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RADIOMETRIC DATING OF THE TERTIARY VOLCANICS IN LOWER SILESIA, POLAND. II. K-Ar AND PALAEOMAGNETIC DATA FROM NEOGENE BASANITES NEAR LĄDEK ZDRÓJ, SUDETES MTS

Krzysztof BIRKENMAJER[1], Zoltán PÉCSKAY[2], Jacek GRABOWSKI[3], Marek W. LORENC[4] & Paweł P. ZAGOŻDŻON[5]

[1] *Institute of Geological Sciences, Polish Academy of Sciences, Cracow Research Centre, Senacka 1, 31-002 Kraków, Poland; e-mail: ndbirken@cyf-kr.edu.pl*

[2] *Institute of Nuclear Research, Hungarian Academy of Sciences, Bem tér. 18c, 4001 Debrecen, Hungary; e-mail: pecskay@moon.atomki.hu*

[3] *Polish Geological Institute, Rakowiecka 4, 00-975 Warszawa, Poland; e-mail: jgra@pgi.waw.pl*

[4] *Institute of Geological Sciences, Polish Academy of Sciences, Sudetic Geology Department, Podwale 75, 50-449 Wrocław; e-mail: mwlorenc@twarda.pan.pl*

[5] *Faculty of Mining, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland e-mail: Pawel.Zagozdzon@ig.pwr.wroc.pl*

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Abstract: K-Ar dating of Cenozoic basaltic rocks (one plug and two lava flows) in the Lądek Zdrój area, Sudetes Mts, Poland (50.5°N, 17°E), has established their Neogene (Messinian–Zanclean) ages: from 5.46 to 3.83 Ma. They are the youngest manifestations of the Cenozoic vulcanicity in the Polish part of the Bohemo-Silesian Belt. According to new petrological and geochemical data, the studied rocks belong to basanites which display slightly differentiated mineral and chemical composition between the exposures. The basanites were magnetized most probably in one or more than one normal subchrons during middle part of the reversed Gilbert chron (between 4.18 and 5.23 Ma).

Key words: K-Ar dating, palaeomagnetism, basaltic rocks (basanites), Neogene (Messinian–Zanclean), Lower Silesia, Poland.

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INTRODUCTION

Basaltic rocks of Lower Silesia belong to the eastern part of the Central European Cenozoic volcanic province – the Bohemo-Silesian Belt (Fig. 1). It forms an arc about 350 km long, stretching from western margin of the Bohemian Massif (Czech Republic), across Lausitz (Germany) to Lower Silesia (Poland) and Moravia (Czech Republic).

In Lower Silesia, the basaltic plugs and lava flows occur both in the Sudetic Foreland (NE of the Sudetic Marginal Fault) and in the Sudetes Mountains (see, e.g., Smulikowski, 1957, 1960; Sawicki, 1966; Śliwa, 1967; Birkenmajer, 1967; Jerzmański & Maciejewski, 1968; Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1970; Oberc, 1972). There are about 200 basaltic occurrences (Wojno *et al.*, 1950), out of which less than one fifth belong to the same lava flows, and about 70–80 exposures are in working or abandoned quarries (Birkenmajer, 1967; Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1970).

Geological ages of the basaltic rocks in question have only locally been constrained by palaeontological dating of associated sediments. Direct radiometric dating of these volcanics is still uncommon: prior to 2000, only two He dates (Urry, 1936) and ten K-Ar dates (Kruczyk *et al.*, 1977; Birkenmajer *et al.*, 1977) were available.

The present paper is a result of bilateral cooperation initiated in 1998 between the Polish Academy of Sciences (Institute of Geological Sciences, Cracow Research Centre: *K. Birkenmajer*) and the Hungarian Academy of Sciences (Institute of Nuclear Research, Debrecen: *Z. Pécskay*), aiming

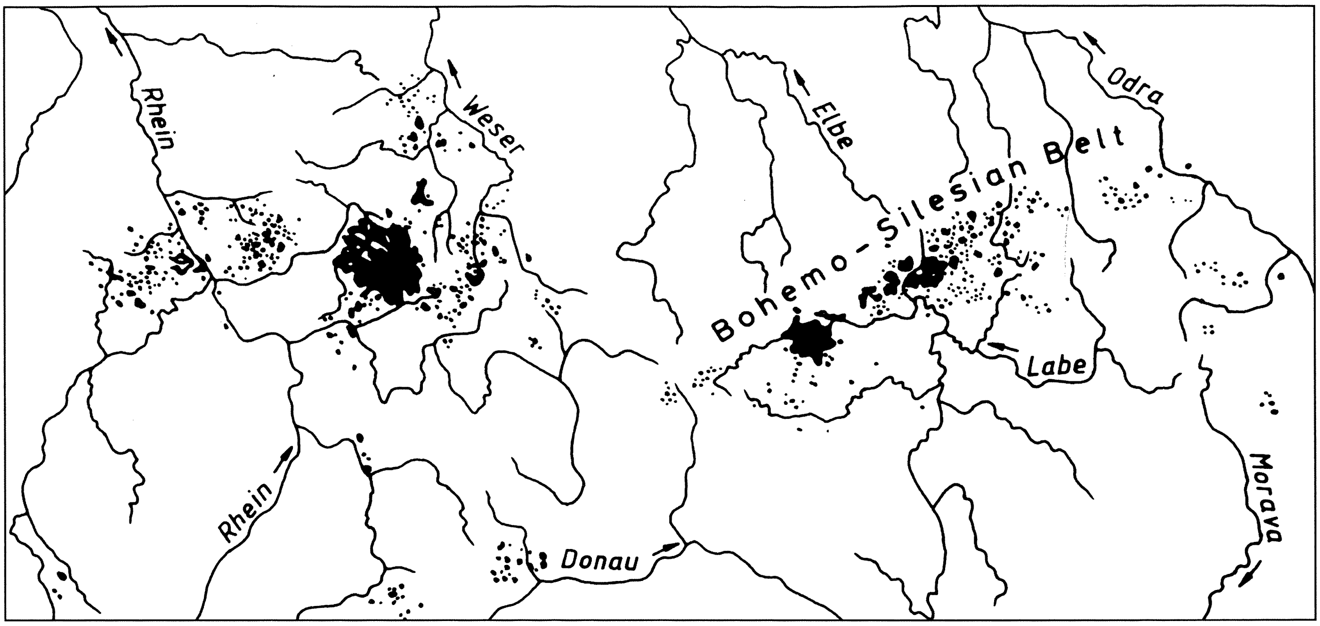


Fig. 1. Position of the Bohemo-Silesian Belt of basaltic volcanics (in black) in the Central European Tertiary volcanic province (simplified from Kopecký, 1966)

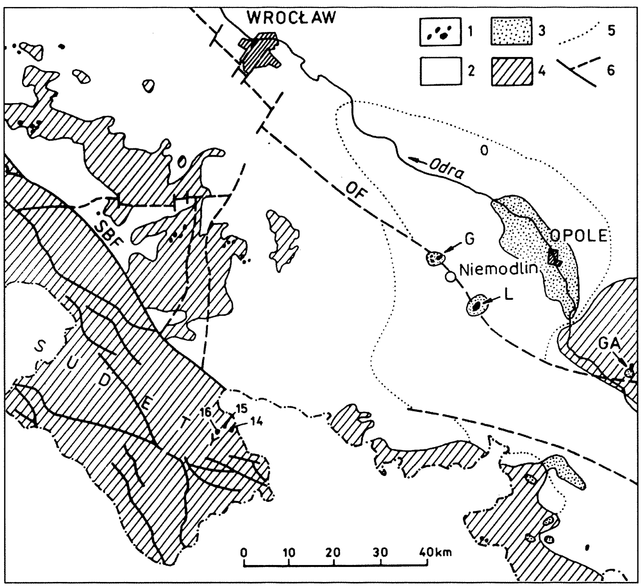


Fig. 2. Location of the K-Ar dated Pliocene basaltic sites (Nos 14–16) near Lądek Zdrój, Central Sudetes Mts (geological features simplified from Sawicki, 1966). 1 – Tertiary basaltic occurrences (K-Ar dated Late Oligocene basaltic volcanics: G – Gracze; GA – Góra Św. Anny; L – Ligota Tułowicka – see Birkenmajer & Pécskay, 2002); 2 – Neogene to Quaternary deposits; 3 – Upper Cretaceous deposits; 4 – pre-Neogene rocks (Sudetes Mts) and pre-Cretaceous rocks (Fore-Sudetic Block); 5 – continuation of Upper Cretaceous sedimentary rocks under Neogene to Quaternary cover; 6 – main faults proven (solid) and supposed (dashed); OF – Odra Fault; SBF – Sudetic Marginal Fault

at detailed K-Ar dating survey of Tertiary volcanics in Poland. Having completed the K-Ar dating of the Middle Miocene (Sarmatian/Serravallian) andesitic intrusions of the Pieniny Mts, West Carpathians (Birkenmajer & Pécskay, 1999, 2000), a new programme has been initiated in 2000 to include alkali basaltic rocks of the Opole region, Lower Silesia. Thirteen K-Ar dates (BP-1–13) from seven sites between Góra Św. Anny in the south-east, and Gracze in the north-west (see Fig. 2), have allowed to establish the age of these volcanics at 26.5 Ma that corresponds to the Late Oligocene (Birkenmajer & Pécskay, 2002).

In 2001, a further collection of basaltic samples for K-Ar dating and related petrographic studies has been made in Lower Silesia. It included the following sites: Lądek Zdrój (Kłodzko area, Sudetes Mts, sites BP-14–16); area of Strzelin–Niemcza–Strzegom (Sudetic Foreland, sites BP-17–29); area between Jawor and Złotoryja (Sudetic Marginal Fault area, sites BP-30–33; and North Sudetic Depression, sites 34–39); finally the area between Jawor and Legnica (Fore-Sudetic Block, sites 40–42). A parallel sampling programme for palaeomagnetic studies has also been carried out (by J. Grabowski and his wife, Polish Geological Institute, Warsaw, Project No 6.20.1719.00.0.). Chemical analyses of the samples collected were performed at the Chemical Laboratory of the Polish Geological Institute in Warsaw.

GEOLOGICAL SETTING

The Tertiary basaltic rocks in the vicinity of Lądek Zdrój, Central Sudetes Mts, belong in the eastern part of the Bohemo-Silesian Belt (Figs 1, 2). Only three exposures are available there for study, the best one being in a basanite plug well exposed in working quarry at Lutynia (Lutynia I); two much poorer exposures in abandoned quarries (Lutynia II and Lądek Zdrój) represent basanite lava flows.

Geological age of these volcanic rocks was formerly determined as Pliocene or Early Pleistocene, based on su-

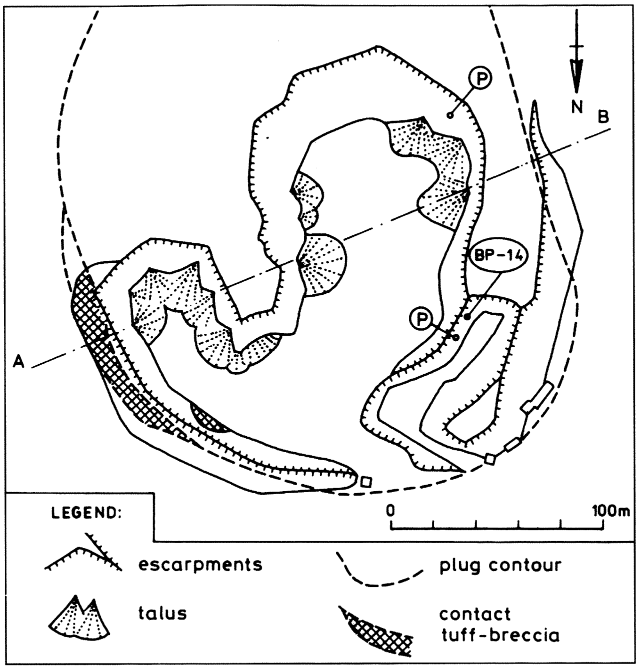


Fig. 3. Lutynia I (working quarry), basanite plug: location of K-Ar dated (BP-14) and palaeomagnetic (P) samples. A-B – geological cross-section (see Fig. 4). Data from Zagożdżon (2001) and the present study

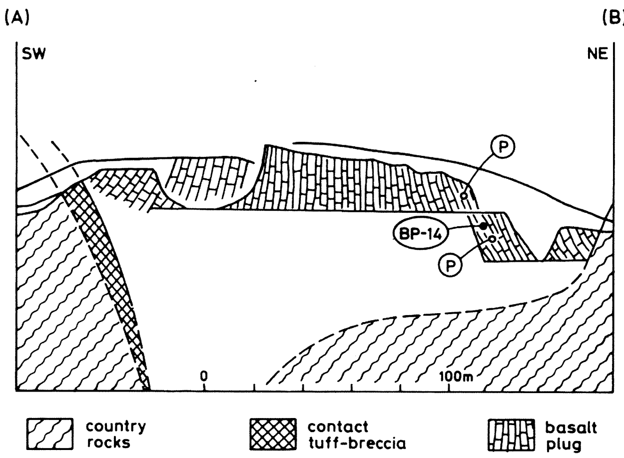


Fig. 4. Lutynia I (working quarry), basanite plug: location of K-Ar dated (BP-14) and palaeomagnetic (P) samples in schematic geological cross-section A-B (see Fig. 3). Data from Majkowska (1989) and the present study

perposition of the Lądek Zdrój basanite lava flow over the Biała Lądecka river terrace gravel (Berger, 1936; Walczak, 1957). Taking into account that the rocks are normally magnetized, their geomagnetic pole position being consistent with the present geomagnetic field, a stratigraphic correlation with the N_1 Brunhes chron (Quaternary: 0.69±0.05 Ma) has been proposed (Birkenmajer *et al.*, 1970).

SAMPLING DATA

Lutynia I (BP-14)

Geology. This is a volcanic plug well exposed in working quarry at Lutynia (Figs 3, 4), Szwedzkie Szańce hill (Festung in pre-World War II German maps), east of Lądek Zdrój (see Wojno *et al.*, 1950; Śliwa, 1967; Birkenmajer *et al.*, 1970: Site 27 Lutynia I). The quarry walls, 15 to over 30 m high, in the middle part of the plug expose vertical columns 0.5–1 m to 1–2 m in diameter which deviate fanwise near plug margins (Fig. 4). The country rocks are represented by the Lower Palaeozoic (?) mica schists (Śliwa, 1967; Gierwielaniec, 1971).

Petrography and geochemistry. This dark-grey rock was originally determined as pyroxene basalt with glass (Wojno *et al.*, 1951; Birkenmajer *et al.*, 1970), later as ankaratrite or basanite (Białowolska, 1980; Kozłowska-Koch, 1976, 1987). New petrologic investigations show that its very fine-grained groundmass consists mainly of augite, opaque minerals, nepheline and labradorite plagioclase (An_{58-60}). Brownish-green glass forms a part of the groundmass. Relatively common phenocrysts are represented by: (i) nepheline (1–3 mm in size) showing magmatic corrosion embayments; (ii) olivine (1 mm in size), sometimes with inclusions of fine-grained groundmass; and (iii) automorphic prisms of augite (<1 mm in size), sometimes twinned.

Taking into account that the olivine content exceeds 10%, and following the IUGS standard of igneous rocks (Le Bas & Streckeisen, 1991), the proper name of our rock is basanite, resp. basanite with glass (Tab. 1; Figs 5, 6). Based on the trace element classification proposed by Winchester and Floyd (1977), our rock plots at the triple point between the fields of basanite, alkali basalt and trachyandesite (Fig. 7). Contents and proportions of such indicative immobile elements as Nb, Y and Zr, show an alkaline within-plate characteristics of the studied rock (Figs 8, 9).

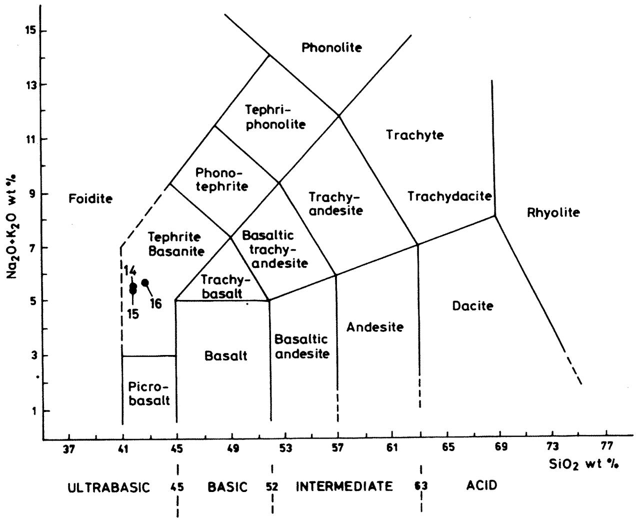


Fig. 5. Plot of basanite samples BP-14–16 in the TAS classification diagramme

Table 1

Chemical composition of basanites from the Lądek Zdrój area, sites BP-14–16 (analysed at the Chemistry Laboratory of the Polish Geological Institute, Warsaw)

	BP-14	BP-15	BP-16
%			
SiO_2	41.91	41.84	42.63
TiO_2	2.41	2.38	2.35
Al_2O_3	13.40	12.91	13.11
Fe_2O_3	12.38	12.35	12.27
MnO	0.20	0.21	0.21
MgO	11.11	11.22	1.58
CaO	10.28	10.76	10.12
Na_2O	3.95	3.85	4.42
K_2O	1.44	1.44	1.08
P_2O_5	0.95	1.02	0.97
SO_3	0.01	0.02	0.01
Cl	0.08	0.08	0.10
F	0.06	0.08	0.01
LOI	1.44	1.40	0.73
SUM	99.60	99.57	99.58
ppm			
As	4	5	4
Ba	362	321	356
Bi	3	3	3
Ce	102	108	106
Co	29	26	33
Cr	261	255	305
Cu	60	66	64
Ga	18	19	19
Hf	7	6	6
La	52	48	48
Mo	2	2	2
Nb	90	95	91
Ni	264	284	329
Pb	5	7	5
Rb	39	53	59
Sr	1049	1411	1070
Ta	6	8	10
Th	9	7	10
U	4.2	3.2	4.4
V	151	145	150
W	5	6	7
Y	31	34	32
Zn	125	127	125
Zr	384	416	391
Ti/Y	466.1	419.6	440.3
Zr/TiO2	0.016	0.017	0.017
Zr/Y	12.39	12.23	12.22
Nb/Y	2.90	2.79	2.84

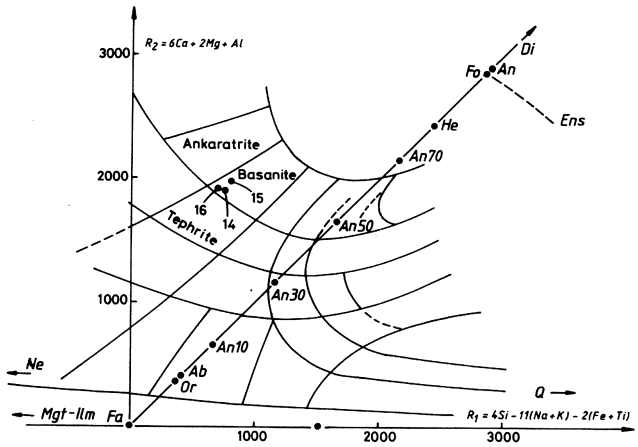


Fig. 6. Plot of basanite samples BP-14–16 in the R_1-R_2 classification diagramme (de la Roche *et al.*, 1980)

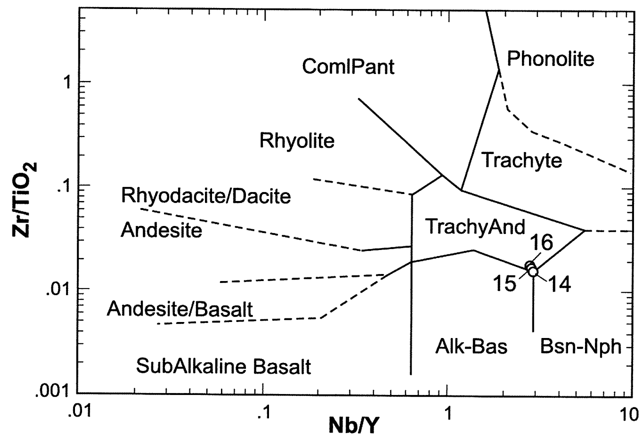


Fig. 7. Plot of basanite samples from sites BP-14–16 in the classification diagramme of Winchester and Floyd (1977)

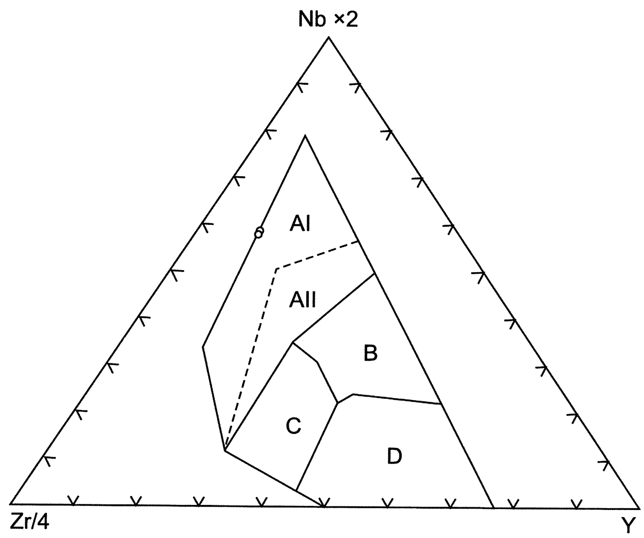


Fig. 8. Plot of basanite samples from sites BP-14–16 in the Zr-Nb-Y discrimination diagramme of Meschede (1986). AI – within-plate alkali basalts; AII – within-plate alkali basalts and within-plate tholeiites; B – E-type MORB; C – within-plate tholeiites and volcanic-arc basalts; D – N-MORB and volcanic-arc basalts

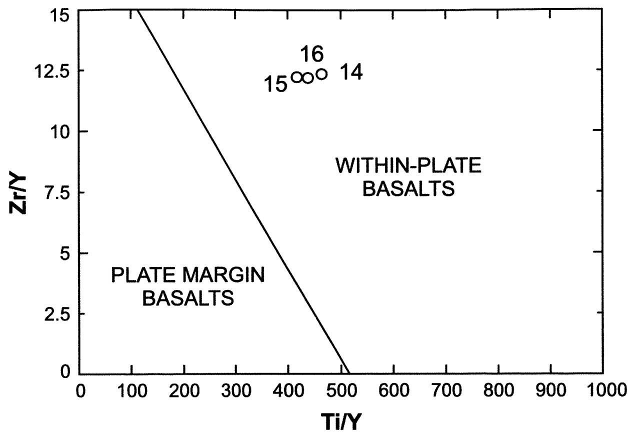


Fig. 9. Plot of basanite samples from sites BP-14–16 in classification diagramme of Pearce and Gale (1977)

The basanite contains numerous xenoliths of various shape, size and rock-type. The most common are fragments of country rocks, up to 15 cm in diameter, represented by granite, gneiss, quartzite and metamorphic schist. Xenoliths of deep origin consist of ultramafic rocks (see Kozłowska-Koch, 1976). Green olivine cumulates 0.5–5 cm in size are frequently met with.

Sampling. Samples BP-14 for K-Ar dating and for palaeomagnetic investigations, were collected in southern part of the quarry, slightly below its upper exploitation level (see Figs 3, 4).

Lutynia II (BP-15)

Geology. A poor exposure of grey basaltic-type rock is visible in woods in a small abandoned quarry at Czarne Urwisko hill (Überscharberg in pre World-War II German maps), nearby Lądek Zdrój (Wojno *et al.*, 1950; Birkenmajer *et al.*, 1970: Site 28 Lutynia II). Subvertical columns 0.5–1 m in diameter steeply tilted eastwards, may indicate that we deal here with a lava flow some 15–20 m thick.

Petrography and geochemistry. The rock was originally determined as basanite (pyroxene-nepheline basalt or nepheline basalt – see Wojno *et al.*, 1950; Birkenmajer *et al.*, 1970), later as ankaratrite or basanite (Białowolska, 1980; Kozłowska-Koch, 1976, 1987). In mineral composition, it is very similar to that from the Lutynia I quarry, the only difference consisting in coarser groundmass and in the presence of a larger amount of fresh olivine grains. The groundmass consists of needle-shaped augite and labradorite (An_{56-58}), irregular grains of nepheline, opaque minerals and greenish glass. The rock is slightly vesicular, some vesicles are filled with zeolites, the presence of which indicates interaction with water.

Based on mineral and chemical compositions, the studied rock (Tab. 1; Figs 5–9) should be classified as basanite (cf. Le Bas & Streckeisen, 1991). Xenoliths of country rocks in this basanite are rare, yellowish olivine cumulates are more frequent. Geochemical classification based upon ratios Zr/TiO_2 vs. Nb/Y (See Fig. 8) suggests that the sample from site BP-15 corresponds to trachyandesite. Similarly as the sample from site BP-14, this is also a within-plate basaltoid (see Fig. 9).

Sampling. Samples BP-15 for K-Ar dating and for palaeomagnetic measurements were collected in lower part of the abandoned quarry.

Lądek Zdrój (BP-16)

Geology. This is a lava flow poorly exposed in a large abandoned quarry, presently a shooting-sports centre (Grauer Stein in pre-World War II German maps; cf. Wojno *et al.*, 1951; Birkenmajer *et al.*, 1970: Site 26 Lądek Zdrój). Irregular curvilinear basaltic columns 0.5–1 m in diameter are still recognizable in northern part of the quarry near car-parking lot.

According to Berger (1932) and Walczak (1957), the basaltic lava flow is underlain by fluvial gravel of the Biała Lądecka river terrace. Thus, a Pliocene or even Pleistocene ages have been considered. Unfortunately, the contact of the lava with the gravel is not available for geological investigations any more.

Petrography and geochemistry. The rock was originally classified as plagioclase-nepheline basalt or nepheline basanite (Wojno *et al.*, 1951; Birkenmajer *et al.*, 1970), later as ankaratrite or basanite (Białowolska, 1980; Kozłowska-Koch, 1976, 1987). It is dark-grey, finer-grained than the basanites from the Lutynia I & II quarries, and shows the presence of *"Sonnenbrand"*, a phenomenon very common in many Lower Silesian basaltoids (Birkenmajer, 1967; Zagożdżon, 2001). The lava is vesicular, the vesicles are empty. The groundmass consists of brownish glass, very fine-grained augite, plagioclase, nepheline and opaque minerals. Among phenocrysts, olivine dominates over augite and nepheline (both are maximum 1 mm in size). A considerable alteration of the rock is manifested in secondary changes of some minerals: the appearance of epidote in plagioclase, chlorite and Fe-oxides in augite, and serpentine and Fe-oxides in olivine.

Our petrologic investigation confirm that presented by Kozłowska-Koch (1976), however there is no reason to use the name ankaratrite as suggested by her. Petrographically, the basaltic rock from Lądek Zdrój differs from those of Lutynia I and II in both mineral and chemical compositions (Tab. 1; Figs 5–9), in finer grain size, structure, and in the lack of xenoliths. However, following the IUGS standard of igneous rocks (Le Bas & Streckeisen, 1991), it should also be classified as basanite. The lava often contains yellow olivine cumulates 2–5 cm in size. According to geochemical classification proposed by Winchester and Floyd (1977), based upon immobile trace elements (see Fig. 7), the sample from site BP-16 corresponds to trachyandesite, being very close to the basanite-alkali basalt-trachyandesite triple point (see Fig. 7). This is also a within-plate basaltoid (see Figs 8, 9).

Sampling. Sample BP-16 for K-Ar dating was taken in the southern part of the quarry (near shooting-sport centre); samples for palaeomagnetic investigation – in northern part of the quarry (near car-parking lot).

K-Ar EXPERIMENTAL METHODS

While sampling for K-Ar dating, a piece of rock (about 2 kg wt) free of xenoliths was chipped off the basaltic exposure. As a whole, the samples collected were hard, fresh-looking, devoid of megascopically recognizable alteration changes.

The K-Ar dating was performed in the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen. The samples were crushed and sieved to 0.25–0.10 mm, depending on mineralogical and petrological character of the rock. A part of each sample was pulverized for potassium content determination using flame-photometric method. For argon isotope analysis, 0.25–0.10 mm grain fraction has been used. The K-Ar dating was carried out on whole-rock samples. Conventional experimental techniques were used for the Ar and K analysis. Details of the procedures are those described in Birkenmajer and Pécskay (2002). The results of calibration of the instruments, and of the methods applied have been described elsewhere (Balogh, 1985).

The K-Ar 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) – Tab. 2. For stratigraphic classification, the Geological Society of America 1999 Geologic Time Scale (Palmer & Geissman, 1999) has been used (see Tab. 3).

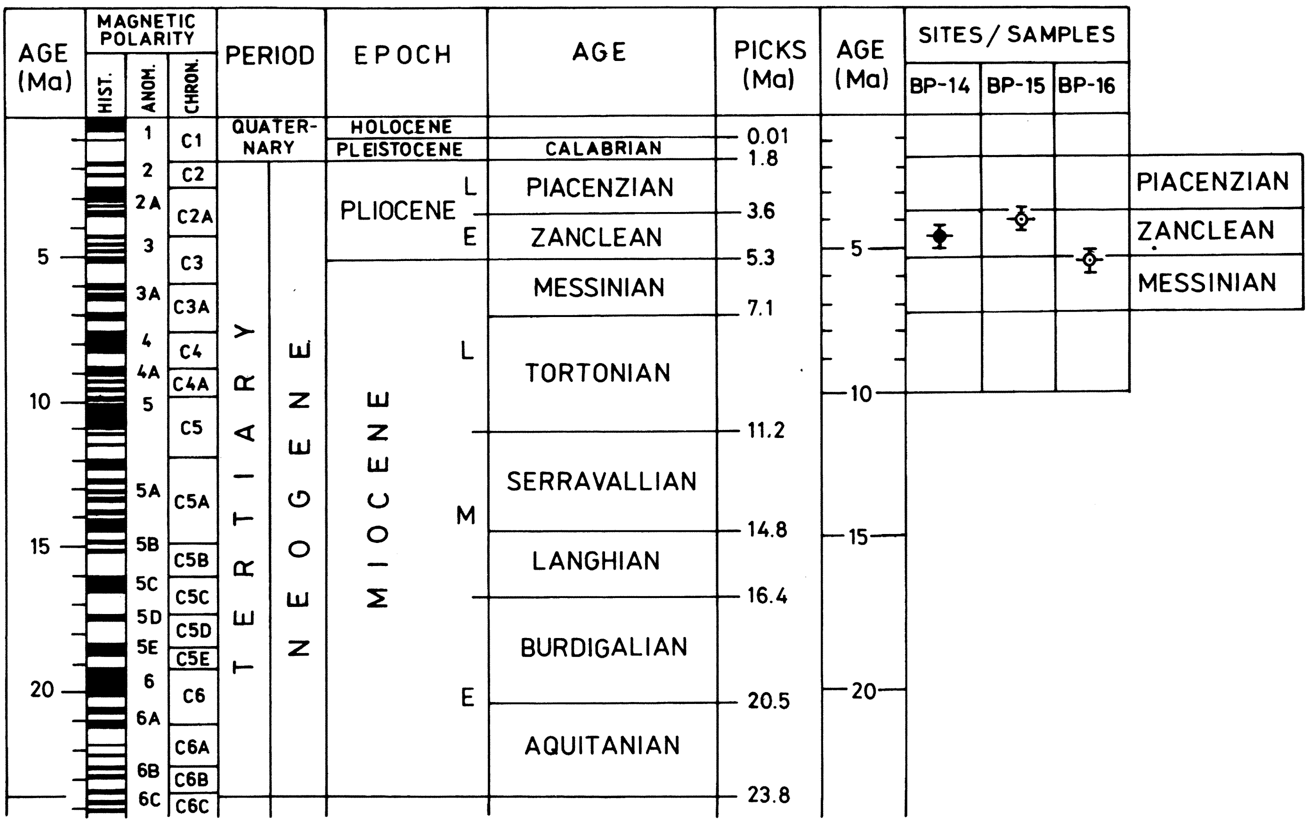
Table 2

Results of K-Ar dating of basanites from the Lądek Zdrój area (sites BP-14–16)

K-Ar No	Sample No	Site	Geology	Dated fraction	K %	^{40}Ar rad cc STP/g	^{40}Ar rad %	K-Ar age Ma
5570	BP-14	Lutynia I	basanite plug	w.r.	1.290	2.293×10^{-7}	43.0	4.56 ± 0.20
5571	BP-15	Lutynia II	basanite lava flow	w.r.	1.255	1.872×10^{-7}	44.2	3.83 ± 0.17
5572	BP-16	Lądek Zdrój	basanite lava flow	w.r.	0.799	1.658×10^{-7}	48.1	5.46 ± 0.23

Table 3

Results of K-Ar dating (with analytical error bars) of basanites (PB-14–16) from the Lądek Zdrój area versus chronostratigraphic and magnetostratigraphic scales (cf. Palmer & Geissman, 1999). Open circles – lava flows; solid circle – plug



PALAEOMAGNETIC METHODS

A palaeomagnetic study performed more than three decades ago (Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1970), has indicated that the rocks are normally magnetized (Tab. 4). The palaeomagnetic procedure then applied included natural remanent magnetization (NRM) measurement by astatic magnetometer, alternating field (AF) demagnetization up to 34 mT (occasionally up to 70 mT), and calculation of site mean direction of magnetization using minimum scatter criterion (Birkenmajer & Nairn, 1969). We decided to re-study the localities applying more updated palaeomagnetic technique.

Cylindrical samples 1" in diameter were drilled using gasoline-powered portable rock drill. Subsequently, the samples were cut into standard specimens, 2.1 cm long. All palaeomagnetic experiments were carried out in the Palaeomagnetic Laboratory of the Polish Geological Institute in Warsaw, in the magnetically shielded space (low-field cage, Magnetic Measurements, UK), reducing the ambient geomagnetic field by about 95%. NRM was measured by JR-5 spinner magnetometer (AGICO, Czech Republic). Thermal demagnetization was performed using non-magnetic oven MMTD (Magnetic Measurement, UK), and AF demagnetization – using Molspin device (max. demagnetizing field available 99 mT). Characteristic remanence magnetization (ChRM) directions were calculated basing on the principal component analysis (see Kirschvink, 1980), and using the PALMAG package of Lewandowski *et al.* (1997).

RESULTS AND DISCUSSION

General remarks

The main aim of the present geochronological study was to establish geological ages of Tertiary basaltic rocks and of phases of vulcanicity in eastern part of the Cenozoic volcanic belt which stretches in West-Central Europe from the Eifel in the west to Lower Silesia in the east (see Birkenmajer & Pécskay, 2002). A complex picture of space and time distribution of this volcanism appears from a study by Lippolt (1982). According to him, around the Oligocene/Miocene boundary, eruptive centres dotted the whole volcanic belt from the Eifel to Lower Silesia. In this belt, volcanic activity had been continuous until about 2.5 Ma (Late Pliocene), then, after a break, it was renewed during the Quaternary (Šibrava & Havliček, 1980; Lippolt *et al.*, 1990; Pécskay *et al.* – unpublished results).

According to the already available K-Ar dating constrained by other geological data, two main Cenozoic volcanic phases can be distinguished in Lower Silesia (Birkenmajer & Nairn, 1969; Birkenmajer *et al.*, 1977; Kruczyk *et al.*, 1977; Birkenmajer & Pécskay, 2002):

(i) An older phase, of Late Oligocene–Miocene age, which reached peak during Early Miocene;

(ii) A younger phase, of post-Late Miocene age.

Comparing the K-Ar dates, 5.46 to 3.83 Ma, of basanites from the Lądek Zdrój area (this paper) with those of northern Bohemia, 3.7–0.81 Ma (Z. Pécskay, unpublished results), we can observe an age shift of this volcanism from north to south. A similar trend has also been recognized in Tertiary basaltic rocks of the Balaton Highland, Nograd–Novohrád area, of the Inner Carpathians (see Balogh *et al.*, 1986; Konečný *et al.*, 1995).

K-Ar dating of basanites from the Lądek Zdrój area

The K-Ar dating results of basanites from the Lądek Zdrój area indicate that we deal here with some episodes of volcanic activity between 5.46 Ma and 3.83 Ma (see Tab. 2), which correspond to the latest Miocene (Messinian) through the Early Pliocene (Zanclean) time span (see Tab. 3). This is the youngest volcanic activity so-far recognized in the Polish part of the Bohemo-Silesian Belt. Differences in K-Ar age of the three basanite sites apparently suggest the succession of volcanic events as follows (see Tab. 3):

(i) Basanite lava flow (BP-16): 5.46 Ma (Messinian/Zanclean);

(ii) Basanite plug (BP-14): 4.56 Ma (Zanclean);

(iii) Basanite lava flow (BP-15): 3.83 Ma (Zanclean). However, if analytical error bars are taken into account, the oldest basanite lava (BP-16) might also fit the Zanclean time span. Differences in K-Ar dates of the basanite lava flows (sites BP-15 and BP-16), and of the basanite plug (site BP-14), seem to indicate that the lavas were not directly related to the Lutynia I volcanic vent. A marked difference in potassium content of the basanite lava flows, 1.255 vs. 0.779 per cent (see Tab. 2), respectively, might also suggest that they belong to two independent volcanic phases.

Palaeomagnetic results

The NRM intensities were of the magnitude of several A/m. Pilot specimens were demagnetized thermally and with AF. Pilot specimens from sites BP-14 and BP-16 were fully demagnetized up to 99 mT (Fig. 10A, D), therefore this method has been chosen for demagnetization of the remaining part of the collection.

The NRM of samples from sites BP-14 and BP-16 reveal mostly univectorial nature: the ChRM is well defined between 5 and 99 mT demagnetization steps. It clusters very well with inclinations of over 60°, and declinations slightly deviating to the NW from the present-day north (Fig. 11A, C). Thermal demagnetization of the basanite samples gave essentially the same results, however demagnetization path was not very smooth and the results were of poorer quality.

Slightly different magnetic properties were revealed by basanite specimens from site BP-15. The AF method was there not fully efficient: up to 20% of the NRM still survived after 99 mT demagnetization (see Fig. 10B). The bulk of collection from this site was thermally demagnetized up to 550°C (Fig. 10C). Both methods applied revealed two components of the magnetization: the first component shows low stability (unblocking values 5 mT and 250°C), its directions being considerably scattered; the second component clusters very well and is quite similar to that from site BP-14 (Fig. 11B).

Relatively low coercivity and unblocking temperatures below 550°C point to a mineral of titanomagnetite group as

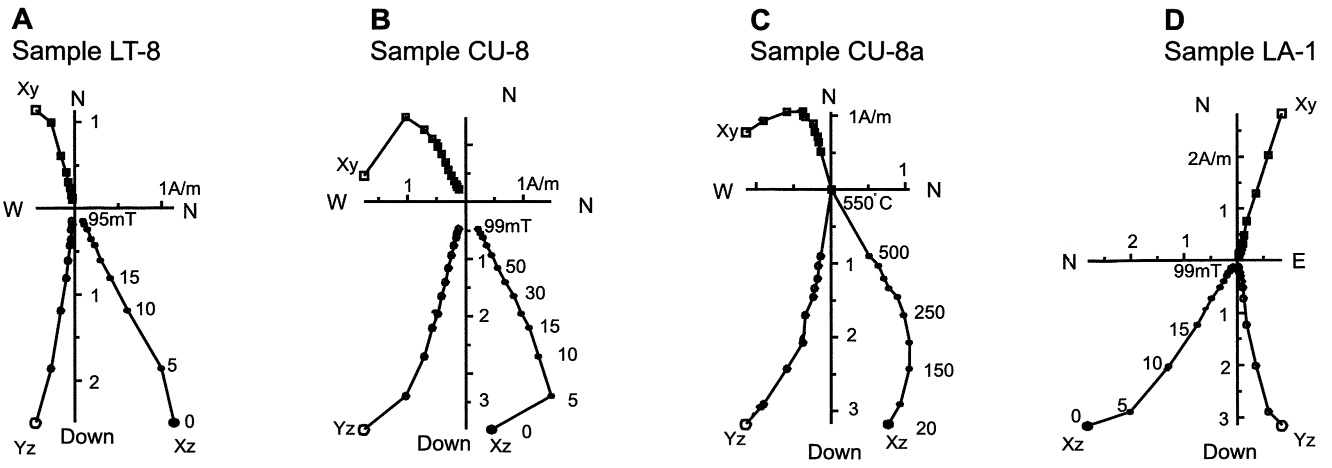


Fig. 10. Orthogonal demagnetization plots of typical basanite specimens from the Lądek Zdrój area. A – site BP-14, AF demagnetization; B – site BP-15, AF demagnetization; C – site BP-15, thermal demagnetization; D – site BP-16, AF demagnetization

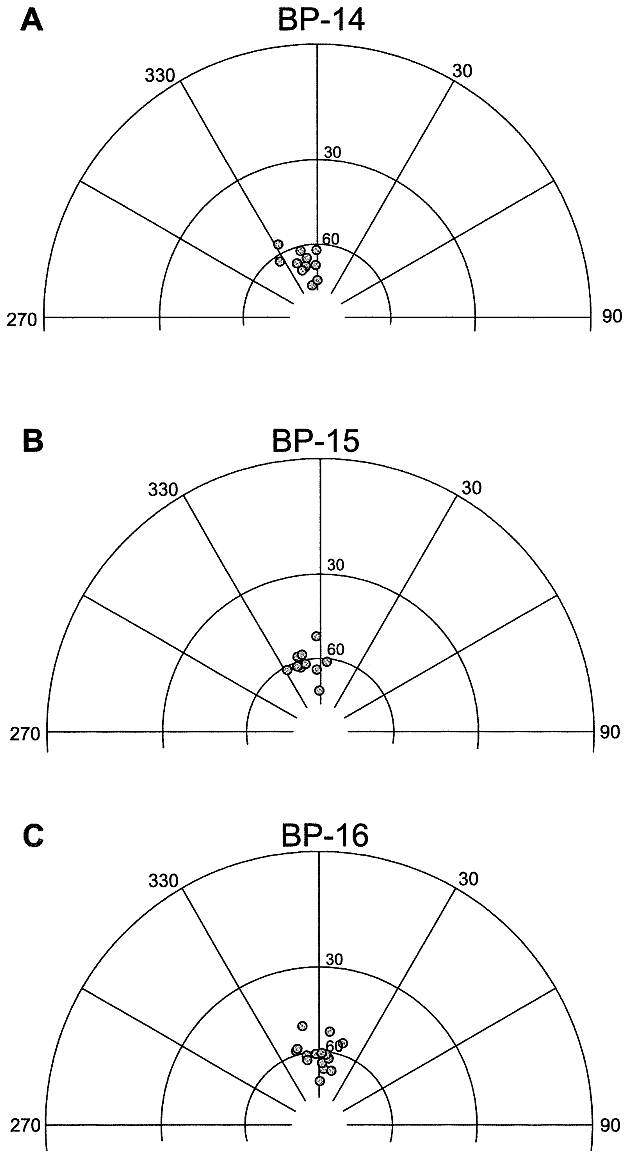


Fig. 11. Stereographic projections of characterstic demagnetizations from basanites of the Lądek Zdrój area (lower hemisphere projection)

the main magnetic carrier. Unblocking temperatures only slightly lower than Curie point of magnetite (585°C) indicate a low Ti content in the magnetite. Most probably, primary titanomagnetite has been exsolved into ilmenite and magnetite lamellae due to high-temperature oxidation (cf. Haggerty, 1976). This suggestion should, however, be verified by an opaque-mineral study which has not been carried out in our project. A slightly greater stability of the specimens from site BP-15 against AF demagnetization might be explained either by a higher degree of oxidation or by finer grain size of magnetic fraction.

Palaeomagnetism vs. K-Ar age

The present study shows that the basanites of all three studied sites were magnetized in the normal regime of geomagnetic field, thus confirming earlier palaeomagnetic results (see Birkenmajer & Nairn, 1969). The mean directions obtained now show, however, that they are slightly, albeit systematically, rotated to the NW in comparison with the previous results (Tab. 4).

Table 4

Palaeomagnetic data from basanites of the Lądek Zdrój area (this paper);
asterisked – after Birkenmajer & Nairn (1969) and Birkenmajer *et al.* (1970). Mean: Dec/Inc 351/63; $\alpha = 7.0$; k = 307; N = 3. Palaeopole: Lat. 82°N, Long. 248°E

Site	Dec/Inc	α_{95}	k	n_o/n
BP-14 (27 = Lutynia I)*	345/67 (353/65)*	3.7 (4.0)*	141	12/12
BP-15 (28 = Lutynia II)*	348/62 (356/65)*	4.4 (4.2)*	123	10/10
BP-16 (26 = Lądek Zdrój)*	359/61 (4/67)*w	3.6 (4.3)*	111	15/15

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

When plotted against the geomagnetic polarity time scale (GPTS) of Cande and Kent (1995), the K-Ar ages fall within the mainly reversed Gilbert chron (Fig. 12). Four normal subchrons are distinguished in the middle part of the Gilbert chron, however only one result (BP-14) correlates well with the normal polarity Nunivak subchron. The K-Ar dates from sites BP-15 and BP-16 fit in the middle of two separate, relatively long, reversed polarity intervals. Such apparent contradiction may be explained by assuming that: (i) The radiometric dating of the global magnetic polarity events is not perfect; or (ii) The magnetization of rocks and blocking of the K-Ar system are not synchronous; or (iii) The real geological ages of particular samples lie slightly outside (below or above) the accepted analytical-error limits of a given K-Ar date.

(i) It should be pointed out that the global polarity time scale applied in Fig. 12 is based upon integration of biostratigraphy, geochronology (mostly $^{40}Ar/^{39}Ar$), isotope stratigraphy, magnetic stratigraphy and astrochronologic calibration (see Opdyke & Channell, 1995, for review). It has been claimed to be very precise, mainly due to application of the astrochronological tuning. A possible error should not exceed 20,000 yrs (i.e., one precession cycle). However, the difference between the K-Ar data obtained in this study and the GPTS considerably exceeds its upper error limit.

(ii) The second option is considered the least probable. If the magnetization in the studied basanites were primary, it would have been blocked at temperatures about 585°C (Curie temperature of magnetite). According to Harland *et al.* (1990), the closure temperature of hornblende is about 500–550°C, and of the biotite – 280±40°C, respectively.

The closure temperatures strongly depend on physical-chemical conditions in the magma, on duration of its cooling process, and on presence or lack of fluids. Theoretically, there might be some temporal shift between the acquisition of magnetization and the K-Ar date, i.e. the magnetization should be older. This effect, if real, should have taken place mainly in plugs but not in lava flows, the latter cooling off very fast. However, an exactly opposite effect is observable in the basanites studied: the plug sample (BP-14) reveals radiometric age conformable with the GPTS, while both lava flows (BP-16 and BP-15) do not match any normal polarity event.

Another possibility is that the basanites were remagnetized after 3.6 Ma, during one of the normal polarity subchrons. Though very unlikely, such a possibility cannot, however, be ruled out. It should be mentioned that total remagnetization of such young volcanic rocks has so far not been mentioned in palaeomagnetic literature. Hardly any mechanism, such as reheating or fluid circulation, might even be indicated in this case. According to Piper (1987), the primary remanence of lava flows does not appear to be reset by hydrothermal metamorphism even up to the epidote grade.

(iii) The third option, according to the results of the present palaeomagnetic study, must be seriously considered. It has been recognized already in the early 1990s (Opdyke & Channell, 1995, and references therein) that K-Ar ages of Plio-Pleistocene volcanic rocks are not concordant with astrochronological and $^{40}Ar/^{39}Ar$ calibration of the GPTS. Moreover, some methodological problems concerning unexpected "excess argon" or "argon loss" have already been reported in the most recent study of Tertiary basaltic rocks of the Opole region, Lower Silesia: anomalous K-Ar dates were obtained from both the volcanic plugs and the lava flows (Birkenmajer & Pécskay, 2002).

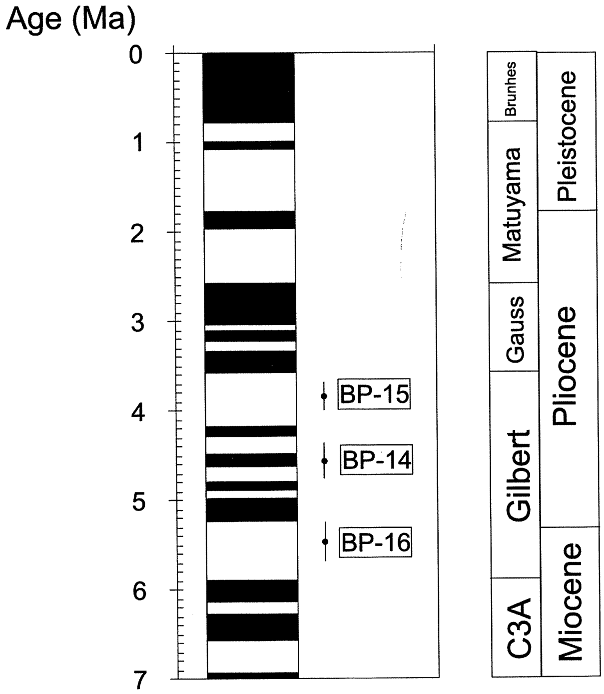


Fig. 12. Results of K-Ar dating of basanites from the Lądek Zdrój area versus geomagnetic polarity time scale (after Cande & Kent, 1995)

Taking this into account, we accept that the K-Ar dates of the basanites from the Lądek Zdrój area, though certainly indicating a Neogene (latest Miocene–Early Pliocene) age of this vulcanicity, do not give a sufficient basis for more detailed stratigraphic conclusions, the correlation with global magnetostratigraphic scale inclusively.

If we accepted the third option (see above), then the most likely conclusion based on the K-Ar and palaeomagnetic data of the Lądek Zdrój basanites would be that the vulcanicity occurred there within one of the four normal polarity events during middle part of the reversed Gilbert chron, i.e. between 4.18 and 5.23 Ma. From palaeomagnetic evidence we cannot, however, answer the question whether we deal here with one or more than one volcanic events.

CONCLUSIONS

1. The basanite rocks of the Lądek Zdrój area, Sudetes Mts, represented by a plug and by two different lava flows, are the youngest volcanic rocks recognized thus far in Poland. They span a period from 5.46 to 3.83 Ma, i.e. latest Messinian (uppermost Miocene) through Zanclean (Early Pliocene). The most probable age of this phase of vulcanicity is Zanclean.

2. The K-Ar dates of these basanites might indicate a

succession of the volcanic events, the basanite lava-flow from site BP-16 being the oldest; the basanite plug of site BP-14 being the next in the succession; and the basanite lava of site BP-15 being the youngest.

3. Comparison of the K-Ar dates of basaltic rocks from the Lądek Zdrój area (5.46–3.83 Ma), with those from the neighbouring northern Bohemia (3.7–0.81 Ma), may suggest a southward migration of volcanic centres with time during the Early Pliocene to Quaternary times.

4. More analytical work is needed, particularly with K-Ar dating of particular mineral fractions, to establish evolution of this magmatism with more precision, and to make a better correlation of its phases with palaeomagnetic epochs.

5. Petrological classification based upon mayor elements shows that the studied rocks belong to basanites (see Figs 5, 6). Based upon trace elements (see Tab. 1 and Figs 7–9), two of our samples (sites BP-15, 16) plot in the trachyandesite field very close to the basanite-alkali basalt-trachyandesite triple point, and one (site BP-14) exactly at the latter point, in the discrimination diagramme of Winchester and Floyd (1977). Relatively high Zr/Y ratios indicate that all studied rocks are typical within-plate alkali basaltoids.

REFERENCES

Balogh, K., 1986. K-Ar dating of Neogene volcanic activity in Hungary: Experimental technique, experiences, and methods of chronological studies. *ATOMKI Report*, D/1: 277–288.

Balogh, K., Árva-Sos, E., Pécskay, Z. & Ravasz-Baranyai, L., 1986. K-Ar dating of post-Sarmatian basaltic rocks in Hungary. *Acta Mineralogica et Petrographica*, 28: 75–93.

Berger, F., 1932. Die Alterstellung des Basalt vom Grauen Stein bei Landeck. *Zentralblatt für Mineralogie*, 8: 545–553.

Białowolska, A., 1980. Geochemical features of some Lower Silesian basaltoids and of their ultramafic inclusions (in Polish, English summary). *Archiwum Mineralogiczne*, 36: 107–171.

Birkenmajer, K., 1967. Lower Silesian basalts as monuments of inanimate nature (in Polish, English summary). *Rocznik Ochrony Przyrody (Kraków)*, 32: 225–276.

Birkenmajer, K. & Nairn, A. E. M., 1969. Palaeomagnetic investigations of the Tertiary and Quaternary igneous rocks. V. The basic Tertiary basalts of Lower Silesia, Poland. *Geologische Rundschau,* 58: 697–712.

Birkenmajer, K. & Pécskay, 1999. K-Ar dating of the Miocene andesite intrusions, Pieniny Mts, West Carpathians, Poland. *Bulletin, Polish Academy of Sciences, Earth Sciences,* 47 (2-3): 155–169.

Birkenmajer, K. & Pécskay, 2000. K-Ar dating of the Miocene andesite intrusions, Pieniny Mts, West Carpathians, Poland: a supplement. *Studia Geologica Polonica*, 117: 7–25.

Birkenmajer, K. & Pécskay, 2002. Radiometric dating of the Tertiary volcanics in Lower Silesia, Poland. I. Alkali basaltic rocks of the Opole region. *Bulletin, Polish Academy of Sciences: Earth Sciences*, 50 (1): 21–40.

Birkenmajer, K., Jerzmański, J. & Nairn, A. E. M., 1970. Palaeomagnetic studies of Polish rocks. IV. Cenozoic basalts of Lower Silesia. *Annales de la Société Géologique de Pologne*, 40: 31–61.

Birkenmajer, K., Jeleńska M., Kądziałko-Hofmokl, M. & Kruczyk, J., 1977. Age of deep-seated fracture zones in Lower Silesia (Poland), based on K-Ar and palaeomagnetic dating of Tertiary basalts. *Annales de la Société Géologique de Pologne*, 47: 545–552.

Cande, S. C. & Kent, D. V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, 100: 6093–6095.

De la Roche, H., Letterier, J., Grandclaude, P. & Marchal, M., 1980. A classification of volcanic and plutonic rocks using R1R2-diagram and mayor element analysis – its relationships with current nomenclature. *Chemical Geology*, 29: 183–210.

Gierwielaniec, J., 1971. Explanations to the geological map Lądek Zdrój, 1:25,000 (in Polish). Instytut Geologiczny, Warszawa.

Haggerty, S. E., 1976. Oxidation of opaque mineral oxides in basalts. In: Rumble, III, D. (ed.), Oxide Minerals. *Mineralogical Society of America, Short Course Notes*: 1–277.

Harland, W. B., Armstrong, R. R., Cox, A. V., Craig, L. E., Smith, A. G. & Smuith, D. G., 1990. A geologic time scale 1989. *Cambridge University Press*, Cambridge etc.: 1–263.

Jerzmański, J. & Maciejewski, S., 1968. Tertiary basalts in Lower Silesia. *Biuletyn Instytutu Geologicznego (Warszawa)*, 227: 247–260.

Kirschvink, J. L., 1980. The least square line and plane and the analysis of palaeomagnetic data. *Journal of the Royal Astronomical Society*, 62: 699–718.

Konečný, V., Lexa, J., Balogh, K. & Konečný, P., 1995. Alkali basalt volcanism in southern Slovakia: volcanic forms and time evolution. *Acta Vulcanologica*, 7: 167–171.

Kopecký, L., 1966. Tertiary volcanics, in: Svoboda, J. (ed.), Regional Geology of Czechoslovakia. I. The Bohemian Massif. Czechoslovak Academy of Sciences (Praha): 554–581.

Kozłowska-Koch, M., 1976. Petrography of ultramafic nodules in basaltoids from the environs of Lądek (Sudetes). *Bulletin, Polish Academy of Sciences: Earth Sciences*, 24: 67–76.

Kozłowska-Koch, M., 1987. Classification and nomenclature of the Tertiary volcanic rocks of the Lower and Opole Silesia (in Polish, English summary). *Archiwum Mineralogiczne*, 42: 43–95.

Kruczyk, J., Kądziałko-Hofmokl, M., Jeleńska, M., Birkenmajer, K. & Arakelyants, M. M., 1977. Tertiary polarity events in Lower Silesian basalts and their K-Ar age. *Acta Geophysica Polonica*, 25: 183–191.

Le Bas, M. J. & Streckeisen, A. L., 1991. The IUGS systematics of igneous rocks, *Journal of the Geological Society (London)*, 148: 825–833.

Lewandowski, M., Nowożyński, K. & Werner, T., 1997. PDA – a package of FORTRAN programs for paleomagnetic data analysis. *Mscr., Institute of Geophysics, Polish Academy of Sciences (Warsaw)*.

Lippolt, J.,1982. K-Ar age determination and the correlation of Tertiary volcanic activity in central Europe. *Geologisches Jahrbuch (Hannover)*, D-52: 113–135.

Lippolt, J., Troesch, M. & Hess, J. C., 1990. Excess argon and dating of Quaternary Eifel volcanism. IV. Common argon with high and lower-than atmospheric $^{40}Ar/^{39}Ar$ ratios in phonolitic rocks, East Eifel, F.R.G. *Earth and Planetary Science Letters*, 101: 19–33.

Majkowska, U., 1989. Geological documentation in categories C_1+C_2 of the "Lutynia" basalt occurrence (in Polish). *Mscr (Przeds. Geol. we Wrocławiu)*.

Meschede, M., 1986. A method of discrimination between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram. *Chemical Geology*, 56: 207–218.

Oberc, J., 1972. Sudetes and adjacent areas (in Polish). In: Budowa Geologiczna Polski (Geology of Poland), 4. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa: 1–307.

Opdyke, N. D. & Channell, J. E. T., 1995. Magnetic stratigraphy.

International Geophysics Series, 64. Academic Press: 346 pp.

Palmer, A. R. & Geissman, J., 1999. *Geologic Time Scale.* Geological Society of America. Product code CTS004.

Pearce, J. A. & Gale, G. H., 1977. Identification of ore deposition environment from trace element geochemistry of associated igneous host rocks. *Geological Society Special Publication (London)*, 7: 14–24.

Piper, J. D. A., 1987. Paleomagnetism and continental crust. Open University Press: 1–434.

Sawicki, L., 1966. Geological map of Lower Silesia (without Quaternary cover), 1:200,000. Instytut Geologiczny, Warszawa.

Šibrava, V. & Havliček, P., 1980. Radiometric age of Plio-Pleistocene volcanic rocks of the Bohemian Massif. *Bulletin of the Geological Survey, Prague*, 55: 129–139.

Śliwa, Z., 1967, Structures in Silesian basalts (in Polish, English summary). *Annales de la Société Géologique de Pologne*, 37: 435–454.

Smulikowski, K.,1957. Tertiary lavas of Lower Silesia. *Congreso Geológico International, XX Sesión (Mexico), Sect. I: Vulcanológia del Cenozóico*, 2.

Smulikowski, K., 1960. Tertiary volcanics (in Polish). In: *Regionalna Geologia Polski (Regional Geology of Poland), Geological Society of Poland (Kraków)*: 321–334.

Steiger, R. H. & Jäger, E., 1977. Subcommission on Geochronology, Convention on the use of decay constants in Geo- and Cosmochronology. *Earth and Planetary Science Letters*, 36: 359–362.

Urry, W. D., 1936. Ages by the helium method. II. Post-Keewenawan. *Bulletin of the Geological Society of America*, 47: 1217–1234.

Walczak, W., 1957. Quaternary deposits and geomorphology of the Kłodzko area, Sudetes Mountains (in Polish). *Przewodnik 30 Zjazdu Polskiego Towarzystwa Geologicznego*; 24–34.

Winchester, J. A. & Floyd, P. A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, 20: 325–343.

Wojno, T., Pentlakowa, Z. & Szarras, S., 1951. Investigations of Lower Silesian basalts in the years 1950–1951 (in Polish, unpublished). *Państwowy Instytut Geologiczny, Archiwum (Warszawa).*

Zagożdżon, P. P., 2001. "Sunburn" ("Sonnenbrand") in Tertiary basalts of Lower Silesia and possibilities of utilizing them (in Polish). *Ph. D. Thesis.*

Streszczenie

DATOWANIE RADIOMETRYCZNE TRZECIORZĘDOWYCH WULKANITÓW DOLNEGO ŚLĄSKA. II. DATY K-Ar I WYNIKI BADAŃ PALEOMAGNETYCZNYCH NEOGEŃSKICH BAZANITÓW OKOLIC LĄDKA ZDROJU W SUDETACH

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

Przeprowadzono badania radiometryczne (K-Ar) i paleomagnetyczne dwóch bazanitowych potoków lawowych oraz bazanitowego czopu wulkanicznego, odsłoniętych w okolicach Lądka Zdroju w Sudetach. Otrzymane daty K-Ar mieszczą się w granicach 5,46–3.83 Ma, co odpowiada najwyższemu miocenowi (messinian) i niższemu pliocenowi (zanclean). Daty te potwierdzają pogląd, że omawiane bazanity są najmłodszymi przejawami trzeciorzędowej działalności wulkanicznej w Polsce. Badania paleomagnetyczne wskazują, że bazanity okolic Lądka Zdroju powstały w czasie odpowiadającym środkowej części chronu Gilberta o odwróconej polaryzacji (między 5,23 a 4,18 Ma) i prawdopodobnie reprezentują więcej niż jeden epizod wulkaniczny.