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ORIGINAL PAPER

Three age ranges of Cenozoic basaltic rocks from Lower Silesia (SW Poland) based on $^{40}Ar/^{39}Ar$ step-heating data

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Abstract

The precise ages of Cenozoic basaltic rocks from 20 localities (24 samples) in south-western Poland were studied by means of the $^{40}Ar/^{39}Ar$ isotope method. Three phases of volcanic activity were identified in this area. The older, Ruphelian phase took place 31–29 Ma ago and the younger, Aquitanian phase occurred 22–21 Ma ago. Significantly younger ages (4.8–4.6 Ma: Zanclean phase) were obtained for the basalts cropping out in the vicinity of Lądek Zdrój only. Most of the analyzed basalts from the Ruphelian phase are classified as nephelinites. They occur in the area of Lausitz Masif, south of Sudetic Marginal Fault and in the Opole Depression. The volcanic rocks from the Aquitanian phase crop out in the wide area north of the Sudetic Marginal Fault. They are composed of alkali basalts. The youngest phase is represented by the basanites only. The deep discontinuous tectonic structures intersecting the areas of volcanic activity in SW Poland, parallel or oblique to the tectonic stress directions previously reconstructed for the Oligocene and Miocene in the Bohemian Massif, were most probably reactivated by an extension approximately parallel or slightly oblique to them, thus opening pathways for the migration of basaltic magma in the Sudetes and their foreland.

Keywords Basalts · $^{40}Ar/^{39}Ar$ chronology · Cenozoic · Poland

Introduction

Cenozoic volcanic rocks are common in Central Europe and crop out in many places in France, Germany, the Czech Republic, Hungary, and Poland. The alkaline magmatism of this age in the Bohemian Massif and its northern foreland forms the easternmost part of the so-called Central European Volcanic Province (CEVP) of Wimmenauer (1974). The volcanic fields are grouped here in the basement of lithospheric terranes that were affected by tectono-thermal events 300–400 Ma ago (e.g., Franke and Żelaźniewicz 2000). They are characterized by higher heat flow and thinner lithosphere than the surrounding larger cratons (Meier et al. 2016). According to Wilson and Downes (2006), the Cenozoic reactivation of Permian/Carboniferous fault systems in the area of CEVP occurred, thanks to the superposition of tectonic stress related to the collision of Iberia with the rest of Europe and tectonic stress transmitted from the front of the Alpine collision. Changes of regional tectonic stress were of key significance for opening the pathways of magma migration (Wilson and Downes 2006; Ulrych et al. 2011). The direction of maximum horizontal stress in Central Europe rotated from the NNE–SSW to the NNW–SSE during the Late Eocene/Early Oligocene, and in the Late Oligocene towards NW–SE (Schreiber and Rotsch 1998).

The magmatic activity in the whole CEVP was associated with a rift system about 1100 km in length. It has been traditionally linked with the modification of lithospheric mantle and existence of mantle plumes (Wilson and Downes 1991; Puziewicz et al. 2011). However, this model was not fully supported by geophysical data. Therefore, it was modified to obtain the so-called "hot fingers" model (Wilson and Patterson 2001), where local passive elevations of the partially melted upper mantle did not have to be linked with

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anomalies of the geothermal field even though high-resolution seismic tomography indicates a positive spatial correlation between the places where Cenozoic volcanic fields occur in Central Europe and the decreasing thickness of the lithosphere (Meier et al. 2016). Piromallo et al. (2001) link the occurrence of the Cenozoic volcanic belt in the foreland of the Alpine orogen with the zone of the deeply buried oceanic lithosphere. On the other hand, Wilson and Patterson (2001) associate phases of magmatic activity with periods of the rising Icelandic mantle plume. The accurate geochronology of the particular volcanic fields of the CEVP is obviously very important for the verification of any of these models.

According to the existing data, the exact time the main phases of volcanic activity ended varies in different parts of the CEVP. Relying on K/Ar isotope ages, Badura et al. (2005) indicate 21 Ma as the lower limit for the main stage of basaltic volcanism in the Lower Silesia. The same time is assumed for this magmatism in the Elbe zone (Ulrych et al. 2008), Vogtland–Mariańskie Łaźnie Fault Zone (Haase and Reno 2008) and the Westerwald (Haase et al. 2004). A slightly younger age, i.e., 19 Ma was estimated for the volcanic field of the Upper Palatinate (Rohrmüller et al. 2005). This age is significantly older in the Hohe Eifel area only, where the main volcanic activity ended 35 Ma ago (Fekiacowa et al. 2007). In many smaller volcanic domains of Germany and Moravia, the extinction of volcanic activity took place 11–18 Ma ago, but in the whole area of the CEVP there are further individual magmatic bodies, which are younger, with an age even below 0.1 Ma (West and East Eifel; Jung et al. 2012).

In the Bohemian Massif, the following three main periods of Cenozoic volcanic activity were distinguished and linked with the geochemical and mineralogical signature of volcanic rocks, and with the succession of paleostress (Ulrych et al. 2011):

- pre-rift period (79–49 Ma) with a compressional stress field;
- syn-rift period (42–16 Ma) with a tensional stress field;
- late-rift period (16–0.26 Ma), subdivided into Mid–Late Miocene episode (16–6 Ma) with a compressional stress field, Late Miocene–Early Pleistocene episode (6–0.9 Ma) with a tensional stress field, and Early–Late Pleistocene episode (0.9–0.26 Ma) with a compressional stress field.

The most extensive volcanic activity took place here during the syn-rift period when a tectonic graben formed under a N–S tensional stress field (34–24 Ma ago). This activity ended under a NW–SE tensional stress field in the early to mid-Miocene (Adamovic and Coubal 1999; Rajchl et al. 2009; Ulrych et al. 2011, 2016). In the Lausitz Volcanic Field, 18 out of 22 Ar/Ar-dated eruptions took place between 34.9 and 28.0 Ma, and 13 of them are tightly clustered between 31.2 and 30.1 Ma (Büchner et al. 2015). This area stretches up to the westernmost part of the region of this study.

The Cenozoic volcanic rocks in Lower Silesia are mainly associated with the deep-seated faults of the Labe-Odra fault system. The westernmost domain of volcanic activity in the Polish part of the Sudetes is situated at the extension of the NE-oriented Ohře Rift Graben that was dissected by the Lusatian Fault (Ulrych et al. 2011). The intrusions of basaltoids are also located in the Opole Depression filled with Cretaceous strata. The basaltic and trachybasaltic volcanoes of Lower Silesia display a diversity of eruptive styles, including effusive and variably explosive eruptions (Awdankiewicz et al. 2016). Most of the volcanic intrusions from SW Poland were dated using the K/Ar method (Birkenmajer et al. 2002a, b, 2004; Badura et al. 2005; Kasiński et al. 2015). The obtained isotope ages were juxtaposed with the magnetic polarity record (Birkenmajer et al. 2002b, 2004). Most of the reversed and normal polarities linked with the K/Ar ages defined for the same samples do not fit the Global Polarity-Time Scale (Gradstein et al. 2012). It means that most of the K/Ar ages cannot be correlated with the time of emplacement of these rocks. Nearly, all the K/Ar ages from SW Poland are distributed evenly between twenty and thirty Ma. Such a distribution of ages does not support the thesis about two phases of volcanic activity (21–24.5 Ma and 31.3–33.7 Ma) as postulated by Birkenmajer and Pecskay (2002) and Birkenmajer et al. (2002a, b, 2004). According to Badura et al. (2005) the K/Ar ages of individual basalts older than Oligocene are not reliable.

The aim of this paper is to present and discuss the newly obtained $^{40}Ar/^{39}Ar$ isotope ages of basalts from SW Poland. The tectonic frames that could determine the magma emplacement will also be shown.

Sampled rocks and methods

The samples for the whole-rock $^{40}Ar/^{39}Ar$ studies were collected from the massive, least altered parts of lava flows or plugs from 20 outcrops and one borehole (Table 1). The sampling localities are grouped in four areas north of Bohemian Massif (Fig. 1A, black frame). Three outcrops (Jasna Góra, Sulików and Bukowa Góra) and one borehole (Opolno Zdrój PIG-1) were sampled in the Zgorzelec area (Figs. 1B, 2, region I). Further east, close to the Sudetic Marginal Fault, samples for isotope studies were taken from 11 localities (Bazaltowa Góra, Dębowiec, Gilów, Gola Dzierżoniowska, Grodziec, Lubień, Męcinka, Strzegom, Targowica, Wilcza Góra and Żelazów) in the Strzelin–Strzegom–Złotoryja area (Figs. 1B, 2, regions II

Table 1 List of studied sampling localities and samples of basalts from the SW of Poland

Area	Location	No of samples	GPS coordinates	Rock type
Zgorzelec area (region I)	Opolno, boreholes S22 (107.3 m) S8 (103.3 m)	2	50° 53′ 08.2″ 14° 59′ 00.4″	Nephelinite
	Sulików, Ognista Góra, quarry	1	51° 04′ 41.140″ 15° 04′ 34.5″	Basanite
	Bukowa Góra, quarry (Księginki)	1	51° 04′ 43.4″ 15° 15′ 4.0″	Nephelinite
	Jasna Góra, outcrop	1	50° 52′ 36.8″ 14° 56′ 34.9″	Trachyte
Opole area (region V)	Góra św. Anny, outcrop	1	50° 27′ 12.4″ 18° 09′ 58.7″	Nephelinite
	Gracze, quarry: IX level (I) VII level (II) V level (III)	3	50° 41′ 04.0″ 17° 33′ 32.4″	Nephelinite
Strzelin–Strzegom–Złotoryja area (regions II and III)	Grodziec, outcrop	1	51° 10′ 36.49″ 15° 45′ 31.87″	Nephelinite
	Wilcza Góra, quarry	1	51° 06′ 19.1″ 15° 54′ 46.4″	Nephelinite
	Lubień, quarry		51° 07′ 39.2″ 16° 13′ 42.0″	Alkali basalt
	Męcinka, quarry	1	51° 05′ 3.2″ 16° 06′ 41.5″	Alkali basalt
	Bazaltowa Góra, old quarry	1	51° 0′ 42.9″ 16° 8′ 6.3″	Alkali basalt
	Żelazów (Żółkiewka), old quarry	1	50° 58′ 35.6″ 16° 17′ 41.5″	Alkali basalt
	Strzegom (Krzyżowa Góra), old quarry	1	50° 58′ 25.3″ 16° 20′ 0.8″	Alkali basalt
	Gilów III, old quarry	1	50° 43′ 56.8″ 16° 46′ 29.8″	Alkali basalt
	Gola Dzierżoniowska, old quarry	1	50° 44′ 48.5″ 16° 47′ 58.2″	Alkali basalt
	Targowica, quarry	1	50° 41′ 17.5″ 16° 57′ 57.5″	Alkali basalt
	Dębowiec I, old quarry	1	50° 35′ 54.8″ 17° 07′ 14.7″	Alkali basalt
Lądek Zdrój area (region IV)	Lutynia, quarry Lower lava flow (I) Upper lava flow (II)	2	50° 21′ 34.7″ 16° 54′ 39.9″	Basanite
	Zalesi, outcrop	1	50° 21′ 18.5″ 16° 55′ 18.7″	Basanite
	Czarne Urwisko, outcrop	1	50° 21′ 27.8″ 16° 53′ 31.7″	Basanite

Regions of sampling are marked on Fig. 1

and III). Two sampling localities (Gracze quarry and Góra Świętej Anny) are east of the Sudetes, in the Opole area (Figs. 1B, 2, region V). Another three localities (Lutynia quarry, Czarne Urwisko, and Zalesi) were studied in the Lądek area located in the zone of the Śnieżnik Massif (Figs. 1B, 2, region IV).

The lithology of the volcanic rocks from the Zgorzelec area is diverse. Basanites (Sulików quarry), nephelinites

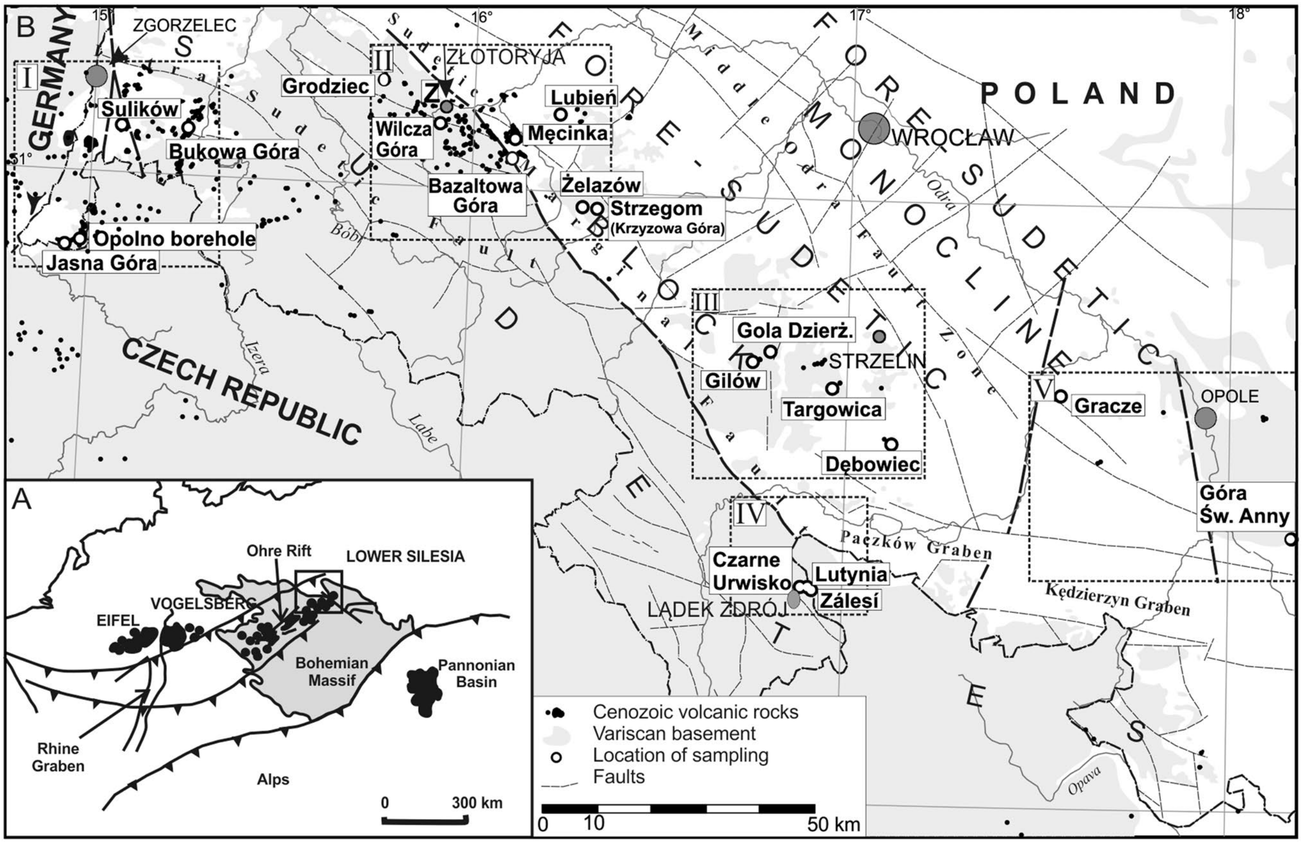


Fig. 1 **A** Location of the study area (black frame) relative to the Ohre Rift and the Bohemian Massif (based on Ulrych et al. 1999, modified). **B** Distribution of alkali basalts in the NW of Poland (based on Sawicki 1967, 1995) and location of the study sites. More detailed geological maps of five regions of sampling (I–V), marked here by rectangles with broken lines, are presented in Fig. 2

(Opolno Zdrój and Bukowa Góra quarry) as well as trachytes can be distinguished (Jasna Góra). Trachytes are fine-grained with fluidal textures emphasized by the orientation of the elongated sanidine crystals (Fig. 3A). The alkali feldspar dominates in the microlithic groundmass of these rocks. The basanites are porphyritic as they contain phenocrysts of olivine and clinopyroxene. Their microlithic groundmass comprises of olivine, clinopyroxene, plagioclases and titanomagnetite (Fig. 3B). The olivine crystals are slightly altered. The olivine nephelinites are porphyritic as they contain olivine and clinopyroxene phenocrysts exceeding 2 mm in length. Nepheline, olivine and clinopyroxene crystals, titanomagnetite and, rarely, Cr-spinels and apatite occur within the groundmass.

All samples from the Opole area are porphyritic olivine nephelinites (Fig. 3C, D). The olivine and clinopyroxene crystals are in the form of phenocrysts, which exceed 4 mm in length, as well as microcrystals. Additionally, nepheline and titanomagnetite crystals are also observed within groundmass.

Most samples from outcrops located close to the Sudetic Marginal Fault are alkali basalts (Fig. 3E–G). Only two of them (from Grodziec and Wilcza Góra) are olivine nephelinite. The alkali basalts display a high textural diversity ranging from massive to amygdaloidal. Most of them are porphyritic. The fluidal texture is rarely emphasized by the orientation of plagioclase laths. All types of basalts from this area contain a very similar mineral assemblage. They consist of phenocrysts of olivine and clinopyroxene (up to 3–4 mm in length). The fine-grained or microlithic groundmass contains olivine, clinopyroxene, plagioclase and, as accessory minerals, apatite and titanomagnetite.

The samples from the Lądek Zdrój area are porphyritic basanites (Fig. 3H). Olivine and clinopyroxene occur here as phenocrysts and also as fine-grained crystals within the groundmass. Additionally, the groundmass contains

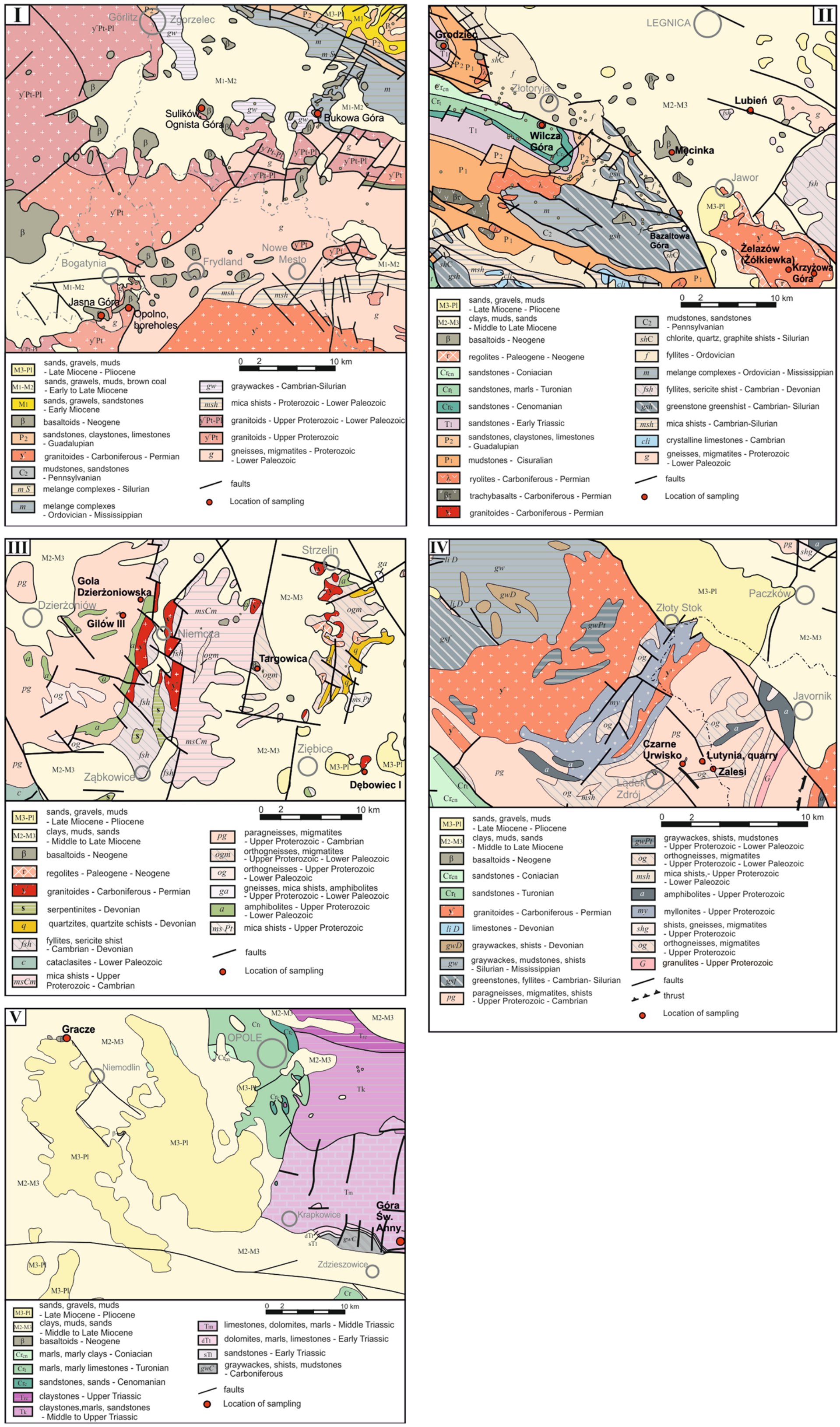
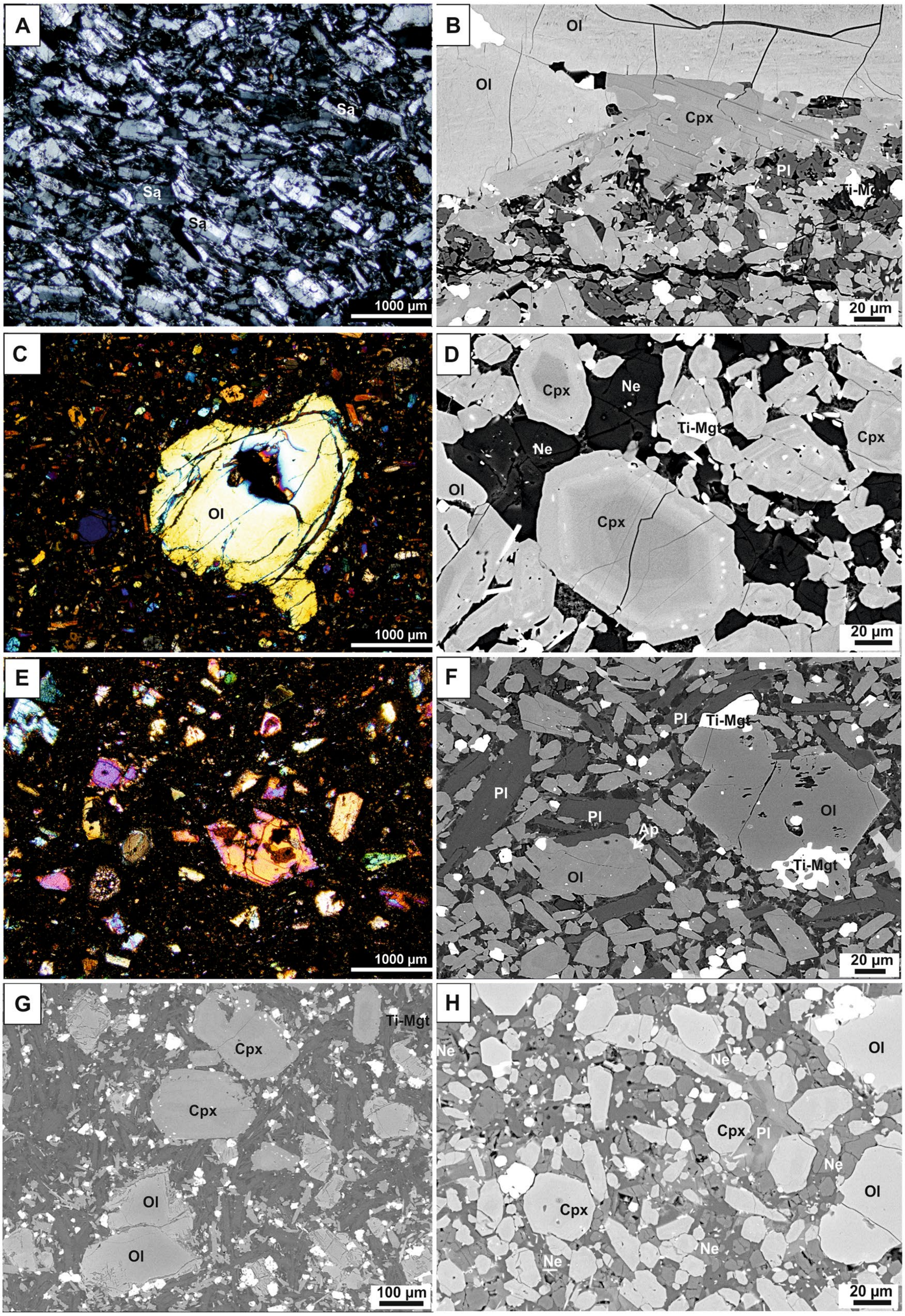


Fig. 2 Geological maps of five regions of study area where samples of basalts for $^{40}Ar/^{39}Ar$ isotope studies were collected (see Fig. 1). Geological backgrounds are based on: Milewicz et al. (1989) (region I), Milewicz et al. (1989) and Bossowski et al. (1981) (region II), Sawicki (1988, 1996), Bossowski et al. (1981) and Przybylski et al. (2020) (region III), Sawicki (1988) and Przybylski et al. (2020) (region IV), Przybylski et al. (2020), Haisig (2008), Kotlicki (1979) and Sawicki (1996) (region V)


A
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◂**Fig. 3** Representative petrographic features of studied rocks. **A** Trachyte; trachytic texture emphasizes the orientation of sanidine crystals (Jasna Góra outcrop; crossed polarized light), **B** basanite (Sulików quarry; BSE image), **C** olivine nephelinite with phenocryst of olivine (Gracze quarry; crossed polarized light), **D** olivine nephelinite with fine-grained groundmass containing clinopyroxene, nepheline, olivine and titanomagnetite crystals (Gracze quarry; BSE image), **E** alkali basalt with olivine and clinopyroxene phenocrysts (Żelazów; crossed polarized light), **F** alkali basalt with olivine and plagioclase phenocrysts within fine-grained groundmass containing plagioclase, olivine, titanomagnetite and apatite crystals (Bazaltowa Góra; BSE image), **G** alkali basalt with olivine and clinopyroxene phenocrysts within fine-grained groundmass containing plagioclase, olivine and titanomagnetite crystals (BSE image), **H** basanite with olivine and clinopyroxene phenocrysts within fine-grained groundmass containing plagioclase, nepheline, olivine, clinopyroxene and titanomagnetite crystals (BSE image). Symbols: BSE image—backscatters electron image; Ap—apatite, Cpx—clinopyroxene, Ne—nefeline, Ol—olivine, Pl—plagioclase, Sa—sanidine, Ti-Mgt—titanomagnetite. BSE images were performed at the Microprobe Analysis Laboratory (PGI-NRI) in Warsaw using a LEO 1410 scanning electron microscope

laths of plagioclase, crystals of nepheline and accessory titanomagnetite.

All samples from the Zgorzelec, Opolno and Lądek Zdrój area fall within the basanite field in the total alkalis versus silica classification diagram (TAS, Fig. 4A). The sample from Jasna Góra that falls within the trachyte field is the only exception. The samples taken close to the Sudetic Marginal Fault fall within the basanite, trachybasalt and basalt field. According to a diagram by Winchester and Floyd (1977), almost all samples from these exposures can be classified as alkali basalts (Fig. 4B).

The basaltic rocks from Lower Silesia commonly contain mantle and lower crustal xenoliths (e.g., Kukula et al. 2015; Ladenberger et al. 2009; Matusiak-Małek et al. 2021). The least altered pieces of volcanic rocks without xenoliths, megacrystals, and crystal aggregates were chosen for isotopic dating. The selected parts of rock were prepared according to the standard procedure for the whole-rock $^{40}Ar/^{39}Ar$ geochronology. Whole-rock analyses have been carried out at the $^{40}Ar/^{39}Ar$ Geochronological Laboratory at the University of Lund, Sweden, using a Micromass 5400 mass spectrometer with a Faraday and electron multiplier. The samples were irradiated together with the TCR sanidine standard (28.34 Ma; according to Renne et al. 1994) for 24 h 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. The decay constants were adopted from Steiger and Jäger (1977). More details of the analytical procedure applied are presented by Dyhr et al.

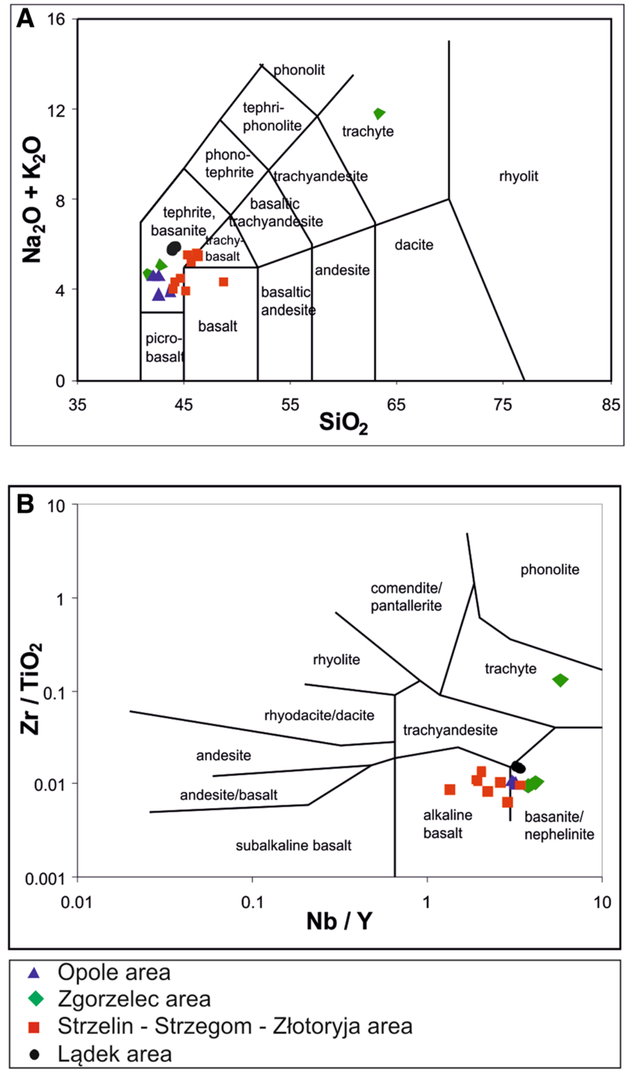

Fig. 4 **A** Chemical classification of the studied rocks in the total alkalis versus silica (TAS) diagram of Le Maitre et al. (1989). **B** Chemical classification of mafic intrusions using the Zr/TiO_2 vs. Nb/Y diagram (Winchester and Floyd 1977)

(2013), Dalrymple and Lamphere (1971). The age plateaus were determined using the criteria summarized by Baksi (2006) indicating the presence of at least three continuous 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 was not obtained, a forced-fit age is given over a certain percentage of gas. The $^{40}Ar/^{39}Ar$ geochronology data were elaborated, plotted and fitted using the

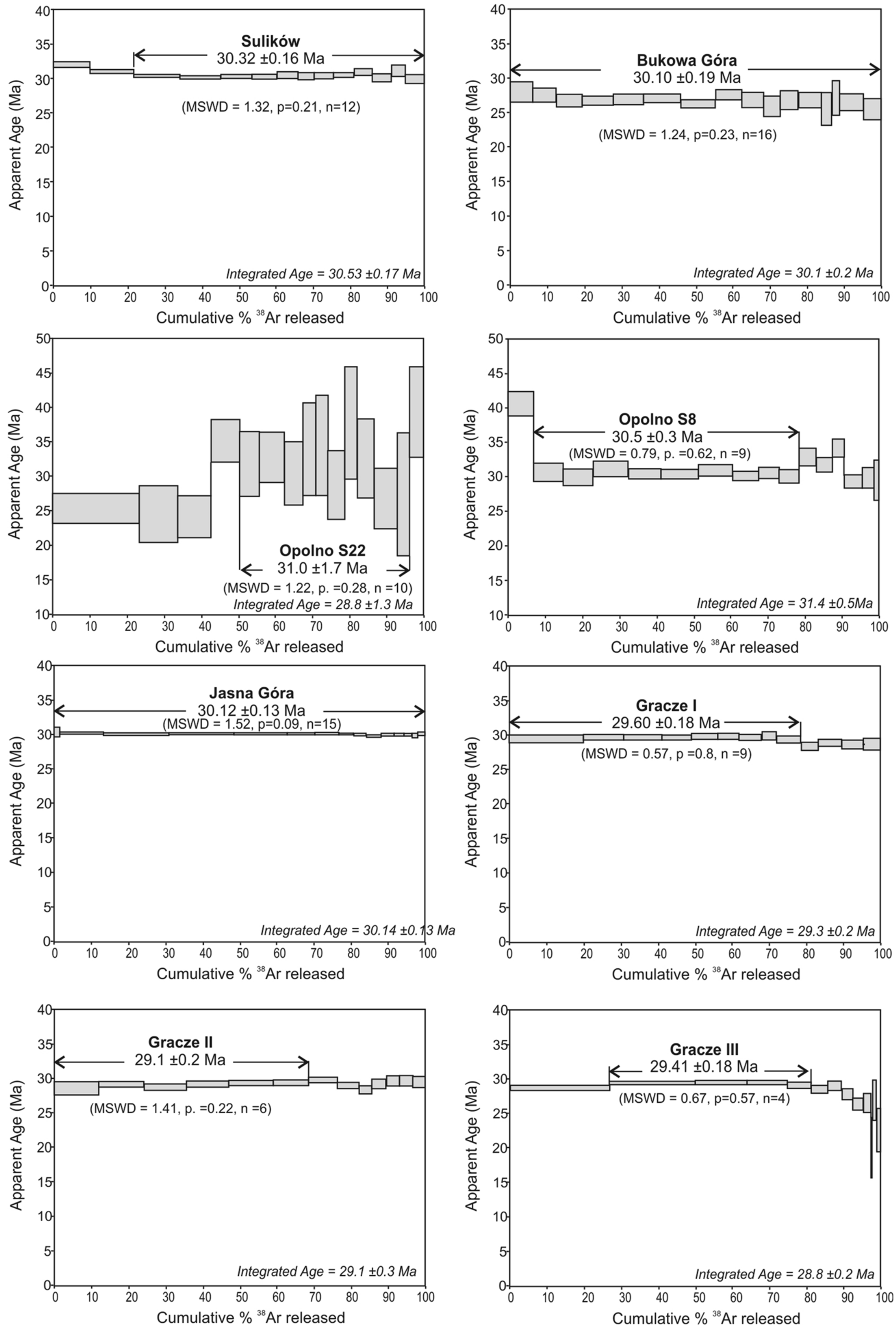

Fig. 5 $^{40}Ar/^{39}Ar$ age spectra of basaltic whole-rock samples from Lower Silesia. Error bars of step apparent ages are drawn at 2σ analytical uncertainties. Plateau and pseudoplateau ages ($\pm 2\sigma$ error) are also listed

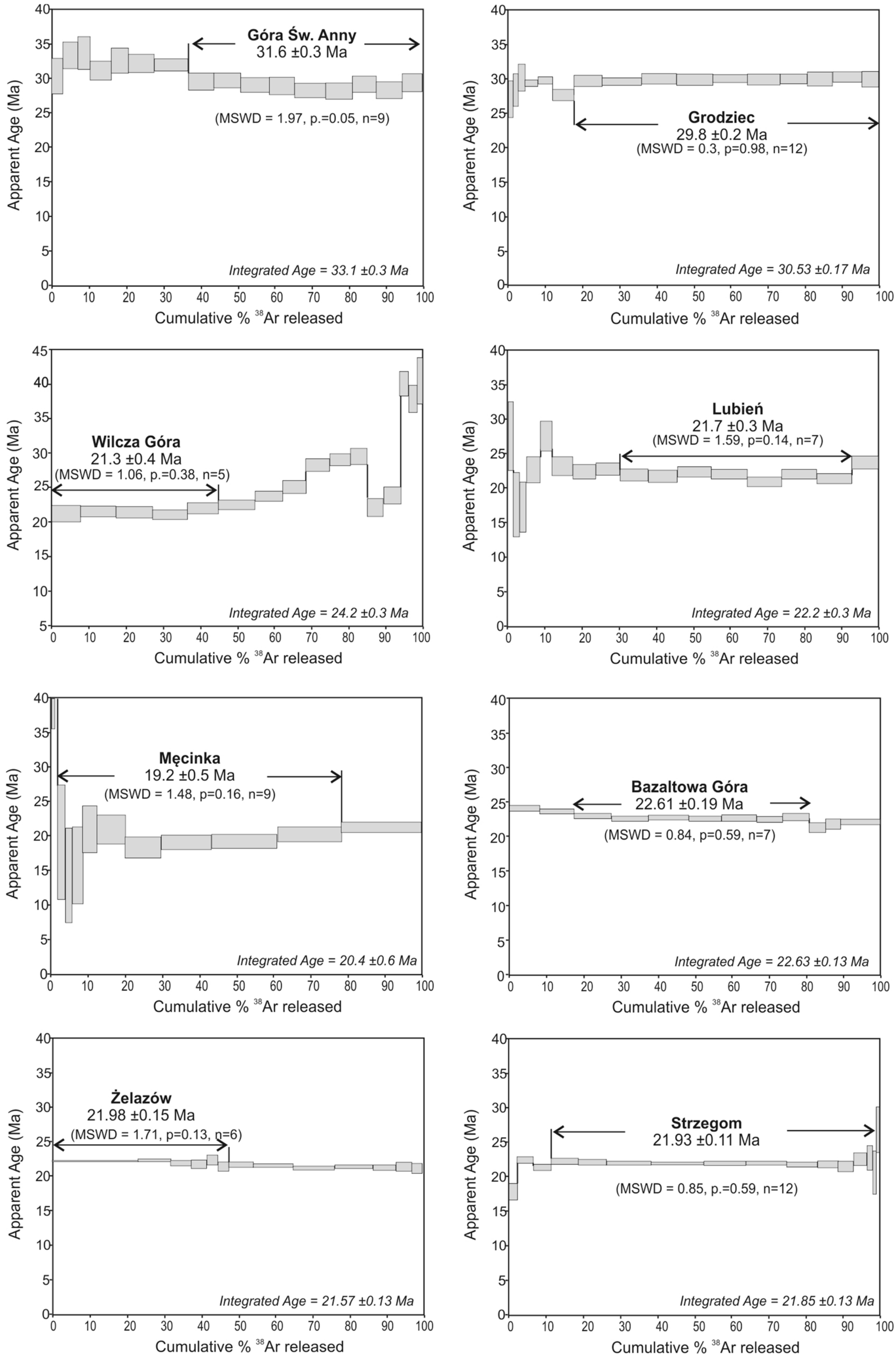

Fig. 6 ^{40}Ar/^{39}Ar age spectra of basaltic whole-rock samples from Lower Silesia (continued). Error bars of step apparent ages are drawn at 2σ analytical uncertainties. Plateau and pseudoplateau ages ($\pm 2\sigma$ error) are also listed

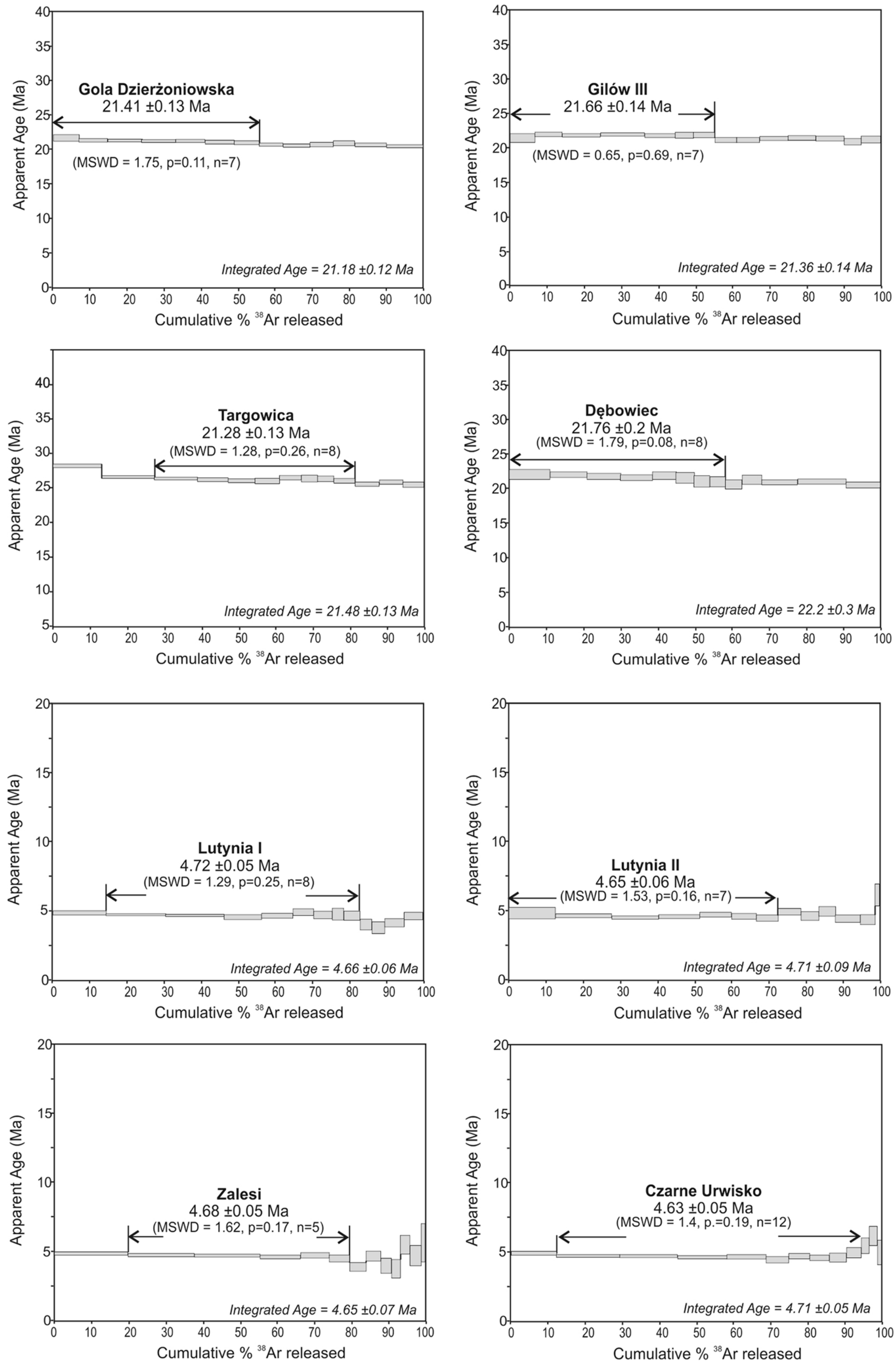

Fig. 7 $^{40}Ar/^{39}Ar$ age spectra of basaltic whole-rock samples from Lower Silesia (continued). Error bars of step apparent ages are drawn at 2σ analytical uncertainties. Plateau and pseudoplateau ages ($\pm 2\sigma$ error) are also listed

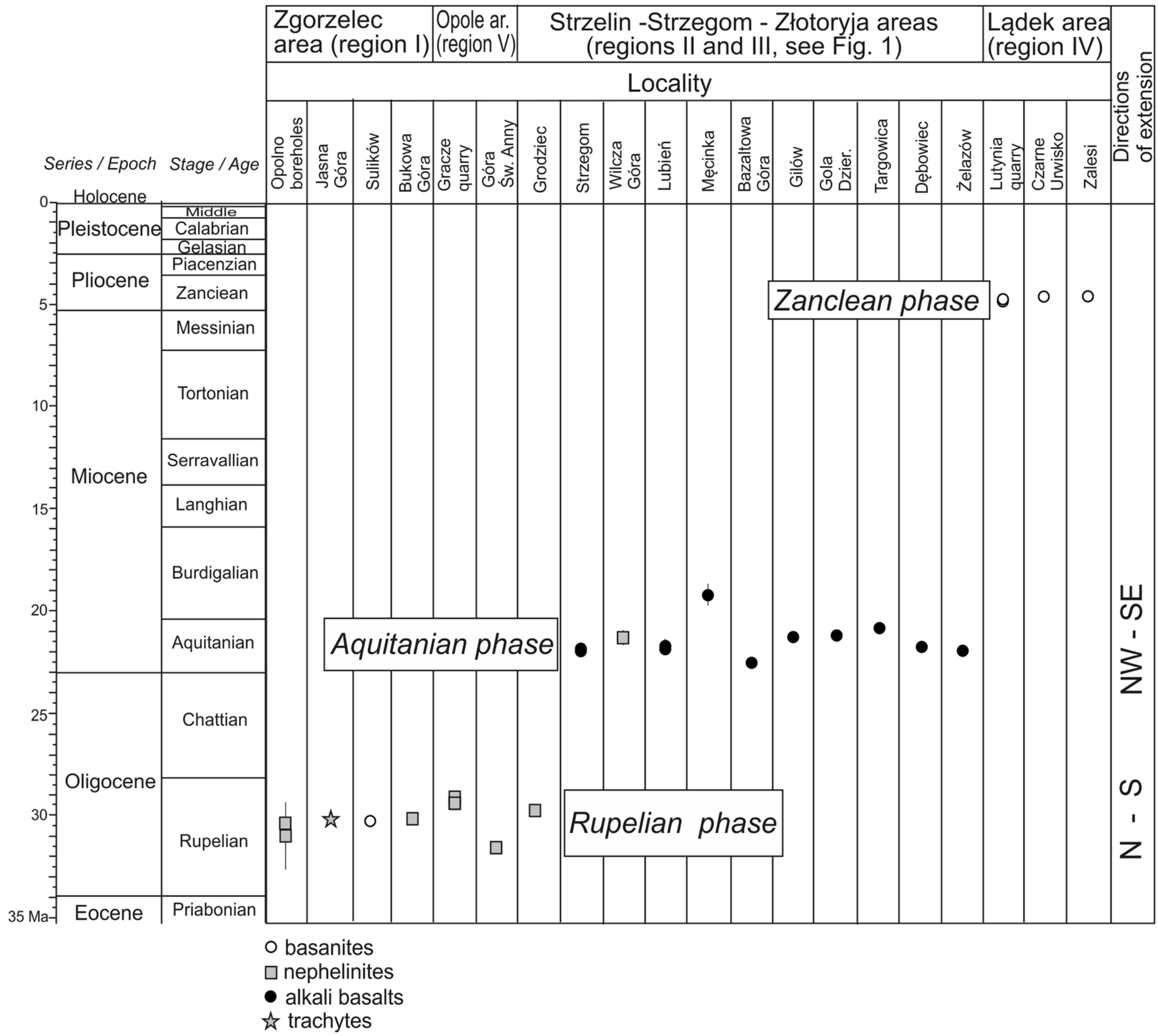

Fig. 8 The isotope $^{40}Ar/^{39}Ar$ ages of basaltoids from particular localities and areas of Lower Silesia on the background of stratigraphic time table (Gradstein et al. 2012) and directions of extension in the Bohemian Massif (Ulrych et al. 2011). Three phases of volcanic activity are distinguished,

argon software "Mass Spec" provided by Al Deino from the Berkeley Geochronology Centre, USA.

Results of radiometric dating

The whole-rock samples from Sulików, Bukowa Góra, Opolno S22, Opolno S8, Jasna Góra, Gracze I, Gracze II and Gracze III yielded $^{40}Ar/^{39}Ar$ plateau ages of 30.32 ± 0.16 Ma, 30.10 ± 0.19 Ma, 31.0 ± 1.7 Ma, 30.5 ± 0.3 Ma, 30.12 ± 0.13 Ma, 29.6 ± 0.18, 29.1 ± 0.2 Ma and 29.41 ± 0.18 Ma, respectively (Fig. 5). Except for the sample Opolno S22 with a moderate quality of isotope age, the other samples provided excellent quality plateau ages (Online Appendix 1). Similarly, well-defined plateau ages were obtained from the samples taken from the outcrops at Góra Świętej Anny (31.6 ± 0.3 Ma) and Grodziec (29.8 ± 0.2 Ma) (Fig. 6). The isotope ages around 30 Ma include from 54 to 100% of the ^{39}Ar released.

The whole-rock samples from the outcrops at Wilcza Góra, Lubień, Męcinka, Bazaltowa Góra, Żelazów and Strzegom provided $^{40}Ar/^{39}Ar$ plateau ages of 21.3 ± 0.4 Ma,

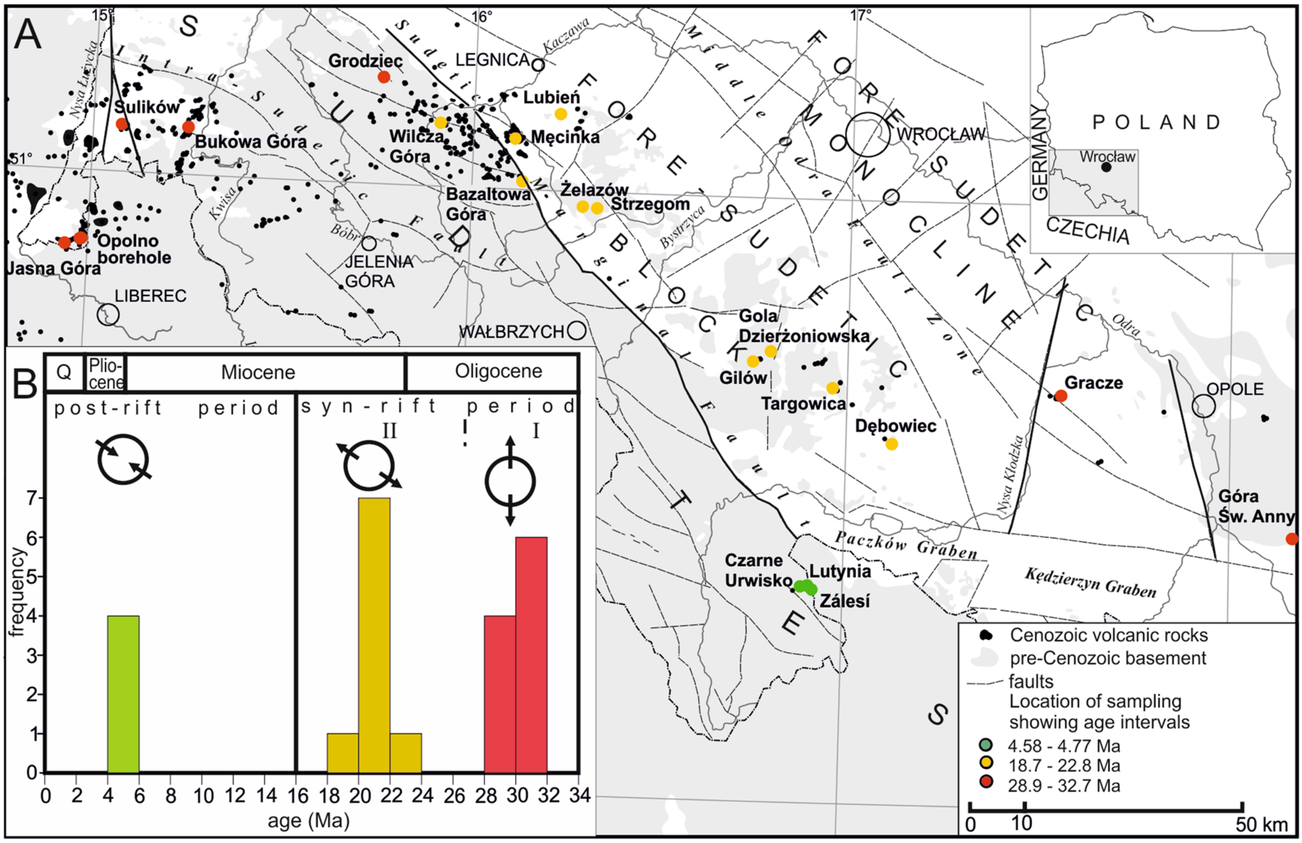

Fig. 9 Spatial distribution of isotope $^{40}Ar/^{39}Ar$ ages of basaltoids from Lower Silesia divided into three phases (**A**) and their frequency referred to paleostress directions (**B**). The paleostress orientations during particular stages of volcanic activity and syn-rift/post-rift intervals of tectonic activity in the Bohemian Massif are shown after Ulrych et al. (2011). *Q* quaternary

21.7 ± 0.3 Ma, 19.2 ± 0.5 Ma, 22.61 ± 0.19 Ma, 21.98 ± 0.15 Ma and 21.93 ± 0.11 Ma, respectively (Fig. 6). Comparable and very consistent $^{40}Ar/^{39}Ar$ plateau ages were also found for the samples from Gola Dzierżoniowska (21.35 ± 0.13 Ma), Gilów III (21.66 ± 0.14 Ma), Targowica (21.26 ± 0.13 Ma) and Dębowiec (21.76 ± 0.2 Ma) (Fig. 7). Only the ages obtained from the Wilcza Góra and Męcinka intrusions is of poorer quality with the initial argon ratio poorly defined (Online Appendix 1).

All samples taken in the vicinity of Lądek Zdrój provided evidently younger and very consistent isotope ages. The basanites from Lutynia I, Lutynia II, Zalesi, and Czarne Urwisko yielded $^{40}Ar/^{39}Ar$ plateau ages of 4.72 ± 0.05 Ma, 4.65 ± 0.06 Ma, 4.68 ± 0.05 Ma, and 4.63 ± 0.05 Ma, respectively (Fig. 7). These samples have well-defined isochron plots with initial argon ratio higher than 296 (Online Appendix 1).

Age ranges and spatial distribution of volcanics

The $^{40}Ar/^{39}Ar$ ages of basaltic rocks from SW Poland are grouped in three ranges with a focus around 32–29 Ma, 22–21 Ma and 4.8–4.6 Ma (Figs. 8, 9, Table 2). For the second group, a slightly younger plateau age (19.2 ± 0.5 Ma) occurs only at the Męcinka locality (Fig. 6). The Pliocene ages were obtained for the basanites cropping out in the vicinity of Lądek Zdrój only. The new ages compared with the K/Ar ages obtained earlier by Birkenmajer et al. (2002a, b, 2004) and Badura et al. (2005) in the same localities differ from each other up to 6 Ma. Birkenmajer et al. (2004, 2007) checked the credibility of K/Ar ages from the Lower Silesia basalts by their comparison with magnetostratigraphy. They also repeated dating of the same lava flow. Results of these studies indicate that the magnetic polarities of most of dated samples do not correlate with the coeval parts of global polarity time scale and the ages of two samples from the same lava flow differ of ca. 3 Ma each other (op. cit.). It should be also noted that the precision of an $^{40}Ar/^{39}Ar$ plateau age generally is better than the precision of K–Ar age because the plateau age is calculated by pooling the ages of several gas increments (e.g., Renne 2006).

Bearing in mind the geologic time scale (Gradstein et al. 2012), three phases of Cenozoic volcanic activity in SW Poland can be distinguished, namely, in stratigraphic order, the Ruphelian, the Aquitanian and the Zanclean (Fig. 8). The basalts from each phase are almost always linked with a particular area and specific geochemical features. Also the time of emplacement of rocks from an individual phase can be correlated with a characteristic period of tectonic stress field regime identified in this part of Europe (Ulrych et al. 2011). Except for the trachytes from Jasna Góra and basanites from Sulików, all the studied basalts representing the Ruphelian phase are classified as nephelinites. With the exception of the rocks from Grodziec, they occur near Zgorzelec, i.e., at the extension of the NE–SW-trending Ohře Rift Graben (Fig. 1), and close to Opole, where NE–SW-oriented structures of the Moravian Tectonic Zone occur in the basement. This zone separates the Brunovistulian Terrane from the tectonic blocks accreted during the Variscan orogeny (e.g., Franke and Żelaźniewicz 2000). Both basaltic intrusions in Grodziec and Wilcza Góra are located not far from each other and south of the Sudetic Marginal Fault (Fig. 1B). They also have the same composition of nephelinites, but the Wilcza Góra sample yielded a younger, i.e., Aquitanian isotope age. However, the plateau diagram with the whole-rock $^{40}Ar/^{39}Ar$ age presented for this sample is complicated due to the excess of ^{40}Ar in the high steps, and ^{39}Ar loss in the lower steps cannot be definitely excluded (Fig. 6, Online Appendix 1).

Outcrops of volcanic rocks from the Aquitanian phase occur in the vast area near Strzelin, Strzegom and Złotoryja,

Table 2 List of 39Ar/40Ar isotope ages obtained from the basaltoids cropping out in the SW of Poland (see Fig. 1)

Area	Location	Rock type	Age (Ma) ± 2δ	% ^{39}Ar in plateau	No. of steps	MSWD	Probability
Zgorzelec area (region I)	Opolno borehole S22 (107.3 m)	Nephelinite	31 ± 1.7	45.6	10	1.2	0.28
	Opolno borehole S8 (103.3 m)	Nephelinite	30.5 ± 0.3	71.8	9	0.8	0.62
	Sulików. Ognista Góra quarry	Basanite	30.32 ± 0.16	78.4	12	1.3	0.21
	Bukowa Góra quarry (Księginki)	Nephelinite	30.1 ± 0.19	100	16	1.2	0.23
	Jasna Góra outcrop	Trachyte	30.12 ± 0.13	100	15	1.5	0.09
Opole area (region V)	Góra św. Anny	Nephelinite	31.6 ± 0.3	63.2	9	2	0.05
	Gracze quarry: IX level (I)	Nephelinite	29.6 ± 0.18	78.6	9	0.57	0.8
	Gracze quarry: VII level (II)	Nephelinite	29.1 ± 0.2	68.5	6	1.4	0.22
	Gracze quarry: V level (III)	Nephelinite	29.41 ± 0.18	54.5	4	0.7	0.57
Strzelin–Strzegom–Złotoryja area (regions II and III)	Grodziec outcrop	Nephelinite	29.8 ± 0.2	82.2	10	0.3	0.98
	Wilcza Góra quarry	Nephelinite	21.3 ± 0.4	45.2	5	1.1	0.38
	Lubień, quarry	Alkali basalt	21.7 ± 0.3	62.7	7	1.6	0.14
	Męcinka quarry	Alkali basalt	19.2 ± 0.5	76.3	9	1.5	0.16
	Bazaltowa Góra, old quarry	Alkali basalt	22.61 ± 0.19	63.2	11	0.8	0.59
	Żelazów (Żółkiewka), old quarry	Alkali basalt	21.98 ± 0.15	47.9	6	1.7	0.13
	Strzegom (Krzyżowa Góra), old quarry	Alkali basalt	21.93 ± 0.11	87.6	12	0.9	0.59
	Gilów III. old quarry	Alkali basalt	21.66 ± 0.14	55.3	7	0.6	0.69
	Gola Dzierżoniowska. old quarry	Alkali basalt	21.41 ± 0.13	55.5	7	1.7	0.18
	Targowica. quarry	Alkali basalt	21.28 ± 0.13	53.8	8	1.28	0.26
	Dębowiec I. old quarry	Alkali basalt	21.76 ± 0.2	58.2	8	1.8	0.08
Lądek Zdrój area (region IV)	Lutynia quarry Lower lava flow (I)	Basanite	4.72 ± 0.05	68.4	8	1.29	0.25
	Lutynia quarry Upper lava flow (II)	Basanite	4.65 ± 0.06	72.4	7	1.53	0.16
	Zalesi	Basanite	4.68 ± 0.05	59.9	5	1.6	0.17
	Czarne Urwisko	Basanite	4.63 ± 0.05	81.5	9	1.4	0.19

north of the Sudetic Marginal Fault (Fig. 9A) which is approximately perpendicular to the Ohře Rift Graben. Except for the above-mentioned nephelinite from Wilcza Góra, located south of this fault, they are composed of alkali basalts. Basalts from the Zanclean phase cropping out near Lądek Zdrój are composed of basanites only. Assuming that all stages of evolution of tectonic stress distinguished by Ulrych et al. (2011) for Bohemia are also valid in SW Poland, we can conclude that the Oligocene basanites were emplaced under a N–S tensional stress field and the intrusions of the Miocene alkali basalts were set up under a NW–SE tensional stress field (Fig. 9B). The NW–SE direction of stress corresponds well to the course of the main tectonic faults occurring in the area of Miocene volcanic activity (Fig. 1). The N–S directed stress is oblique with respect to the NNE–SSW-trending discontinuous tectonic structures in the area where the Oligocene basanites occur. It is possible that some of these discontinuities in both areas were reactivated by an extension approximately parallel or slightly oblique to them, opening pathways for magma migration.

The ages of basalts from the westernmost part of the area under study (the Lausitz Massif) and the Opole Depression fit very well with the $^{40}Ar/^{39}Ar$ age spectrum obtained for the basaltoids from the German part of the Lausitz Volcanic Field (Büchner et al. 2015). The volcanic rocks from the Aquitanian phase are common in many areas of the CEVP (Haase et al. 2004; Haase and Reno 2008; Ulrych et al. 2008; Büchner et al. 2015). Slightly younger ages of basaltoids (18–19 Ma), for example in the Marcinka locality, were obtained only in a few locations in the CEVP only (Rohrmüller et al. 2005).

Conclusions

Based on our studies of basaltoids from Lower Silesia in Poland, the following conclusions can be drawn:

1. The $^{40}Ar/^{39}Ar$ ages of Cenozoic basaltic rocks from SW Poland display three phases of volcanic activity, i.e., the Ruphelian (32–29 Ma), the Aquitanian (22–21 Ma) and the significantly younger Zanclean (4.8–4.6 Ma). The Zanclean ages were obtained for basanites cropping out in the vicinity of Lądek Zdrój only. New $^{40}Ar/^{39}Ar$ isotope data yield substantially more precise and narrower timeframes previously determined using the K/Ar method.
2. Most of the basalts from the Ruphelian phase are classified as nephelinites. They occur in the area of the Lausitz Masif, south of the Sudetic Marginal Fault and in the Opole Depression. The volcanic rocks from the Aquitanian phase crop out in the wide area north of the Sudetic Marginal Fault. Except for the nephelinites from Wilcza Góra with an uncertain age, they are composed of alkali basalts.
3. Prominent tectonic faults occurring in the fields of volcanic activity studied here, parallel or slightly oblique to tectonic stress directions reconstructed for the Oligocene and Miocene time in the Bohemian Massif, were most probably reactivated at that time and the pathways for the migration of the basaltic magma in the Sudetes and its close foreland were opened.

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Data availability All isotope data obtained here are listed in Appendix 1. The rest of data i.e. the results of chemical analyses and thin sections are available upon request.

Declarations

Conflict of interest The authors do not have any conflicts of interest to declare.

References

Adamovic J, Coubal M (1999) Intrusive geometries and Cenozoic stress history of the northern part of the Bohemian Massif. Geolines 9:5–14

Awdankiewicz M, Rapprich V, Míková J (2016) Magmatic evolution of compositionaly heterogeneous monogenetic Cenozoic Strzelin volcanic field (Fore-Sudetic Block, SW Poland). J Geosc 61:425–450. https://doi.org/10.3190/jgeosci.221

Badura J, Pecskay Z, Koszowska E, Wolska A, Zuchewicz W, Przybylski B (2005) New age and petrological constraints on Lower Silesian basaltoids, SW Poland. Acta Geodyn Geomater 2:7–15

Baksi AK (2006) Guidelines for assessing the reliability of $^{40}Ar/^{39}Ar$ plateau ages: application to ages relevant to hotspot tracks. Manuscript. https://www.mantleplumes.org/ArAr.html. Accessed 2 Apr 2006

Birkenmajer K, Pecskay Z (2002) Radiometric dating of the Tertiary volcanics in Lower Silesia, Poland. I. Alkali basaltic rocks of the Opole Region. Bull Pol Acad Sci Earth Sci 51:31–50

Birkenmajer K, Pecskay Z, Grabowski J, Lorenc MW, Zagożdżon PP (2002a) Radiometric dating of the Tertiary volcanics in Lower Silesia, Poland. III. K–Ar and palaeomagnetic data from early Miocene basaltic rocks near Jawor, Foresudetic Block. Ann Soc Geol Polon 72:241–253

Birkenmajer K, Pecskay Z, Grabowski J, Lorenc MW, Zagożdżon PP (2002b) Radiometric dating of the Tertiary volcanics in Lower Silesia, Poland. II. K–Ar and palaeomagnetic data from Neogene basanites near Lądek Zdrój, Sudetes Mts. Ann Soc Geol Pol 72:119–129

Birkenmajer K, Pecskay Z, Grabowski J, Lorenc MW, Zagożdżon PP (2004) Radiometric dating of Tertiary volcanics in Lower Silesia, Poland. IV. Further K–Ar and palaeomagnetic data from late Oligocene to early Miocene basaltic rocks of the Fore-Sudetic Block. Ann Soc Geol Pol 74:1–19

Birkenmajer K, Pecskay Z, Grabowski J, Lorenc MW, Zagożdżon PP (2007) Radiometric dating of the Tertiary volcanics in Lower Silesia, Poland. V. K–Ar and palaeomagnetic data from late Oligocene to early Miocene basaltic rocks of the North-Sudetic depression. Ann Soc Geol Polon 77:1–16

Bossowski A, Sawicki L, Wroński J (1981) Mapa Geologiczna Polski 1:200 000, B-mapa bez utworów czwartorzędowych, arkusz Wałbrzych. Wydawnictwa Geologiczne

Büchner J, Tietz O, Viereck L, Suhr P, Abratis M (2015) Volcanology, geochemistry and age of the Lausitz Volcanic Field. Int J Earth Sci 104:2057–2083. https://doi.org/10.1007/s00531-015-1165-3

Dalrymple GB, Laphere MA (1971) $^{40}Ar/^{39}Ar$ technique of K–Ar dating: a comparison with the conventional technique. Earth Planet Sc Lett 12:300–308

Dyhr CT, Holm PM, Llambías EJ, Scherstén A (2013) Subduction controls on Miocene back-arc lavas from Sierra de Huantraico and La Matancilla and new $^{40}Ar/^{39}Ar$ dating from the Mendoza Region, Argentina. Lithos 179:67–83. https://doi.org/10.1016/j.lithos.2013.08.007

Fekiacowa Z, Mertz DF, Renne PR (2007) Geodynamic setting of the tertiary Hocheifel Volcanism (Germany), part I: 40Ar/39Ar geochronolgy. In: Ritter JRR, Christensen UR (eds) Mantle plumes. Springer, Berlin, pp 185–206

Franke W, Żelaźniewicz A (2000) The eastern termination of the Variscides: terrane correlation and kinematic evolution. In: Franke W, Haak V, Oncken O, Tanner D (eds) Orogenic processes: quantification and modelling in the Variscan belt. Geological Society Special Publications, London 179, pp 63–86

Gradstein FM, Ogg JG, Schmitz M, Ogg G (2012) The geologic time scale 2012. Elsevier B.V., New York, p 1144

Haase KM, Reno AD (2008) Variation of magma generation and mantle sources during continental rifting observed in Cenozoic lavas from the Eger Rift, central Europe. Chem Geol 257:195–205. https://doi.org/10.1016/j.chemgeo.2008.09.003

Haase KM, Goldschmidt B, Garbe-Schonberg CD (2004) Petrogenesis of tertiary Continental Intra-plate Lavas from the Westerwald Region, Germany. J Petrol 45:883–905. https://doi.org/10.1093/petrology/egg115

Haisig J (2008) Mapa Geologiczna Polski 1:200,000, B-mapa bez utworów czwartorzędowych, arkusz Kluczbork. Państwowy Instytut Geologiczny

Jung S, Vieten K, Romer RL, Mezger K, Hoernes S, Satir M (2012) Petrogenesis of tertiary alkaline magmas in the Siebengebirge, Germany. J Petrol 53:2381–2409. https://doi.org/10.1093/petrology/egs047

Kasiński JR, Badura J, Pańczyk M, Peckay Z, Sternus A, Słodkowska B, Urbański P (2015) Paleogen deposits in the polish part of Zittau Basin—new light on the age of tectonic depression. Bull Pol Geol Inst 461:295–324 (**In Polish**)

Kotlicki S (1979) Mapa Geologiczna Polski 1:200,000, B-mapa bez utworów czwartorzędowych, arkusz Gliwice. Wydawnictwa Geologiczne

Kukula A, Puziewicz J, Matusiak-Malek M, Ntaflos T, Buchner J, Tietz O (2015) Depleted subcontinental lithospheric mantle and its tholeiitic melt metasomatism beneath NE termination of the Eger Rift (Europe): the case study of the Steinberg (Upper Lusatia, SE Germany) xenoliths. Min Petrol 109:761–787. https://doi.org/10.1007/s00710-015-0405-3

Ladenberger A, Lazor P, Michalik M (2009) CO_2 fluid inclusions in mantle xenoliths from Lower Silesia (SW Poland): formation conditions and decompression history. Eur J Mineral 21:751–761. https://doi.org/10.1127/0935-1221/2009/0021-1930

Le Maitre RW, Bateman P, Dudek A, Keller J, Lameyre J, Le Bas M, Sabine PA, Schmid R, Sorensen H, Streckeisen A, Wooley AR, Zanettin B (1989) A classification of igneous rocks and glossary of terms. Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks. Blackwell, Oxford

Matusiak-Małek M, Puziewicz J, Ntaflos T, Woodland A, Uenver-Thiele L, Buchner J, Gregoire M, Aulbach S (2021) Variable origin of clinopyroxene megacrysts carried by Cenozoic volcanic rocks from the eastern limb of Central European Volcanic Province (SE Germany and SW Poland). Lithos. https://doi.org/10.1016/j.lithos.2020.105936

Meier T, Soomro RA, Viereck L, Lebedev S, Behrmann JH, Weidle C, Cristiano L, Hanemann R (2016) Mesozoic and Cenozoic evolution of the Central European lithosphere. Tectonophysics 692:58–73. https://doi.org/10.1016/j.tecto.2016.09.016

Milewicz J, Szałamacha J, Szałamacha M (1989) Mapa Geologiczna Polski 1:200,000, B-mapa bez utworów czwartorzędowych, arkusz Jelenia Góra. Wydawnictwa Geologiczne

Piromallo C, Vincent AP, Yuen DA, Morelli A (2001) Dynamics of the transition zone under Europe inferred from wavelet cross-spectrum of seismic tomography. Phys Earth Planet Inter 125:125–139. https://doi.org/10.1016/S0031-9201(01)00249-7

Przybylski B, Badura J, Ciszek D (2020) Mapa Geologiczna Polski 1:200,000, B-mapa bez utworów czwartorzędowych, arkusz Nysa. Państwowy Instytut Geologiczny—Państwowy Instytut Badawczy

Puziewicz J, Koepke J, Grégoire M, Ntaflos T, Matusiak-Małek M (2011) Lithospheric mantle modification during Cenozoic rifting in Central Europe: evidence from the Księginki nephelinite (SW Poland) xenolith suite. J Petrol 55:2107–2145. https://doi.org/10.1093/petrology/egr041

Rajchl M, Uicny D, Grygar R, Mach K (2009) Evolution of basin architecture in an incipient continental rift; the Cenozoic Most Basin, Eger Graben (Central Europe). Basin Res 21:269–294. https://doi.org/10.1111/j.1365-2117.2008.00393.x

Renne PR (2006) Progress and challenges in K–Ar and $^{40}Ar/^{39}Ar$ geochronology. Paleontol Soc Pap (geochronology: Emerging Opportunities) 12:47–66. https://doi.org/10.1017/S1089332600001340

Renne PR, Deino AL, Walter RC, Turrin BD, Swisher CC, Becker TA, Curtis GH, Sharp WD, Jaouni A-R (1994) Intercalibration of astronomical and radioisotopic time. Geology 22:783–786

Rohrmüller J, Horn P, Peterek A, Teipel A (2005) Specification of the excursion stops—first day: geology and structure of the lithosphere. Introduction. In: Kämpf H et al (eds) The KTB Deep Crustal Laboratoryand the western Eger Graben. GeoErlangen 2005, Excursion 25.-29.09, pp 46–50

Sawicki L (ed) (1967) Geological map of the Lower Silesia region 1: 200 000 (without Quaternary). Instytut Geologiczny, Warszawa (in Polish)

Sawicki L (1988) Mapa Geologiczna Polski 1:200,000, B-mapa bez utworów czwartorzędowych, arkusz Kłodzko. Wydawnictwa Geologiczne

Sawicki L (1995) Geological map of Lower Silesia with adjacent Czech and German territories (without Quaternary deposits) 1:100,000. Państwowy Instytut Geologiczny, Warszawa (in Polish)

Sawicki L (1996) Mapa Geologiczna Polski 1:200,000, B-mapa bez utworów czwartorzędowych, arkusz Wrocław. Polska Agencja Ekologiczna

Schreiber U, Rotsch B (1998) Cenozoic block rotation according to a conjugate shear system in central Europe-indications from palaeomagnetic measurements. Tectonophysics 299:111–142. https://doi.org/10.1016/S0040-1951(98)00201-7

Steiger RH, Jäger E (1977) Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth Planet Sci Lett 36:359–362

Ulrych J, Pivec E, Lang M, Balogh K, Kropáček V (1999) Cenozoic intraplate volcanic rock series of the Bohemian Massif: a review. Geolines 9:123–129

Ulrych J, Dostal J, Hegner E, Balogh K, Ackerman L (2008) Late Cretaceous to Paleocene melilitic rocks of the Ohre/Eger Rift in northern Bohemia, Czech Republic: insights into the initial stages of continental rifting. Lithos 101:141–161. https://doi.org/10.1016/j.lithos.2007.07.012

Ulrych J, Dostal J, Adamovic J, Jelinek E, Spacek P, Hegner E, Balogh K (2011) Recurrent Cenozoic volcanic activity in the Bohemian Massif (Czech Republic). Lithos 123:133–144. https://doi.org/10.1016/j.lithos.2010.12.008

Ulrych J, Krmiček L, Tomek Č, Lloyd FE, Ladenberger A, Ackerman L, Balogh K (2016) Petrogenesis of Miocene alkaline volcanic suites from western Bohemia: whole rock geochemistry and Sr-Nd-Pb isotopic signatures. Chem Erde 76:77–93. https://doi.org/10.1016/j.chemer.2015.11.003

Wilson M, Patterson R (2001) Intraplate magmatism related to short-wavelength convective instabilities in the upper mantle: evidence from the Tertiary—Quaternary volcanic province of western and central Europe. In: Ernst RE, Buchan KL (eds) Mantle plumes: their identification through time, vol 352. Geol Soc Amer. Spec Paper, pp 37–58

Wilson M, Downes H (1991) Tertiary-Quaternary extension-related alkaline magmatism in western and central Europe. J Petrol 32:811–850. https://doi.org/10.1093/petrology/32.4.811

Wilson M, Downes H (2006) Tertiary-quaternary intra-plate magmatism in Europe and its relationship to mantle dynamics. Geol Soc Lond Mem 32:147–166. https://doi.org/10.1144/GSL.MEM.2006.032.01.09

Wimmenauer W (1974) The Alcaline province of Central Europe and France. In: Sorensen H (ed) The alkaline rocks. Wiley, New York, pp 238–271

Winchester JA, Floyd PA (1977) Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chem Geol 20:325–343