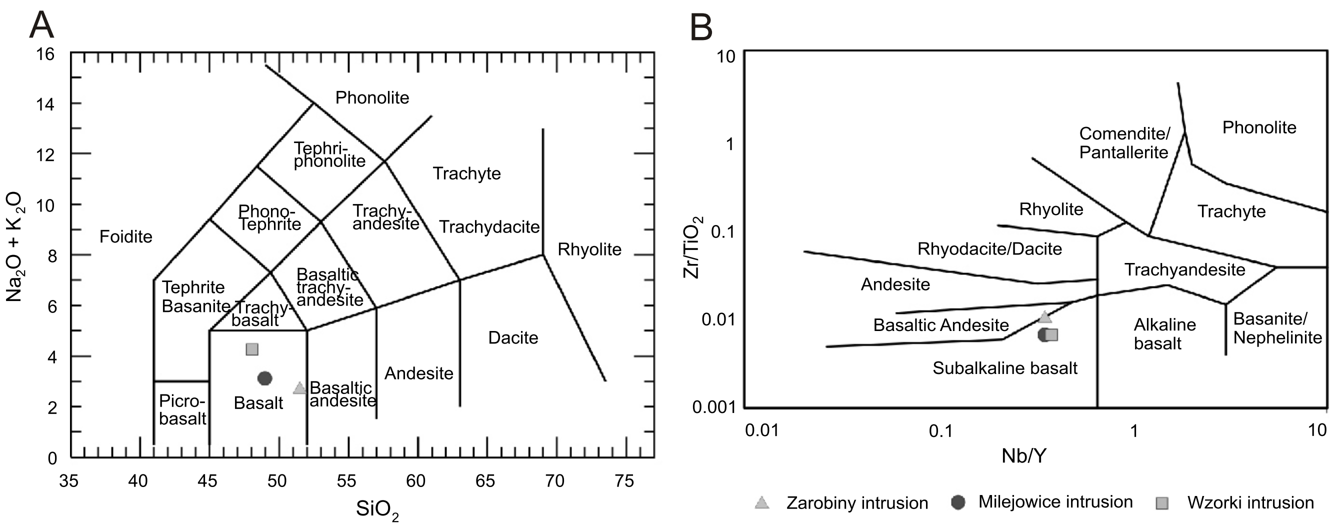

Fig. 4A – chemical classification of the rocks studied on the total alkalis *versus* silica (TAS) diagram of Maitre et al. (1989); B – chemical classification of mafic intrusions using a Zr/TiO$_2$ *vs*. Nb/Y diagram (Winchester and Floyd, 1977)

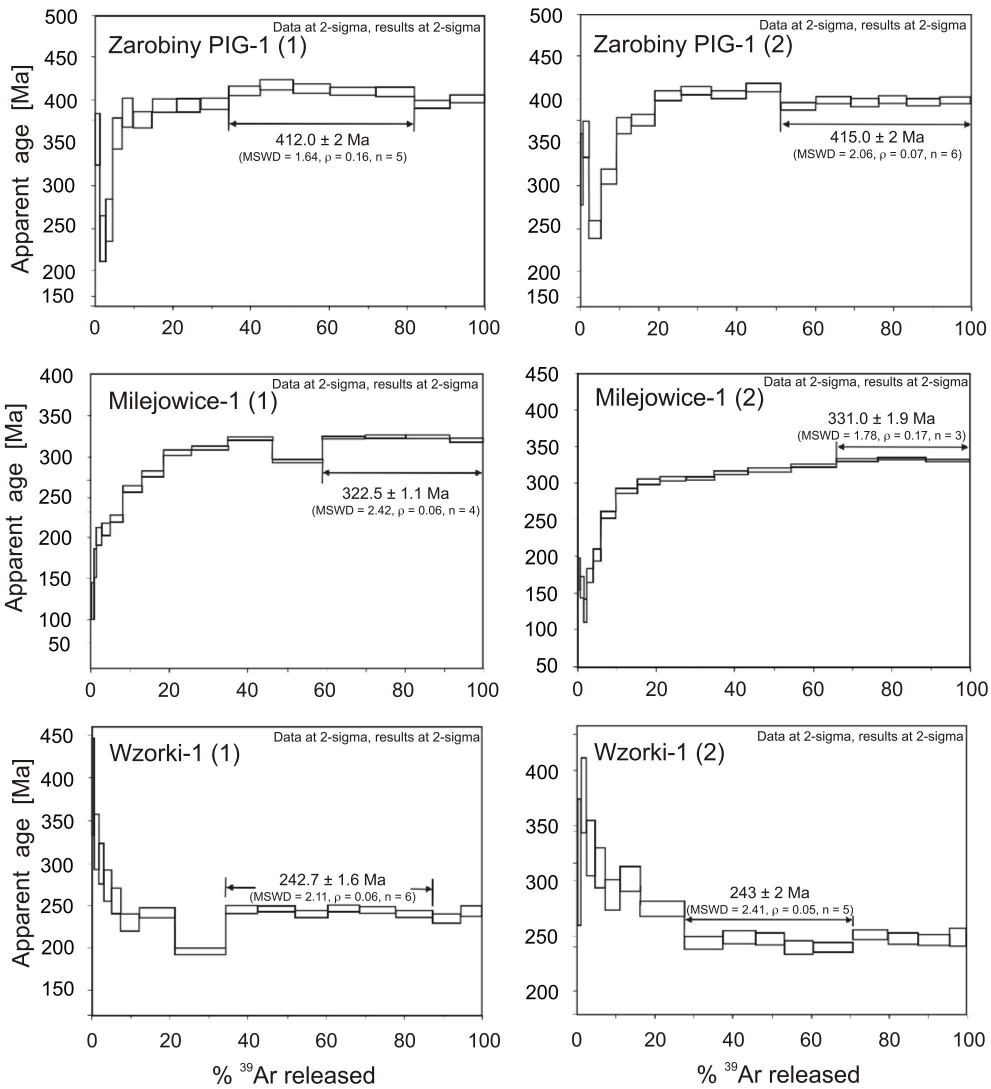

Fig. 5. ^{40}Ar-^{39}Ar age spectra of diabase whole-rock samples from the HCM

Error bars of step apparent ages are drawn at 1σ analytical uncertainties; plateau and pseudoplateau ages (±2σ error) are also listed; MSWD – mean square weight deviation, ρ – probability of occurrence based on Chi Square Tables, n – number of steps defining the plateau age

0.000264, ^{39}Ar-^{37}Ar(Ca) = 0 .000695, and ^{40}Ar-^{39}Ar(K) = 0.00073. The ^{40}Ar blanks were calculated before every new sample and after every three sample steps. The blank values were subtracted for all incremental steps from the sample signal. The laboratory was able to produce very good incremental gas splits, using a combination of increasing time at the same laser output, followed by increasing laser output. The age plateaus were determined using the criteria of Dalrymple and Lamphere (1971), which specify the presence of at least three contiguous incremental heating steps with statistically indistinguishable ages and constituting more than 50% of the total ^{39}Ar released during the experiment. In some places where a statistical overlap of steps is not obtained, a forced-fit age is given over a certain percentage of gas. The ^{40}Ar-^{39}Ar geochronology data were produced, plotted and fitted using the argon programme provided by *Al Deino* from the Berkeley Geochronology Centre, USA.

RESULTS

The Bardo diabase whole-rock subsamples 2063-01 and 2063-02 from the Zarobiny PIG-1 borehole gave well-defined Ar-Ar plateau ages of 412 ± 2 Ma and 415 ± 2 Ma, respectively (Appendix 1, Fig. 5), with medium MSWDs (1.64 and 2.06) and medium to low (subsample 2063-02) probabilities of X^2 distribution. The age spectra show an irregular increase of apparent age from the low temperature steps towards the intermediate temperature steps.

Subsamples 2060-01 and 2060-02 from the diabase intrusion drilled in the Milejowice-1 borehole revealed the presence of whole-rock ^{40}Ar-^{39}Ar pseudoplateau ages 322.5 ± 1.1 Ma and 331.0 ± 1.9 Ma, respectively. In this case the age spectra show a regular increase of apparent age from the low temperature steps toward the high temperature steps.

Very consistent plateau and pseudoplateau ages of 242.7 ± 1.6 Ma and 243 ± 2 Ma, respectively were determined for subsamples 2064-01 and 2064-02 taken from the Wzorki-1 borehole. In contrast to the previous samples, the age spectra here show a regular decrease of apparent age from the low temperature steps towards the intermediate temperature steps (Fig. 4). In spite of distinct age consistency, the medium values of MSWDs are accompanied here by rather low probabilities of X^2 distribution, which are nevertheless acceptable.

DISCUSSION

The results of ^{40}Ar-^{39}Ar dating reveal the presence of two events of magmatic activity expressed by the diabase intrusions in the study area. The oldest of these is documented by the Bardo diabase drilled by the Zarobiny PIG-1 borehole. The relatively precise age of this intrusion can be inferred from the isotope ages presented here and the results of the correlation of normal polarity palaeomagnetic record obtained from the diabase of both limbs of the Bardo Syncline (Nawrocki, 2000) with the global polarity-time scale (GPTS; Fig. 6). Even assuming an uncertainty (non-analytical) error of isotope age estimations, a Late Lochkovian–Early Emsian age of the Bardo intrusion can be excluded because this time interval is represented by a geomagnetic field of reversed polarity. The real age of this intrusion lies the between latest Ludlow (age of rocks containing the intrusion) and earliest Lochkovian, where the normal polarity time interval at the GPTS overlaps with the ^{40}Ar-^{39}Ar ages obtained here. Thus, the Bardo diabase emplaced in the age in-

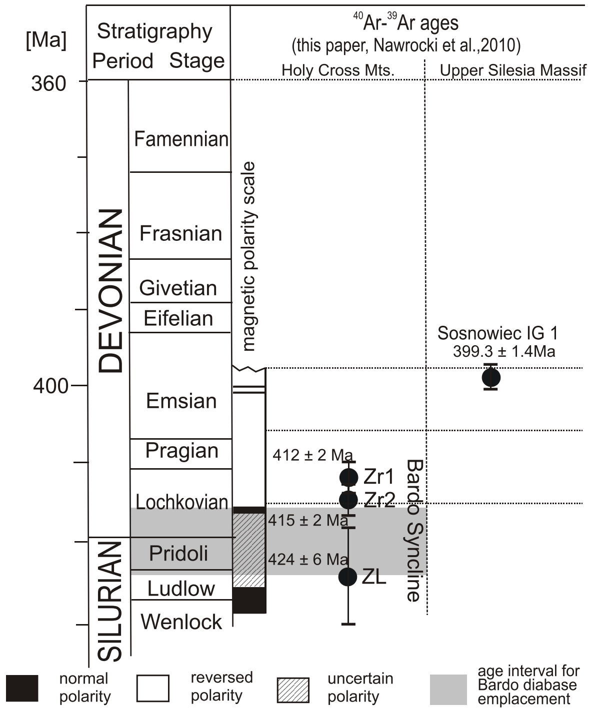

Fig. 6. ^{40}Ar-^{39}Ar ages of diabase intrusions from the Bardo Syncline (Zalesie Ravine, Nawrocki et al., 2007; Zarobiny PIG-1 borehole, this paper) and NE part of the Upper Silesia Massif (Sosnowiec IG 1 borehole; Nawrocki et al., 2010) *vs.* a stratigraphic chart with a part of the global polarity-time scale (after Gradstein et al., 2012)

The Bardo diabase reveals the presence of normal palaeomagnetic polarity only (see Nawrocki, 2000)

terval enclosed between ca. 424 and 416 Ma preceding the Late Lochkovian tectonic event expressed by the Miedziana Góra and Gruchawka Conglomerates, and a tectonic discordance (Kowalczewski and Migaszewski, 1993; Malec, 1994).

The younger event of the magmatic activity in the HCM is manifested by the Milejowice diabase intrusion sampled in the Milejowice-1 borehole. According to the new isotope data, this intrusion was emplaced in the Serpukhovian ca. 331–323 Ma. The older ^{40}Ar-^{39}Ar age (331 Ma) corresponds well with the ^{40}Ar-^{39}Ar age of a diabase intrusion from the Brunovistulian side of the Kraków–Lubliniec Fault Zone drilled in the WB-137 borehole (Table 1; see Nawrocki et al., 2010).

The Milejowice and Wzorki diabase intrusions partly correspond to the major transverse faults that are almost perpendicular to the Holy Cross Fault (Fig. 1). The isotopic studies do not show the age of emplacement of the Wzorki intrusion. The sample studied has been strongly affected by hydrothermal processes. As a result of these processes the ^{40}Ar-^{39}Ar plateau and pseudoplateau ages for the Wzorki diabase define most probably the time of its strong hydrothermal alteration that took place in the Middle Triassic, at 243 Ma (Anisian). The tectonic setting can point to the same Variscan age of the emplacement of the Wzorki-1 diabase as in the case of the Milejowice intrusion.

The possible link between hydrothermal mineralisation and magmatic events in the HCM postulated by several authors (Czarnocki, 1950; Rubinowski, 1962, 1971) can be constrained by the new isotope ages, assuming that the magmatic intrusions and the epigenetic mineralisation have the same deep source (Kardymowicz, 1967; Rubinowski, 1971). The first stage of post-Caledonian hydrothermal activity in the HCM that pro-

Table 1

^{40}Ar-^{39}Ar ages of diabase intrusions from near the Kraków–Lubliniec Tectonic Fault Zone and the Holy Cross Mountains (Nawrocki et al., 2007, 2010, this paper)

Kraków–Lubliniec Tectonic Fault Zone		Holy Cross Mountains	
Brunovistulian Terrane	Małopolska Proximal Terrane	Małopolska Proximal Terrane	Łysogóry Unit
Niedźwiedzia Góra Quarry: 296.6 ± 1.5 Ma borehole Sosnowiec IG 1 (3336 m, diabase): 289.1 ± 1.8 Ma (3259 m, diorite): 399.3 ± 1.4 Ma borehole WB-137 (436m): 331.3 ± 3.6 Ma	borehole PZ-10 (284 m): 298.7 ± 0.9 Ma (287 m): 292.6 ± 1.3 Ma (289 m): 295.1 ± 1 Ma	Bardo Syncline Zalesie: 424 ± 6 Ma borehole Zarobiny PIG-1 (84.8 m): **412 ± 2 Ma** **415 ± 2 Ma**	borehole Milejowie-1 (96.4 m): **322.5 ± 1.1 Ma** **331.0 ± 1.9 Ma** borehole Wzorki-1 (72.4 m): **242.7 ± 1.6 Ma*** **243.0 ± 2 Ma***

* – most probably secondary ages defining hydrothermal alteration of the Wzorki diabase; ages presented in this paper are bolded

duced the polymetallic copper and the iron-bearing mineral associations (Rubinowski, 1971) may be linked with the Serpukhovian magmatic phase defined here. The second stage of hydrothermal activity, associated with the lead-zinc mineralisation (Rubinowski, 1971) may be correlated with the Anisian when the Wzorki diabase underwent strong hydrothermal alteration. It should be stressed, however, that any spatial and temporal relationship of mineralisation and magmatic activity should be examined by more detailed geochemical and mineralogical studies.

CONCLUSIONS

1. The new isotopic ages, partly controlled by magnetostratigraphy, substantially refine the existing stratigraphic setting of the Holy Cross Mts. diabases. The Bardo diabase is evidently older than the Late Lochkovian. The age of its emplacement is enclosed between the latest Ludlow and earliest Lochkovian i.e. between ca. 424–416 Ma. The Milejowice diabase intrusion was formed during the Variscan stage of tectonic evolution of the Holy Cross Mts. It was emplaced during the Serpukhovian (ca. 331–323 Ma ago).

2. The ^{40}Ar-^{39}Ar plateau ages for the Wzorki diabase define the time of its strong hydrothermal alteration that took place in the Middle Triassic, at 243 Ma (Anisian). The isotopic studies do not allow us to estimate the age of emplacement of this intrusion, but its tectonic setting points to the same Variscan age as for that of the Milejowice intrusion.

3. The post-Caledonian hydrothermal activity in the HCM that produced the polymetallic copper and the iron-bearing mineral associations may be linked with the Serpukhovian magmatic phase defined here. Another hydrothermal activity event (producing the lead-zinc mineralisation) may have taken place in the Anisian when the Wzorki diabase was hydrothermally altered. Hypotheses concerning the temporal relationships of magmatic/hydrothermal activity and mineralisation events in the HCM should, however, be constrained by further detailed geochemical and mineralogical studies.

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