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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

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Abstract: This is the fifth contribution to geochronological, petrologic-geochemical and palaeomagnetic studies of the Tertiary basaltoids of Lower Silesia, Poland. It covers the area of the North-Sudetic Depression close to its contact with the Fore-Sudetic Block (6 new sites). The oldest K-Ar date was obtained from basanite plug at Sichów (BP-34: 27.80±1.27 Ma) located exactly on the Sudetic Marginal Fault. It determines the age of the fault as Late Oligocene. Five other sites (BP-35–39) yielded radiometric ages between 20.07±0.90 Ma and 18.72±0.81 Ma (Early Miocene). The volcanics investigated are typical within-plate basaltoids represented by ankaratrite and basanite. The Late Oligocene Sichów intrusion (BP-34) is normally magnetized, the Early Miocene basaltic rocks (ankaratrite BP-39 and basanites: BP-35–38) reveal reversed magnetization.

Key words: K-Ar dating, basaltoid volcanics, palaeomagnetism, Late Oligocene, Early Miocene, Lower Silesia, Poland.

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INTRODUCTION

The present paper is the fifth contribution to a geochronological, petrologic-geochemical and palaeomagnetic study of the Tertiary basaltic rocks in Lower Silesia, Poland. It covers an area of the North-Sudetic Depression. Our previous studies included the areas of the Fore-Sudetic Block (Birkenmajer & Pécskay, 2002; Birkenmajer *et al.*, 2002b, 2004), and the Sudety Mts (Birkenmajer *et al.*, 2002a). Fourty two K-Ar dates have thus far been obtained from basaltoid sites located in the Fore-Sudetic Block (between Opole in the east and Legnica in the west), the Sudety Mts (Lądek Zdrój), and the North Sudetic Depression (this paper). Additional 15 K-Ar dates have recently been published from Tertiary basaltoids of Lower Silesia by Badura *et al.* (2005).

The Tertiary basaltoids of Lower Silesia belong to eastern branch of the Bohemo-Silesian volcanic belt, part of the Central European Tertiary intra-plate volcanic province (Fig. 1). To the north of the Sudetic Marginal Fault, and in the North Sudetic Depression, the volcanic activity usually started in Early Oligocene and continued through Early Miocene (Aquitanian–Burdigalian), with a c. 3 Ma break at the Miocene/Oligocene boundary. Another, much shorter cycle of basaltoid volcanic activity, dating from the Miocene/Pliocene (Messinian–Zanclean) boundary through

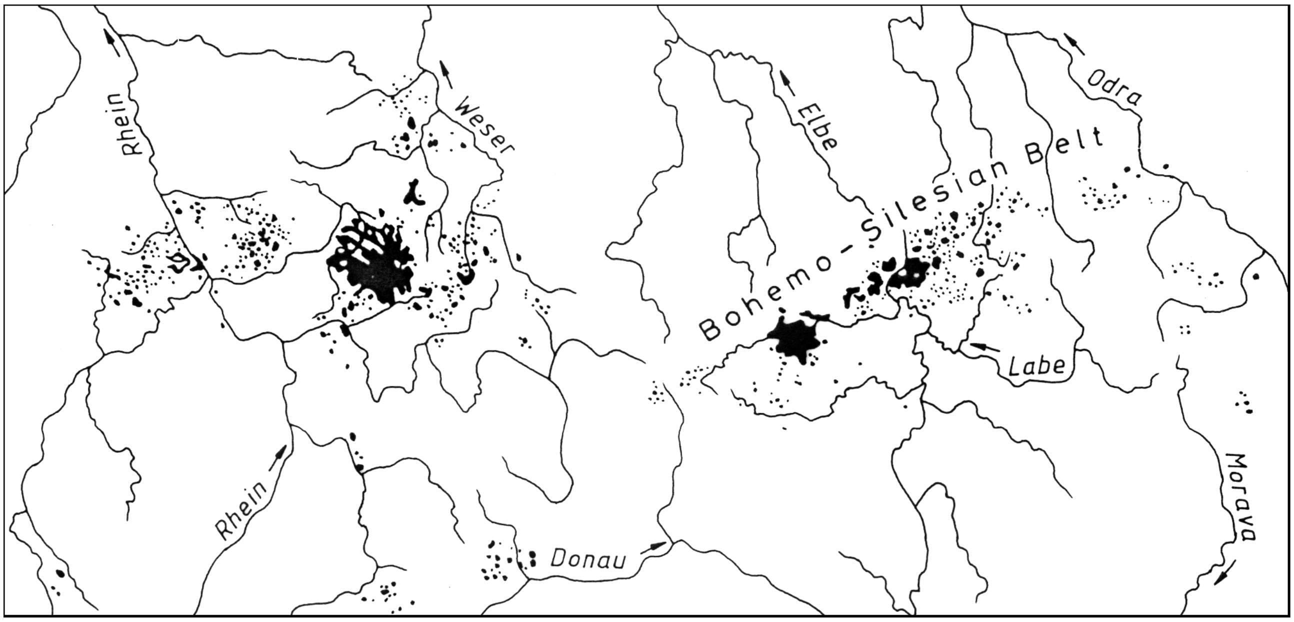


Fig. 1. Basaltoid volcanics of the Bohemo-Silesian Belt in Central European Tertiary volcanic province (simplified from Kopecký, 1966)

Early Pliocene (Zanclean) was recognized in the eastern part of the Sudetes Mts.

The Tertiary volcanic activity in Lower Silesia produced numerous basaltoid stratocones with or without central plugs and, often extensive, lava flows (flow-basalts). Internal structure of these volcanic bodies is often well exposed in working and abandoned quarries. A purely intrusive phase is represented by less frequent dykes and sills (e.g., Birkenmajer, 1967; Śliwa, 1967; Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1970, 2002a, b, 2004; Birkenmajer & Pécskay, 2002; Badura *et al.*, 2005).

The geochronological study reported here is a result of bilateral co-operation between the Polish Academy of Sciences (Institute of Geological Sciences, Cracow Research Centre) and the Hungarian Academy of Sciences (Institute of Nuclear Research, Debrecen), which began in 1998 aiming at K-Ar dating of the Polish Tertiary volcanics (Birkenmajer & Pécskay, 1999, 2000). Since 2000, it has been extended towards a systematic K-Ar age determination of the Tertiary basaltic rocks in Lower Silesia. The following occurrences of basaltoid rocks have so far been elaborated by us: (I) The Late Oligocene melabasanite plugs and lavas of the Opole area, Fore-Sudetic Block (Birkenmajer & Pécskay, 2002); (II) The Neogene basanite plug (Messinian/Zanclean) and lava flows (Zanclean) of the Lądek Zdrój area, Sudetes Mountains (Birkenmajer *et al.*, 2002a); (III and IV) The Late Oligocene to Early Miocene basaltoid rocks (ankaratrite, basanite, tephrite, alkali basalt) in the Fore-Sudetic Block between Strzelin in the east and Legnica in the west (Birkenmajer *et al.*, 2002b, 2004).

Since 2001, a palaeomagnetic sampling programme has supplemented our geochronological study of the Lower Silesian Tertiary basaltic rocks, involving the Polish Geological Institute in Warsaw (see Birkenmajer *et al.*, 2002a, b, 2004). It aims at refining and revision of palaeomagnetic data from these rocks published earlier (e.g., Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1970, 1972, 1977; Kruczyk *et al.*, 1977a, b, and references therein). From 2001 to 2004, new petrological-geochemical studies of the basaltic rocks in question, were carried out as part of scientific plans of the Institute of Geological Sciences, Polish Academy of Sciences. Geochemical analyses were performed in the Central Chemical Laboratory of the Polish Geological Institute in Warsaw.

GEOLOGICAL SETTING AND PETROLOGY

In the area of the North-Sudetic Depression between Jawor and Złotoryja (Fig. 2) six samples for K-Ar dating and petrologic-geochemical study, and an appropriate number of samples for palaeomagnetic investigation were collected in 2001 at four sites (BP-34–39).

SAMPLING DATA

Sichów (BP-34)

Geology. This is a volcanic plug located at a junction of the Sudetic Marginal Fault (WNW–ESE) which separates the North-Sudetic Depression from the Fore-Sudetic Block (Figs 2, 3), with another (W–E-trending) fault which cuts Cambro-Silurian rocks of the Kaczawskie Mts (see Jerzmański, 1956, fig. 1; 1965, fig. 2). In an abandoned quarry (Fig. 3), we see small-size, gently tilted ankaratrite columns, diverging fan-wise in the western part of the exposure (see Birkenmajer, 1967, fig. 15; Site No 12 in Birkenmajer *et al.*, 1970).

Petrology and geochemistry. This rock was originally classified as plagioclase-nepheline basalt with glass (Wojno *et al.,* 1951), later as basanite (Birkenmajer *et al.*, 1970),

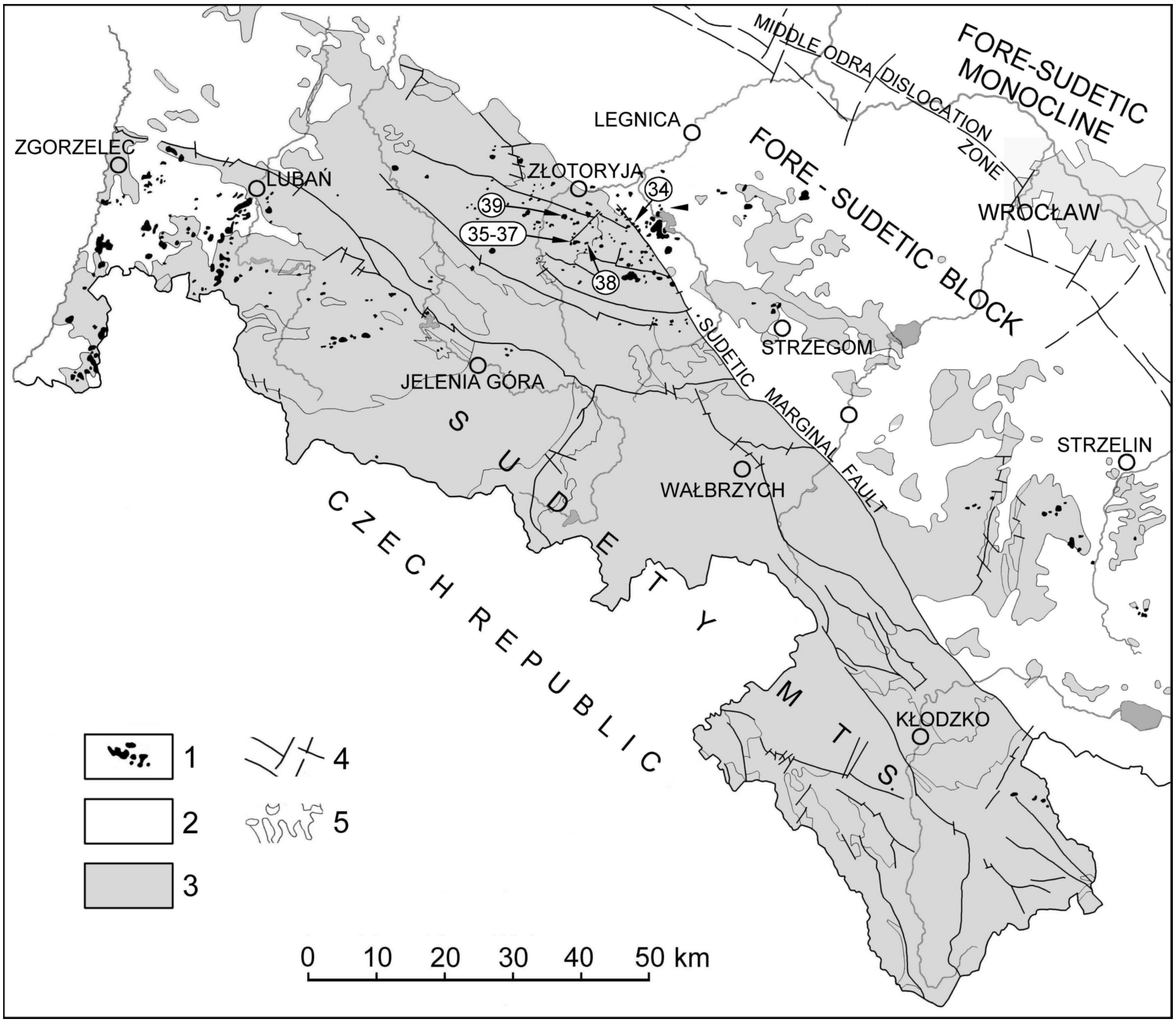


Fig. 2. Location of basaltoid sampling sites (BP-35–39: circled numbers) in North Sudetic Depression, Lower Silesia, Poland. 1 – Tertiary basaltic rocks; 2 – Cenozoic sedimentary cover; 3 – pre-Cenozoic rocks; 4 – major faults; 5 – main lithologic boundaries

melabasanite (Birkenmajer *et al.*, 1977), and tephrite (Kozłowska-Koch, 1987). The rock is black, fine-grained, without directional structure. Its groundmass consists of brownish glass and very fine phenocrysts of nepheline, K-feldspar and pyroxene. Isotropic, euhedral crystals of opaque minerals are abundant. Among phenocrysts, euhedral and subhedral olivine dominates: its size is usually 0.5 mm, exceptionally reaching up to 1.5 mm. Subordinate phenocrysts of pyroxene (Ti-aguite, $z/\gamma = 37°$) are euhedral or subhedral, commonly twinned, sometimes showing internal zoning, rarely also an hourglass structure. Small aggregates composed of fine pyroxene and olivine crystals appear here or there. Very rare vesicles are filled with calcite, chalcedony and quartz.

Based on mineral and chemical composition (Tab. 1; Figs 9–11), and following the IUGS standard for systematics of igneous rocks (Le Bas & Streckeisen, 1991), our rock should be classified as *ankaratrite (olivine melanephelinite)*.

Sampling. Samples BP-34 for K-Ar dating and for palaeomagnetic measurements (SI 1 & 2) were collected in south-eastern part of the quarry (Fig. 3A, B).

Wilków (BP-35–37)

Geology. This is a large basaltoid plug well exposed in a working quarry (Kahle Berg on German maps; Site No 18 in Birkenmajer *et al.*, 1970: Krzeniów III). It shows several systems of thermal jointing well expressed in arrangement of vertical (at lower exploitation level) to moderately-to-steeply inclined columns (Fig. 4A, B), probably representing more than one intrusive phase. Two south-dipping basaltoid dykes (Fig. 4C), moreover several vertical faults and brecciated zones, have been recognized (Figs 4A–C). Associated tuff breccias contain xenoliths of Upper Cretaceous sandstones which do represent host rocks of the plug (Birkenmajer, 1967).

Petrology and geochemistry. The rock was originally classified as nephelinite (Birkenmajer, 1967; Birkenmajer

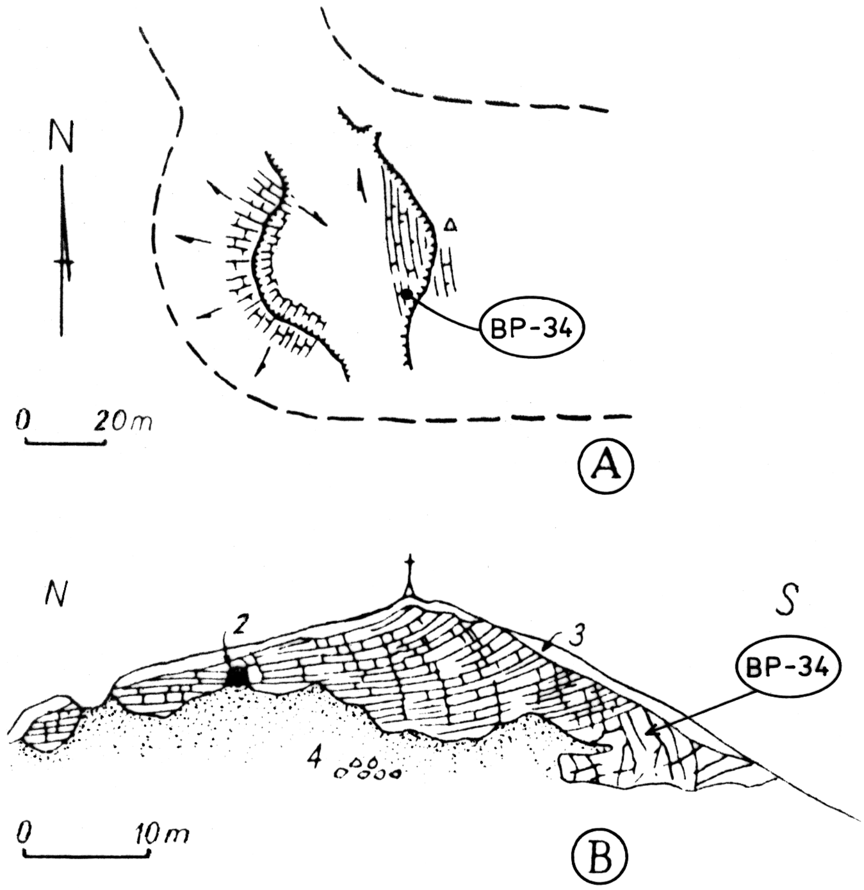


Fig. 3. Sichów, Site BP-34 (abandoned quarry), location of samples. Arrows (in **A**) show arrangement of ankaratrite columns; dashed – possible boundaries of the plug; 1 – ankaratrite; 2 – large xenolith of metamorphic rocks; 3 – Quaternary cover; 4 – scree (after Birkenmajer 1967, fig. 15, explanations modified)

& Nairn, 1969; Birkenmajer *et al.*, 1977), later – as basanite passing into basalt (Krzyśków, 1986; Białowolska, 1993).

Three samples taken from the upper (BP-35), middle (BP-36) and lower (BP-37) exploitation levels of the quarry (Fig. 4A–C) were studied. Black colouration and very fine grain are typical for the samples. The rock at upper level (BP-35) is porphyric; at middle level (BP-36) – aphanitic; and at lower level (BP-37) – showing fluidal structure. Its groundmass consists of very fine plagioclase plates (labradorite An_{53-55}) with albitic twins, and of twinned pyroxene (z/γ = 38–42°), sometimes showing hourglass structure. Black opaque minerals occur infrequently. Plagioclase and pyroxene phenocrysts are coated with glass (in sample BP-37, the groundmass components express sericitization of plagioclase and chloritization of both pyroxene and glass). Among small (<1 mm in size) phenocrysts, euhedral or subhedral olivine predominates. In some cases (BP-36), the phenocrysts are surrounded by very fine iddingsite rims, in others (BP-37) their microcracks are secondarily filled with minerals of serpentine group. In sample BP-38, single pyroxene phenocrysts of uniform size (ca 1 mm) occur.

A rock sample from upper level of the quarry (BP-35) contains numerous vesicles 3–5 mm in size. Some are filled with euhedral olivine crystals showing a network of microcracks filled with serpentine group minerals. Other vesicles are filled with very fine pyroxene and, subordinately, nepheline, the latter brown-coloured by iron-pigment.

Volcanics at the upper (BP-35) and middle (BP-36) exploitation levels of the quarry are rich in xenoliths: much altered Upper Cretaceous sandstone xenoliths prevail at the upper, while ultramafic rock xenoliths – at the middle exploitation levels. The ultramafic xenoliths consist mainly of olivine with kelyphitic rims and crowns made up of fine pyroxene crystals and calcic plagioclase relicts; secondary calcite is also present.

Based on mineral and chemical compositions of the rocks examined (Tab. 1, Figs 9–11), they should be classified as *basanite*. This is partly in agreement with some previous studies (see Krzyśków, 1986; Białowolska, 1993).

Sampling. Samples for K-Ar dating and for palaeomagnetic measurements were collected at two exploitation levels: BP-35 and palaeomagnetic samples WL 1 & 2 – at second level, in SE part of the quarry (Fig. 4A); BP-36 and palaeomagnetic samples WL 3 & 4 – at second level, middle part (Fig. 4B); BP-37 and palaeomagnetic samples WL 5 & 6 – at third level, middle part (Fig. 4C).

Trupień (BP-38)

Geology. This is a small basaltoid plug exploited in a new working quarry east of Wilków site (BP-35–37). The quarry exposes marginal part of the plug, at its contact with Upper Cretaceous sedimentary rocks (Fig. 5A, B).

Petrology and geochemistry. This rock was previously classified as basalt (Frąckiewicz, 1955), basanite (Białowolska, 1980; Kochanowska & Żygadło, 1984; Kozłowska-Koch, 1987), or basanite and basalt (Białowolska, 1993). The rock is black, very fine-grained, showing porphyric and, locally, fluidal structure. Its groundmass consists of very fine fresh plagioclase (labradorite An_{58-60}) showing distinct albitic and periclinic twins, dispersed in fresh glass with small amount of opaque minerals. Among relatively small phenocrysts (maximum 1.5 mm in size), euhedral olivine phenocrysts predominate; some are surrounded by kelyphitic rims. Single, rare pyroxene phenocrysts are mostly chloritized and partly replaced by pennine. The rock shows presence of small vesicles filled with fine pyroxene crystals, usually growing radially from outside inwards.

Our petrologic and geochemical studies (Tab. 1; Figs 9–11) confirm previous classifications: the studied rock (BP-38) represents a *basanite*. It is of similar type as that from the Wilków quarry (BP-25–37).

Sampling. Basanite samples (BP-38) for K-Ar dating, and samples TR 1 & 2 for palaeomagnetic measurements, were collected at lower exploitation level, in SW part of the quarry, as far as possible from basanite contact with sedimentary rocks (Fig. 5).

Wilcza Góra (BP-39)

Geology. This is a basanite plug well exposed in an abandoned quarry near Złotoryja (Site No 7 in Birkenmajer *et al.*, 1970). It cuts Permian, Triassic and Upper Cretaceous rocks (Fig. 7). Yellowish Upper Cretaceous (Turonian) sandstones occur also as large xenoliths within the plug (Figs 6–8).

Petrology and geochemistry. This rock was previously classified as plagioclase-nepheline basalt or nepheline basanite (Wojno *et al.*, 1951; Birkenmajer *et al.*, 1970), as basanite (Birkenmajer, 1967; Birkenmajer *et al.*, 1977; Grocholski & Jerzmański, 1975; Kozłowska-Koch, 1987), and melabasanite (Białowolska, 1980). The rock is black, very fine-grained, with clearly expressed porphyric structure. Its groundmass is composed of partly chloritized glass with very fine pyroxene and nepheline phenocrysts in equal proportions. The phenocrysts are 0.5–1.5 mm in size, with olivine predominating. They are euhedral or subhedral, usually fresh, however some of them show irregular network of microcracks filled with minerals of serpentine group and with calcite. Euhedral or subhedral nepheline phenocrysts are less common than olivine. Rare pyroxene (Ti-augite, z/γ = 37°) phenocrysts are usually partly chloritized. They commonly show internal zoning and hourglass structure (Fig. 12). Sometimes they contain anhedral inclusions of olivine that allows to establish crystallization succession of these two primary minerals (Fig. 13). Locally, small vesicles filled with very fine nepheline and olivine occur, both overgrown with anhedral grains of K-feldspar.

The rock is rich in xenoliths, particularly in central part of the quarry: some xenoliths are ultramafic rocks similar to those from the Wilków quarry (see BP-35, 36). The sand-

Table 1

Chemical composition of Tertiary basaltoid rocks from the North Sudetic Depression (Sites 34-39), Lower Silesia. Analyzed at the Chemistry Laboratory, Polish Geological Institute, Warsaw (Project No. 620.1719.00.0)

	BP-34	BP-35	BP-36	BP-37	BP-38	BP-39
			%			
SiO_2	40.09	43.66	43.20	42.67	42.79	40.66
TiO_2	2.60	2.44	2.63	2.65	2.51	2.64
Al_2O_3	12.73	14.22	14.40	14.28	13.76	13.31
Fe_2O_3	12.25	12.03	12.15	12.17	12.10	12.00
MnO	0.19	0.18	0.18	0.18	0.18	0.21
MgO	11.75	11.56	10.82	11.41	12.64	11.60
CaO	12.46	9.77	9.91	10.12	10.08	12.25
Na_2O	3.31	3.67	3.96	3.50	3.29	3.32
K_2O	0.90	1.12	1.35	1.29	1.16	1.01
P_2O_5	1.07	0.66	0.71	0.66	0.61	0.66
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cl	0.07	0.11	0.11	0.12	0.10	0.03
F	<0.01	0.05	0.05	0.05	<0.01	0.06
LOI	2.16	0.16	0.24	0.61	0.43	1.88
SUM	99.55	99.70	99.69	99.69	99.65	99.63
			ppm			
As	4	<3	<3	<3	3	4
Ba	595	453	391	613	469	579
Bi	<3	<3	<3	<3	<3	4
Ce	95	72	72	89	75	104
Co	44	51	37	62	58	43
Cr	304	343	242	356	402	364
Cu	74	52	53	53	81	64
Ga	17	19	20	21	19	19
Hf	6	5	6	5	5	10
La	58	32	35	55	41	54
Mo	2.5	2.0	<2.0	<2.0	<2.0	<2.0
Nb	87	63	74	67	65	102
Ni	279	259	220	228	347	205
Pb	<3	3	<3	<3	<3	<3
Rb	33	40	46	41	39	31
Sr	992	674	742	701	652	784
Ta	6	7	7	8	5	9
Th	9	9	12	8	9	11
U	2.9	4.2	4.8	3.8	4.4	4.7
V	187	180	161	228	205	215
W	<5	<5	6	<5	<5	6
Y	28	31	34	32	31	33
Zn	110	115	119	118	113	108
Zr	290	268	297	276	255	282
Ti/Y	556.7	472.8	463.7	496.5	485.4	479.5
Zr/Y	10.36	8.65	8.74	8.63	8.22	8.55
R1	912	959	785	926	1044	926
R2	2166	1898	1880	1929	1976	2147

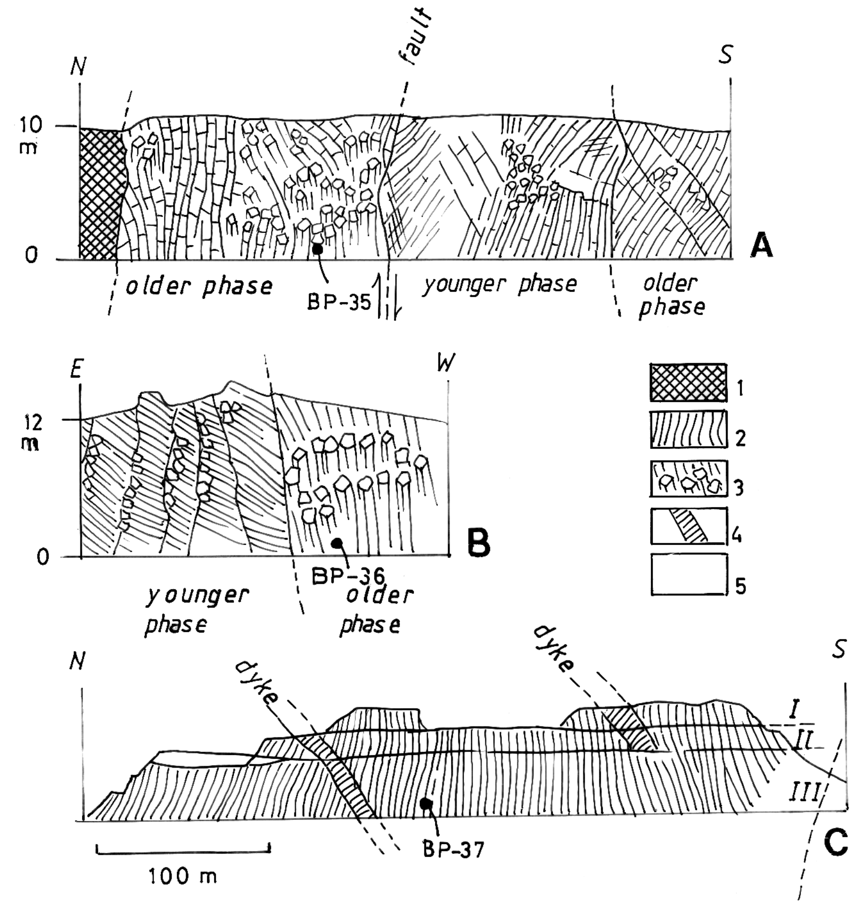


Fig. 4. Wilków, Sites BP-35–37 (working quarry), basanite, showing thermal jointing patterns (columns) and location of samples. A – middle exploitation level, II, SE part (BP-35); B – middle exploitation level, II (BP-36); C – general view of the quarry (I – upper; II – middle; III – lower exploitation levels); 1 – basanite breccia; 2, 3 – columnar basanite; 4 – basaltic breccia; 5 – Quaternary cover

stone (Upper Cretaceous) and siliceous schist xenoliths are strongly altered at contacts with igneous rock. Some xenoliths are traversed by thin carbonate ($CaCO_3$) veins, others are strongly Fe-enriched (Fig. 14).

Based on mineral and chemical composition of the studied sample (Tab. 1), and using the IUGS standard of systematics of igneous rocks (Figs 9, 10), our rock should be classified as *ankaratrite (olivine melanephelinite*).

Sampling. Samples BP-39 for K-Ar dating and samples WG 1 & 2 for palaeomagnetic measurements were collected from columnar ankaratrite at the lowest exploitation level (Figs 7, 8).

GEOCHEMICAL REMARKS

Geochemical classification, based upon contents and ratios of oxides and immobile trace elements, shows a clear clustering of plotted points representing the studied rocks (Figs 9, 10). Although it could be expected that the two ankaratrites (BP-34 and BP-39) be similar in their chemical composition, the ankaratrite from Sichów (BP-34) plots slightly away from that of Wilcza Góra (BP-39), the latter being very close to basanites from both Wilków (BP-35–37) and Trupień (BP-38).

A discrimination diagramme, based upon the ratios Zr/Y vs. Ti/Y (Fig. 11), clearly shows that all the rocks studied are typical within-plate basaltoids. The oldest rock (BP-34), which is a Late Oligocene ankaratrite (melabasanite), shows a relatively low potassium content (0.90% – Tab. 1; 0.786% – Tab. 2). It increases in Early Miocene rocks from 1.12% to 1.38% (Tab. 1), respectively to 1.003% and 1.141% (Tab. 2) in samples BP-35, 36 and 38, reaching up to 1.29% (Tab. 1), respectively 1.67% (Tab. 2) in the youngest basanite sample (BP-37). A similar evolutionary trend is also shown by cobalt content (Tab. 1): 44 ppm (BP-34), through 37–58 ppm (BP-35, 36, 38) to 62 ppm (BP-37).

K-Ar DATING

Six samples, all of them from volcanic plugs, were analysed by conventional K-Ar dating techniques. Analytical work has been carried out on whole-rock samples, the potassium and argon determinations were performed at the Institute of Nuclear Research, Hungarian Academy of Sciences (ATOMKI, Debrecen).

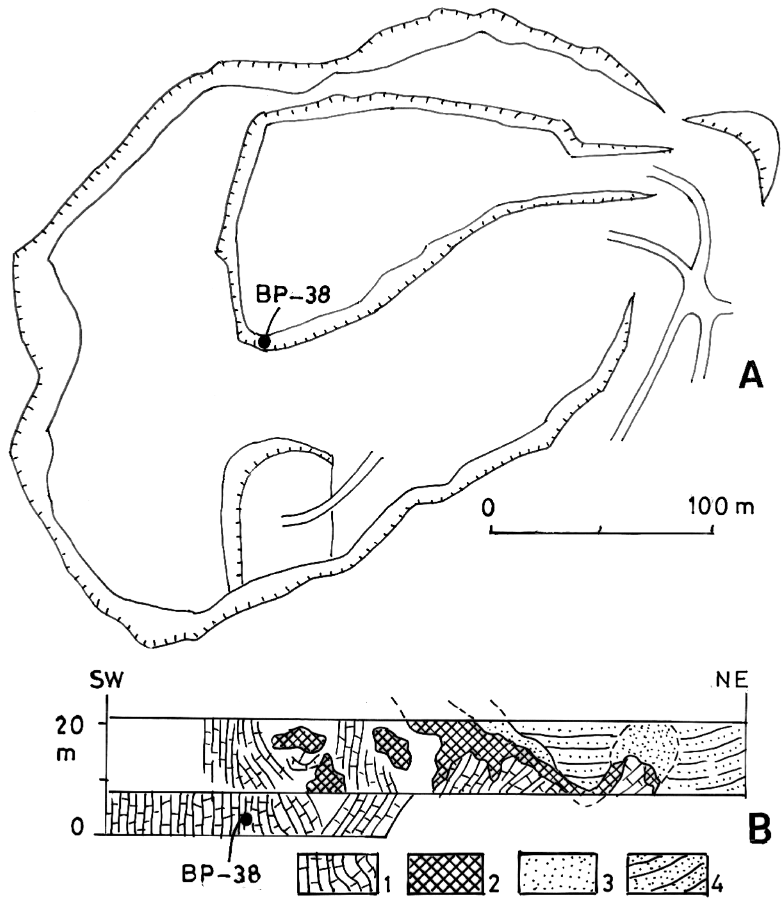


Fig. 5. Trupień, Site BP-38 (working quarry), basanite plug. **A.** plan of the quarry (after Zagożdżon, 2001) with location of sample BP-38. **B.** sketch of NW wall of the quarry; 1 – basanite plug; 2 – basanite/sediment breccia; 3 – yellowish-whitish sandstone; 4 – reddened sandstone (3, 4 – Upper Cretaceous)

The most suitable samples were crushed and sieved. A split of the crushed rock was selected and finely ground for potassium determination. The whole-rock samples, approximately 500 mg wt, were further used for Ar analysis. For details of the procedures – see Birkenmajer and Pécskay (2002), for calibration of the instruments and methods applied – see Balogh (1985).

Apparent ages were calculated using the decay constants as proposed by Steiger and Jäger (1977). All analytical errors represent one standard deviation (68% analytical confidence level). The results of K-Ar age determination of collected rock samples are given in Tab. 2. For stratigraphic evaluation of the results, the International Commission on Stratigraphy Geologic Time Scale 2004 (Gradstein *et al.*, 2004) – see Tab. 3 was used.

RESULTS OF K-Ar DATING

In K-Ar dating, the assumption that the non-radiogenic argon has atmospheric isotope composition allows calculation of amount of radiogenic ^{40}Ar by subtracting the non-radiogenic ^{40}Ar (obtained from multiplying ^{36}Ar by the atmospheric ^{40}Ar/^{36}Ar ratio = 295.5) from the total amount of ^{40}Ar. The fact that the majority of basaltic rocks investigated yielded geologically significant K-Ar ages, gives strong evidence that the non-radiogenic argon component in these samples has a ^{40}Ar/^{36}Ar ratio close to atmospheric value. In some cases, petrological investigations suggest a probability of some Ar loss by later reheating (i.e. apparent rejuvenation of sample's geological age). Since xenoliths frequently occur in the rocks studied, special care was taken during preparation of the samples to avoid them in sieved fractions.

(1) The oldest ankaratrite plug investigated (27.80± 1.27 Ma), sitting directly upon the Sudetic Marginal Fault at Sichów (BP-34), indicates the age of the fault as Late Oligocene. This is the most primitive rock (ankaratrite), with relatively low K-content (0.786%). Due to glassy groundmass of the rock, some Ar loss cannot be excluded. Therefore, the K-Ar age should be considered a minimum one.

(2) A break in volcanic activity between the Oligocene and the Miocene recognized in the Fore-Sudetic Block volcanics, amounting to about 3 Ma (see Birkenmajer *et al.*, 2004, fig. 18), seems to be further supported by our new data from the North-Sudetic Depression.

(3) Another ankaratrite plug (BP-39 at Wilcza Góra) is considerably younger, 20.07±0.90 Ma (Early Miocene). Glassy groundmass of the rock is slightly altered, however there are no indications of a significant rejuvenation. This ankaratrite could belong to a new volcanic phase resumed

Fig. 6. Wilcza Góra, Site BP-39 (abandoned quarry), ankaratrite plug. A large xenolith of Upper Cretaceous (Turonian) sandstone visible at lower exploitation level, middle part

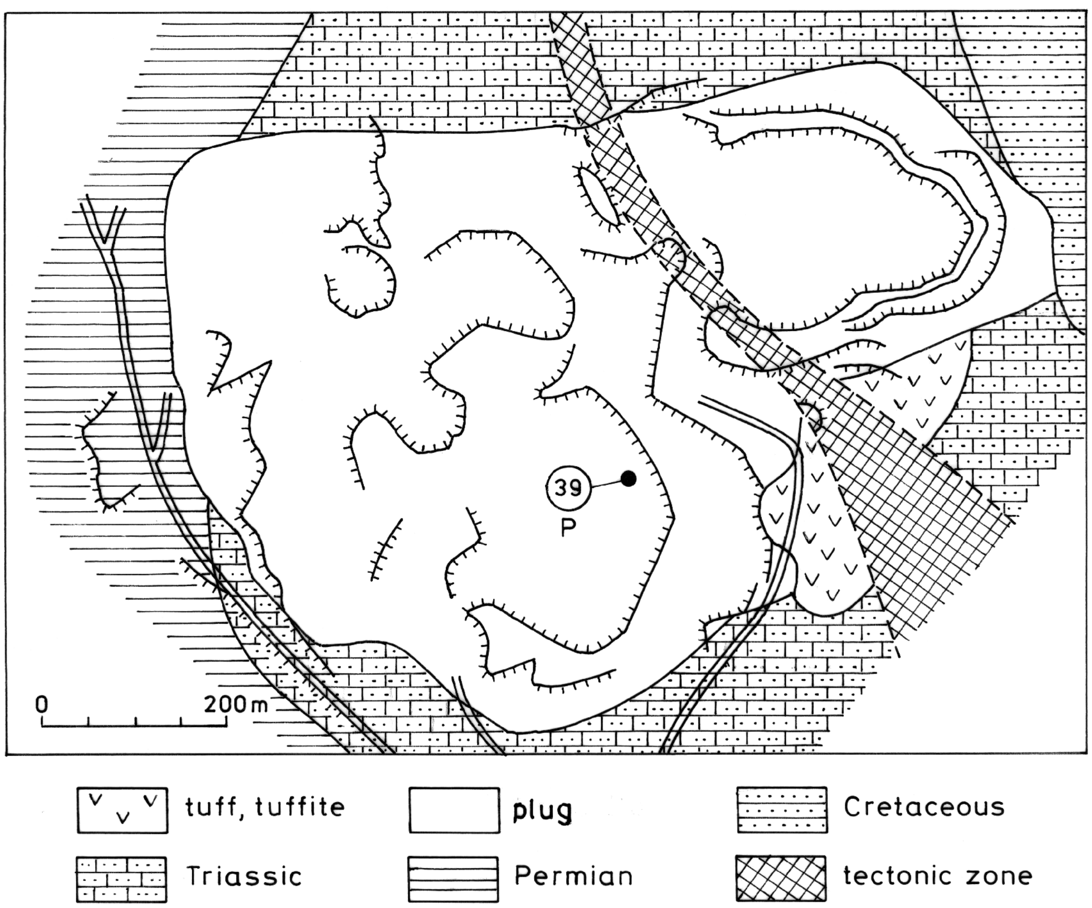


Fig. 7. Wilcza Góra, Site BP-39 (geological map of abandoned quarry after Zagożdżon, 2001), ankaratrite plug, showing location of samples (39 – for K-Ar dating; P – for palaeomagnetic measurements)

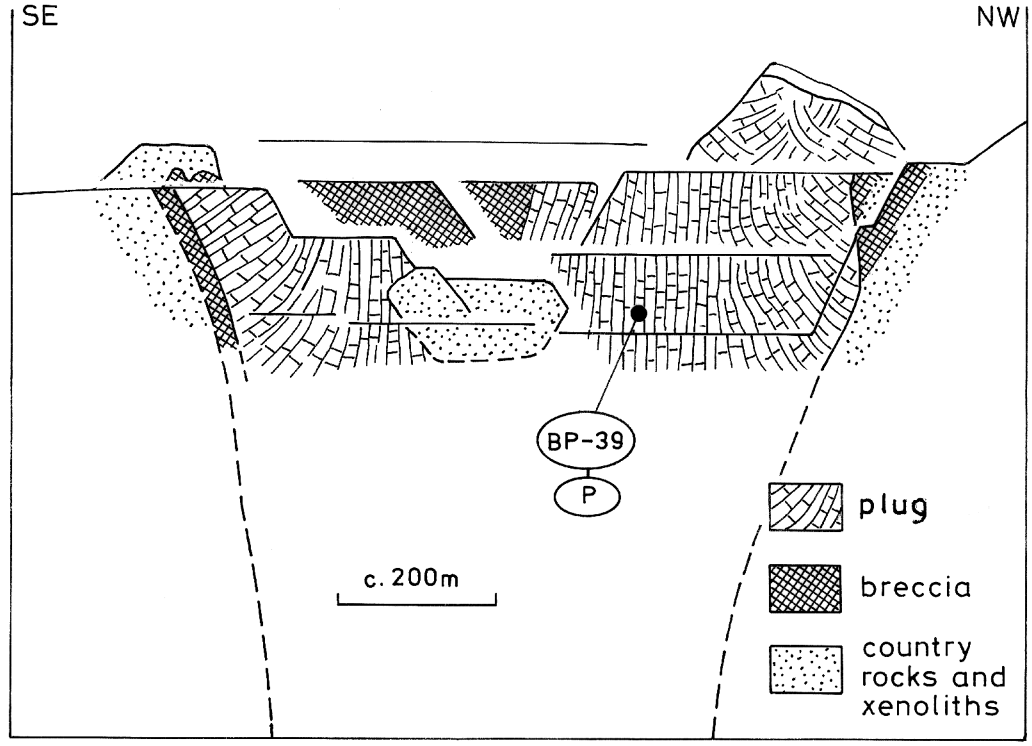


Fig. 8. Wilcza Góra, Site BP-39, schematic reconstruction of ankaratrite plug

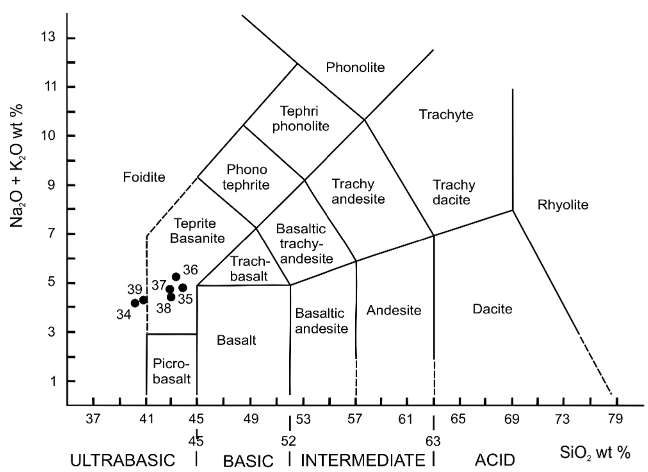


Fig. 9. Plot of Tertiary basaltoid rock samples from the North Sudetic Depression, TAS classification diagramme (Le Bas *et al.*, 1986). Numbers refer to sites (BP) investigated

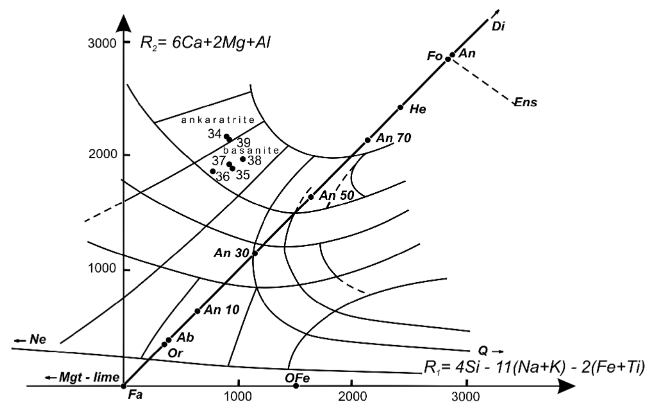


Fig. 10. Plot of Tertiary basaltoid rock samples from the North Sudetic Depression, R1-R2 classification diagramme (De la Roche *et al.*, 1986). Numbers refer to sites (BP) investigated

after the Oligocene/Miocene temporary break in vulcanicity (see above).

(4) Four K-Ar dates: 19.41±0.88 Ma (BP-35: basanite); 19.57±0.79 Ma (BP-36: basanite); 20.19±0.94 Ma (BP-38: basanite); and 20.07±0.90 Ma (BP-39: ankaratrite), represent a younger age set, attributable to an Early Miocene (Burdigalian–Aquitanian) volcanic phase as already recognized in the Fore-Sudetic Block by Birkenmajer *et al.* (2002b, 2004). In these rocks, K-content increases from 1.003 (BP-38) to 1.141% (BP-36).

(5)The youngest date, 18.72±0.81 Ma (BP-37), with K = 1.167% (basanite), refers to a sample taken from central part of the plug, from uniformly vertically stacked basanite columns: it may represent the latest Early Miocene (Aquitanian) volcanic event at the Wilków site.

PALAEOMAGNETISM

Palaeomagnetic studies of basaltic rocks from sites BP-34 (Sichów) and BP-39 (Wilcza Góra) were already performed several decades ago (Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1970; Kruczyk *et al.*, 1977). Taking into account that these results were presented only in

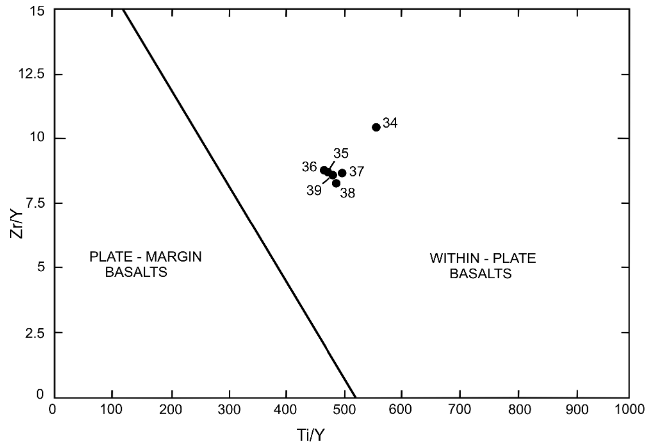


Fig. 11. Plot of Tertiary basaltoid rock samples from the North Sudetic Depression, Pearce and Gale (1977) classification diagramme. Numbers refer to sites (BP) investigated

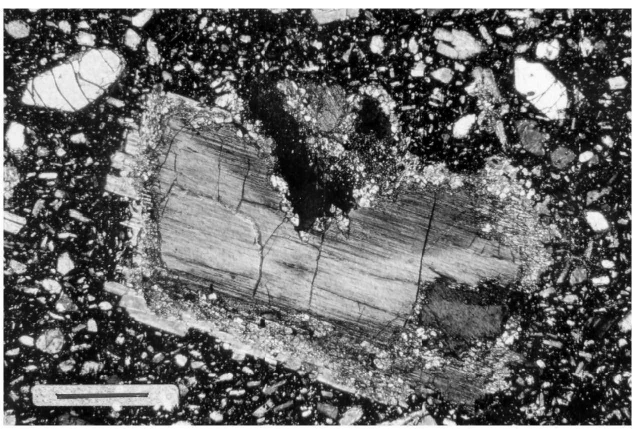


Fig. 12. Wilcza Góra (BP-39), ankaratrite plug: pyroxene phenocryst with hourglass structure, outer zone partly chloritized. Scale bar – 0.55 mm

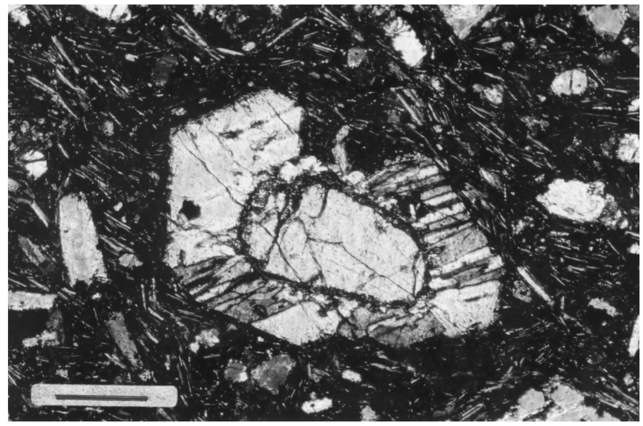


Fig. 13. Wilcza Góra (BP-39), ankaratrite plug: olivine inclusion in pyroxene phenocryst. Scale bar – 0.22 mm

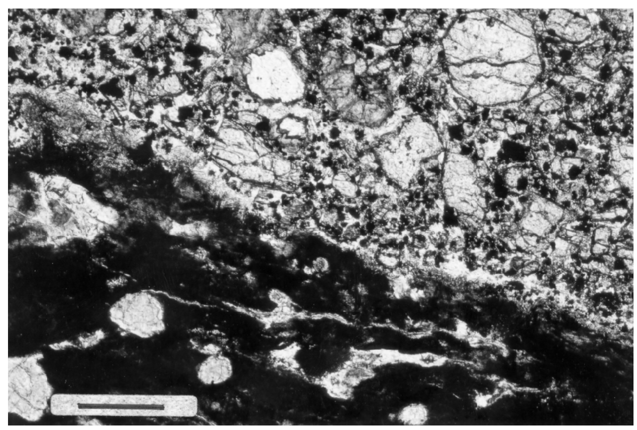


Fig. 14. Wilcza Góra (BP-39), ankaratrite plug: contact zone of ankaratrite with xenolith of thoroughly transformed sedimentary rock. Scale bar – 0.22 mm

text-tables, without details of demagnetization, we have decided to re-study these localities. New results from sites BP-35–38, which have not been palaeomagnetically studied so far, are presented in Tabs 4–7.

All palaeomagnetic experiments were carried out in the Palaeomagnetic Laboratory of the Polish Geological Institute, Warsaw (PGI Project No 6.20.1719.00.0), in the magnetically shielded space (low-field cage, Magnetic Measurements, UK) reducing the ambient geomagnetic field by about 95%. From each hand sample, 3–4 cylindrical specimens were obtained. Natural remanent magnetization (NRM) was measured using the JR-5 spinner magnetometer (AGICO, Czech Republic). Alternating field (AF) demagnetization was performed using Molspin device (max. demagnetizing field available 99 mT), and thermal demagnetization – using non-magnetic oven MMTD (Magnetic Measurements, UK). Characteristic remanent magnetization (ChRM) directions were calculated based on the principal component analysis (see Kirschvink, 1980), and using the PALMAG package (Lewandowski *et al.*, 1997). Most samples were treated with the AF. Thermal demagnetization was applied to pilot specimens, demagnetization paths were, however, more noisy than in the case of the AF treatment and, sometimes, it was not possible to isolate ChRM.

PALAEOMAGNETIC RESULTS

(1) The normal polarity of the ChRM was confirmed in Site BP-34 (Sichów) – see Tab. 4. After removing a weak low coercivity (probably viscous) component up to 10 mT, a second, high coercivity component (interpreted as primary) appeared with westerly declination and very steep downward inclination (Fig. 15A).

(2) Reversed polarity directions were revealed in the remaining sites (Figs 15B–F; see also Tabs 4–6). In samples from Sites BP-35 and BP-36, a low coercivity component was significantly stronger than high coercivity component (Fig. 15B). Palaeodeclinations of primary magnetization in Sites BP-35–38 are consistently plotting in SE quadrant of stereonet (Fig. 16). ChRM in Site BP-39 reveals abnormally steep inclination and anomalous declination quite similar to those from Sites BP-27 and 28 near Strzegom (see Birkenmajer *et al.*, 2004).

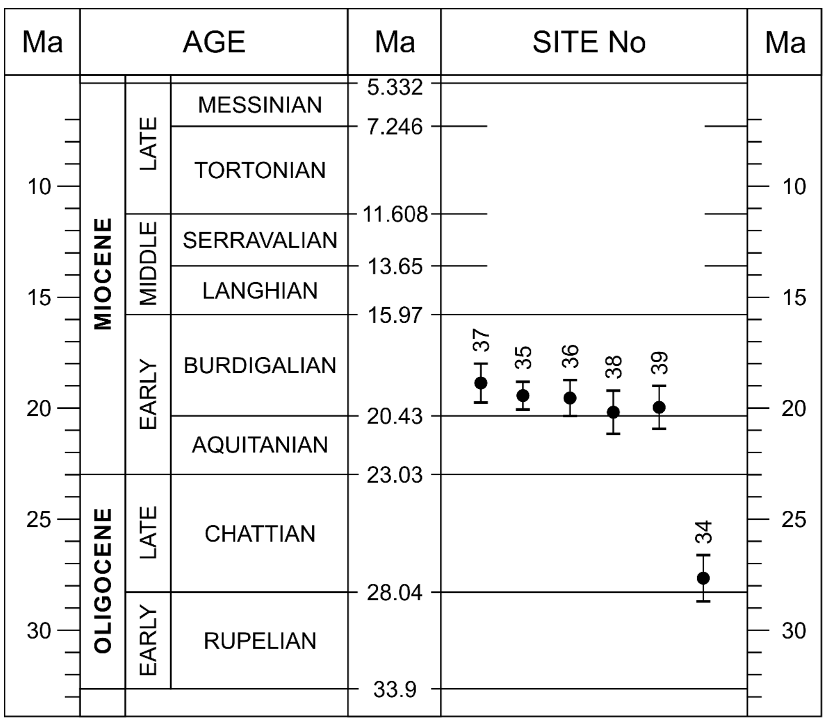
Table 2

Results of K-Ar dating of basaltoid rocks from the North Sudetic Depression, Lower Silesia (performed at the Institute of Nuclear Research, Hungarian Academy of Sciences, Debrecen, ATOMKI). Whole-rock fractions dated. Two main volcanic phases: I – Oligocene (ca 28 Ma); II – Early Miocene (20.1–18.7 Ma: ca 20.1 Ma; 19.5 Ma, 18.7 Ma?)

K-Ar No	Sample No	Site/geology	K %	^{40}Ar rad %	^{40}Ar rad ccSTP/g	K-Ar age Ma	Phase
5590	BP-34	Sichów, ankaratrite plug	0.786	40.7	8.561×10^{-7}	27.80 ± 1.27	I
5591	BP-35	Wilków, basanite plug	1.045	41.3	7.029×10^{-7}	19.41 ± 0.88	II
5592	BP-36	Wilków, basanite plug	1.141	57.6	8.728×10^{-7}	19.57 ± 0.79	
5593	BP-37	Wilków, basanite plug	1.167	47.0	8.535×10^{-7}	18.72 ± 0.81	
5594	BP-38	Trupień, basanite plug	1.003	39.1	7.920×10^{-7}	20.19 ± 0.94	
5595	BP-39	Wilcza Góra, ankaratrite plug	1.015	42.9	7.965×10^{-7}	20.07 ± 0.90	

Table 3

K-Ar ages (with analytical error bars) of basanite (BP-35 – BP-38) and ankaratrite (BP-34, 39) plugs of the North Sudetic Depression. Chronostratigraphic scale from Gradstein *et al.* (2004)



(3) New results obtained in this study were plotted against the geomagnetic polarity time scales and compared with previous radiometric datings, summarized in Birkenmajer *et al.* (2004). Sites BP-35 to 39 belong to the second phase of intrusions dated as Early Miocene (Fig. 17). Bulk of the second-phase basaltoid intrusions reveals reversed polarity of magnetization: they most probably intruded within a single polarity event. This concerns especially the intrusions BP-18 (Targowica), BP-25–27 (Gilów and Strzegom I and III), BP-30 and 32 (Jawor area – Birkenmajer *et al.*, 2004), and BP-35–39 (this paper). Their radiometric ages range between 19.41±0.88 Ma (BP-35) and 21.62±0.93 Ma (BP-30).

(4) The agreement between the age of basaltoid volcanics and polarity patterns is not perfect. Analytical error of K-Ar ages is significantly larger than the frequency of geomagnetic reversals during the Early Miocene. However, the mean age of the cluster (20.23±0.87 Ma) falls within the reversed magnetozone C6r (Fig. 17). This supports our estimates (Birkenmajer *et al.*, 2004) that Early Miocene volcanic activity in Lower Silesia might have taken place mostly within this magnetozone. It corresponds to the Jawor

Table 4

Palaeomagnetic results from Sichów (BP-34), ankaratrite plug

Sample	Dec/Inc	α_{95}	k	n_o/n
SI 1	241/65	15.8	34.5	4/4
SI 2	262/75	8.1	129.3	4/4

Dec – declination; Inc – inclination; α_{95}, k – Fisher statistics parameters; n_o – number of specimens demagnetized; n – number of specimens used for calculation of the site (sample) mean direction

Table 5

Palaeomagnetic results from Wilków (sites BP-35 to BP-37), basanite plug

Sample	Dec/Inc	α_{95}	k	n_o/n
WL 1	144/–53	24.2	10.8	5/5
WL 2	143/–52	–	–	1/1
BP-35 mean	143–53	–	–	2/2
WL 3	135/–42	–	–	2/2
WL 4	166/–52	12.2	102.8	3/4*
BP-36 mean	149/–48	–	–	2/2
WL 5	159/–47	2.6	233	3/3
WL 6	130/–29	19.8	39.3	3/4*
BP-37 mean	154/–39	–	–	2/2

* – thermal demagnetiztion rejected
For explanations – see Tab. 4

Table 6

Palaeomagnetic results from Trupień (BP-38), basanite plug

Sample	Dec/Inc	α_{95}	k	n_o/n
TR 1	magnetization not consistent			
TR 2	159/–65	25.8	23.5	3/4*

* – thermal demagnetiztion rejected
For other explanations – see Tab. 4

Table 7

Palaeomagnetic results from Wilcza Góra (BP-39), ankaratrite plug

Sample	Dec/Inc	α_{95}	k	n_o/n
WG 1	267/–80	9.2	99.5	4/4
WG 2	321/–69	12.7	95.5	3/4*

* – thermal demagnetiztion rejected
For explanations – see Tab. 4
Mean (this study): 304/–76, N = 2.
(after Birkenmajer & Nairn, 1969): 131.7/–85.9, α_{95} = 7.1, n_o/n = 6/6
(afret Kruczyk *et al.*, 1977): 229/–75, α_{95} = 5.6, k + 39.2, N = 18

event of Kruczyk *et al.* (1977) and Birkenmajer *et al.* (1977), but its age is ca 4.7 older than originally suggested.

(5) Site BP-34 represents the older, Late Oligocene phase of basaltoid volcanism. Its age is slightly older than the age of normally magnetized intrusions (BP-2, 6, 4 and 42) assigned to the Gracze event (Birkenmajer *et al.*, 2004; see Fig. 18). Originally, existence of a separate Sichów event was postulated (Kruczyk *et al.*, 1977) which apparently marked the onset of volcanic acivity in Lower Silesia (Birkenmajer *et al.*, 1977). However, in the light of new K-Ar datings, it seems that the Sichów plug is younger than most of the plugs assigned to the Odra event. Taking into account the analytical error, the Sichów plug might be contemporaneous with normally magnetized plugs of the Gracze event, the latter corresponding to magnetozone C8n (Birkenmajer *et al.* , 2004). However, it cannot be excluded that the Sichów plug emplacement occurred between the Gracze and Odra events, during magnetozone C9.

DISCUSSION AND CONCLUSIONS

(1) The K-Ar ages of six basaltoid samples taken from the North-Sudetic Depression range between 27.8 Ma (Sichów, BP-34) and 18.72 (Wilków, BP-37), Late Oligocene and Early Miocene, respectively. Within this interval, two successive volcanic events have been distinguished in the Fore-Sudetic Block: (I) The (Early)–Late Oligocene phase, and (II) The Early Miocene (Aquitanian–Burdigalian) one.

There is a much wider spread of K-Ar dates obtained from the Lower Silesian basaltoids by Badura *et al.* (2005). Three of their dates correspond to Early Miocene, nine dates are widely distributed between Early and Late Oligocene, two dates fall within Eocene, and the oldest one – within Paleocene epochs.

(2) The oldest K-Ar date obtained, 27.8±1.27 Ma (Sichów, BP-34), from a basanite plug located at the Sudetic Marginal Fault, suggests geological age of the fault as Late Oligocene (Chattian).

(3) All six investigated rock samples collected from four sites located in the North-Sudetic Depression are typical within-plate basaltoids. Geochemical difference between the Oligocene basaltoids and the Early Miocene ones, supports a multiphase volcanism concept of the Lower Silesian volcanic subprovince.

(4) The oldest rock investigated (ankaratrite, BP-34), 27.80±1.27 Ma old (Late Oligocene) is normally magnetized, the remaining five (ankaratrite, BP-39 and basanites, BP-35–38), from 20.07±0.90 Ma to 18.72±0.81 Ma old, are reversely magnetized.

(5) The basaltoid rocks of the North Sudetic Depression, represented by ankaratrite (olivine melanephelinite: Sichów BP-34 and Wilcza Góra BP-39) and basanite (Wilków BP-35–37 and Trupień BP-38) are within-plate basaltoids. They formed under the same geotectonic regime.

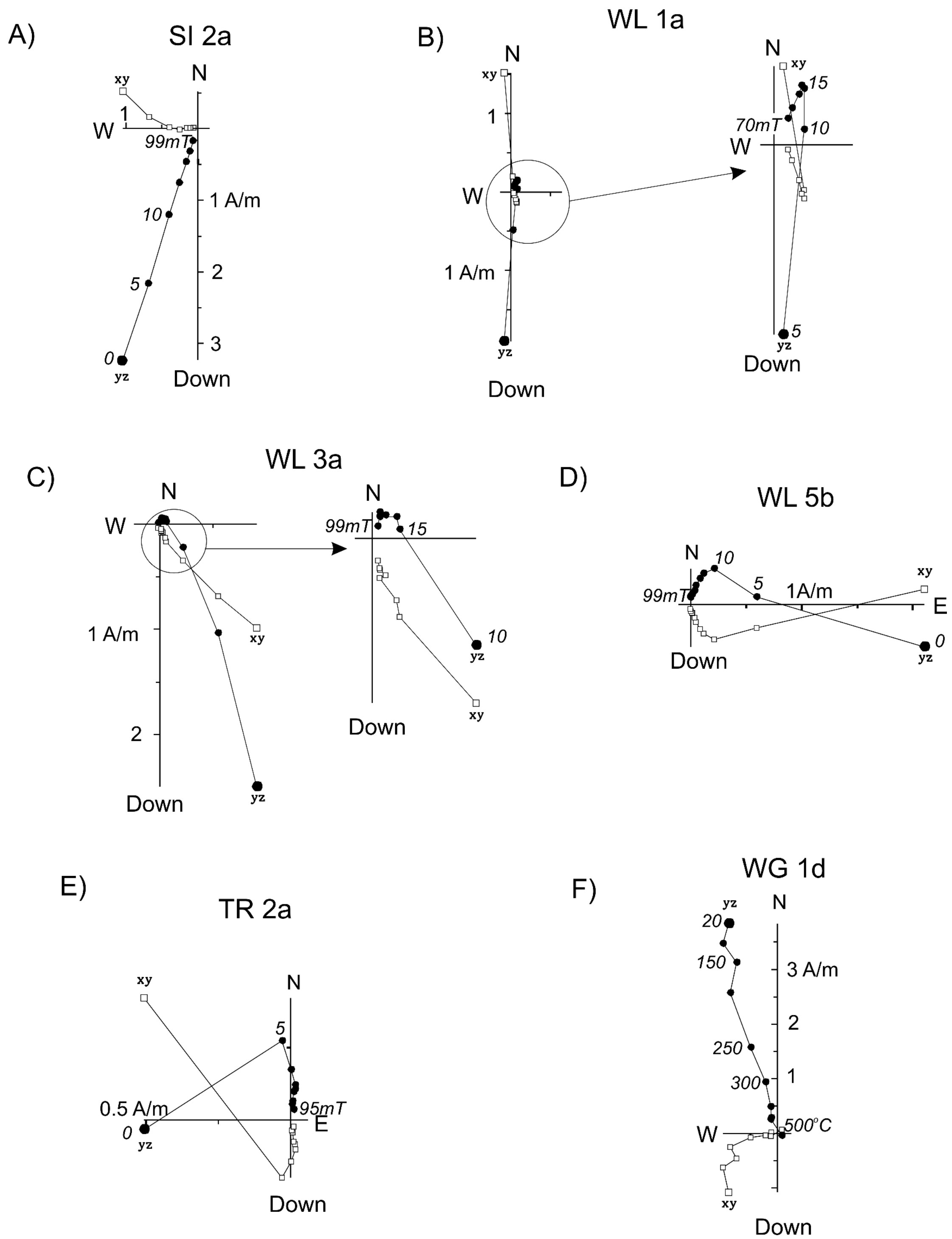


Fig. 15. Orthogonal projection of typical AF and thermal demagnetization paths: **A** – BP-34; **B** – BP-35; **C** – BP-36; **D** – BP-37; **E** – BP-38; **F** – BP-39. xy – horizontal; yz – vertical plane projection

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Dr. Anna Ladenberger, Jagiellonian University, Cracow, has kindly reviewed the manuscript and offered constructive editorial remarks.

The present paper is a further contribution to geochronological and geochemical-petrologic study of the Tertiary basaltoid rocks of Lower Silesia, Poland, carried out under agreement of bilateral co-operation between the Polish Academy of Sciences (Institute of Geological Sciences: Cracow Research Centre, and Department of Geology of the Sudetes) and the Hungarian Academy of Sciences (Institute of Nuclear Research, Debrecen). Palaeomagnetic studies and geochemical analyses were part of the project No. 6.20.1719.00.0 of the Polish Geological Institute, Warsaw.

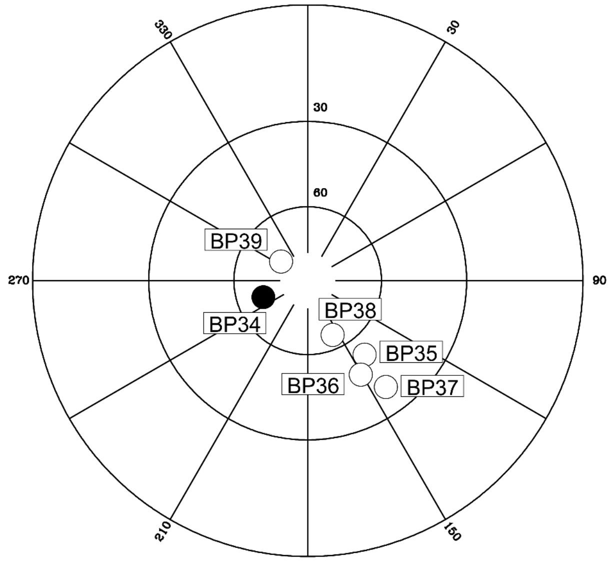

Fig. 16. Stereographic projection of the site-mean directions. Open circles – upper hemisphere projection; full circles – lower hemisphere projection

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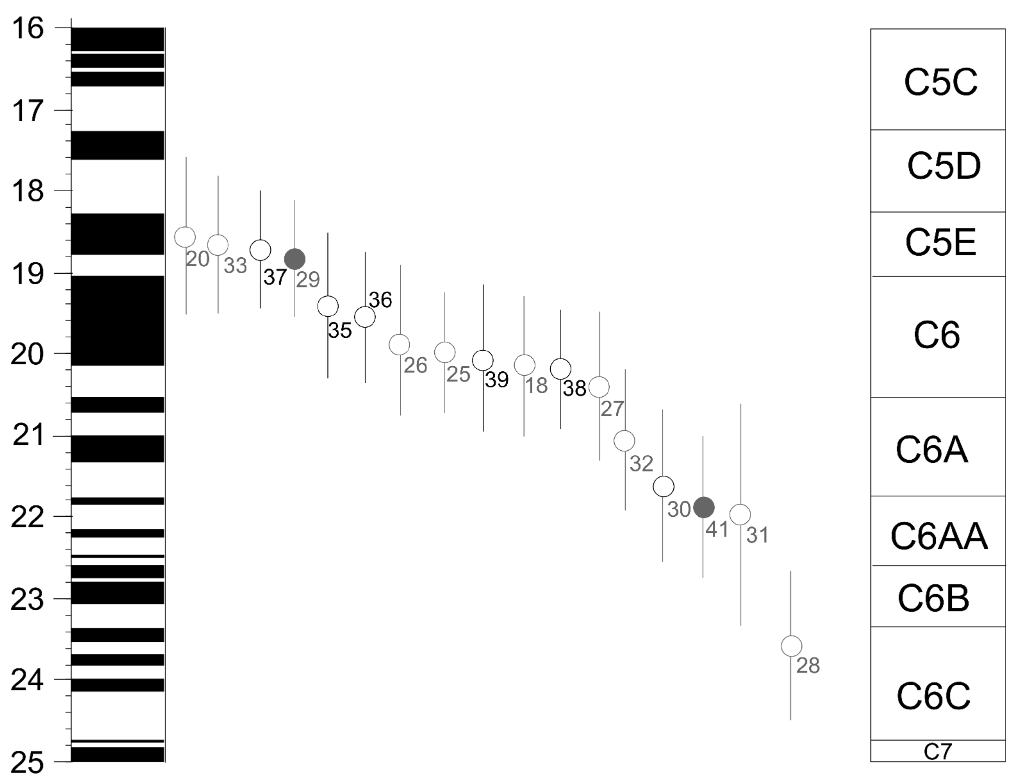

Fig. 17. Early Miocene basaltoids of the Fore-Sudetic Block and the North Sudetic Depression: K-Ar-dated samples (BP numbers) plotted against geomagnetic polarity scale of Cande and Kent (1995). Left side – radiometric scale in Ma, and polarity column; right side – magnetozones; full circles – normal polarity; open circles – reversed polarity. Black numbers – new sites investigated (this study); grey numbers – results from previous studies (see Birkenmajer & Pécskay, 2002; Birkenmajer *et al.*, 2002b, 2004)

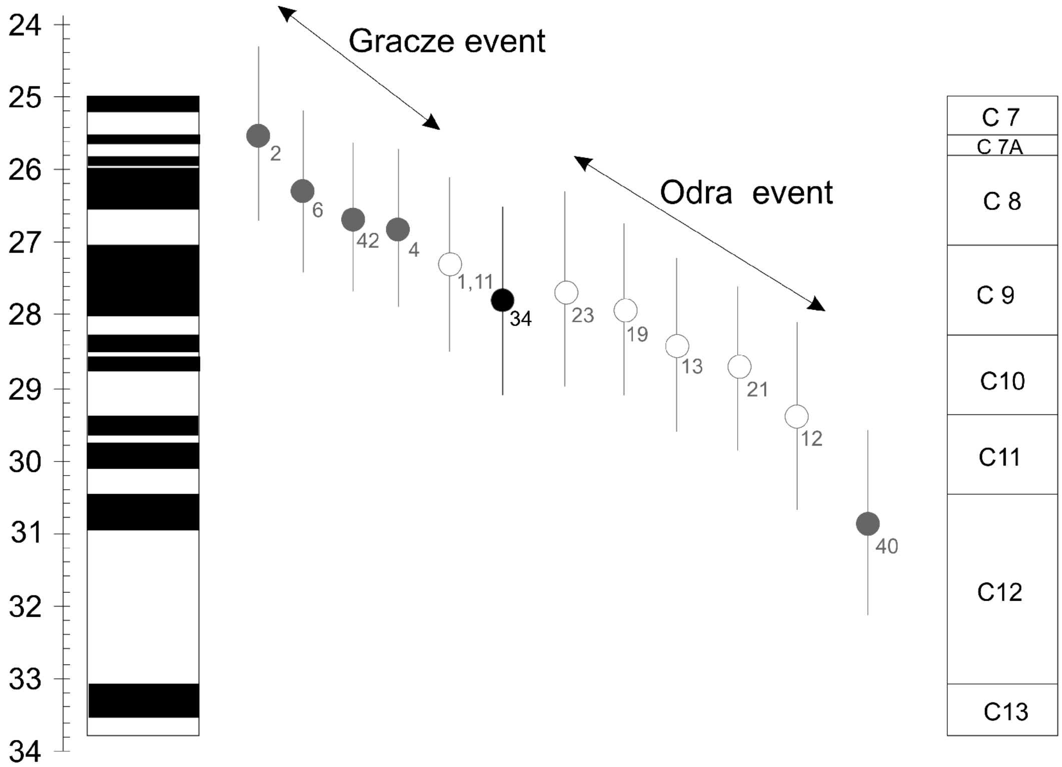

Fig. 18. Oligocene basaltoids of the Fore-Sudetic Block and the North Sudetic Depression: K-Ar-dated samples (BP numbers) plotted against geomagnetic scale of Cande and Kent (1995). Left side – radiometric scale in Ma, and polarity column; right side – magnetozones; full circles – normal polarity; open circles – reversed polarity. Black number – new site investigated (this study); grey numbers – results from previous studies (Birkenmajer & Pécskay, 2002; Birkenmajer *et al.*, 2002b , 2004)

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Streszczenie

DATOWANIE RADIOMETRYCZNE TRZECIORZĘDOWYCH WULKANITÓW DOLNEGO ŚLĄSKA. V. DATY K-Ar I WYNIKI BADAŃ PALEOMAGNETYCZNYCH PÓŹNOOLIGOCEŃSKICH I WCZESNOMIOCEŃSKICH SKAŁ BAZALTOWYCH NIECKI PÓŁNOCNOSUDECKIEJ

Krzysztof Birkenmajer, Zoltán Pécskay, Jacek Grabowski, Marek W. Lorenc & Paweł P. Zagożdżon

Piąta część datowań K-Ar i badań paleomagnetycznych trzeciorzędowych wulkanitów Dolnego Śląska obejmuje odsłonięcia tych skał w obszarze niecki północnosudeckiej, w sąsiedztwie sudeckiego uskoku brzeżnego. Otrzymano sześć dat w granicach 27,80±1,27 Ma (późny oligocen: Sichów, BP-34) – 18,72±0,81 Ma (niższy miocen = burdygał: Wilków, BP-37). Późnooligoceńska data dla ankaratrytowego czopu Sichowa (BP-34), który znajduje się na sudeckim uskoku brzeżnym, określa taki wiek tego uskoku. Zbadane skały bazaltowe – bazanity i ankaratryty (melabazanity) są typowymi przedstawicielami wulkanizmu śródpłytowego. Skład chemiczny ogniska magmowego podlegał ewolucji, co przejawiło się w badanych skałach wzrostem zawartości potasu i kobaltu w okresie czasu między wyższym oligocenem a niższym miocenem. Czopy ankaratrytu i bazanitu zostały zbadane pod względem paleomagnetycznym: najstarszy z nich, 27,80 Ma (BP-34: ankaratryt) wykazuje namagnesowanie normalne, pozostałe pięć, 20,07–18,72 Ma (BP-39: ankaratryt; BP-35–38 – bazanity) wykazuje namagnesowanie odwrócone.