RADIONOMIC DATING OF THE TERTIARY VOLCANICS IN LOWER SILESIA, POLAND. VI. K-Ar AND PALAEOMAGNETIC DATA FROM BASALTIC ROCKS OF THE WEST SUDETY MOUNTAINS AND THEIR NORTHERN FORELAND

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Abstract: This article presents the sixth and final contribution in a series of papers focused mainly on the K-Ar dating of the Oligocene and Neogene (Miocene and Pliocene) intraplate basaltic volcanics of the Lower Silesia, SW Poland. The present paper includes 22 new K-Ar dates from the West Sudety Mountains and their northern foreland. The K-Ar dates range from 30.7 to 22.2 Ma. The data are supplied with geological description of the sampled outcrops, petrographic, geochemical and palaeomagnetic data of the analysed samples. Palaeomagnetic investigation confirmed the existence of two important volcanic episodes distinguished already in 1997: the reversed polarity Odra Event (mean age 28.2±1.2 Ma), and the normal polarity Gracze Event (mean age 26.28±1.8 Ma).

Key words: K-Ar dating, Oligocene, Miocene, intraplate basaltic volcanics, Lower Silesia, Poland.

INTRODUCTION

The present paper is the sixth and final contribution to a geochronological study of the Oligocene, Miocene and Pliocene basaltic rocks from the Lower Silesia, Poland. This work focuses on the area of the West Sudety Mountains and their northern Foreland. Our previous studies included the areas of the Fore-Sudetic Block (Birkenmajer & Pécskay, 2002; Birkenmajer et al., 2002b, 2004), eastern and central parts of the Sudety Mts. (Birkenmajer et al., 2002a), and the North Sudetic Depression (Birkenmajer et al., 2007). Additional K-Ar dating results of the Tertiary basaltic rocks in Lower Silesia have been presented by Badura et al. (2005).

The Tertiary basalts of Lower Silesia belong to the eastern branch of the Bohemo-Silesian volcanic belt, part of the Central European Tertiary intraplate volcanic province (Fig. 1). The volcanic activity started during Early Oligocene (Rupelian) and continued through Early Miocene (Aquitanian–Burdigalian) time in the platform area to the north of the Sudetic Marginal Fault, and in the North Sudetic Depression, with ca. 3 Ma break at the Oligocene/Miocene boundary. Another, much shorter cycle of basaltic volcanic activity, dated from the Miocene/Pliocene (Messinian/Zanclean) boundary through the Early Pliocene (Zanclean), was recognised in the eastern part of the Sudety Mountains.

The Tertiary volcanism in Lower Silesia includes a variety of forms and structures: stratocones (usually consider-

**GEOLOGICAL SETTING AND PETROLOGY**

**West Sudety Mountains**

**Pilchowice (BP-43)**

**Geology.** The volcanic plug (Birkenmajer, 1967) is exposed in an old quarry ca. 300 m NE from dam of the Pilchowice artificial lake. It sits at the Intra-Sudetic Fault which separates Cambrian–Silurian mica schists from augen gneisses and a protolith (Szalamacha, 1974). The age of protolith to the gneiss was constrained to 515–480 Ma (Korytowski et al., 1993; Zelaźniewicz et al., 2003).

**Petrography.** The sample is a black fine-crystalline rock with a clear porphyric structure. Its groundmass is composed of glass (partly chloritized) with very fine pyroxene and nepheline crystals in equal amounts. Euhedral to subhedral, usually fresh olivine (sometimes with irregular network of microcracks) dominates among phenocrysts, which are 0.5–1.5 mm in size. Euhedral to subhedral nepheline phenocrysts are second in frequency. Rare pyroxene (Ti-augite, \( z/\gamma = 36\)) phenocrysts, usually with hourglass structure, are partly chloritized.

The rock was previously classified as basanite (Kozłowska-Koch, 1987), however, based on its mineral composition and chemistry (cf. Le Bas & Streckeisen, 1991) it...
should be reclassified as ankaratrite (olivine melanephelinite) (Table 1, Figs 2, 3).

**Palaeomagnetic sampling.** Two representative hand samples (43-1; 43-2) were collected from the abandoned quarry, with location of ca. 2 m apart.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical composition of Tertiary basaltic rocks from the West Sudety Mts (Sites BP-43-46, SK-10)</th>
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<td>R2</td>
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Analysed at the Chemistry Laboratory, Polish Geological Institute, Warsaw (Project No 620.1719.00.0)

**Fig. 2.** Plot of Tertiary basaltic rock samples, West Sudety Mountains, TAS classification diagramme (Le Bas & Streckeisen, 1991). Numbers refer to the investigated sites (BP; SK)

**Wojciechów (BP-44A)**

**Geology.** The sample is situated in a working quarry (Fig. 4), ca. 1 km S from Wojciechów (near Lubomierz). The rock is exposed in a working quarry, ca. 1 km S from Grudza, near Stara Kamienica. It probably represents a volcanic vent with remnants of lava flows and pyroclastic rocks.

**Petrology.** The sample is a black, fine-crystalline rock, devoid of fluidal structure. Its groundmass consists of brownish chloritized glass, with fine nepheline and pyroxene crystals. Isotropic, euhedral grains of opaque minerals abound. Euhedral to subhedral olivine, 0.5 mm (sometimes up to 1 mm) in size, predominates among phenocrysts. Pyroxene phenocrysts (Ti-augite, $z/γ = 37–40°$) with similar size are often twinned, sometimes showing hourglass structure. The largest phenocrysts of pyroxene (ca. 3 mm in size) are thoroughly chloritized and surrounded by rims of not altered, very small augite ($z/γ = 35°$) crystals. Abundant opaque minerals, mainly iron-oxides, are dispersed within the groundmass. The rock was classified by Domañski (1970) as basedonite. Our data (Table 1; Figs 2, 3) confirm his classification.

**Palaeomagnetic sampling.** One hand sample (44-1 labelled as BP-44A radiometric sample), was taken from the northern wall. Additionally, two hand samples (44-2 and 44-3) were collected from the southern wall of the quarry.

**Grudza (BP-45)**

**Geology.** The rock is exposed in a working quarry, ca. 1 km S from Grudza, near Stara Kamienica. It probably represents a volcanic vent with remnants of lava flows and pyroclastic rocks.

**Petrography.** The sample is a black, fine-crystalline rock, devoid of fluidal structure. Its groundmass consists of brownish chloritized glass, with fine nepheline and pyroxene crystals. Isotropic, euhedral grains of opaque minerals abound. Euhedral to subhedral olivine, 0.5 mm (sometimes up to 1 mm) in size, predominates among phenocrysts. Pyroxene phenocrysts (Ti-augite, $z/γ = 38°$), usually subhedral, are second in frequency. The pyroxene is commonly twinned, sometimes showing very typical hourglass struc-
ture. Small aggregates of fine pyroxene and olivine crystals occur.

The bulk chemistry (Table 1, Figs 2, 3) indicates that the previous classification as the pyroxene basalt (Wojno et al., 1951; Szalamacha, 1970) should be changed to the ankaratrite (olivine melanephelinite).

**Palaeomagnetic sampling.** Two hand samples (45-1; 45-2) were collected from the same wall of the quarry.

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**Rębiszów (BP-46A)**

**Geology.** A working quarry, 1.5 km E from Przecznica village in the Lysa Góra area, exposes a volcanic vent with lava flows (Stachowiak, 1981). The vent is located at a tectonic contact of the Neoproterozoic Stara Kamienica mica schist unit (Maciejewski, 1957) with the gneisses and granitic gneisses of the Izera complex. The protolith age of the latter ones was constrained to 515–480 Ma (Korytowski et al., 1993; Żelaźniewicz et al., 2003).

**Petrography.** The sample is a black rock without fluidal structure. Its groundmass consists of fine nepheline, pyroxene and glass. Isotropic opaque minerals are commonly dispersed in the groundmass. Large phenocrysts (1–5 mm in size) include mainly olivine with an irregular network of microcracks filled with secondary minerals of serpentine group, or fine plagioclase and biotite. Pyroxene (Ti-augite, $z'/y = 37^\circ$) phenocrysts are second in frequency, and smaller than the olivine. Some pyroxenes are relatively fresh, showing hourglass structure.

According to our data (Table 1; Figs 2, 3), the previously classified rock as nephelinite (Wojno et al., 1951; Birkenmajer et al., 1970) should be reclassified to the ankaratrite (olivine melanephelinite).

**Palaeomagnetic sampling.** Two hand samples (46-1; 46-2) were collected from the southern part of the quarry. The label is equal to the BP-46A radiometric sample.

**Śnieżne Kotły (SK-10)**

**Geology.** An exposure is located in the western wall of the Mały Kociół Śnieżny glacial cirque (the so-called Bazaltowy Żleb gully). Samples were collected from an axial part of the basaltoid intrusion (Fig. 5), which cuts the...
Karkonosze granite pluton of Carboniferous age (see Zagoźdźon & Zagoźdźon, 2006).

Petrography. The rock is dark-grey, often vesicular, with porphyric structure, without fluidal structure. Its groundmass consists of strongly chloritized brownish glass, very fine crystals of augite, and altered plagioclase and nepheline. Numerous opaque minerals are dispersed in the groundmass. Pyroxene phenocrysts (1–2 mm in size), usually strongly altered (pseudomorphs filled with chlorite and iron-oxides), are most frequent. The phenocrysts of similar size plagioclase (labradorite An56–58) with albite twinning are partly sericitized. Occasional vesicles are filled with quartz crystals enveloped by dark rims of very fine pyroxene that grows perpendicularly to surface of the vesicles.

Fig. 5. Site SK-10 Śnieżne Kotły, basanite (after Zagoźdźon & Zagoźdźon, 2006). 1 – talus cones; 2 – basanite; 3 – columnar jointing; 4 – intrusive breccia; 5 – contact breccia; 6 – granite; 7 – strike and dip of contact surface; 8 – lithologic boundaries (a – certain; b – probable); 9 – dislocation zone; 10 – sampling site.
Our data (Table 1; Figs 2, 3) indicate that the studied sample is the basanite as was classified previously by Koźłowska-Koch (1987).

Area between Lubań and Opolno Zdrój

Leśna-Brzóz (BP-47A, B)

Geology. A massive lava flow (Śliwa, 1971) exposed in an abandoned quarry was sampled (note: a plug might occur SW of the quarry; Kochanowska, 1995).

Petrography. The sample is a very fine-crystalline dark-grey rock. Its groundmass consists of fresh, fluidally arranged laths of plagioclase (labradorite An50-55) and Ti-augite ($z/\gamma = 45-48^\circ$). Circular aggregates of green glass, <0.5 mm in size, are scattered within the groundmass and surrounded by plagioclase laths. Long, thin calcite veins run parallel to fluidal structure of the rock.

The rock was originally classified as plagioclase basalt or trachybasalt (Wojno et al., 1951), later reclassified as ankaratrite and, subordinately, basalt (Kochanowska, 1995). Our study (Table 2; Figs 2, 3, 6) indicates a within-plate trachybasalt affinity.

Palaeomagnetic sampling. Two hand samples (47-1; 47-2) were collected from two different lava columns located ca. 2 m apart, in the lower part of escarpment just above the lake. Two more hand samples (47-3; 47-4) were collected in a higher part of the escarpment, above the road.

Stożek Perkuna (BP-48A)

Geology. The natural exposure is situated at the top of the hill, while the old quarry is located in its western part. The elongated plug (Birkenmajer, 1967; volcanic vent of Śliwa, 1971) cuts augen gneisses (Berezowska & Berezowski, 1962a) attributed to the Upper Cambrian (Korytowski et al., 1993; Żelaźniewicz et al., 2003). Samples (BP-98A, B) were collected separately from two generations of basaltic rock (Figs 7, 8).

Petrography. The rock sample is dark-grey and exhibits its porphyritic structure. Its groundmass consists of very fine pyroxene and plagioclase laths, green glass and abundant opaque minerals (mainly iron-oxides). Fresh olivine and nepheline phenocrysts are usually 1 mm in size, occasionally reaching size of 2−5 mm. Rare pyroxene (augite $z/\gamma = 37^\circ$) phenocrysts sometimes show the presence of circular olivine inclusions.
The rock in previous studies was classified as plagioclase basalt or trachybasalt (Wojno et al., 1951), basalt (Birkenmajer et al., 1970; Grocholski & Jerzmañski, 1975), and nepheline (Kozłowska-Koch, 1987). Data from this study (Table 2; Figs 2, 3) indicate that the sample is an olivine melanephelinite (ankantrite – a variety of foidite), which is interpreted as originated from an alkaline within plate type magma (Fig. 6).

**Palaeomagnetic sampling.** The following three hand samples were collected from Stożek Perkuna: 48-1 – from the lower western part of the exposure (equal to the BP-48C radiometric sample); 48-2 – from the lower eastern part of...
Palaeomagnetic sampling. Two hand samples (49-1; 49-2) were collected from the lower part of the quarry (equal to the BP-49 radiometric sample).

Lubań I (BP-50)

Geology. The exposure is located in a three-level working quarry, about 2.5 km south of the Lubań centre. The exposed extensive lava flow (Birkenmajer, 1967; Śliwa, 1971) is located partly upon the Ordovician phyllites, and partly upon the Miocene clays (Berezowski, 1956). The sample was collected at the lowest exploitation level.

Petrography. The sample is a dark-grey rock with porphyric structure. Its groundmass consists of very fine pyroxene and plagioclase, and a considerable amount of green glass. Abundant black opaque minerals are regularly dispersed in the glass. Pyroxene (augite z/γ = 37°) and olivine, up to 2 mm in size, are the only phenocrysts present. Pyroxene is commonly twinned or shows a typical hourglass structure. The olivine phenocrysts contain microcracks filled with serpentine group minerals, and are rimmed by a red iddingsite.

The rock was previously classified as a plagioclase-nepheline basalt or nepheline basanite (Wojno et al., 1951), nephelinite (Birkenmajer et al., 1970; Grocholski & Jerzmanowski, 1975; Białowolska, 1980), or basanite and tephrite (Kozłowska-Koch, 1987). The data from this study (Table 2; Figs 2, 3) indicate that the rock belongs to within-plate olivine melanephelinite (ankararite).

Palaeomagnetic sampling. Two hand samples (50-1; 50-2) were collected (labelled also as the BP-50 radiometric sample).

Lubań II (BP-51)

Geology. The samples were collected from the same extensive lava flow as at site BP-50 (Lubań I) located in an old quarry at the Kamienna Góra town-park at Lubań (see Birkenmajer et al., 1970; Grocholski & Jerzmanowski, 1975) (Fig. 9).

Petrography. The sample is a dark-grey, very fine-crystalline rock with porphyric structure. Its groundmass consists mainly of very fine nepheline crystals and green glass. Very fine plagioclase and pyroxene laths, both too small to be precisely determined, are less frequent. Abundant opaque minerals occur. Among phenocrysts, nepheline and olivine (<1 mm in size) predominate. The latter is partly altered, with red iddingsite rims, showing a microcrack network filled with secondary minerals of serpentine group. Smaller olivine phenocrysts are totally transformed into iddingsite. Pyroxene phenocrysts (Ti-augite z/γ = 48°) are less frequent.

The rock was originally named nepheline (Birkenmajer et al., 1970) and tephrite (Kozłowska-Koch, 1987). The new data (Table 2; Figs 2, 3) indicate that it should be reclassified as olivine melanephelinite (ankararite), while its primary magma belonged to an alkaline within-plate type (Fig. 6).

Bukowa Góra (BP-49)

Geology. The exposure is located in a working quarry (Ksiegiński II) in a ca. 5 km distance SW from Lubań. The lava flow (Birkenmajer, 1967; Śliwa, 1971) rests directly upon Cambro-Silurian phyllites (Berezowska & Berezowski, 1962a; Kural, 1967). The samples were collected in the eastern part of the lowest exploitation level.

Petrography. The rock sample is dark-grey, very fine-crystalline, with well developed fluidal structure. Its groundmass consists mainly of very fine nepheline crystals and green glass. Very fine plagioclase and pyroxene laths, both too small to be precisely determined, are less frequent. Abundant opaque minerals occur. Among phenocrysts, nepheline and olivine (<1 mm in size) predominate. The latter is partly altered, with red iddingsite rims, showing a microcrack network filled with secondary minerals of serpentine group. Smaller olivine phenocrysts are totally transformed into iddingsite. Pyroxene phenocrysts (Ti-augite z/γ = 38°) are less frequent.

The rock was originally named nepheline (Birkenmajer et al., 1970) and tephrite (Kozłowska-Koch, 1987). The new data (Table 2; Figs 2, 3) indicate that it should be reclassified as olivine melanephelinite (ankararite), while its primary magma belonged to an alkaline within-plate type (Fig. 6).

Uniegoszcz (PB-52)

Geology. The samples were collected from a basaltic volcanic vent exposed in an old, two-level quarry at Ostróżek hill (see Birkenmajer, 1967, text figs 26, 27), SE from
Lubań. The vent is associated with lava flow (Birkenmajer et al., 1970; Krzyśków, 1985) resting upon Ordovician phyllites (Berezowski, 1956).

**Petrography.** The sample is a dark-grey, very fine-crystalline rock with flow structure. The groundmass consists mainly of brownish glass, very fine plagioclase and pyroxene laths, and frequent opaque minerals. Olivine dominating among phenocrysts contains microcracks filled with serpentine group minerals. Augite ($z'/\gamma = 38^\circ$) is usually twinned and shows hourglass structure.

The rock was previously classified as a nepheline basalt (Wojno et al., 1951), nepheline (Birkenmajer et al., 1970) and basanite (Krzyśków, 1985). Our data (Table 2; Figs 2, 3, 6) confirm that the rock is a within-plate basanite.

**Palaeomagnetic sampling.** Two hand samples (52-1; 52-2) were collected from a central part of the abandoned quarry (BP-52 radiometric sample).

**Zaręba (BP-53A-E)**

**Geology.** The samples were collected from a two-level working quarry at Zaręba (Księginki I), located about 3 km SW from Lubań centre. The site exposes a fragment of the same extensive lava cover as at sites BP-50 (Lubań I) and BP-51 (Lubań II), showing the presence of regular pyroclastic intercalations, often with lava breccias. Five samples (BP-53A-E) were collected from the lava (Fig. 10).

**Petrography.** The sample is a very dark, nearly black, very fine-crystalline rock. The groundmass contains high amount of glass, as well as fresh, very fine augite ($z'/\gamma = 38^\circ$) and plagioclase laths. Abundant black opaque minerals are dispersed within the groundmass. Relatively large (0.5–1 mm) olivine grains are entirely transformed into red iddingsite. Single nepheline phenocrysts of similar size occur.

The rock was previously classified as nepheline (Birkenmajer et al., 1970), however, the new data (Table 2; Figs 2, 3) indicate that the sample is a basanite. Relatively large amount of nepheline shifts its position in respective diagrams near to the olivine mela-nepheline (ankaratrite) within-plate field (Fig. 6).

**Palaeomagnetic sampling.** The following six hand samples were collected: two samples (53-1; 53-2) from the upper part of the quarry (BP-53A, B radiometric samples); and four samples from the lower part of the quarry, i.e. 53-3 (BP-53C radiometric sample); 53-4 (BP-53D radiometric sample); 53-5, 6 (BP-53D and BP-53E radiometric samples, respectively).

**Sulików (BP-54)**

**Geology.** The site exposes a lava flow in a three-level working quarry located about 0.5 km NE from Sulików centre. A volcanic vent probably occurs N of the quarry (Birkenmajer, 1967; Jakubowska et al., 1987). The site is located at the contact of the ca. 570 Ma Lausitian greywackes (Żelaźniewicz et al., 2003), and the 540–530 Ma Zawidów granodiorite (Berezowska & Berezowski, 1962b; Korytowski et al., 1993). A sample was collected from the lava flow exposed in the southern part of the lowest exploitation level.

**Petrography.** The sample is a dark-grey, very fine-crystalline rock with scattered phenocrysts of pyroxene and olivine which do not exceed 0.5 mm in size. Olivine is entirely replaced by red iddingsite.

The rocks from the Sulików quarry were previously classified as nepheline basalt, plagioclase basalt and nepheline (Wojno et al., 1951), and nepheline (Birkenmajer et al., 1970; Kozłowska-Koch, 1987). The sample in our study (Table 2; Figs 2, 3) is classified as belonging to olivine mela-nepheline (ankaratrite).

**Palaeomagnetic sampling.** Two hand samples were collected at the same site (BP-54 radiometric sample).

**Markocice (BP-55)**

**Geology.** The old quarry (called “Wojtek”) at Bogatynia exposes rocks representing the central part of an extensive lava flow which covers the 514–480 Ma Rumburk granite (Żelaźniewicz et al., 2003).

**Petrography.** The sample is a dark-grey, very fine-crystalline rock with porphyritic structure. Its groundmass consists of very fine fresh-preserved plagioclase (labradorite An$_{58-60}$) and pyroxene laths, with a small admixture of nepheline and opaque minerals, and brownish-green glass. Idiomorphic pyroxene (augite, $z'/\gamma = 48^\circ$) prisms predominate among phenocrysts; they are commonly twinned, with a typical hourglass structure. Olivine phenocrysts are second in frequency. They commonly show traces of magmatic corrosion in form of embayments filled with glass. Microcracks in olivine are filled with minerals of serpentine group. The rock was previously classified as trachyandesite (Smulikowski, 1960) and basanite (Berezowski, 1973). Our study (Table 2; Figs 2, 3) confirms attribution of the rock to within-plate basanite.

**Palaeomagnetic sampling.** One hand sample has been collected (BP-55 radiometric sample).

**Opolno Zdrój (BP-56A, B)**

**Geology.** Samples (BP-56A, B) were collected in an old quarry which exposes a lava flow with centrally located vent (Birkenmajer, 1967, text fig. 31). The country rocks are represented by the 514–480 Ma Rumburk granite (Żelaźniewicz et al., 2003) and augen gneisses of the Izera complex, with a protolith age constrained to 515–480 Ma (Korytowski et al., 1993; Żelaźniewicz et al., 2003).
Results of K-Ar dating of basaltic rocks from the West Sudety Mts

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<th>No. of sample</th>
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<td>Sniżne Kotły</td>
<td>basanite</td>
<td>1.08</td>
<td>1.100×10^{-6}</td>
<td>35.5</td>
<td>26.0±1.3</td>
</tr>
</tbody>
</table>

The analyses were performed at the Institute of Nuclear Research, Hungarian Academy of Sciences (ATOMKI), Debrecen. The whole rock fraction was analysed.

**Petrography.** The sample is a light-coloured (pale-green), fine-crystalline porphyritic rock. Its groundmass is composed of elongated (<0.3 mm) plagioclase (oligoclase An_{28-30}) laths with albite twinning, and K-feldspar showing Carlsbad twinning. Needle-shaped pyroxene (augite z/γ = 48°) also occurs in the groundmass. K-feldspar (up to 2 mm in size), being the only phenocryst, is sub-idiomorphic and forms very fine granophyric intergrowths with quartz and polysynthetic feldspar twins. Zircon, the only accessory mineral, rarely occurs within the groundmass.

The rock was previously classified as plagioclase basalt or trachyphonolite (Smulikowski, 1960; Birkenmajer, 1967; Birkenmajer et al., 1970), phonolite (Berezowski, 1971, 1973), and trachyte (Kozłowska-Koch, 1987). Our data (Table 2; Figs. 2, 3) confirm the latter attribution.

**Palaeomagnetic sampling.** One hand sample (56-1) was collected. Because the site is in a very bad condition and the phonolite occurs as isolated blocks, it is uncertain whether these blocks are in situ.

**POTASSIUM-ARGON DATING**

**Dating methods and age calculations**

The methods used to determine K-Ar ages of the basaltic rocks have been described in detail elsewhere (Birkenmajer & Pécsey, 2002). The K was analysed using the flame photometry, while the radiogenic Ar was measured by isotope dilution after extraction of the Ar in a high-vacuum line. The isotopic composition of the Ar was determined using a mass spectrometer (90° magnetic sector type of 150 mm radius – see Balogh, 1985) which was operated in the static regime. The precision of the K and Ar measurements was regularly checked by interlaboratory standards: LP-G, GL-O, HD-B1 and Asia 1/65 (see Odin et al., 1982). Atomic constants suggested by Steiger and Jäger (1977) were used for calculating the ages. All of the analytical errors represent one standard deviation (68% confidence level). Details of the instruments have been described elsewhere (Balogh, 1985).

**Jelena Góra area**

Five locations have been sampled in the Jelena Góra area (Fig. 1). The basaltic rocks (basanite and ankaratrite) yielded K-Ar ages ranging from 27.8 Ma to 23.4 Ma (Table 3).

Except for the K-Ar age of 23.4±1.1 Ma obtained on sample BP-43, there is an agreement in ages between the remaining samples to within analytical errors. It is thought, therefore, that loss of radiogenic Ar was the reason for rejuvenated age of sample BP-43. Such an assumption is supported by the presence of glassy groundmass and secondary nepheline in this sample. Similar mineralogical-petrographic observations were also made in other samples, e.g. BP-44A, 45, 46A, and SK-10. It is well known (e.g., McDougall, 1966) that lavas most suitable for K-Ar dating of the whole-rock samples should be holocrystalline and not altered. Unfortunately, many basaltic rocks from our study contain varying proportions of poorly crystallized groundmass or glass which contains potassium. Therefore, the constrained radiometric K-Ar ages should be generally regarded as the minimum ages.

On the other hand, the highly concordant ages determined in samples from four locations suggest that volcanism in this area was restricted to a relatively short period between 27.8 Ma and 25.3 Ma, i.e. to the Late Oligocene ( Chattian). The 26.2 Ma value, a mean of four dates (27.8±1.2 Ma, 25.3±1.0 Ma, 26.0±1.0 Ma and 26.0±1.3 Ma), probably reflects the main volcanic episode, with ankaratrite being slightly younger than the basanite.

A general agreement between the K-Ar and palaeomagnetic data (Table 3 and Figs 11–13) suggest that the different K-Ar ages might represent different volcanic episodes.

**Lubań area**

The Lower Silesia Basaltic Province extends westwards from the Lubań area to Germany, and to the south to the Czech Republic. In the Lubań area, 17 representative basaltic samples were collected for K-Ar dating from nine exposures in working and abandoned quarries (Fig. 1). The dating results ranging from 30.7 to 22.2 Ma are shown in Table 4.

(1) The oldest dates of about 30 Ma were determined in two high-K basaltic rocks (BP-47A, B and BP-56A, B) classified as trachybasalt and trachyte, respectively. We consider these dates as representing real geological ages. The age difference between samples BP-47A and BP-47B might reflect some slight rejuvenation of the K-Ar age in sample BP-47B with a lower K content.

(2) The K-Ar dates obtained from the Stożek Perkuna quarry (BP-48A-C) do not agrees with their relative geologi-
Fig. 11. K-Ar dating results from sites where more than one sample was radiometrically dated versus geomagnetic scale of Cande and Kent (1995), and results from the Oligocene basaltic rocks of the Lower Silesia (Birkenmajer & Pécsvay, 2002; Birkenmajer et al., 2002b, 2004, 2007, this paper). Left side – radiometric scale in Ma and polarity column; right side – magnetozones. Full circles – normal polarity; open circles – reversed polarity. Site mean ages are drawn in a bold line. (A) Site BP-53A-E; (B) Site B-57A, B; (C) Site 56A-C; (D) Site BP-56A, B.

Fig. 12. K-Ar dating results from sites where more than one sample was radiometrically dated versus geomagnetic scale of Cande and Kent (1995), and results from the Oligocene basaltic rocks of the Lower Silesia (data from Birkenmajer et al., 2000b, 2004, 2007, this paper) versus geomagnetic scale of Cande and Kent (1995); full circles – normal polarity; open circles – reversed polarity. Site mean ages are drawn in a bold line.

Fig. 13. Correlation of K-Ar dating results of the Miocene basaltic rocks from the Lower Silesia (data from Birkenmajer et al., 2000b, 2004, 2007, this paper) versus geomagnetic scale of Cande and Kent (1995); full circles – normal polarity; open circles – reversed polarity; numbers of sites investigated in this paper are given in bold figures.
Results of K-Ar dating of basaltic rocks from the northern foreland of the Sudety Mts

<table>
<thead>
<tr>
<th>No of K/Ar</th>
<th>No of sample</th>
<th>Location</th>
<th>Rock type</th>
<th>K (%)</th>
<th>$^{40}\text{Ar}_{\text{tot}}$ (ccSTP/g)</th>
<th>$^{40}\text{Ar}_{\text{ex}}$ (%)</th>
<th>K/Ar age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6215</td>
<td>BP-47A</td>
<td>Leśna-Brzozky quarry S</td>
<td>trachybasalt</td>
<td>2.01</td>
<td>2.418×10^{-6}</td>
<td>78.6</td>
<td>30.7±1.2</td>
</tr>
<tr>
<td>6216</td>
<td>BP-47B</td>
<td>Leśna-Brzozky quarry N</td>
<td>trachybasalt</td>
<td>1.59</td>
<td>1.751×10^{-6}</td>
<td>73.8</td>
<td>28.1±1.1</td>
</tr>
<tr>
<td>6217</td>
<td>BP-48A</td>
<td>Stożek Perkuna quarry, upper</td>
<td>ankaretite</td>
<td>0.81</td>
<td>8.148×10^{-7}</td>
<td>53.9</td>
<td>25.7±1.1</td>
</tr>
<tr>
<td>6218</td>
<td>BP-48B</td>
<td>Stożek Perkuna quarry, lower E</td>
<td>ankaretite</td>
<td>0.58</td>
<td>6.171×10^{-7}</td>
<td>38.9</td>
<td>27.2±1.1</td>
</tr>
<tr>
<td>6219</td>
<td>BP-48C</td>
<td>Stożek Perkuna quarry, lower W</td>
<td>ankaretite</td>
<td>0.65</td>
<td>6.360×10^{-7}</td>
<td>42.8</td>
<td>25.0±1.0</td>
</tr>
<tr>
<td>6220</td>
<td>BP-49</td>
<td>Bukowa Góra quarry</td>
<td>ankaretite</td>
<td>0.75</td>
<td>8.406×10^{-7}</td>
<td>31.0</td>
<td>28.7±1.5</td>
</tr>
<tr>
<td>6221</td>
<td>BP-50</td>
<td>Ksieginki quarry</td>
<td>ankaretite</td>
<td>0.46</td>
<td>1.356×10^{-6}</td>
<td>16.1</td>
<td>34.6±3.1 (?)</td>
</tr>
<tr>
<td>6222</td>
<td>BP-51</td>
<td>Lubań quarry</td>
<td>basanite</td>
<td>0.60</td>
<td>6.406×10^{-7}</td>
<td>45.6</td>
<td>27.3±1.2</td>
</tr>
<tr>
<td>6223</td>
<td>BP-52</td>
<td>Uniegoszcz</td>
<td>basanite</td>
<td>1.19</td>
<td>1.031×10^{-7}</td>
<td>60.7</td>
<td>22.2±0.7</td>
</tr>
<tr>
<td>6224</td>
<td>BP-53A</td>
<td>Zaręba, Josef quarry upper</td>
<td>ankaretite</td>
<td>0.70</td>
<td>6.883×10^{-7}</td>
<td>56.1</td>
<td>25.1±0.9</td>
</tr>
<tr>
<td>6225</td>
<td>BP-53B</td>
<td>Zaręba, Josef quarry upper</td>
<td>ankaretite</td>
<td>0.60</td>
<td>5.819×10^{-7}</td>
<td>49.5</td>
<td>24.8±0.9</td>
</tr>
<tr>
<td>6226</td>
<td>BP-53C</td>
<td>Zaręba, Josef quarry upper</td>
<td>ankaretite</td>
<td>0.58</td>
<td>7.250×10^{-7}</td>
<td>42.5</td>
<td>31.9±1.2</td>
</tr>
<tr>
<td>6227</td>
<td>BP-53D</td>
<td>Zaręba, Josef quarry upper</td>
<td>ankaretite</td>
<td>0.61</td>
<td>6.349×10^{-7}</td>
<td>52.7</td>
<td>26.6±0.9</td>
</tr>
<tr>
<td>6228</td>
<td>BP-53E</td>
<td>Zaręba, Josef quarry upper</td>
<td>basanite</td>
<td>0.79</td>
<td>8.630×10^{-7}</td>
<td>74.2</td>
<td>27.9±0.9</td>
</tr>
<tr>
<td>6229</td>
<td>BP-54</td>
<td>Sulików quarry</td>
<td>ankaretite</td>
<td>0.69</td>
<td>7.971×10^{-7}</td>
<td>70.6</td>
<td>29.4±1.1</td>
</tr>
<tr>
<td>6230</td>
<td>BP-55</td>
<td>Markocice quarry</td>
<td>basanite</td>
<td>0.67</td>
<td>6.987×10^{-7}</td>
<td>51.8</td>
<td>26.5±1.1</td>
</tr>
<tr>
<td>6231</td>
<td>BP-56A</td>
<td>Opolno Zdrój</td>
<td>trachyte</td>
<td>4.20</td>
<td>4.821×10^{-7}</td>
<td>88.1</td>
<td>29.3±1.1</td>
</tr>
<tr>
<td>6232</td>
<td>BP-56B</td>
<td>Opolno Zdrój</td>
<td>trachyte</td>
<td>4.20</td>
<td>4.448×10^{-6}</td>
<td>86.9</td>
<td>27.0±1.0</td>
</tr>
</tbody>
</table>

Dated at the Institute of Nuclear Research, Hungarian Academy of Sciences (ATOMKI), Debrecen. The whole rock fraction was analysed.

An older ankaretite lava flow exposure from Lubań (the Bukowa Góra quarry, BP-49, base of the section) yielded K-Ar date of 26.5±1.1 Ma. The youngest basanite rock (alkaline basanite, BP-52) was taken from a volcanic vent in Uniegoszcz and yielded a date of 22.2±0.7 Ma. This is a clear evidence of the presence of the Early Miocene volcanism in the Lubań area, which, however, is areally more restricted than the Oligocene one in contrast to the northern (Jawor) and eastern parts of the Lower Silesia Basaltic Province (Birkenmajer et al., 2002).

The most detailed sampling was made in a melanephelinite (ankaretite) lava flow at Józef quarry near Zaręba. The two samples (BP-53A, B) were taken from the upper part, and three (BP-53C-E) from the lower part of the quarry (Fig. 10). Palaeomagnetic study (see later) confirms that the samples represent a single lava flow. However, because the K-Ar geochronology provides a wide range of dates from 31.9 Ma to 24.8 Ma (Table 4), it appears that this ankaretite lava flow cannot be considered as the isotopically “closed system”. The scattered K-Ar data could be a result of Ar loss in sample BP-53C (lowest K content and, thus, the highest age) and the presence of some Ar excess. Nevertheless, other samples (BP-53A, B, and BP-53D-E) yielded concordant ages.

Moreover, assuming that the samples from the upper part of the quarry had lost some Ar, the age obtained on sample BP-53E (27.9±0.9 Ma) might be the best estimation. This would be in good agreement with the age determined for sample BP-51 (27.3±1.2 Ma). However, we cannot exclude a possibility that the different ages refer to two volcanic events.

(7) The constrained K-Ar date of sample BP-54 (29.4±1.1 Ma) seems to be older than the geological age: therefore, it can be considered a maximum age.

(8) A basanite sample (BP-55) collected near the Polish–Czech state border yielded a date of 26.5±1.1 Ma. We interpret this date as the age of crystallization of the lava flow. This age is similar to that established for volcanics in the adjacent area of the Czech Republic (Cajz et al., 1999).

PALAEOMAGNETISM

Palaeomagnetic studies of basaltic rocks from locations marked in here as BP-43, 47, 48, and 52–56 were initiated already almost a century ago (Birkenmajer & Nairn, 1969; Birkenmajer et al., 1970). Because previous results were presented in text-tables only, without details of demagnetization, we have decided to re-study these locations. For comparison, the previously published data are included in Table 5.
Palaeomagnetic methods

All palaeomagnetic experiments were carried out at 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%. From each hand sample, 3–4 cylindrical specimens were prepared. Natural remnant 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 remnant magnetization (ChRM) directions were calculated based on the principal component analysis (see Kirschvink, 1980), and using the PALMAG package (Lewandowski et al., 1997). Most of the samples were treated with the AF. Thermal demagnetization was applied to pilot specimens, demagnetizing paths were, however, more noisy than in the case of the AF treatment, and sometimes it was not possible to isolate ChRM.

Palaeomagnetic results

After extraction of a small low coercivity component (following 5–10 mT demagnetization steps) a stable characteristic magnetization was revealed, which was interpreted as primary (Fig. 14). Characteristic magnetizations from all sites are quite dispersed (Fig. 15), i.e. only some of them are discordant with Neogene directions “expected” for the European Platform, with minor deviations which might be explained by secular variations. These are normal polarity results from sites BP-43 and BP-48 (Fig. 14A), and reverse
polarity results from sites BP-45, BP-46, BP-53 (Fig. 14B), and BP-54. Characteristic magnetizations at other sites were divergent from Neogene geomagnetic dipole field: these directions were interpreted as virtual magnetizations, i.e. acquired during an intermediate (anomalous) position of geomagnetic dipole during inversion or geomagnetic excursion. This concerns especially sites BP-44 (Fig. 14D) and BP-49–51 (Fig. 14C).

Magnetizations in basaltic flows of the same age correlate over long distances and might be used as stratigraphic markers (e.g., Coe et al., 2005). Based on this assumption, basalts from sites BP-49–51 might be interpreted as the same volcanic event. Indeed, K-Ar dates from sites BP-49 and BP-51 overlap within the error limit.

Discussion: magnetostratigraphy

Integration of magnetostratigraphy and K-Ar dating gives an unique opportunity to verify the reliability of both methods. In case of samples BP-53A-E, which were collected from the same lava flow, consistent reversed magnetization was revealed in all of them (Table 5). However, the K-Ar dates obtained from these samples were spread between 31.9 (±1.2) and 24.8 (±0.9) Ma (Table 5; Fig. 11A), i.e. over a time span that considerably exceeded the analytical errors of the radiometric method applied. The mean age from five measurements, 27.3±1 Ma, falls at the close of the reversed Odra Event (Fig. 11A).

It thus appears that analytical error for a single K-Ar dating is underestimated. As can be seen from results obtained at site BP-53, it amounts to 3.0–3.5 Ma. Therefore, for comparison with the global polarity time scale, mean ages were calculated for those sites where more than one K-Ar data was available (i.e., BP-53, BP-57, BP-58, and BP-56 – see Fig. 11). This approach seems justified since all samples from these sites revealed the same polarity (BP-47 and 53 – reversed; BP-48 – normal).

Mean date from BP-47 (29.4±1.1 Ma) is concordant with the beginning of the Odra Event (Fig. 11B), while that from BP-48 falls in the middle part of the Graczce Event (25.9±1 Ma – see Fig. 11C). Additionally, mean age was calculated also for site BP-56, where only a single palaeomagnetic result was obtained (Fig. 11D): it agrees with the Odra Event.

Most of the intrusions studied are of Oligocene age (Fig. 12). The overall pattern of predominantly normal polarity of younger intrusions (Graczce Event), and reversed polarity of older intrusions (Odra Event), was confirmed. The most abundant were reversed polarity intrusions aged between 27.3±1.2 Ma (BP-51) and 29.4±1.1 Ma (BP-47 and 54). Together with dates obtained in our previous studies (Birkenmajer et al., 2002b, 2004, 2007), they constitute an almost continuous data set divided by only one entry of nor-
normal polarity (BP-34). Within the error limit, they might represent a single volcanic phase – the Odra Event as defined by Birkenmajer et al. (1977). Its mean age would be 28.2±1.2 Ma, which is close to the Early/Late Oligocene boundary (after Gradstein et al., 2004). When compared to GPTS, it might be correlated with magnetozones C9r or C10r.

Two normal polarity intrusions, BP-48 and BP-55, might be assigned to the Graze Event (as defined by Birkenmajer et al., 1977). Its mean age amounts to 26.28±1.08 Ma, which might correspond to magnetozone C8n in the middle part of the Late Oligocene.

Two dates obtained at sites BP-43 and BP-52 fall within the latest Oligocene, close to the Oligocene/Miocene boundary (Fig. 13). They plot between the Graze and Javor events (as defined by Birkenmajer et al., 1977), in the interval with relatively few datings, that might indicate decrease in volcanic activity (Pecskay et al., 2004).

CONCLUSIONS

(1) Considering the geological age-ranges and spatial distribution of our K-Ar dated Oligocene and Miocene basaltoid rocks in Lower Silesia, we could not discern signs of a preferential younging of volcanism in any particular geographic direction.

(2) There seems also to be no preferential pattern in changes of geochemical composition of these volcanics, both stratigraphically and/or areally.

(3) Palaeomagnetic investigations generally confirm the existence of a volcanic episode of reversed polarity close to the Early/Late Oligocene boundary. This episode was distinguished by Birkenmajer et al. (1977) as the Odra Event (see also Birkenmajer et al., 2004, 2007). Its mean age might be estimated at 28.2±1.2 Ma.

(4) Another volcanic episode of normal polarity occurred during the Late Oligocene. It was distinguished by Birkenmajer et al. (1977) as the Graze Event (see also Birkenmajer et al., 2004, 2007). Its mean age might be estimated at 26.28±1.8 Ma.

(5) We do not imply that the Graze and Odra events were two separate phases of volcanic activity. This activity might have been continuous throughout two or more polarity zones. However, as real error of K-Ar dating of our Oligocene volcanic samples might be as high as 3 Ma (see above), we decided to keep the divisions of Birkenmajer et al. (1977) until more precise radiometric data will be available.

(6) A multiple palaeomagnetic-radiometric sample investigations at site BP-53 (Zareba) have revealed that a real error in K-Ar dating of the Neogene volcanics at this site might amount to 3–3.5 Ma. This suggests that more palaeomagnetic and radiometric investigations should be performed at this site to obtain a reliable dispersal of data.

(7) The basaltoid volcanics acquired their magnetization in the course of rapid cooling. Therefore, “intermediate” magnetizations from the time of magnetic reversals were usually preserved. In such cases, anomalous magnetizations might be treated as a stratigraphic tool to correlate the same lava flows over a considerable distance.

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