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Palaeomagnetism and magnetic properties of Tertiary basaltic rocks from Gracze, Lower Silesia

ABSTRACT: The Tertiary basaltic rocks of Gracze near Opole, Lower Silesia (Poland), belong to the eastern extremity of the Central European volcanic province and are part of the Bohemo-Silesian belt. They are represented by melanocratic type of nepheline basanite (melabasanite) with local transitions to ankaratrite, and occur as plugs, vent fills of craters and lava flows. The present paper details: (*a*) palaeomagnetic investigations based on the determination of directions of the natural remanent magnetization of rocks (NRM) and their magnetic stability; (*b*) investigations of magnetic properties of basaltic rocks as related to their mineral content. The latter include measurements of changes in saturation parameters as a function of temperature; determination of Curie points; determination of Fe and Ti contents in the magnetic fraction; and microscopic analysis of polished sections in reflected light.

INTRODUCTION

The Tertiary basaltic rocks of Gracze near Opole (Lower Silesia, Poland) belong to the eastern extremity of the Central European volcanic province and are part of the Bohemo-Silesian belt (Fig. 1). They are represented by melanocratic type of nepheline basanite (melabasanite) with local transitions to ankaratrite, and occur as plugs, vent fills of craters and lava flows.

The palaeomagnetic characteristics of the plugs and vent fills of Gracze have been presented by Birkenmajer & Nairn (1969) and Birkenmajer & al. (1970), based on pilot samples (up to 6 samples per exposure), and the geological forms of the basaltic rocks have been discussed separately by Birkenmajer (1966, 1967). The present paper is based on investigations of a much larger collection of oriented samples (up to c. 20 samples per exposure), including all major rock types and volcanic forms (plugs, vent fills and lava flows) recognized in the field; it is supplemented by petrological and chemical analyses.

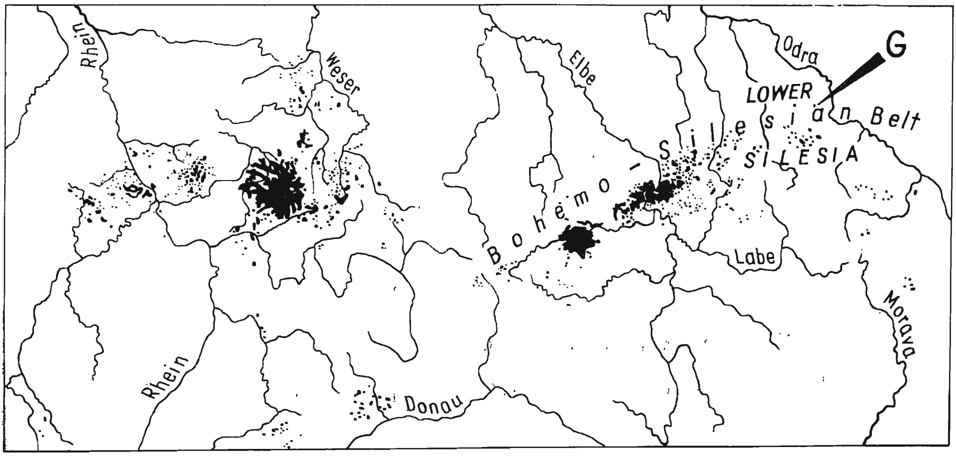


Fig. 1

Position of the Lower Silesian basaltic rocks within the Central European Tertiary volcanic province

G melabasanites of Gracze

The present paper details: (*a*) palaeomagnetic investigations based on determination of directions of the natural remanent magnetization of rocks (NRM) and their magnetic stability; (*b*) investigations of magnetic properties of basaltic rocks as related to their mineral content. The latter include: measurements of changes in saturation parameters as a function of temperature; determination of Curie points; determination of Fe^{2+}, Fe^{3+} and Ti contents in the magnetic fraction; and microscopic analysis of polished sections in reflected light (ore microscopy).

The preliminary results of the investigations described in the present paper are given by Birkenmajer & al. (1972) and Kądziałko-Hofmokl & Kruczyk (1972).

OUTLINE OF GEOLOGY

General remarks

In the vicinity of Gracze there occur several separate volcanic plugs clustered in the zone of the NW-SE-trending Odra fault of Tertiary age, and associated with lava flows (Fig. 2). Based on preliminary petrological investigations (Wojno & al. 1951) these volcanic rocks have been classified as nephelinite, basanite and basalt (Birkenmajer & Nairn 1969, Birkenmajer & al. 1970). The present investigations show, however, that all are varieties of melabasanite.

The volcanic plugs cut through the Upper Cretaceous marine marly clays. Baked fragments of Cretaceous rocks may also be found as xenoliths in melabasanite plugs and lava flows and, especially, in volcanic breccias separating the flows or forming vertical pipes. The age of volcanic activity is believed to be Tertiary (without closer determination). The Miocene-Pliocene fresh-water sediments which surround the basaltic rocks (*cf.* Sawicki 1966) are supposed to post-date the volcanic activity of the area. As no radiometric dating of the melabasanites have been available so far, the exact age determination of the volcanic activity at

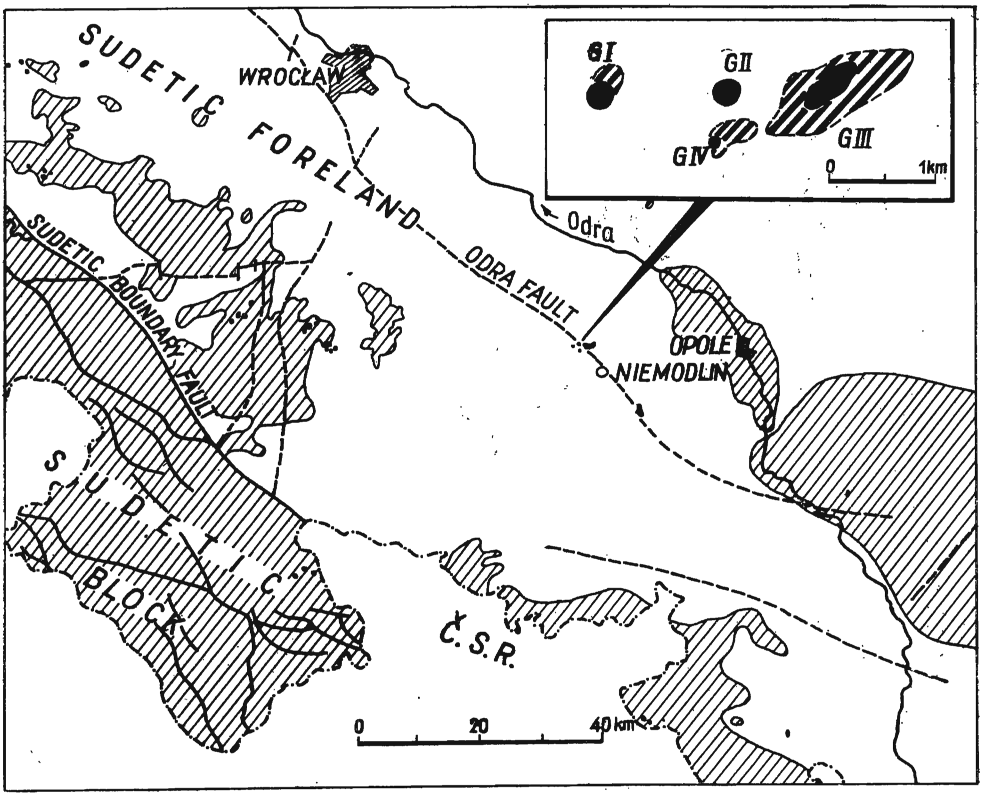


Fig. 2

Localization of sampling sites at Gracze *G I* — *G IV*, Lower Silesia

Basaltic rocks in black; Neogene sediments blank; pre-Neogene rocks hatched; heavy lines denote major dislocations. In the box: melabasanite plugs in black; melabasanite lava sheets hatched

Gracze cannot yet be established. For more geological information the reader is referred to papers by Birkenmajer (1966, 1967) and Alexandrowicz & Birkenmajer (1972).

Description of localities

Site G I (Radoszowice). Melabasanite plug (nepheline basalt of Wojno & al. 1951; nephelinite of Birkenmajer & Nairn 1969, and Birkenmajer & al, 1970: Site *63*), possibly elongated SW-NE, with columnar and platy jointing arranged in a system typical of plugs (*cf.* Birkenmajer 1966, Figs 9 & 11; 1967, Figs 35 & 38). Exposure in an old quarry shows besides the melabasanite also the presence of weathered tuffs with fragments of altered Cretaceous marls. Country rocks represented by argillaceous sediments of Upper Cretaceous (Coniacian) age, baked at the contact with the plug. In the NE and NW parts of the quarry, the melabasanite caps the baked Cretaceous sediments; there it possibly represents a lava flow. Localization of samples is shown in Fig. 3; 18 samples were analysed.

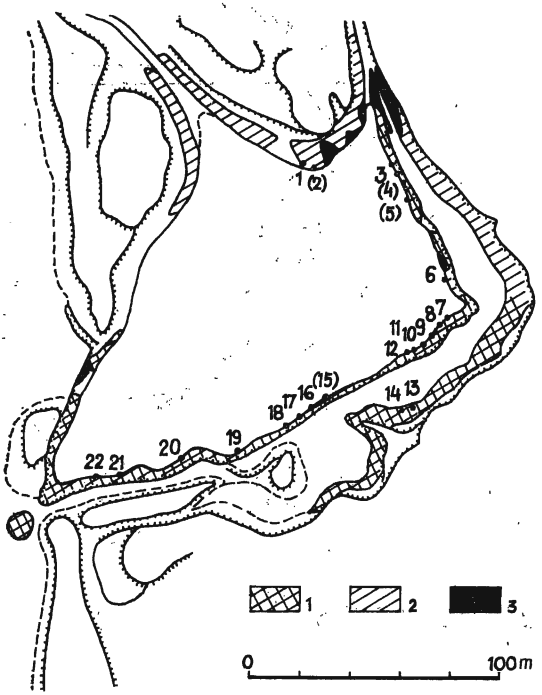


Fig. 3

Localization of samples at Radoszowice *(G I)*

1 exposures in melabasanite plug; 2 exposures in melabasanite lava flow; 3 altered Upper Cretaceous sediments and contact breccias. Numbers and thick dots refer to samples. Numbers in brackets refer to samples not used for investigations

Site G II ("Ameryka"). Melabasanite plug (plagioclase-nepheline basalt with glass of Wojno & al. 1951; basanite of Birkenmajer & Nairn 1969, and Birkenmajer & al. 1970: Site *64*), with platy and columnar jointing arranged in a system typical of plugs (*cf.* Birkenmajer 1966, Figs 9 & 11; 1967, Figs 35 & 38). Exposure in an old quarry called "Ameryka" shows besides the melabasanite also the presence of baked Upper Cretaceous (Coniacian) shales and clays at the contact with the plug. Localization of samples is shown in Fig. 4; 15 samples were analysed.

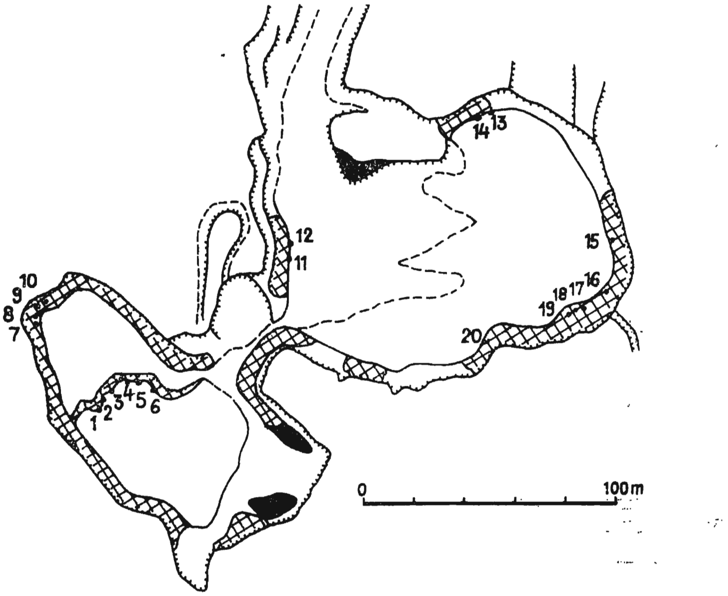


Fig. 4

Localization of samples at Gracze-"Ameryka" *(G II)*. For explanations *see* Fig. 3

Site G III (Gracze, main quarry). Melabasanite (plagioclase-nepheline basalt with glass of Wojno & al. 1951; basanite of Birkenmajer & Nairn 1969, and Birkenmajer & al. 1970: Site *65*) plug, resp. vent fill of crater, distinctly elongated SW-NE, with well developed columnar jointing. Surrounded by melabasanite lava flows, massive and columnar in the lower part and scoriaceous in the upper part, alternating with tuff breccias containing fragments of baked Upper Cretaceous marls. Two lava flows have been distinguished, interstratified with breccias. These have been interpreted as lower part of a strato cone (Fig. 5; *cf.* Birkenmajer 1966 Figs 9—11; 1967, Figs 35, 37—38). Other tuff breccias with abundant xenoliths of baked Cretaceous marls occur at the boundary of the strato cone and the vent fill (plug), in the form of pipes (Fig. 5). The substrate of the lavas and the country rocks for the plug are represented by Upper Cretaceous sediments. Localization of samples in the big working quarry is shown in Fig. 6; 60 samples were analysed.

Site G IV (Rutki). Melabasanite plug (plagioclase basalt of Wojno & al. 1951; basalt of Birkenmajer & Nairn 1969, and Birkenmajer & al. 1970: Site *66*), with platy jointing, contacting with melabasanite lava flow, possibly slightly younger than the latter. The lava flow is columnar, contacting with baked Upper Cretaceous marls (*cf.* Birkenmajer 1967, Figs 35—36). The country rocks farther from the contact are represented by dark grey shales and clays with Upper Cretaceous (Coniacian) marine foraminifers and other microfossils. For localization of samples see Fig. 7; 15 samples were analysed.

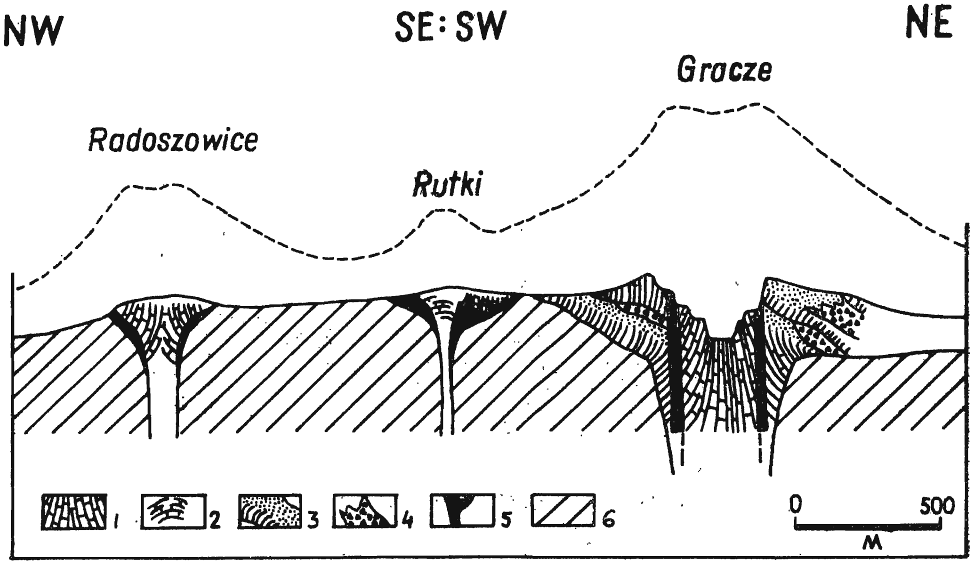


Fig. 5

Geological reconstruction of central volcanoes of Gracze-Radoszowice (*after* Birkenmajer 1967, slightly modified)

1, 2 plugs and lava-filled vents; *3* lava flows (massive, columnar lava in the lower part, and vesicular resp. scoriaceous lava in the upper part); *4—5* tuff breccias with xenoliths of Upper Cretaceous rocks; *6* Upper Cretaceous sediments

PETROGRAPHIC CHARACTERISTICS OF VOLCANIC ROCKS

The basic volcanics in the vicinity of Gracze consist of black aphanitic rocks in which only olivine phenocrysts, a few millimetres in size, are visible to the naked eye. Under the microscope, the rocks show characters of typical melanocratic lavas belonging to basanites, which locally pass into ankaratrites.

A rather uniform variety of basanite of seriate-porphyritic texture occurs in all mentioned sites. It abounds in microlitic groundmass devoid of glass (Pl. 1, Fig. 1). Mafic minerals such as titanaugite and basaltic augite and olivine of the Fa_{12-15} chrysolite member ($2V\alpha = 88.6$—89.7°) are the essential components. Augite and

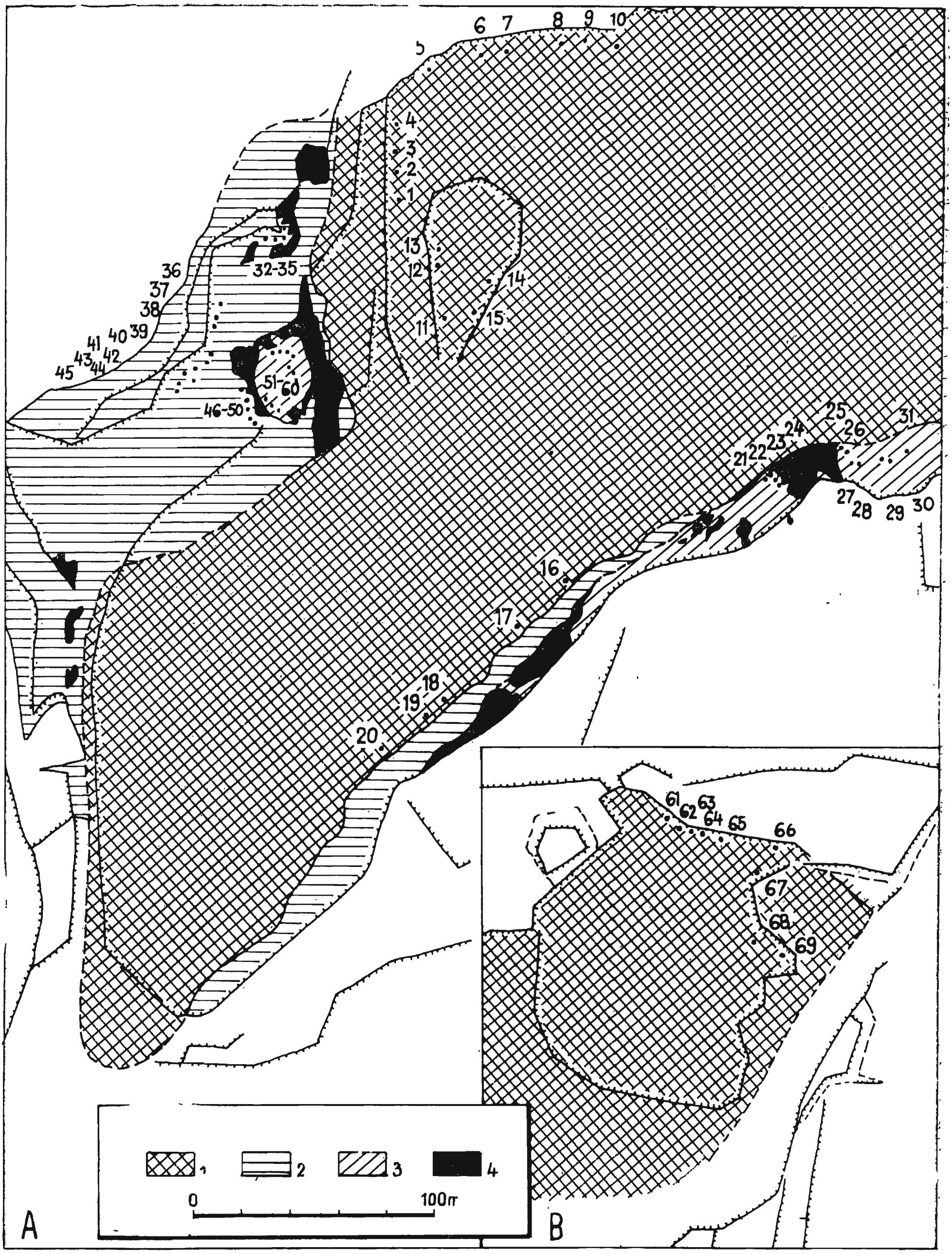


Fig. 6

Localization of samples at Gracze, main quarry *(G III): A* — SW part of the quarry, *B* — NE part of the quarry

1 melabasanite plug; *2* lower melabasanite lava flow; *3* upper melabasanite lava flow; *4* volcanic breccias. Numbers and thick dots refer to samples olivine form crystals of various size between phenocrysts and microlites (Pl. 1, Fig. 2; Pl. 2, Figs 1—2). The olivines from the upper lava flow at Gracze (Locality *G III*: NW upper lava flow) and from volcanic plugs close to the contact with the country rocks (*e.g.* at Localities *G III* and *G IV*) are almost completely altered into iddingsite (Pl. 2), the latter being characterized by reddish-yellow colour and extremely variable axial angle ($2V\alpha = 46$—66°). Serpentine and magnesite are less frequent alteration products.

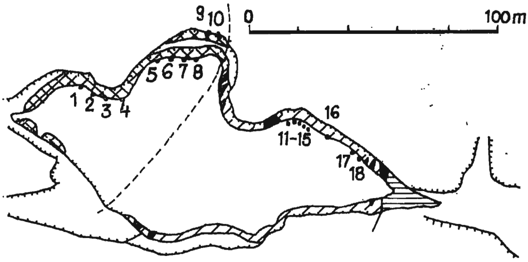


Fig. 7

Localization of samples at Rutki (*G IV*)

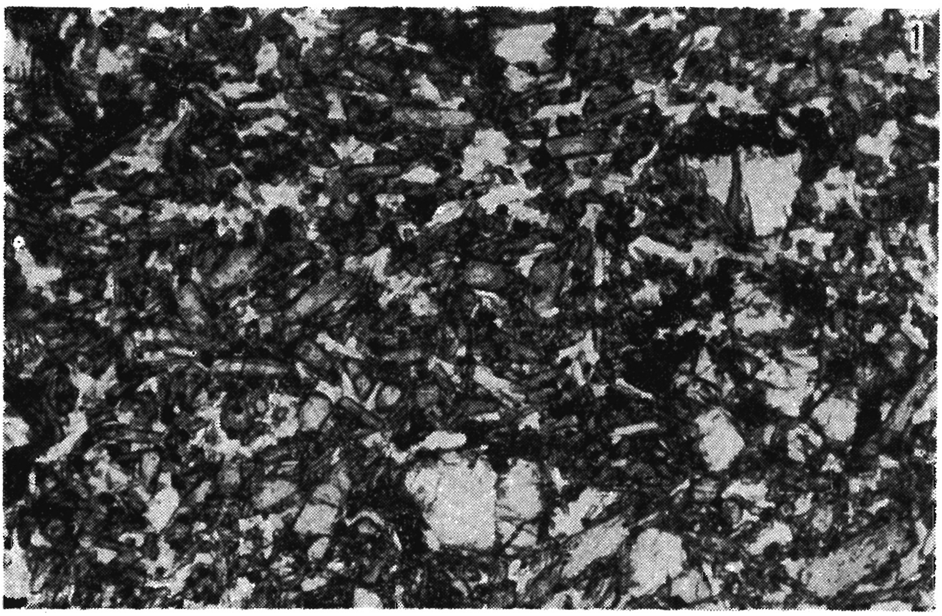
Horizontally hatched unaltered Lower Senonian clays. For other explanations *see* Fig. 3

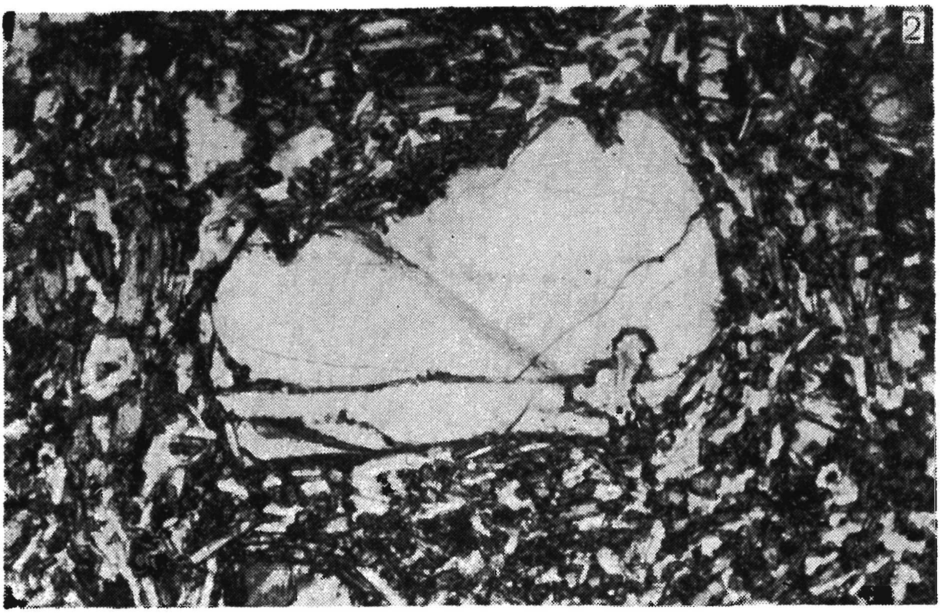
Hourglass structure is a characteristic feature of pyroxenes, sometimes in combination with zoning structure. Wide-angle sectors of prisms are formed of titanaugite or basaltic augite ($Z/\gamma = 51$—56°, $2V\gamma = 48$—53°), whereas the diopside augite or common augite are involved in narrow-angle sectors ($Z/\gamma = 46$—49°, $2V\gamma = 56$—58°). The same varieties of augite take part in pyroxenes of zoning structure, and the outer rims are always enriched in iron and titanium. Sometimes one may observe clustered augite-phenocrysts which are either radially arranged or non-oriented (Pl. 3, Fig. 1). The share of felsic minerals usually in form of microlitic nepheline prisms and small laths of plagioclases does not exceed 1/5-th of all components (Tab. 1: col. *1—4*). The proportions of both minerals even in the same exposure are highly variable, showing prevalence either of nepheline, or of labradorite An_{50-70}, the latter being usually closed in an andesine An_{36} rim. It is worth of note that relative larger but xenomorphic nepheline grains are observed in basanites from the volcanic plugs, attaining a diameter of 1—2 mm (*e.g.* Gracze *G III*, Rutki *G IV*). They overgrow many augite microlites and better crystallized laths of labradorite in form of poikilitic grains.

Miarolitic cavities filled in with nepheline or andesine An_{36} are connected with basanites from plugs as well as with the upper lava flow of Gracze G III (Pl. 3, Figs 1—2). The andesine, because of a delicate twin structure, is most similar to anorthoclase, from which it differs in larger extinction angles $\alpha'/(010)$ and optic axes ($2V\alpha = 74°$). This plagioclase is certainly younger than nepheline microlites of the rock groundmass, as the latter form frequent inclusions in it. Miaroles are limited usually by augite prisms. Beside of nepheline or andesine, fibrous calcite also occurs in them with analcite inclusions and oxidated iron sulphides. The presence of those minerals proves that local concentrations of gaseous components took part in the formation of the miarolitic forms.

Other components of the rock groundmass are titanomagnetite and various accessories such as apatite, analcite and, in some samples, also biotite. Analcite is interstitial and in some cases it fills in small miaroles. The latter contain sometimes only calcite or chlorite.

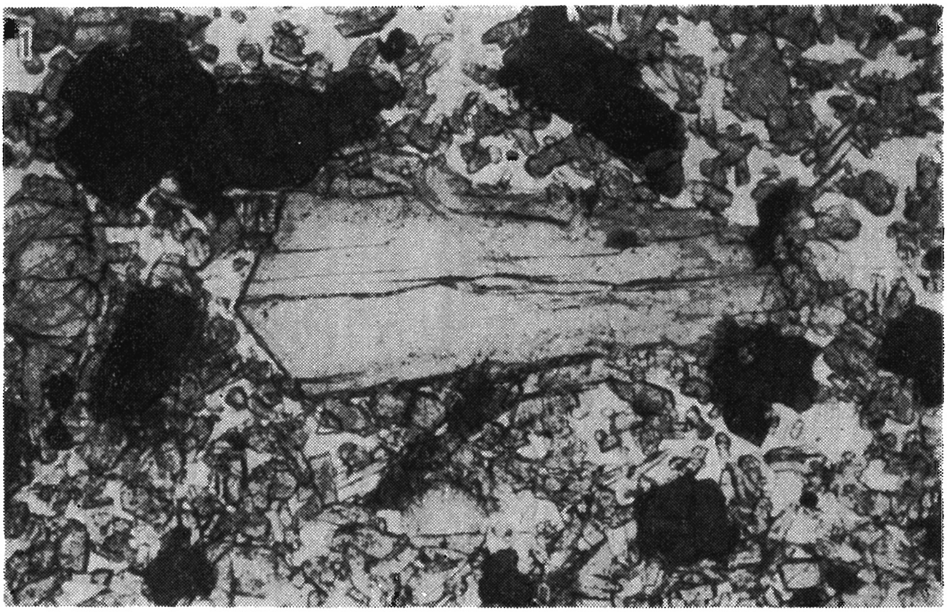
The quantitative mineral composition of the investigated basanites is presented in Table 1. It takes into account only the better crystallized

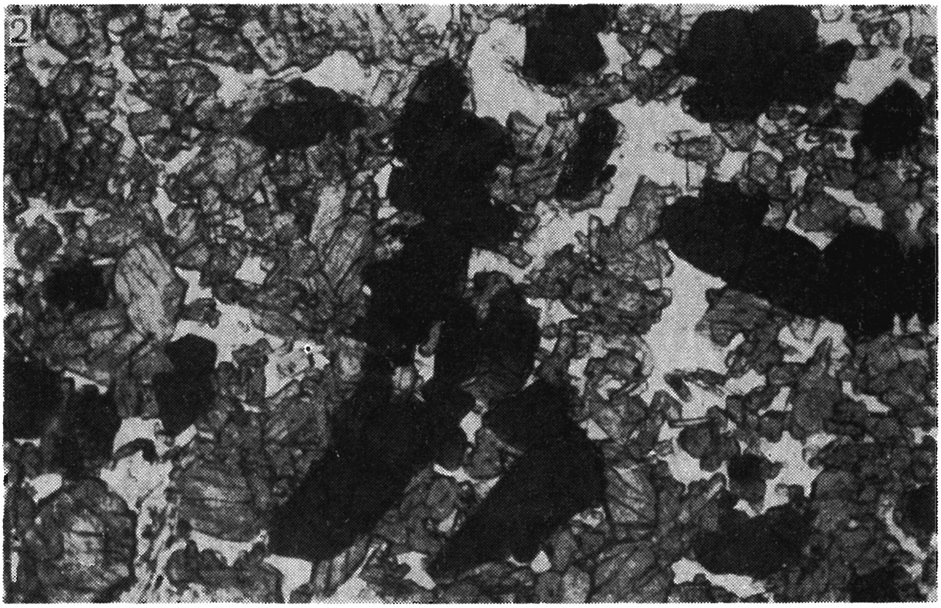




1 — Seriate-porphyritic texture of melabasanite (plug) from Gracze-"Ameryka" (*G II*). One polarizer, × 100.

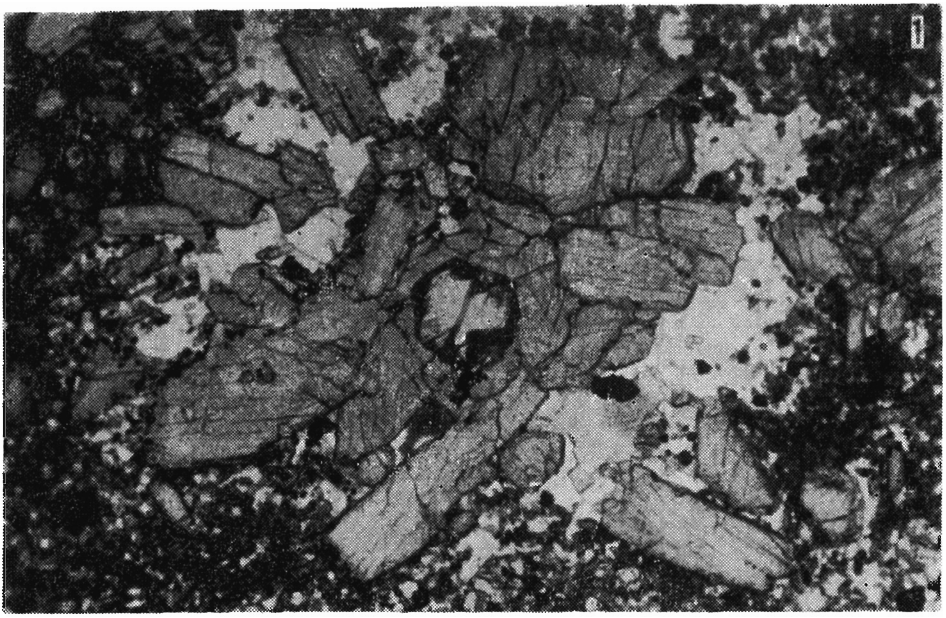
2 — Melabasanite (plug) from Gracze-"Ameryka" (*G II*). Olivine phenocryst in fine-grained matrix of augite, labradorite, nepheline and titanomagnetite. One polarizer, × 88.

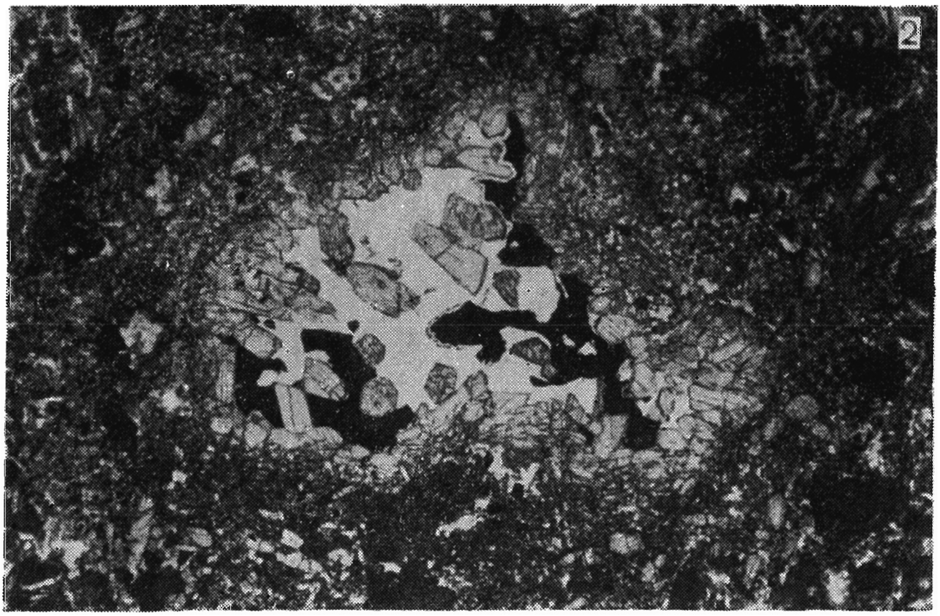




1 — Melabasanite (plug), Gracze — main quarry (*G III*). Phenocrysts of titaniferous augite, and iddingsite after olivine (dark in the microlitic matrix of augite, labradorite and nepheline. One polarizer, × 88.

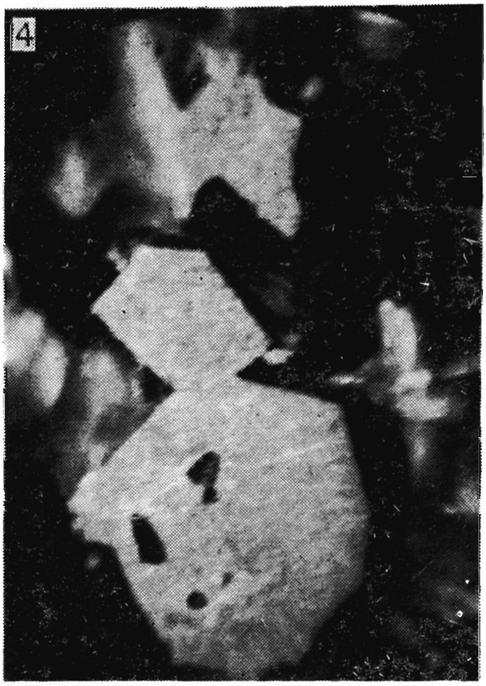
2 — Melabasanite (plug), Gracze — main quarry (*G III*). Iddingsite pseudomorphs after olivine phenocrysts (dark) in the microlitic matrix of augite, labradorite and nepheline. One polarizer, × 89.





1 — Melabasanite (plug), Radoszowice (*G I*). Aggregation of titaniferous augite phenocrysts surrounding a single olivine phenocryst. The miarolitic cavities (white) between the pyroxene prisms and groundmass are filled with andesine, calcite and analcite. One polarizer, × 82.

2 — Melabasanite (plug), Rutki (*G IV*). Miarolitic cavity filled with large nepheline grain (white), titaniferous augite prisms and altered iron sulphides. One polarizer, × 38.



1 — Shapes of titanomagnetite grains (white) in melabasanite from Gracze, main quarry (*G III*), upper NW lava. Reflected light, × 250.
2 — Frequently found poikilitic structure of titanomagnetite grain (white) in melabasanite from Gracze, main quarry (*G III*), plug. Reflected light, × 250.
3 — Fresh grain of optically homogenous titanomagnetite in melabasanite from Gracze, main quarry (*G III*), plug. Reflected light, × *c.* 1000.
4 — Grain of optically homogeneous titanomagnetite after heating in air at 600° C for 24 hrs. Visible characteristic mosaic of newly formed titanohaematite. Gracze, main quarry (*G III*), plug. Reflected light, × 1000.

Table 1

Mineral composition of melabasanites from Rutki, Gracze and Radoszowice in volume percentages

	1	2	3	4	5
Olivine	18.0	17.3	17.1	16.3	-
Titaniferous augite	54.0	57.5	60.2	63.9	54.5
Nepheline + plagioclase + analcite + apatite	20.0	19.0	13.9	12.0	28.9
Titanomagnetite	8.0	6.2	8.8	7.8	5.1
Glass	-	-	-	-	5.0
Calcite, zeolites	-	-	-	-	6.5
Colour index	80	81	86	88	c. 60

1 quarry at Rutki *(G IV)*, plug; *2* quarry at Gracze *(G III)*, plug, western part; *3* quarry at Gracze *(G III)*, upper SE lava flow; *4* quarry at Radoszowice *(G I)*, plug; *5* quarry at Gracze *(G III)*. Mesotype doleritic variety of basalt from a thin vein in melabasanite *(after* Chodyniecka 1971)

Table 2

Chemical composition of melabasanites from Radoszowice and Gracze, in weight percentages

	1	2	3	4
SiO_2	43.60	44.40	40.75	44.45
Al_2O_3	11.96	11.91	10.55	15.80
Fe_2O_3	4.84	4.42	6.86	11.82
FeO	6.50	7.51	5.72	3.05
MgO	10.70	11.85	11.69	3.41
CaO	13.49	12.47	13.70	8.41
Na_2O	3.90	3.50	3.35	3.35
K_2O	1.20	0.90	0.84	1.40
H_2O^+	0.51	0.70	0.08	1.49
H_2O^-	0.22	0.26	0.57	1.44
TiO_2	1.70	1.55	3.27	2.41
P_2O_5	0.98	0.79	0.96	0.76
MnO	0.12	0.13	n. d.	n. d.
CO_2	0.87	-	1.46	1.80
Cr_2O_3	n. d.	n. d.	0.09	0.20
NiO	n. d.	n. d.	0.14	0.05
CoO	n. d.	n. d.	0.007	0.004
S	0.02	0.02	-	-
CuO	n. d.	n. d.	0.17	0.03
Σ	100.61	100.41	100.207	99.874

1 quarry at Radoszowice *(G I)*, plug, nepheline-rich variety of melabasanite (analysed by A. Nowakowski); *2* quarry at Gracze-"Ameryka" *(G II)*, plug, plagioclase-rich variety of melabasanite (analysed by A. Nowakowski); *3* main quarry at Gracze *(G III)*, melabasanite *(after* Chodyniecka 1971); *4* main quarry at Gracze *(G III)*, mesotype doleritic variety of basalt from a thin vein in melabasanite *(after* Chodyniecka 1971) varieties, as only such ones were suitable to micrometric analysis. The rocks in question belong to a melanocratic type of nepheline basanite (melabasanite) of variable amount of mafic and felsic essential components. The plagioclase and nepheline contents are most diversified. As the result, the basanites in which labradorite exceeds nepheline (Tab. 1: col. *1*—*3*) show transitions to the rocks rich in nepheline and containing only a subordinate quantity of plagioclase, usually of andesine range (Tab. 1: col. *4*). In some cases, however, the andesine disappears almost completely, and such a rock shows petrographic character of ankaratrite.

Such fluctuations in plagioclase and nepheline content are also observable in normative composition. The basanite rich in plagioclase contains more normative anorthite and less nepheline than its equivalent with prevalence of modal nepheline (Tabs 2 & 3: col. *1*—*2*).

A considerable deficiency of silica in the basanites is reflected both in the normative composition, and in the modal one, in the presence of olivine and nepheline (Tabs 1—3). This is a common feature of the Tertiary basaltic lavas of Lower Silesia, which represent Atlantic type of magmatic differentiation (*cf.* Smulikowski 1957). The dolerite basalt devoid of olivine from a thin vein cutting through the basanites at

Table 3

Mineral norms (C. I. P. W.) composition of melabasanites from Radoszowice and Gracze in weight percentages (*1*—*4* as in Table 2)

		1	2	3	4
Quartz	Q	–	–	–	3.8
Orthoolase	Or	7.2	5.3	5.0	8.3
Albite	Ab	6.2	8.0	8.6	28.3
Anorthite	An	11.6	14.3	11.3	23.9
Nepheline	Ne	14.5	11.6	10.7	–
	Σ_{Sal}	39.5	39.2	35.6	64.3
Diopside	Di	35.2	34.0	32.5	1.4
Hypersthene	Hy	–	–	–	7.8
Olivine	Ol	10.8	15.0	9.8	–
Magnetite	Mt	7.8	6.5	9.8	2.7
Chromite	Cm	–	–	0.2	0.3
Ilmenite	Il	3.2	3.0	6.2	4.6
Haematite	Hm	–	–	0.1	10.0
Apatite	Ap	2.1	1.8	2.1	1.7
Pyrite	Pr	0.04	0.04	–	–
Caloite	Co	2.0	–	3.3	4.1
	Σ_{Fem}	60.34	60.34	64.0	32.6
	Sal + Fem	99.84	99.54	99.6	96.9
Mol. An percent in normative plagioclase		64	63	55	80

1 — III (IV). 6 (7). 2 (3). 4′ [′2.2.2(3).2]
2 — III (IV). 6. 3. 4 (5) [′2.2.2.2]
3 — (III) IV. 6 (2) 3. 4 (5) [2.2.2.2]
4 — II′. 5. 3. 4.

Gracze, found by Chodyniecka (1971), is a definite deviation. There quartz is present in the normative composition of the dolerite although, in fact, it contains 9 vol. per cent of nepheline (Tab. 1: col. 5; Tabs 2 & 3: col. 4). Probably secondary alterations are the main cause of this striking discordance, what seems to be supported by a large quantity of water and trivalent iron.

PALAEOMAGNETIC INVESTIGATION

Natural remanent magnetization (NRM) has been measured by means of an astatic magnetometer *MA-21*. From each sample taken in the field, two oriented cubes with dimensions of 24 × 24 × 24 mm were cut. One of these was demagnetized with the use of alternating magnetic field (*cf.* Kądziałko-Hofmokl & al. 1972), the other with temperature. The purpose of applying both the alternating field and the thermal demagnetization, was to study the stability of NRM.

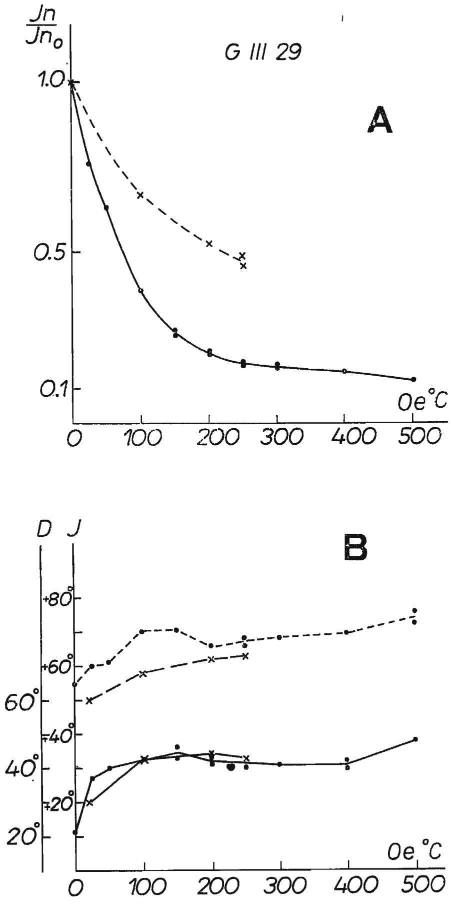


Fig. 8

Thermal and A. C. demagnetization curves for sample *G III-29*: *A* — changes in value of NRM, *B* — changes in direction of NRM

Dashed curve — thermal demagnetization; solid curve — A. C. demagnetization; *Jno* NRM before cleaning; *Jn* NRM after each cleaning step; *D* declination; *J* inclination

The alternating magnetic field demagnetization was carried out in a stepwise manner, every 50—100 Oe, with maximum amplitude of the field increasing from 50 to 500 Oe. The thermal demagnetization was performed by consecutive heating of samples in permalloy screens to temperatures of 50, 100, 150, 200, 250 and 300°C. It was expected that by using such two procedures, it would be possible to obtain the fraction of the remanent magnetization synchronous with the formation of the rock (*cf.* Pietrowa & Kruczyk 1966).

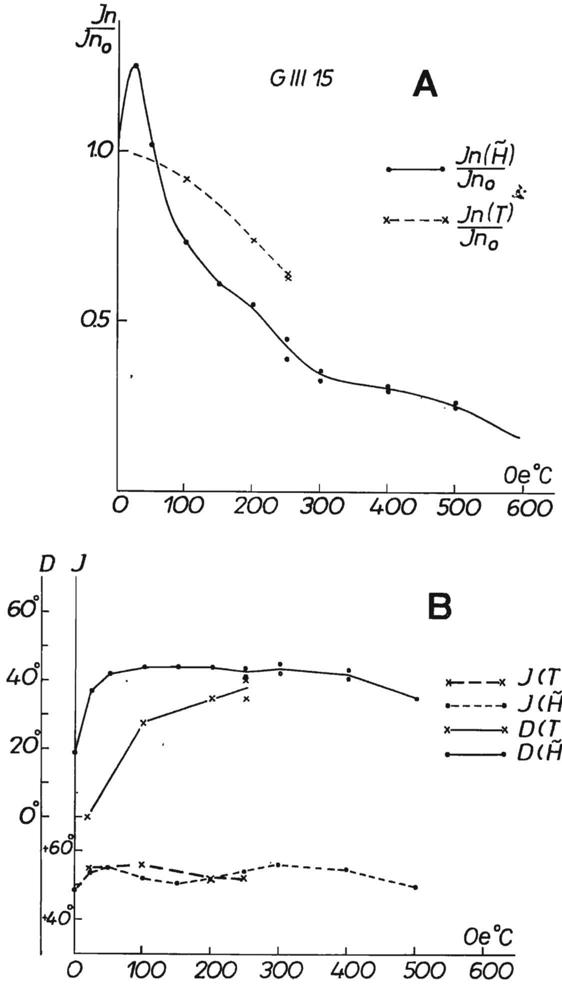


Fig. 9

Thermal and A. C. demagnetization curves for sample *G III-15*
For explanations *see* Fig. 8

Figures 8—10 present characteristic demagnetization curves. In most cases, the presence of two components of NRM with different stabilities was found. The first, less stable component, was demagnetized in the field of the order of 50—100 Oe, which was marked by a change in the *D* and

J angles (declination and inclination). This less stable component was demagnetized at temperatures of about 100°C. An application of alternating fields of more than 100 Oe and temperatures of more than 100°C did not change the NRM directions.

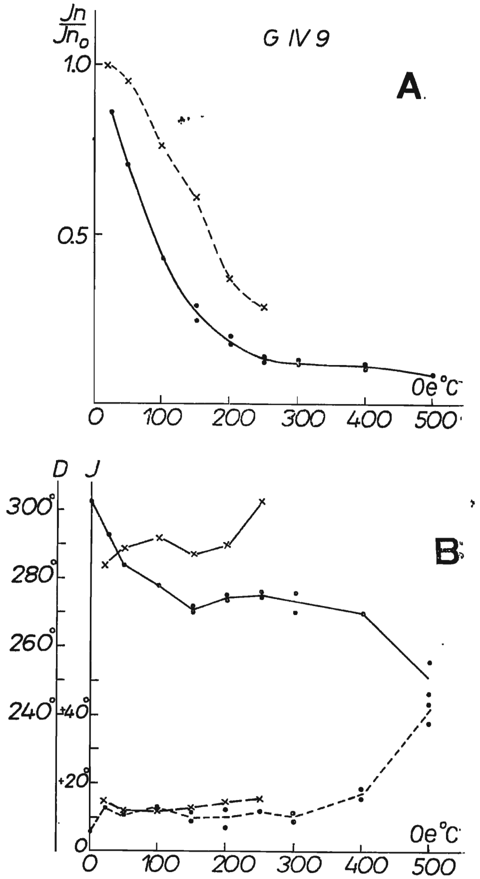


Fig. 10

Thermal and A. C. demagnetization curves for sample *G IV-9*
For explanations see Fig. 8

As a result of the above measurement, the *D* and *J* angles obtained after the demagnetization by means of alternating magnetic field of 200—250 Oe and temperature of 150—200°C were assumed to be the directions of the stable component of NRM.

Figures 11—13 present the "cleaned" NRM directions for separate groups of the rocks under investigation. The groups correspond to the sites localized in the preceding chapters. Fig. 11 gives the distribution of directions for the samples from sites *G I* and *G II*. It is supposed that in these rocks part of the primary remanent magnetization is preserved.

Figure 12 refers to site *G III*, where the following groups have been distinguished: the plug, the upper south-east lava flow, the lower north--west lava flow and the upper north-west lava flow.

Figure 13 refers to site *G IV*. The scatter of directions is here so large that the samples are unsuitable for palaeomagnetic measurements. The samples, except for a few ones, turned out to be rather unstable under alternating field demagnetization: after demagnetization with an amplitude of 200 Oe, only about 10—15 per cent of NRM was preserved. The secondary remanence with low stability prevails in the majority of samples from this site.

The least scatter of the directions of remanent magnetization was found in the samples from the plug and from the upper south-east lava flow of site *G III*. The samples from the upper- and lower north-west lava flows of site *G III*, and from the plugs of sites *G I* and *G II* show larger scatter (Fig. 11).

The majority of samples are magnetically stable when subject to demagnetization under alternating field and temperature; these samples preserved a part of the primary remanent magnetization. The directions shown in Figs 11—13 are similar to those already found in the Gracze volcanics by Birkenmajer & Nairn (1969) and Birkenmajer & al. (1970). Part of the present samples have the "cleaned" NRM directions deviating from the majority of samples. It is supposed that their NRM is either a superposition of secondary over primary remanences which have a similar stability, or is a stable secondary remanence.

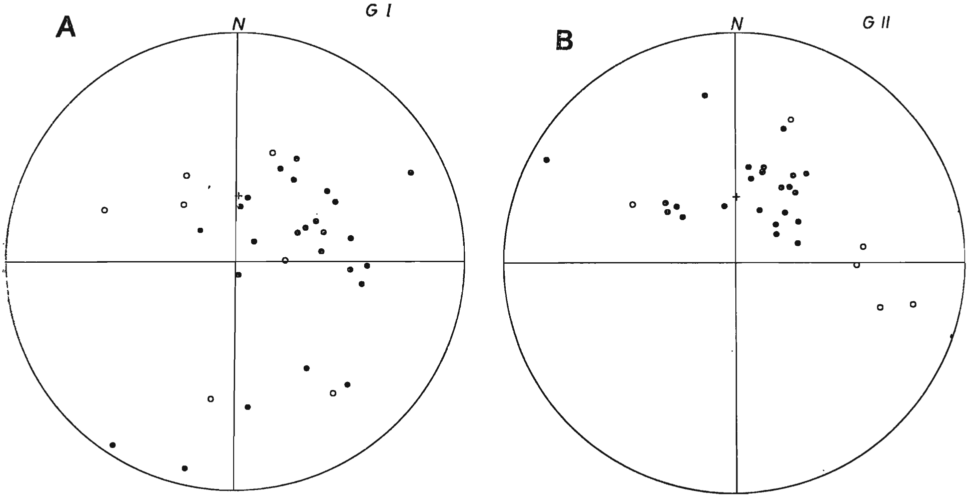


Fig. 11

Directions of NRM cleaned by temperature and A. C. field for sites *G I* and *G II*
Present geomagnetic field direction marked by cross

COMPOSITION OF MAGNETIC FRACTION

To solve the question whether the NRM found in the rocks under investigation is primary or secondary, microscopic analysis of polished sections and determination of composition of magnetic fraction were made (such investigations have been performed already for the Tertiary andesites of the Polish Carpathians — *cf.* Kruczyk 1970).

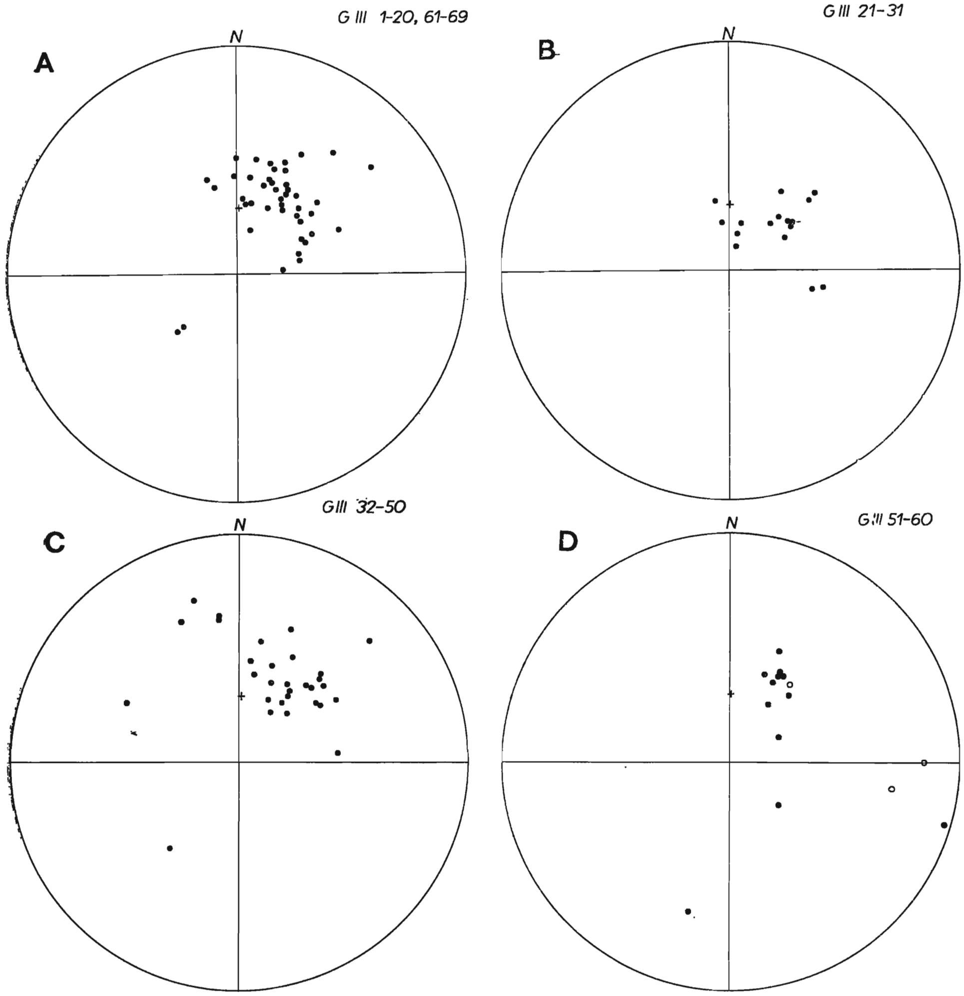


Fig. 12

Directions of NRM cleaned by temperature and A. C. field for site *G III: A* — plug, *B* — upper south-east lava flow, *C* — lower north-west lava flow, *D* — upper north-west lava flow

Present geomagnetic field marked by cross

Magnetic properties of rocks depend on the character of minerals containing Fe and Ti oxides, which form the magnetic fraction. These occur mainly in the form of two mineral series, $TiFe_2O_4$—Fe_3O_4 and $TiFeO_3$—αFe_2O_3, and constitute up to about 10 per cent of the mineral content in basalts (Hargraves & Petersen 1971). Those Fe—Ti oxidic minerals which crystallize from the magma at temperatures of more than 1000°C are titanium-rich. Formed under such conditions, the minerals of the $TiFe_2O_4$—Fe_3O_4 series are characterized by Curie temperatures from —50 to +300°C, while those of the $TiFeO_3$—αFe_2O_3 series — by temperatures from —200 to —50°C. Thus, if a rock of basaltic type has Curie temperatures higher than +300°C, its Fe—Ti oxidic minerals have been oxidized.

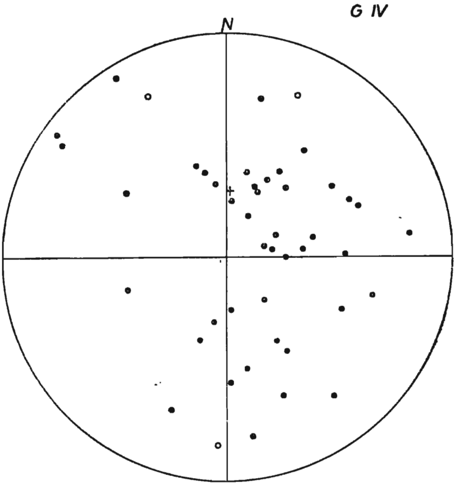


Fig. 13

Directions of NRM cleaned by temperature and A. C. field for site *G IV*
Present geomagnetic field marked by cross

At temperatures higher than 600°C (between 1000 and 600°C) — temperatures close to the Curie point of magnetite — oxidation processes in magma lead to changes in the composition of titanomagnetite and titanohaematite. The titanomagnetite oxidizes producing both the lamellae of ilmenite-rich titanohaematite and the ulvospinel-poor titanomagnetite. The oxidation of titanohaematite produces ulvospinel-poor titanomagnetite.

At temperatures below 600°C, exsolution of ulvospinel and magnetite begins in minerals of the titanomagnetite series. In minerals of the titanohaematite series this process does not occur. The resulting association of magnetic minerals contains thus both the initial and final members of the titanomagnetite and titanohaematite series.

At temperatures lower than 600°C, and in the presence of a large amount of volatiles and water solutions, the oxidation processes lead to the formation of stable titanomaghemite. This mineral may be also stabilized in the presence of kations Mg^{2+} or Al^{3+} in the lattice.

Oxidation processes at low temperatures depend on conditions to which the rock is being subject, *e.g.* on hydrothermal action. Generally, these processes develop along the same line as that described above, leading to the formation of Ti-poor titanomagnetite (resp., in the extreme case, of magnetite), and titanohaematite, which subsequently oxidize into Fe_2O_3 and TiO_2 (*cf.* Hargraves & Petersen 1971, Creer 1971).

Microscopic analysis of polished sections

On the basis of microscopic analysis of the basaltic rocks under investigations, it was found the Fe—Ti oxidic minerals constitute from 4.5 to 7 vol. per cent of the rock. These are mainly titanomagnetite represented by two generations of grains: (*a*) finer, isometric, hypautomorphic or automorphic grains with diameters of 0.001 to 0.01 mm, and (*b*) larger grains xenomorphic with numerous automorphic inclusions of non-ore minerals, with diameters of 0.01 to 0.1 mm. In all melabasanites, except for the plug *G II*, the majority of grains are the finer ones (some typical examples are shown in Pl. 4, Figs 1—2).

Thirty six polished sections were analysed[1]. In 15 samples, the presence of an optically homogenous titanomagnetite was stated. In the remaining 11 samples, bleaching of a part of titanomagnetite crystals on their whole surface, or in spots, was observed. In 5 samples, titanohaematite lamellae were found to occur in single crystals of titanomagnetite. In 4 samples there occurred both the bleaching of titanomagnetite crystals and the titanohaematite lamellae. In one sample there were observed titanomagnetite crystals with systems of exsolution titanohaematite lamellae surrounded by strong bleaching haloes.

The appearance of bleaching may indicate the formation of titanohaematite or titanomaghemite in the titanomagnetite grains. This problem can be elucidated by thermomagnetic analysis.

Thermomagnetic analysis

The thermomagnetic analysis of the basaltic rocks from Gracze consisted in studying the changes of saturation remanent magnetization I_{rs} with temperature. On curves $I_{rs}(T)$ we sought inflexion points and points in which I_{rs} decreased to zero. In the case of a single-phase ferromagnetic mineral, its Curie temperature is the temperature at which I_{rs} equals zero. In the case magnetic fraction consists of several minerals, the Curie temperatures of individual minerals are marked by the inflexion points on the $I_{rs}(T)$ curve. The $I_{rs}(T)$ curves of solid solutions of titanomagnetite,

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[1] The microscopic analysis of polished sections was made by Messrs. S. Kubicki M. Sc. and J. Siemiątkowski M. Sc. at the Geological Survey of Poland, Warsaw.

titanohaematite and titanomaghemite are devoid of inflexion points. Four kinds of magnetic fraction have been distinguished, and these are discussed below.

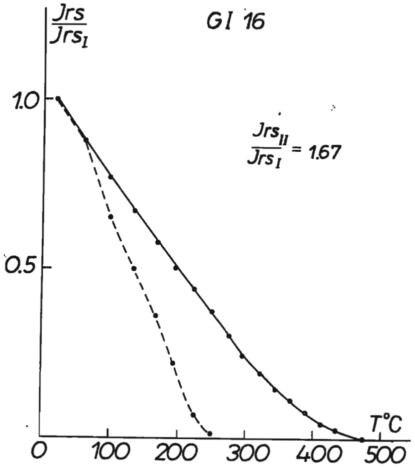

Fig. 14

Thermomagnetic curve typical for samples with single-phase titanomagnetite, sample *G I-16*

Dashed curve — first heating; solid curve — second heating; *IrsI* remanent saturation magnetization at room temperature; *Irs* remanent saturation magnetization at temperature *T*; *IrsII* remanent saturation magnetization after first heating to 600°C

(*1*) Homogenous titanomagnetite (7 samples) with single Curie point, with temperature range between 200 and 300°C, thus corresponding to titanomagnetite with 40—60 per cent of ulvospinel (Fig. 14). Characteristic for these samples is a substantial increase of I_{rs} after heating to 600° C, which indicates the oxidation of titanomagnetite and the formation of either Ti-poor titanomagnetite or magnetite during heating. This is also indicated by an increase of the Curie temperature after reheating (*cf.* Creer 1971, Kądziałko-Hofmokl & Kruczyk 1972).

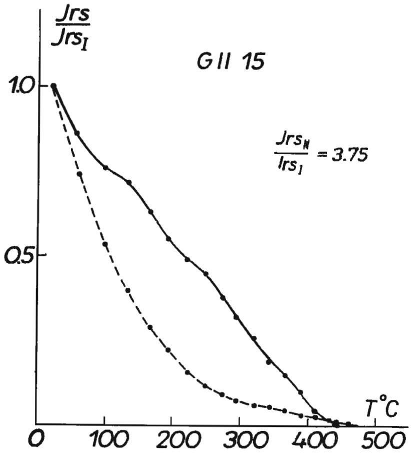

Fig. 15

Thermomagnetic curve typical for samples with two-phase titanomagnetite, sample *G II-15*

For explanations see Fig. 14

(*2*) Two-phase titanomagnetite (11 samples) with Curie temperatures between 200 and 280° C, and between 300 and 450° C (Fig. 15). It is supposed that the phase with the higher Curie point was formed as a result of partial oxidation of that with the lower Curie point. The curves of the first and second types were obtained for the samples in which an optically uniform titanomagnetite was observed on polished sections.

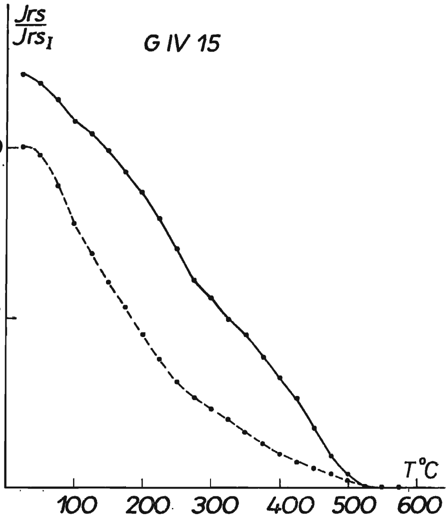

Fig. 16

Thermomagnetic curve typical for samples with titanohaematite and one- or two-phase titanomagnetite, sample *G IV-15*

For explanations *see* Fig. 14

(3) Two-phase titanomagnetite and titanohaematite (7 samples) — Fig. 16. The titanohaematite phase has a Curie temperature between 100 and 140° C. Both titanomagnetite phases are the same as those described under (2). It is supposed that a partial decay of the low-temperature phase of titanomagnetite took place, according to the reactions (*cf.* Buddington & Lindsley 1964, Unan 1971):

$$6\ Fe_2TiO_4 + O_2 \longrightarrow 2\ Fe_3O_4 + 6\ FeTiO_3 \qquad (a)$$
$$4\ Fe_2TiO_4 + O_2 \longrightarrow 4\ FeTiO_3 + 2\ Fe_2O_3 \qquad (b)$$

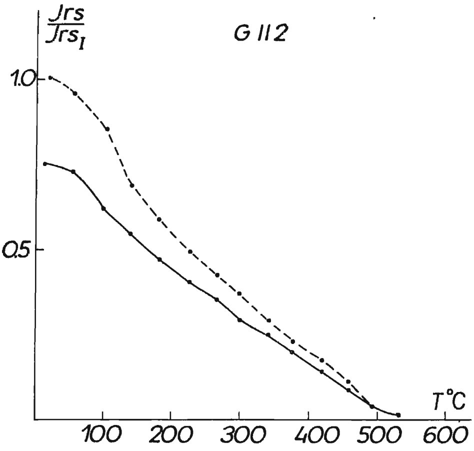

Fig. 17

Thermomagnetic curve typical for samples with supposed titanomaghemite and titanomagnetite or titanohaematite, sample *G II-2*

For explanations *see* Fig. 14

The final products of these reactions are: Ti-poor titanomagnetite and Ti-rich titanohaematite for (*a*), and Ti-rich titanohaematite and Ti-poor haematite for (*b*). Usually, both reactions take place simultaneously.

The curves shown in Fig. 16 were obtained for the samples in which titanohaematite lamellae and bleaching of titanomagnetite grains were observed on polished sections.

(4) On the thermomagnetic curves of the fourth type (3 samples) we see Curie points corresponding to low-temperature phase of titanomagnetite or titanohaematite and, also, to a high-temperature phase with Curie point of about 500° C. The shape of $I_{rs}(T)$ curves may indicate that the latter corresponds to titanomaghemite (Fig. 17). The curves of this type were obtained for the samples in which the spotty bleaching of titanomagnetite grains was observed on polished sections.

Oxidation processes of titanomagnetite in laboratory conditions were observed in some samples. These samples when heated for 24 hrs at 600° C showed characteristic titanohaematite mosaic or network conformable with the (111) planes of titanomagnetite. A titanomagnetite grain before and after heating is presented in Pl. 4, Figs 3—4.

Variability of magnetic fraction at different sites

In order to obtain more detailed information on the magnetic fraction of the studied rocks, the bivalent and trivalent iron and titanium were determined in the magnetic fraction from 25 samples [2]; the results are presented in Table 4.

Assuming that the magnetic fraction consisted of a uniform titanomagnetite of the $(1-x)Fe_3O_4 \cdot x\,Fe_2TiO_4$ series, the ulvospinel content (x) was calculated for each sample. The Curie points corresponding to various values of x were obtained on the assumption of a linear dependence between the Curie temperature of 575° C for $x = 0$, and —275° C for $x = 1$ (*cf.* Creer & Valencio 1969). Good consistency was obtained between the Curie points calculated and those measured for the samples containing homogenous titanomagnetite. For the sample with a more complex composition of the magnetic fraction, such consistency, of course, does not exist. The data concerning the Curie points are presented in Table 5.

As can be seen from Table 5, the magnetic fraction of the samples from site *G I* consists of a single- (homogenous) or two-phase titanomagnetite with low Curie points. The samples of site *G I* are not very stable: during demagnetization with alternating magnetic field and temperature, the *D* and *J* angles changed markedly; this indicates the presence of secondary remanences which is understandable in the light of the low Curie points found. The great scatter of the directions of the "cleaned" NRM observed on stereograms (*cf.* Fig. 11) is the result of the above.

The magnetic fraction from the *G II* samples is very variable. It shows the presence of the types (2), (3) and (4) — see above, with the

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[2] The determination of the bi- and trivalent iron was made by Mr. J. Pałyska M. Sc., and the determination of titanium by Mr. W. Szczepanowski, M. Sc., both from the Geological Survey of Poland, Warsaw.

Table 4

Chemical composition of magnetic fraction, melabasanites from Radoszowice (*G I*), Gracze-"Ameryka" (*G II*), Gracze, main quarry (*G III*), and Rutki (*G IV*)

Group	Sample No.		Total Fe weight %	Ti weight %	TiO_2 mol. %	Fe_2O_3 mol. %	FeO mol. %	Fe_2TiO_4 mol. %	Fe_2TiO_4 mean mol. %
G I	3		68.6	8.9	14.8	45.4	39.8	42.5	40.5
	14		68.2	9.3	15.4	45.4	39.8	44.5	
	18		67.1	7.3	12.1	47.1	40.8	35.0	
G II	1		63.0	9.4	15.6	50.3	34.1	45.0	35.0
	6		61.4	10.1	16.8	50.8	32.4	48.0	
	10		61.3	11.3	18.7	51.6	29.7	53.5	
	12		75.0	8.4	13.5	53.4	33.1	40	
	15		67.8	8.3	13.7	53.9	32.4	39.5	
	20		87.7	6.3	10.5	57.0	32.6	30	
G III	16	plug	70.3	10.0	16.6	44.9	38.5	47.5	48
	18		66.2	10.1	16.8	42.2	41.1	48	
	25	SE lava	70.9	8.6	14.2	46.7	39.1	41	39.5
	27		71.5	8.0	12.9	42.2	44.9	38	
	36	NW lower lava	70.1	10.6	17.6	44.2	38.2	50.5	45
	39		69.4	9.9	16.4	48.1	35.4	47	
	50		60.9	7.6	12.7	55.5	31.9	36.5	
	52	NW upper lava	61.3	9.1	15.2	50.7	34.1	43.5	41.5
	53		61.4	8.3	13.7	51.6	34.6	39.5	
	61	plug	71.8	9.9	16.4	41.9	41.7	47	48
	66		63.8	10.7	17.9	49.3	32.7	51	
G IV	3	plug	60.2	7.5	12.4	58.2	29.4	36	40.5
	4		68.0	8.6	14.3	48.6	37.1	41	
	10		67.0	9.4	15.6	48.3	36.0	45	
	13	lava	61.4	8.7	14.4	51.1	34.5	41.5	42.5
	15		61.5	9.2	15.2	43.1	41.6	44	

exception of type (*1*) — homogenous titanomagnetite. Probably, the oxidation processes took place partly at high, and partly at low temperatures. During the magnetic field- and thermal demagnetizations, the NRM directions did not change very much. Taking into account the scatter of the directions in Fig. 11 we can suppose that we deal here with a stable NRM, which in part of the samples is synchronous with the rocks, and in the rest of samples is secondary.

The samples taken from the plug and from different lava flows at site *G III* should be considered separately. The magnetic fraction from the plug consists of two phases of titanomagnetite. The NRM shows a good stability of directions against the demagnetizing field and temperature. Good concentration of the directions of the "cleaned" NRM (Fig. 12) ma-

Table 5

Curie temperatures measured and calculated, melabasanites from Radoszowice (*G I*), Gracze-"Ameryka" (*G II*), Gracze, main quarry (*G III*), and Rutki (*G IV*)

Group	Sample No.		T_c measured /centigrades/			T_c calculated /centigrades/	T_c from mean comp. /centigrades/
G I	12		–	260	370	–	290
	13		–	280	–	–	
	14		–	250	–	260	
	16		–	230	–	–	
G II	1		–	260	520	260	330
	2		140	–	500	–	
	15		–	280	450	300	
	17		–	250	400	–	
	19		100	250	520	–	
	20		90	220	400	360	
G III	4	plug	–	260	400	–	250
	13		–	280	450	–	
	14		–	260	380	–	
	15		–	260	450	–	
	16		–	200	300	240	
	18		130	220	300 /trace/	240	
	61		–	220	380	–	
	66		–	250	450	200	
	68		–	220	340	–	
	23	SE lava	–	260	–	–	300
	36	NW lower lava	110	–	500	220	260
	38		100	320	520	–	
	52	NW upper lava	150	220	450	270	290
	53		–	300	–	300	
	54		–	200	400	–	
G IV	3	plug	140	260	340	320	290
	8		–	270	–	–	
	9		110	260	350	–	
	11	lava	130	270	320	–	280
	12		–	–	350	–	
	13		110	240	380	290	
	15		160	250	360	270	

kes it possible to conclude that, in the plug, the primary remanent magnetization is preserved. The oxidation processes which produced two phases of titanomagnetite took place at high temperatures.

The samples of the lava flows from site *G III* have a variable magnetic fraction (*cf.* Tab. 5). However, they are stable under the demagnetizing action of the alternating field and temperature. As it appears from the distribution of the "cleaned" directions of NRM (Fig. 12), the majority of these samples show the presence of the primary NRM connected either

Table 6

Palaeomagnetic directions and pole positions for melabasanites of Radoszowice (*G I*), Gracze-"Ameryka" (*G II*) and Gracze, main quarry (*G III*); φ — 50.7° N, λ — 17.3° E.

Site	Volcanic form	N	D	J	K	α	Φ	Λ	Θ_1	Θ_2
G I	plug	19	60°	+60°	13.2	10	48.6°N	96.9°E	14.6°	11.1°
G II	plug	18	30	+56	29.2	7	64.5°N	128.8°E	9.4	6.8
G III	plug	43	30	+55	24.7	4	63.3°N	130.8°E	6.3	4.5
	SE upper lava	15	37	+64	37.2	6	65.3°N	103.6°E	10.2	8.1
	NW lower lava	23	35	+52	34.5	5	59.2°N	129.4°E	7.2	4.9
	NW upper lava	11	34	+53	90.9	5	60.1°N	129.9°E	6.6	4.6

Palaeomagnetic pole for *G I* — *G III* sites: $N = 129$; $D = 36$; $J = +57$; $K = 23.1$; $\alpha = 3$; $\Phi = 61.3$N; $\Lambda = 121.7$E; $\Theta_1 = 3.8$; $\Theta_2 = 2.7$

Table 7

Some European Cenozoic palaeomagnetic directions and pole positions

Location	Rock unit	Age	Directions of magnetization		Polarity	Palaeo-magnetic pole	Reference
			D	J			
Bulgaria /41°N-25°E/	Andesites	Oligocene	19	+61	N	76°N-105°E	McElhinny, 1968
Scotland /56.4°N-5.8°W/	Mull intrusives	Eocene-Oligocene	16	+60	N	72°N-133°E	Irving, 1964
Scotland* /55.5°N-7.2°W/	Arran dykes	Eocene-Oligocene	7	+63	N	78°N-149°E	Irving, 1964
British Isles /56°N-5°W/	Tertiary igneous rocks combined	Eocene-Oligocene	6	+63	N	78°N-153°E	Irving, 1964
Germany /50.3°N-7°E/	Igneous rocks, Eifel	Oligocene-Recent	26	+66	N	73°N-92°E	Irving, 1964
Germany /50.7°N-8°E/	Igneous rocks, Westerwald	Oligocene-Miocene	23	+55	N	68°N-132°E	Irving, 1964
Germany /50.7°N-7.5°E/	Igneous rocks, Siebengebirge	Oligocene-Miocene	34	+61	N	65°N-104°E	Irving, 1964
Germany /50.6°N-7.5°E/	Igneous rocks, Rheinland, Pfalz	Oligocene-Quaternary	28	+62	N	70°N-108°E	Irving, 1964
Denmark /62°N-7°E/	Faeroe Islands volcanics	Eocene	-	-	N	77°N-161°E	McElhinny, 1972

* K-Ar dating of Arran rocks given ages 55—65 My (Sabine & Watson 1965).

with homogenous titanomagnetite or with the products of its oxidation at high temperatures. Moreover, we may suppose that a part of the samples were altered at low temperatures, which could account for the observed scatter of the NRM directions (*e.g.* the upper north-west lava).

The magnetic fraction of the samples from site *G IV*, both from the plug and the lava flow, consists of three phases (except for two samples): two-phase titanomagnetite and titanohaematite. An analysis of the polished sections confirms the assumption that these rocks are highly oxidized. Titanohaematite lamellae or the bleaching of titanomagnetite grains were observed in all samples from this site. The observed scatter of NRM directions (Fig. 13) and the low magnetic stability suggest that the secondary changes in magnetic fraction occurred at relatively low temperatures.

The results of the investigations described above indicate that, in the majority of samples from sites *G I*, *G II* and *G III*, part of the natural remanent magnetization is preserved. Its carrier is the primary titanomagnetite containing 40—60 per cent of ulvospinel. This remanence is sufficiently stable to be used for determination of the position of the geomagnetic pole at the period of rock formation. The results are given in Table 6.

The data obtained for the samples from site *G IV* were not taken into account in the calculations, because of the great scatter of the NRM directions. The latter is due to the secondary changes in the magnetic fraction.

CONCLUSIONS

The petrographic analysis showed that the basaltic rocks from Gracze and its vicinity are melanocratic lavas belonging to basanite (melabasanite) which locally pass into ankaratrite.

The present palaeomagnetic measurements confirm the results of earlier investigations (Birkenmajer & Nairn 1969, Birkenmajer & al. 1970) that the melabasanite plugs of Gracze are normally magnetized, and belong to the same palaeomagnetic epoch.

The melabasanite lava flows of the biggest exposure, *G III*, are alsc normally magnetized and show values for *D* and *J* similar to those of the plugs.

The similarity of palaeomagnetic results is consistent with the suggestion based on geological grounds that both the lava flows and the plugs originated in the same palaeomagnetic epoch. This is also confirmed by petrological investigations which show close affinities of all the rocks sampled (melabasanites with local transitions to ankaratrites).

The geological age of the palaeomagnetic epoch represented by the results from Gracze cannot yet be solved due to the lack of radiometric dating. The volcanic events cannot be older than Upper Cretaceous (Coniacian), but most probably are Tertiary. This is confirmed by comparison of palaeomagnetic data from Gracze (Tab. 6) with those available from the Tertiary rocks of Europe (Tab. 7).

A relatively small scatter of the NRM directions from the upper south-east lava at site *G III*, which shows a steep dip of about 45 degrees (Fig. 12), indicates that the tilt of the lava is primary.

The primary NRM is supposed to be connected with the products of oxidation of the lava at high temperatures, before its consolidation. Our investigation shows that in order to state whether the stable part of NRM dates from the period of lava consolidation or not, it is necessary to perform thorough examination of the composition and structure of the magnetic fraction.

An interrelation of composition (and, consequently, the Curie points) of the primary, single-phase titanomagnetite and the depth of magmatic chamber for basaltic lavas is suggested by Bagin & al. (1970). Using the data presented by them, and assuming that the single-phase titanomagnetite with a Curie point of 250—350° C is primary, we found that the magmatic chamber for the basaltic lavas of Gracze was located at a depth of 30—46 km, possibly slightly below the Moho discontinuity. The latter was estimated on deep seismic soundings to occur in the Odra fault region at a depth of about 30—32 km (Guterch & al. 1972).

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PALEOMAGNETYZM I WŁASNOŚCI MAGNETYCZNE TRZECIORZĘDOWYCH SKAŁ BAZALTOWYCH Z GRACZY NA DOLNYM ŚLĄSKU

(Streszczenie)

Trzeciorzędowe skały bazaltowe z Graczy w okolicach Opola na Dolnym Śląsku należą do wschodniego zakończenia środkowo-europejskiej prowincji wulkanicznej i stanowią część pasa czesko-śląskiego. Są to czopy, wypełnienia kraterów wulkanicznych i pokrywy lawowe melanokratycznej odmiany bazanitu nefelinowego (melabazanitu) z lokalnymi przejściami do ankaratrytu.

W pracy opisano: (*a*) badania paleomagnetyczne oparte na pomiarach kierunku naturalnego namagnesowania szczątkowego skał i ich stabilności magnetycznej, (*b*) badania własności magnetycznych skał bazaltowych w zależności od ich składu mineralnego. Te ostatnie badania obejmują: pomiary zmian parametrów nasycenia jako funkcji temperatury; określenie punktów Curie; określenie zawartości Fe i Ti we frakcji magnetycznej; analizę mikroskopową naszlifów w świetle odbitym.

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