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Neoproterozoic flood basalts of Zabolottya and Babino Beds of the volcanogenic Volhynian Series and Polesie Series dolerites in the western margin of the East European Craton

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ABSTRACT:

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In the Volhynia region, on the western slope of the Ukrainian Shield, occurs a large complex of Lower Neoproterozoic III (Lower Vendian) effusive-tuffogenic rocks, referred to the Volhynian Series. This series belongs to a large province of flood basalts extending over an area of ca 140 000 km^2 in the western part of the East European Craton. The series is underlain by the terrigenous rocks of the Polesie Series, with volcanic ashes and dolerites in its upper part. The effusive-tuffogenic rocks of both series, together with hypabyssal dolerites, represent the Volhynian Trap Formation. Within the lower – Zabollotya and Babino Beds of the Volhynian Series there have been found alkali basalts and olivine tholeiites, whereas the basalts of the upper, Ratno Beds are quartz tholeiites exclusively. All the basalts are mainly within plate continental basalts. The diversity of basalt composition within the Volhynian Series suggests that in the Early Vendian, during the process of formation of parent magmas for basalts of particular beds, the mantle material beneath Volhynia has been melted to various degrees. Distinct variability can also be observed in basaltic pyroxene composition (particularly in the Babino and Ratno Beds) as well as in variations of REE distribution patterns in the studied basalts. Most likely, the strongly differentiated pyroxenes were not in a state of equilibrium with the magma. The native copper mineralization of basalts from the Ratno, Babino and Zabolottya Beds is described. Higher concentration of Au and Ag in the rocks with a high content of copper supports the hypothesis that the mineralizing hydrothermal solutions originated in a common igneous source. The Vendian magmatic activity in the study area was associated with the last stages of breakup of the Rodinia supercontinent.

Key words: Volhynian Series, Polesie Series, Volhynian Trap Formation, Zabolottya Beds, Babino Beds, Riphean dolerites, flood basalts, Rodinia breakup.

INTRODUCTION

Two large terranes of the East European Craton, Fennoscandia and Sarmatia, were joined together during the Late Palaeoproterozoic, between 2.0 and 1.7 Ga ago (BOGDANOVA 1999). Along the Fennoscandia–Sarmatia Suture (FSS), the Sarmatian crust is mainly Archean, whereas the Fennoscandian one is mainly

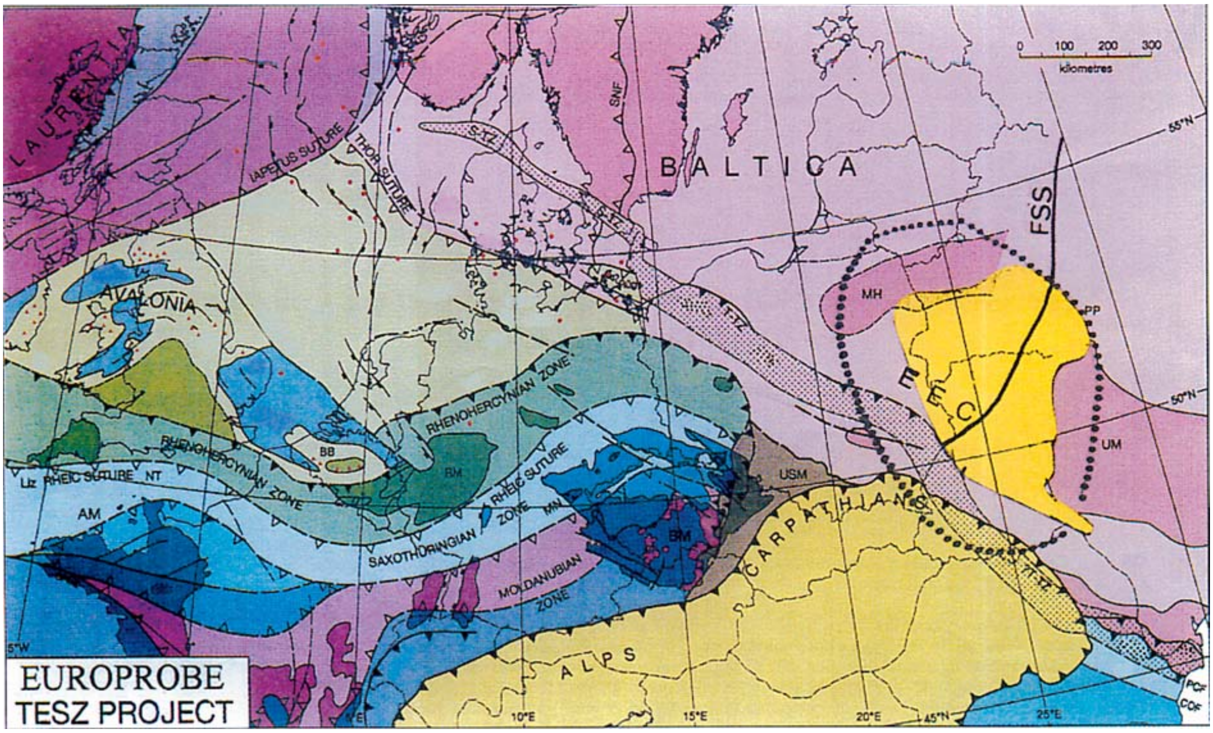

Fig. 1. Tectonic sketch map of the Trans-European Suture Zone and adjacent areas, according to Pharaoh (1999), modified by Białowolska *& al.* (2002). Oceanic sutures, open ticks; orogenic frontal zones, filled ticks. Proterozoic-Palaeozoic tectonic elements: AM- Armorican Massif; BB- Brabant Massif; BM- Bohemian Massif; EEC- East European Craton; FSS- Fennoscandia-Sarmatia Suture (Bogdanova 1999); MH- Mazurska High; PP- Pripyat Trough; RM- Rhenish Massif; SNF- Sveconorwegian Front; S-TZ- Sorgenfrei-Tornquist Zone; T-TZ- Tornquist-Teisseyre Zone; UM- Ukrainian Shield; USM- Upper Silesian Massif. Deep yellow colour in western margin of EEC stands for the extension of flood basalts of the Volhynian Series according to Biryulev (1969); the dotted line delineates the maximum area of occurrence of pyroclastics connected with the Vendian volcanic activity

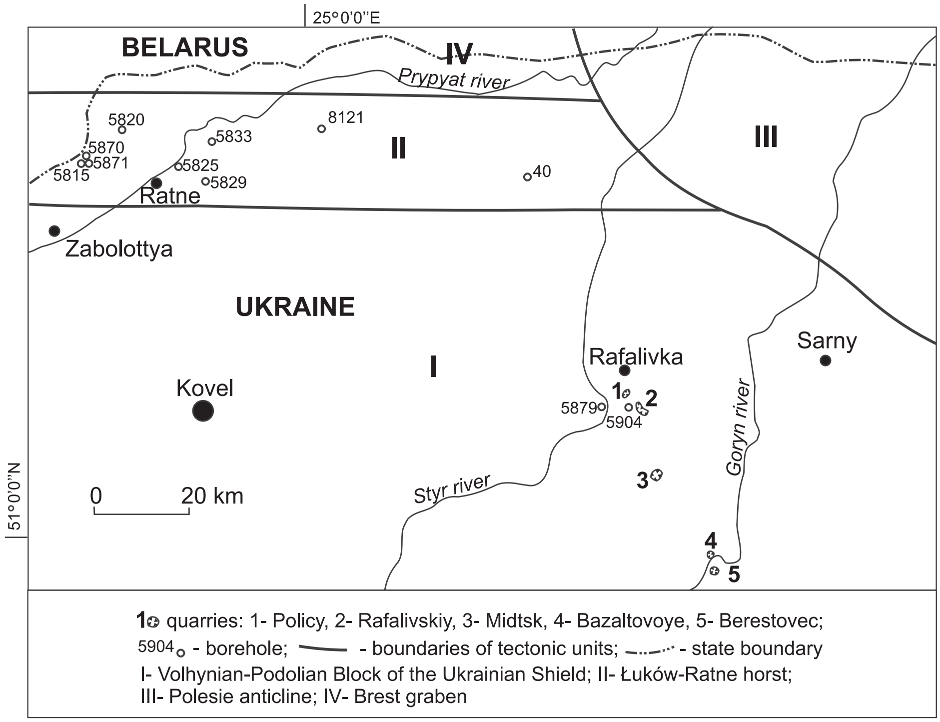

Fig. 2. Tectonic sketch map of the area of investigations in the northwest Ukraine

Palaeoproterozoic. During the Late Mesoproterozoic (1.3–1.0 Ga), the Orsha–Volhynia aulacogen developed along the FSS (ŻELAŹNIEWICZ 1998). Most likely, the faulting and rifting in the FSS was rejuvenated at the end of the Riphean, resulting in an intensive Early Vendian basaltic volcanism in the western part of the East European Craton, with the covered area estimated at about 140 000 km^2 (BIRYULEV 1969; cf. Text-fig. 1). In the Ukrainian territory (Volhynia), the volcanism resulted in a complex of effusive-tuffogenic rocks, which comprises basalts, their breccias and tuffs, known collectively as the Volhynian Series (with basalts occurring at its top). These basalts crop out and are exploited in numerous quarries (Basaltovoye, Policy and Ivance). The basalts are also known from borehole 5879 on the left bank of the River Styr (Text-fig. 2); these belong to the Ratno Beds (Text-fig. 3) and were studied previously (BAKUN-CZUBAROW *& al*. 2000, 2001; BIAŁOWOLSKA *& al.* 2002).

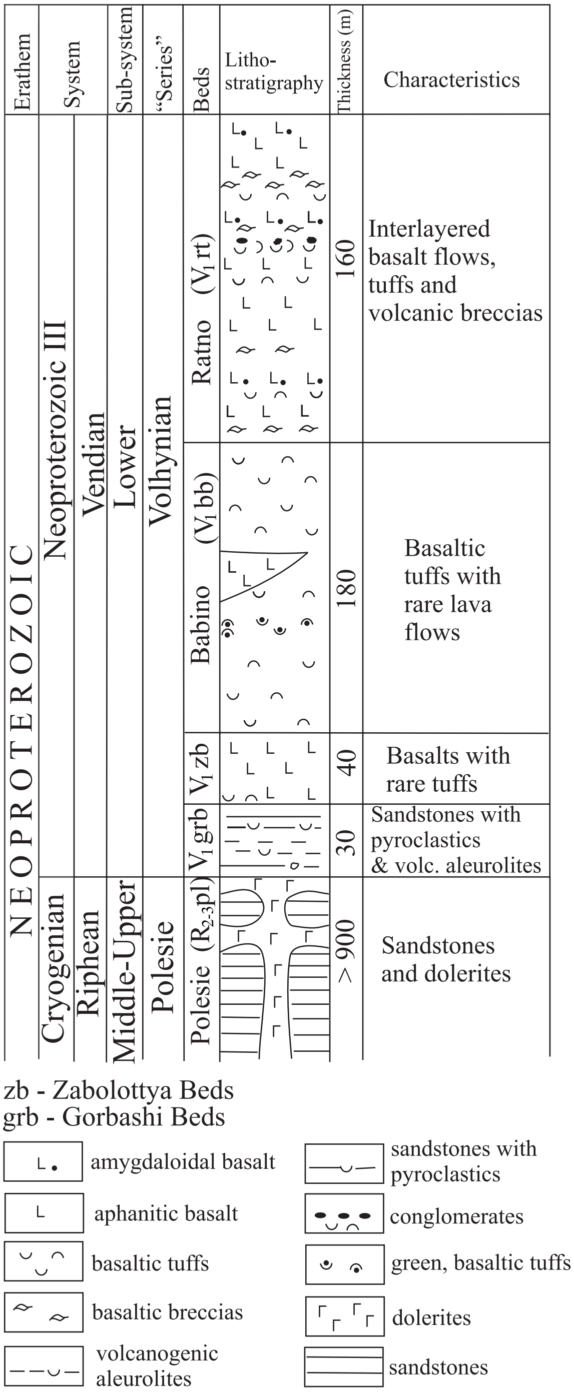

Fig. 3. A generalized cross-section of the Volhynian Series and the underlying Polesie Series on the western slope of the Ukrainian Shield, according to Ya. KOSOVSKI (unpublished), modified by the authors

Although the basalts of the Volhynian Series were intensively studied (e.g. KAMIEŃSKI 1929; KRAJEWSKI 1935; SAMSONOWICZ 1936; JANCZEWSKI & SAMSONOWICZ 1936; MAŁKOWSKI 1923, 1926, 1951; LAZARENKO *& al.* 1960; VOLOVNIK 1971, 1975) most of the researchers referred only to the basalts of the Ratno Beds.

The extention of the Volhynian Series in eastern Poland is known as the volcanogenic Sławatycze Series, found exclusively in boreholes (JUSKOWIAKOWA 1971; SZCZEPANOWSKI 1977).

The aim of the present paper is a comprehensive petrological study of basalts of the Volhynian Series of northwest Ukraine (Text-figs 1-2), with the focus on basalts from the Zabolottya and Babino Beds and dolerites of the Polesie Series. Geochemical and petrographical characteristics of these rocks is given and the palaeogeotectonic position of magmatism, together with magma generation and differentiation processes, are discussed. In addition, the problem of the origin of native copper mineralization in some basalts is discussed.

GEOLOGICAL SETTING OF THE STUDIED DOLERITES AND BASALTS

ALENKO *& al.* (1990) divided the Volhynian Series into the Gorbashi, Zabolottya, Babino and Ratno Beds (Text-fig. 3). The Gorbashi Beds are represented by partly tuffogenic sedimentary rocks and are transitional between the terrigenous deposits of the Polesie Series (sandstones and mudstones) and the effusive-tuffogenic deposits of the upper Volhynian Series. The upper part of the Gorbashi Beds contains laminae and nests of volcanic ashes and tuffs, that form up to 40-50 vol. % of the deposits (VLASOV *& al* 1972). The profile of borehole 8121, described below, is representative for the transition between the Polesie and Volhynian Series as well as for the sequence of beds in the Volhynian Series (although the Zabolottya Beds are lacking in this profile).

Borehole 8121 entered the top of the Polesie Series at the depth of 351 m, penetrating this series to the depth of 432 m. Hypabyssal rocks, assigned to the Riphean, occur locally near the top of the Polesie Series. Their presence was documented by the borehole 40, where they occur at a shallow depth, less than 140 m. The deposits from the Polesie Series in borehole 8121 are brownish fine-grained sandstones interlayered with fine-grained reddish-brown mudstones. The Gorbashi Beds, about 28 m thick, are represented by sandstones, conglomerates and brownish-red tuffs. Above the Gorbashi Beds, between 323 and 240 m depth lie the Babino Beds. These are thinly bedded tuffs with rare lava flows and tuffogenic-sedimentary rocks, massive and brownish in colour. Layers of conglomerates not exceeding 1 m in thickness, may be observed there. The Babino Beds are covered by the Ratno Beds composed of basalts, their breccias and tuffs. Cretaceous deposits lie discordantly on the Ratno Beds. In the contact zone, the basalts are sometimes strongly altered. In the depth interval from 210 to 197 m they are mineralized with native copper.

The basalts of the Zabolottya and Babino Beds, studied in the present paper, occur in the lower part of the Volhynian Series. The Zabolottya Beds display an average thickness of about 40 m and contain volcanogenic material with a distinct predominance of basalts. In the Babino Beds, ranging in thickness between 100 and 200 m, basalts are subordinate in their abundance relative to tuffs (Text-fig. 3). In that aspect they differ both from the basalts of the Zabolottya Beds and those of the Ratno Beds, the latter situated at the top of the Volhynian Series and studied earlier by the authors of the present paper (BIAŁOWOLSKA *& al.* 2002).

METHODS OF INVESTIGATIONS

150 thin sections from different types of basalts from the Zabolottya and Babino Beds of the Volhynian Series and of the dolerites of the Polesie Series were studied microscopically, both in transmitted and reflected light.

Bulk chemical composition (major, minor and some trace elements) of the selected basalts (7 samples) was analyzed by means of ICP-AES (inductively coupled plasma – atomic emission spectrometry), and the trace elements including REE were analyzed by the use of ICP-MS (-mass spectrometry) technique at the Activation Laboratories Ltd., Canada, via Laboratory for Geochemical–

	Babino Beds		Zabolottya Beds			Riphean dolerites	
	B 5871/426	B 5870/453	Z 5871/519	Z 5820/497	Z 5815/529	Rd 40/119	Rd 40/133
SiO_2	46.58	45.99	48.89	46.65	48.27	45.58	44.24
TiO_2	1.50	1.40	1.22	1.30	1.36	3.57	3.63
Al_2O_3	15.10	15.63	13.94	14.95	14.48	15.69	15.87
Fe_2O_3	13.00	12.29	11.19	8.75	11.12	12.81	13.11
MnO	0.27	0.17	0.33	0.24	0.22	0.17	0.23
MgO	5.93	5.45	9.30	9.92	7.90	4.83	5.76
CaO	8.42	8.94	4.40	8.36	5.37	9.15	7.15
Na_2O	3.05	2.93	3.98	2.80	4.49	2.83	2.72
K_2O	1.15	0.98	1.87	0.33	1.67	1.13	1.21
P_2O_5	0.29	0.25	0.19	0.20	0.20	0.52	0.58
LOI	4.26	4.30	4.74	6.45	5.25	3.30	5.62
Sum	99.55	98.33	100.05	99.95	100.33	99.58	100.12
CIPW norms							
Qtz	-	-	-	-	-	-	-
Or	7.20	6.22	11.69	2.10	10.46	7.01	7.65
An	25.50	28.50	15.45	29.30	15.25	28.03	29.38
Ab	27.30	26.57	35.55	25.47	37.24	25.08	24.58
Di	13.78	14.27	5.14	11.22	9.38	13.30	4.00
Hy	9.54	9.75	6.93	16.32	-	11.72	17.04
Ol	6.31	5.02	15.85	8.21	16.31	1.13	3.41
Mt	6.69	6.24	6.51	4.26	6.56	5.43	5.22
Ilm	3.02	2.85	2.45	2.66	2.74	7.11	7.37
Ne	-	-	-	-	1.60	-	-
Ap	0.67	0.59	0.44	0.47	0.46	1.19	1.35
mg	57.6	56.6	72.6	76.5	69.5	50.8	53.9

Table 1. Chemical composition of the basalts from the Babino and Zabolottya Beds as well as of the Riphean dolerites (wt %%) together with the CIPW norms; in the sample numbers the first number stands for the borehole number, whereas the second one indicates the depth of the sample

Mineralogical Analyses in Cracow. The microprobe chemical analyses of basaltic minerals were carried out with the JEOL scanning electron microscope JSM 840 A equipped with the energy-dispersive analytical system LINK AN 10000/85 S at the Laboratory of Scanning Electron Microscopy and Microanalysis, Institute of Geological Sciences, Polish Academy of Sciences. Operating conditions: 15 kV accelerating voltage, 3.5 x 10^{-9}A beam current and 100 s life time were applied. Natural minerals, as well as metals, synthetic silicates and oxides were used as standards. The ZAF program on-line was used for raw data corrections. The data in Tables 3-7 are representative for 25 samples of basalts, for which over 900 microprobe analyses of minerals are available.

PETROGRAPHY AND MINERAL CHEMISTRY

Dolerites of the Polesie Series

The dolerites of the Polesie Series form veins which cut the terrigeneous deposits (Text-fig. 3). Samples of these rocks come from the following depths in borehole 40: 119 m, 121m, 127 m and 133 m (samples Rd 40/119, Rd 40/121, Rd 40/127, and Rd 40/133 respectively). Samples Rd 40/119 and Rd 40/121 represent the medium-grained dolerites, and Rd 40/127 and Rd 40/133 are fine-grained dolerites. Both doleritic varieties display an ophitic texture (Pl. 1, Figs 1-2). No essential difference is

	Babino Beds		Zabolottya Beds			Riphean dolerites	
	B 5871/426	B 5870/453	Z 5871/519	Z 5820/497	Z 5815/529	Rd 40/119	Rd 40/133
Sc	31	29	32	33	33	26	28
Ti	9050	8390	7310	7790	8150	21400	21760
V	298	285	246	266	268	352	331
Cr	53	95	281	326	262	125	68
Mn	2090	1320	2560	1860	1700	1320	1780
Co	61	50	37	41	40	49	56
Ni	114	118	96	104	76	75	73
Cu	1185	65	88	53	752	56	125
Zn	107	95	65	97	69	129	141
Ag	0.4	bdl	bdl	bdl	0.5	bdl	bdl
Ga	25	24	17	21	20	26	24
Ge	1.4	1.2	1.3	1.5	1.4	1.6	1.3
Rb	19	12	46	3	40	20	22
Cs	bdl	bdl	0.5	bdl	17	0.2	bdl
Sr	359	391	399	349	522	488	478
Ba	518	486	790	247	476	511	563
Y	26.4	24.7	20.0	20.8	23.2	29.2	28.6
La	26.4	26.9	17.3	16.3	19.8	25.3	26.7
Ce	50.8	50.0	34.8	34.4	39.5	53.0	52.8
Pr	6.3	5.9	4.5	4.4	5.0	7.1	7.73
Nd	27.5	25.9	19.2	19.7	21.5	33.8	34.9
Sm	5.2	4.9	4.3	4.2	4.8	7.0	7.31
Eu	1.8	1.7	1.5	1.5	1.6	3.1	3.08
Gd	4.9	4.7	4.1	4.2	4.7	6.5	6.47
Tb	0.9	0.8	0.7	0.7	0.8	1.1	1.06
Dy	5.0	4.5	4.0	4.0	4.4	6.1	5.52
Ho	1.0	0.9	0.8	0.8	0.9	1.1	1.05
Er	2.7	2.5	2.1	2.1	2.4	2.9	2.73
Tm	0.4	0.4	0.3	0.3	0.3	0.4	0.371
Yb	2.6	2.2	1.8	2.0	2.1	2.2	2.24
Lu	0.4	0.4	0.3	0.3	0.3	0.3	0.317
Zr	142	134	108	118	133	201	207
Hf	3.8	3.7	2.8	3.1	3.5	5.3	4.0
Nb	17.9	16.5	6.8	7.0	8.3	22.4	27.8
Th	1.9	1.9	1.5	1.5	1.7	1.6	1.64
U	0.4	0.4	0.3	0.3	0.3	0.4	0.47

bdl- below the detection limit

Table 2. Minor and trace element contents in basalts from the Babino and Zabolottya Beds and in the Riphean dolerites (in ppm)

	1	2	3	4	5	6	7	8	9	10
SiO_2	56.48	49.87	54.32	57.87	51.10	54.80	57.95	50.67	52.46	49.87
TiO_2	0.11	0.19	0.09	0.17	0.19	0.13	0.23	0.10	0.19	0.14
Al_2O_3	26.30	30.98	28.07	25.53	29.65	27.40	25.01	30.34	28.67	30.53
FeO	0.88	0.94	1.25	1.14	1.03	0.90	1.42	0.65	1.26	0.95
CaO	9.70	14.80	10.77	8.29	14.38	11.34	8.48	15.07	13.35	15.74
Na_2O	5.74	2.91	4.85	6.41	3.27	4.72	6.27	2.99	3.83	2.81
K_2O	0.50	0.19	0.53	0.90	0.34	0.44	0.91	0.23	0.39	0.18
Sum	99.71	99.88	99.88	100.01	99.96	99.77	100.27	100.05	100.15	100.22
cations per 8 oxygens										
Si	2.558	2.288	2.469	2.605	2.342	2.491	2.613	2.318	2.395	2.287
Al	1.404	1.675	1.504	1.354	1.602	1.468	1.329	1.636	1.543	1.650
Ti	0.004	0.007	0.003	0.006	0.007	0.004	0.008	0.003	0.007	0.005
Fe	0.033	0.036	0.048	0.043	0.039	0.034	0.054	0.025	0.048	0.036
Ca	0.471	0.727	0.524	0.400	0.706	0.552	0.410	0.739	0.653	0.773
Na	0.504	0.259	0.427	0.559	0.291	0.416	0.548	0.265	0.339	0.250
K	0.029	0.011	0.031	0.052	0.020	0.026	0.052	0.013	0.023	0.011
An	46.9	72.9	53.4	39.5	69.4	55.6	40.6	72.6	64.4	74.8
Ab	50.2	26.0	43.5	55.3	28.6	41.8	54.2	26.1	33.4	24.2
Or	2.9	1.1	3.1	5.2	2.0	2.6	5.2	1.3	2.2	1.0

1-2 – plagioclases from basalt sample no. Z 5820/497 (borehole 5820, depth 497.2 m); 3-4 – plagioclases from basalt sample no. Z 5870/547 (borehole 5870, depth 547 m); 5 – core of plagioclase grain from basalt sample no. B 5870/453 (borehole 5870, depth 453 m); 6 – rim of plagioclase no. 5; 7 – fine plagioclase lath in basalt sample no. B 5870/453; 8 – relict of plagioclase in basalt sample no. B 5870/453; 9 – plagioclase in basalt sample no. B 5871/422 (borehole 5871, depth 422 m); 10 – plagioclase from Riphean dolerite sample no. Rd 40/119 (borehole 40, depth 119 m)

Table 3. Representative microprobe analyses of plagioclases from basalts of the Zabolottya and Babino Beds of the Volhynian Series and the Riphean dolerite (wt %%)

present in their mineral composition. Plagioclases and clinopyroxenes are the main minerals, and iron and titanium oxides are accessory. Alkali feldspars, chlorite and biotite are subordinate. The two latter secondary minerals are most abundant in the fine-grained dolerites. Also present is brown, commonly recrystallized palagonite, occurring in oval aggregates (Pl. 1, Figs 3-4). The habit, texture (curved cracks) and composition of the palagonite aggregates suggest that these may be pseudomorphs after olivine. Plagioclase in the medium-grained dolerite has the composition of andesine (An_{42-50}), and, more rarely, bytownite (An_{71-77}). Plagioclase in the fine-grained dolerites is of labradorite composition (An_{52-65}). Clinopyroxenes in both dolerite types have the same composition, corresponding to augite.

The chemical composition of the dolerites is shown in Tables 1 and 2, and the composition of their minerals is shown in Tables 3, 4 and 6.

Basalts from the Zabolottya and Babino Beds of the Volhynian Series

The basalts, studied here, from the Zabolottya and Babino Beds of the Volhynian Series were encountered in numerous boreholes (e.g. 5815, 5820, 5825, 5870, 5871 and 8121) in the Volhynia (Text-fig. 2). Chemical composition of selected basalt samples from the Zabolottya Beds and from the Babino Beds is shown in Tables 1 and 2.

Basalts from the Zabolottya Beds

Borehole 5815, depth 546.5-523.4 m: At the depth of 546.5 m the basalts are altered and display an amygdaloidal texture. Pyroxenes are scarce and olivine is absent. The amygdales are 5–6 mm in size and are filled with chalcedony. At depth 543–524 m the basalts are relatively poor in the altered volcanic glass, being similar to the dolerites in their grain size. Their normative composition corresponds to alkali basalt (Table 1). The abundance of the altered glass increases toward the top of the interval considered, which proves the lower crystallinity of these rocks. The degree of alteration of the basalts also increases, leading to a total replacement of glass, and a partial replacement of clinopyroxene grains and plagioclase laths, by chlorite, montmorillonite and ore minerals. Palagonite is strongly replaced by chlorite aggregates. The contact of the basalts with the overlying tuffs is seen at 523.4 m depth. The basalts in the contact zone (the top of the flow) are aphyric and totally altered into an opaque, brownish montmorillonite aggregate.

		1	2	3	4	5	6	7	8	9	10
SiO_2		51.86	50.71	48.25	48.23	48.86	53.63	53.21	52.32	50.18	49.76
TiO_2		0.58	1.15	0.84	1.70	1.56	0.39	0.56	0.66	1.12	1.55
Al_2O_3		2.16	1.64	5.29	4.12	3.22	1.77	1.49	1.79	1.75	2.34
Cr_2O_3		0.40	0.10	0.08	0.02	0.03	0.60	0.02	0.20	0.00	0.12
FeO		7.62	12.33	17.55	12.30	15.88	7.70	9.55	11.98	14.23	11.73
MnO		0.11	0.35	0.49	0.30	0.34	0.24	0.32	0.37	0.36	0.23
MgO		15.86	14.48	10.45	12.03	11.17	17.30	16.19	16.29	11.39	12.04
CaO		20.08	17.83	16.28	20.55	18.46	18.58	18.65	17.01	20.34	21.13
Na_2O		0.38	0.19	0.19	0.42	0.51	0.00	0.29	0.07	0.43	0.10
K_2O		0.04	0.05	0.02	0.04	0.12	0.02	0.06	0.11	0.00	0.06
Sum		99.09	98.83	99.44	99.71	100.15	100.23	100.34	100.80	99.80	99.06
cations per 6 oxygens											
	Si	1.928	1.926	1.861	1.825	1.861	1.962	1.963	1.934	1.914	1.902
T	Al^{IV}	0.072	0.073	0.139	0.175	0.139	0.038	0.037	0.066	0.079	0.098
	Ti^{IV}		0.001							0.008	
	Al^{VI}	0.023	0.000	0.102	0.008	0.006	0.038	0.028	0.012	0.000	0.008
	Ti^{VI}	0.016	0.032	0.024	0.048	0.045	0.011	0.016	0.018	0.024	0.045
	Cr	0.012	0.003	0.002	0.001	0.001	0.017	0.001	0.006	0.000	0.004
M1	Fe^{3+}	0.034	0.023	0.001	0.103	0.086	0.000	0.001	0.021	0.062	0.008
	Fe^{2+}	0.171	0.290	0.416	0.247	0.340	0.185	0.235	0.261	0.341	0.324
	Mn	0.003	0.009	0.012	0.008	0.009	0.006	0.008	0.009	0.010	0.007
	Mg	0.741	0.644	0.442	0.585	0.514	0.743	0.712	0.672	0.563	0.606
	Fe^{2+}	0.032	0.079	0.149	0.039	0.080	0.050	0.059	0.088	0.051	0.043
	Mn	0.001	0.002	0.004	0.001	0.002	0.002	0.002	0.003	0.002	0.001
M2	Mg	0.138	0.176	0.159	0.094	0.121	0.201	0.178	0.225	0.085	0.080
	Ca	0.800	0.726	0.673	0.833	0.754	0.728	0.737	0.674	0.831	0.865
	Na	0.027	0.014	0.014	0.031	0.038	0.000	0.021	0.005	0.032	0.007
	K	0.002	0.002	0.001	0.002	0.006	0.001	0.003	0.005	0.000	0.003

1- core of clinopyroxene grain in basalt sample no. Z 5820/497 (borehole 5820, depth 497.2 m); 2- rim of clinopyroxene grain no. 1; 3- fine, homogenous clinopyroxene grain in basalt sample no. Z 5820/497; 4- core of clinopyroxene grain in basalt sample no. Z 5870/547 (borehole 5870, depth 547 m); 5- rim of clinopyroxene grain no. 4; 6- core of clinopyroxene grain in basalt sample no. Z 5871/519 (borehole 5871, depth 519 m); 7- rim of clinopyroxene grain no. 6; 8- homogenous clinopyroxene grain in basalt sample no. Z 5871/519; 9 & 10- clinopyroxene grains from Riphean dolerite sample no. Rd 40/119 (borehole 40, depth 119 m).

Table 4. Representative microprobe analyses of clinopyroxenes from basalts of the Zabolottya Beds of the Volhynian Series and the Riphean dolerite (wt %%)

Borehole 5820, depth 542-493 m: Based on the chemical analysis of the relatively fresh basalt (sample Z 5820/497), the normative composition of this rock may be determined as olivine tholeiite. It displays the highest magnesium number (*mg* =76.5) from all of the studied samples. The chemical composition of the main and accessory minerals of this tholeiite (plagioclase, clinopyroxene, iron and titanium oxides) is shown in Tables 3, 4 and 6. Plagioclase is developed as laths of various size. Its composition is highly variable. The fine-grained plagioclase has the composition of andesine (An_{47}), while big laths are even bytownites (An_{73}). The latter belong to the early generation of phenocrysts. The phenocrysts of clinopyroxenes (augites) are also variable in their size and composition. Both chemically homogeneous grains of Wo_{36} En_{33} Fs_{31} and zoned phenocrysts (Wo_{42} En_{46} Fs_{12} in cores, Wo_{38} En_{42} Fs_{20} at rims) occur. The iron-titanium oxides are represented by titanomagnetite, displaying up to 72 mol. percent of Ulv and by ilmenite containing up to 10 mol. percent Hem (Table 6).

Borehole 5825, depth 386.5-386 m: The primary components of the basalts here are plagioclases, pyroxenes and ore minerals. At 386.5 m depth the rocks are greyish-brown in color and contain rare amygdales filled with zeolites and chlorites. These basalts contain native copper. The rocks display microporphyric texture while their matrix displays intersertal texture. At 386 m, the number of amygdales increases and the rock is more altered. The amygdales are filled with zeolites, chlorites, micas and chalcedony.

Borehole 5870, depth 547-544 m: From here come fairly fresh basalts with amygdaloidal texture. The amygdales are filled with chalcedony. The matrix texture is intersertal. The major components of the basalts are

		1	2	3	4	5	6	7	8	9	10
SiO_2		49.23	48.90	49.88	51.09	50.49	50.51	49.29	50.21	50.44	49.73
TiO_2		1.42	1.83	1.28	1.05	0.15	0.07	0.06	0.46	0.68	0.01
Al_2O_3		3.34	2.51	3.30	1.33	0.35	0.24	0.21	0.73	0.81	0.27
Cr_2O_3		0.00	0.06	0.15	0.03	0.00	0.00	0.00	0.00	0.14	0.05
FeO		13.07	15.49	11.60	13.71	31.74	34.30	34.34	25.34	17.40	33.28
MnO		0.18	0.31	0.13	0.38	0.58	0.63	0.52	0.82	0.48	0.68
MgO		12.48	11.10	13.19	12.76	11.99	12.57	12.48	12.22	10.47	12.94
CaO		20.42	19.11	20.88	19.70	5.04	2.24	2.04	9.94	18.97	1.97
Na_2O		0.52	0.65	0.46	0.45	0.22	0.45	0.07	0.01	0.36	0.00
K_2O		0.04	0.09	0.03	0.05	0.00	0.00	0.03	0.07	0.03	0.00
Sum		100.70	100.05	100.90	100.55	100.56	101.01	99.04	99.80	99.78	98.93
cations per 6 oxygens											
T	Si	1.843	1.865	1.854	1.922	1.985	1.979	1.977	1.964	1.947	1.991
	Al^{IV}	0.147	0.113	0.145	0.059	0.015	0.011	0.010	0.034	0.037	0.009
	Ti^{IV}	0.010	0.022	0.001	0.019		0.002	0.002	0.002	0.016	
	Fe^{3+}						0.008	0.011			
M1	Al^{VI}	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.004
	Ti^{VI}	0.030	0.030	0.035	0.011	0.004	0.000	0.000	0.012	0.004	0.000
	Cr	0.000	0.002	0.004	0.001	0.000	0.000	0.000	0.000	0.004	0.002
	Fe^{3+}	0.127	0.103	0.107	0.072	0.022	0.053	0.028	0.017	0.054	0.003
	Fe^{2+}	0.242	0.327	0.220	0.303	0.570	0.554	0.577	0.509	0.423	0.578
	Mn	0.005	0.008	0.004	0.010	0.011	0.011	0.009	0.017	0.013	0.012
	Mg	0.596	0.529	0.632	0.603	0.392	0.382	0.386	0.447	0.502	0.402
M2	Fe^{2+}	0.041	0.063	0.034	0.056	0.452	0.510	0.537	0.303	0.084	0.534
	Mn	0.001	0.002	0.001	0.002	0.009	0.010	0.009	0.010	0.003	0.011
	Mg	0.100	0.102	0.099	0.112	0.311	0.352	0.360	0.266	0.100	0.371
	Ca	0.819	0.781	0.831	0.794	0.212	0.094	0.088	0.417	0.784	0.085
	Na	0.038	0.048	0.033	0.033	0.017	0.034	0.005	0.001	0.027	0.000
	K	0.002	0.004	0.001	0.002	0.000	0.000	0.002	0.003	0.001	0.000

1- core of clinopyroxene grain in basalt sample no. B 5870/453 (borehole 5870, depth 453 m); 2- rim of clinopyroxene grain no. 1; 3- core of clinopyroxene grain in basalt sample no. B 5871/422 (borehole 5871, depth 422 m); 4- rim of clinopyroxene grain no. 3; 5- core of another grain of clinopyroxene from basalt sample no. B 5871/422; 6- rim of clinopyroxene grain no. 5; 7- orthopyroxene from basalt sample no. B 5871/422; 8 & 9- clinopyroxenes in basalt sample no. B 5871/426 (borehole 5871, depth 426 m); 10- orthopyroxene from basalt sample no. B 5871/426.

Table 5. Representative microprobe analyses of pyroxenes from the Babino Beds of the Volhynian Series (wt %%)

plagioclase and clinopyroxene, ore minerals and volcanic glass being accessory. Locally the glass is replaced by montmorillonite. Aggregates of palagonite also occur. The rock is most strongly altered around these aggregates (Pl. 2, Fig. 1). The chemical composition of the plagioclase, clinopyroxene and Ti and Fe oxides was determined in sample Z 5870/547 (Tables 3, 4 and 6). The plagioclases are andesines (An_{40}) and labradorites (An_{53}). They are developed as laths of variable size. Clinopyroxene phenocrysts display both homogeneous and zoned textures. A zoned grain composition is shown in Table 4 (analyses 4 and 5). The core of the grain contains Wo_{44} En_{36} Fs_{20}, and in the rim the composition is Wo_{40} En_{27} Fs_{33}. Iron and titanium oxides have the titanomagnetite composition (Ulv_{78}; cf. Table 6). At 542 m depth the altered volcanic glass has the character of a pumice. Exsolved forms of acidic glass occur in the palagonite (Pl. 2, Fig. 2).

Borehole 5870, depth 541-539 m: A transition to dolerite-like basalt is observed here (Pl. 2, Fig. 3). The rock contains small amounts of altered volcanic glass. The texture tends to be ophitic-doleritic and the rock consists of plagioclase and clinopyroxene. Olivine in individual crystals co-occurs with the above mentioned minerals. The rock shows a microporphyric texture due to the presence of large, xenomorphic and lath-like plagioclases. The primary minerals have been altered to a variable degree. Ore minerals are abundant in the most strongly altered zones.

Borehole 5871, depth 522-519 m: This is the top of the borehole, almost at the contact with the Babino Beds. Microporhyric, amygdaloidal basalts with palagonite aggregates occur at 521 m depth. The texture of the rock is generally intersertal. Pyroxene grains are not abundant. The rock displays various degrees of alteration. Higher in

	titanomagnetites					Cr - spinels		ilmenites	
	1	2	3	4	5	6	7	8	9
SiO_2	0.80	0.28	0.17	0.32	0.58	0.39	0.17	0.20	0.12
TiO_2	19.27	25.74	23.63	26.52	4.22	1.19	1.35	46.13	51.85
Al_2O_3	23.66	2.17	1.18	1.13	0.69	13.15	12.48	0.52	0.00
Cr_2O_3	0.20	0.16	0.12	0.87	0.02	35.26	29.31	0.24	0.09
Fe_2O_3	1.38	15.57	21.06	11.79	56.71	16.87	23.41	10.40	1.92
FeO	46.66	45.84	51.09	52.91	34.61	25.10	26.02	40.41	43.46
MnO	6.12	9.23	0.57	0.36	0.04	0.35	0.19	0.23	0.57
MgO	0.35	0.20	0.84	0.78	0.10	6.18	5.35	0.56	1.54
NiO	0.07	0.00	0.00	0.30	0.00	0.00	0.13	0.09	0.00
CaO	0.32	0.03	0.09	0.02	0.12	0.10	0.11	0.00	0.00
Sum	98.83	99.22	98.48	95.00	97.09	98.59	98.52	98.78	99.55
	4 oxygens							3 oxygens	
Si	0.027	0.010	0.006	0.012	0.023	0.013	0.006	0.005	0.003
Al.	0.935	0.095	0.052	0.052	0.032	0.529	0.508	0.016	0.000
Ti	0.486	0.721	0.668	0.776	0.124	0.031	0.035	0.885	0.978
Cr	0.005	0.005	0.004	0.027	0.001	0.951	0.801	0.005	0.002
Fe^{3+}	0.035	0.437	0.596	0.345	1.673	0.433	0.609	0.200	0.036
Fe^{2+}	1.308	1.428	1.605	1.721	1.135	0.716	0.752	0.862	0.911
Mn	0.174	0.291	0.018	0.012	0.001	0.010	0.006	0.005	0.012
Mg	0.017	0.011	0.047	0.045	0.006	0.314	0.276	0.021	0.058
Ni	0.002	0.000	0.000	0.009	0.000	0.000	0.004	0.002	0.000
Ca	0.011	0.001	0.004	0.001	0.005	0.004	0.004	0.000	0.000
Ulv	48.6	72.1	66.8	77.6	12.4	3.1	3.5		
Ilm								88.0	91.0
Gei								1.6	5.8
Pyr								0.4	1.2
Hem								10.0	2.0

1 & 2- fine titanomagnetites in basalt sample no. Z 5820/497 (borehole 5820, depth 497.2 m); 3- titanomagnetite included within ilmenite grain no. 8; 4- titanomagnetite from basalt sample no. Z 5870/547 (borehole 5870, depth 547 m); 5- titanomagnetite from basalt sample no. Z 5871/519 (borehole 5871, depth 519 m); 6 & 7- Cr-spinels from basalt sample no. Z 5871/519; 8- ilmenite from basalt sample no. Z 5820/497; 9- ilmenite from Riphean dolerite sample no. Rd 40/119 (borehole 40, depth 119 m).

Table 6. Representative microprobe analyses of Fe-Ti oxides and Cr-spinels from basalts of the Zabolottya Beds of the Volhynian Series and the Riphean dolerite (wt %%)

the sequence (up to 519 m) there occur palagonitic basalts with amygdaloidal texture (Pl. 2, Fig. 4; Pl. 3, Fig. 1). The matrix has locally a poikilitic-ophitic texture. The rock is built mostly of a fresh pyroxene and partly altered plagioclase. Altered volcanic glass is also present, being generally replaced by the chlorite-montmorillonite-ore aggregates. Aggregates of palagonite have been replaced by chlorite. The chemical composition of minerals of sample Z 5871/519 has been determined. The normative composition corresponds to olivine tholeiite (Table 1). Clinopyroxenes of this tholeiite display either a homogeneous composition or a zoned structure. A homogeneous composition is most characteristic of the small clinopyroxene grains richest in ferrosillite (Wo_{35} En_{46} Fs_{19}). In zoned grains, the content of ferrosillite increases rimwards at the expense of enstatite (Table 4). The presence of euhedral chromium spinels, not observed in basalts from the Zabolottya Beds in other boreholes, is significant in this sample (their composition is presented in Table 6). The amygdales in the amygdaloidal basalts are filled with chalcedony and chlorite. The amount of these amygdales, the content of the palagonitic aggregates as well as the crystallinity of basalts are variable throughout.

Basalts from the Babino Beds

Borehole 5820, depth 454-453 m: The mineral composition of these basalts is similar to that of the basalts from the Zabolottya Beds occurring at depths between 499.5 and 498 m in the same borehole.

Borehole 5870, depth 455.0-446.5 m: The basalts here display microporphyric texture and the matrix texture varies from intersertal- through ophitic to poikilitic-ophitic. At the bottom of the studied interval, basalts with intersertal or ophitic textures predominate (Pl. 3, Fig. 2). These

	titanomagnetites						ilmenite
	1	2	3	4	5	6	7
SiO_2	0.20	0.26	0.22	0.97	0.30	0.36	0.36
TiO_2	29.59	18.64	23.49	23.53	21.57	20.27	48.68
Al_2O_3	0.43	3.34	2.22	1.39	0.95	0.92	0.34
Cr_2O_3	0.08	1.72	0.42	0.53	0.08	0.12	0.16
Fe_2O_3	9.83	26.78	18.43	18.46	24.48	26.40	3.17
FeO	54.97	44.54	49.15	48.09	45.90	48.14	43.41
MnO	0.17	3.20	3.14	5.12	4.90	0.37	0.10
MgO	1.80	0.70	0.25	0.38	0.16	0.70	0.34
NiO	0.00	0.14	0.04	0.00	0.00	0.08	0.00
CaO	0.09	0.16	0.02	0.18	0.07	0.05	0.08
Sum	97.16	99.48	97.38	98.65	98.41	97.41	96.64
4 oxygens							3 oxygens
Si	0.008	0.010	0.008	0.036	0.011	0.014	0.009
Al.	0.019	0.146	0.099	0.061	0.043	0.041	0.010
Ti	0.842	0.518	0.672	0.664	0.616	0.583	0.953
Cr	0.002	0.050	0.013	0.016	0.002	0.004	0.003
Fe^{3+}	0.280	0.746	0.527	0.521	0.700	0.760	0.062
Fe^{2+}	1.739	1.379	1.563	1.509	1.458	1.541	0.944
Mn	0.005	0.100	0.101	0.163	0.158	0.012	0.002
Mg	0.101	0.039	0.014	0.021	0.009	0.040	0.013
Ni	0.000	0.004	0.001	0.000	0.000	0.002	0.000
Ca	0.004	0.006	0.001	0.007	0.003	0.002	0.002
Ulv	84.2	51.9	67.2	66.4	61.6	58.3	
Ilm							95.4
Gei							1.2
Pyr							0.2
Hem							3.2

1 &2- titanomagnetites from basalt sample no. B 5870/453 (borehole 5870, depth 453 m); 3- titanomagnetite from basalt sample no. B 5871/422 (borehole 5871, depth 422 m); 4 - titanomagnetite from basalt sample no. B 5871/426 (borehole 5871, depth 426 m); 5 & 6- titanomagnetites from rim of titanomagnetite grain no. 4; 7- ilmenite from basalt sample no. B 5870/453.

Table 7. Representative microprobe analyses of Fe-Ti oxides from basalts of the Babino Beds of the Volhynian Series (wt %%)

are very similar to basalts from the underlying Zabolottya Beds, but are devoid of olivine. The acid glass, present in these basalts is surrounded sometimes by the chlorite formed, probably, after palagonite (Pl. 3, Fig. 3). According to the chemical and normative composition of sample B 5870/453 the rock is olivine tholeiite. The plagioclases of this rock are developed as laths of variable size, generally well preserved and zoned. The core of a zoned plagioclase shows the composition of labradorite (An_{69}), and the rim of the grain is the anorthite-poorer labradorite (An_{56}) (Table 3, analyses 5 and 6). The finest plagioclase laths are relatively poor in the anorthite molecule. They are andesines (An_{41}). Also present are relics of plagioclase of bytownite composition. They represent an early generation of the plagioclase phenocrysts (Pl. 3, Fig. 4). Thus, in the course of plagioclase crystallization from the basaltic magma, the anorthite content in the plagioclases decreases. The plagioclase laths, sometimes replaced by highly birefringent chlorites, also belong to the early generation of phenocrysts (Pl. 4, Fig. 1). The highly birefringent chlorites possibly originated at the expense of the primary mafic minerals (Pl. 4, Fig. 2). The clinopyroxenes often display zoning. Their rims are richer in ferrosillite and poorer in wollastonite and enstatite than the cores. Iron and titanium oxides are represented by titanomagnetite and ilmenite (Table 7).

Borehole 5871, depth 461-422 m: In the lower part of this interval (461.0 m depth) there occur sintered vitroclastic tuffs, in which the glass has been replaced by chlorite, montmorillonite, chalcedony and ore minerals. At 425 m there occur strongly altered basalts with intersertal texture. On the basis of chemical composition of the relatively fresh basalt (sample B 5871/426), the rock, according to its normative mineral composition can be classified as olivine tholeiite. Pyroxenes from this rock vary markedly in their composition. They are: augites, subcalcic augites, ferroaugites and orthopyroxenes (Table 5; Text-fig. 4). The iron and titanium oxides are represented by titanomagnetite, occasionally zoned (Table 7). The mineral chemi-

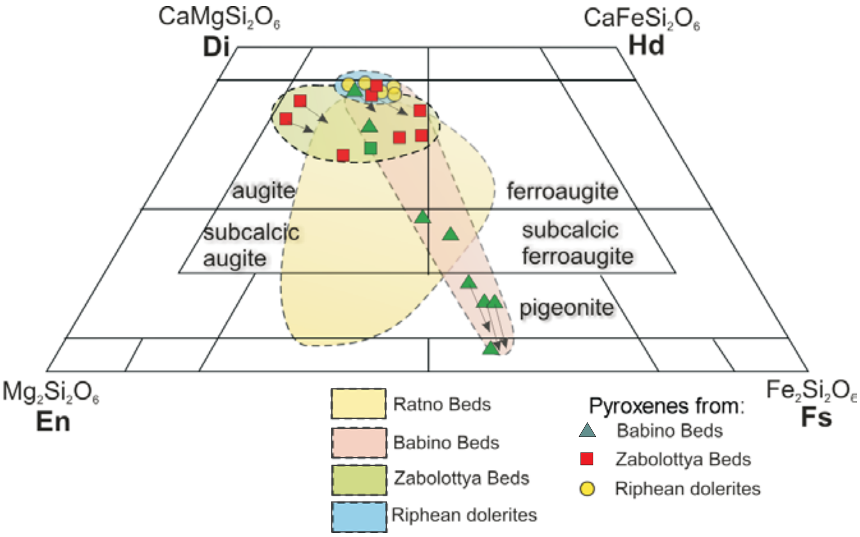

Fig. 4. Composition of representative pyroxenes from the Riphean dolerites of the Polesie Series as well as from the basalts of the Zabolottya and Babino Beds of the Volhynian Series, together with the fields of variation of pyroxenes within particular beds. Arrows stand for the rim composition of the pyroxene grains. The basaltic clinopyroxenes from the Ratno Beds show the biggest field of variation (BIAŁOWOLSKA *& al.* 2002)

stry was also studied in the tholeiite sample B 5871/422. The plagioclases are labradorites (An$_{64}$), and clinopyroxenes (augite and ferropigeonite) are often zoned (Table 5). Also found is orthopyroxene (Table 5). The accessory iron and titanium oxides are titanomagnetites (Table 7).

Borehole 8121, depth 351-240 m: The basalts here display glomeroporhyritic texture (Pl. 4, Fig. 3). The rocks of the Babino Beds are covered by the Ratno Beds with tholeiitic basalts, their breccias and tuffs. In relatively fresh basalts of these beds the amygdales are filled with chlorite intergrown with ore minerals (Pl. 4, Fig. 4). The ore minerals (native copper) commonly occupy the central part of the amygdales and are surrounded by chlorite. Most likely, such a filling of amygdales was formed in the course of recrystallization of palagonitic material, abundant in the basalts from the Ratno Beds.

GEOCHEMICAL CHARACTERISTICS

Dolerites of the Polesie Series

The studied Riphean dolerites, which represent medium (Rd 40/119) to fine-grained (Rd 40/133) varieties, differ only slightly in the magnesium and iron contents; the fine-grained dolerite shows a little higher magnesium number (Table 1) than the medium-grained one. Also notable are differences in calcium contents and the loss on ignition (LOI) values (Table 1). The higher calcium and the lower LOI in the medium-grained dolerite may result from the presence of the basic plagioclases (bytownites) and lower content of biotite and chlorite. Major differences occur in chromium and copper contents; the medium-grained dolerite contains twice as much chromium and twice as little copper than the fine-grained rock (Table 2). The contents of other trace elements (including REE) are similar in both rock types (Table 2; Text-fig. 5). It may be seen in the diagrams of REE contents normalized to the C1 chondrite (EVENSEN & *al.* 1978) that there is a distinct positive

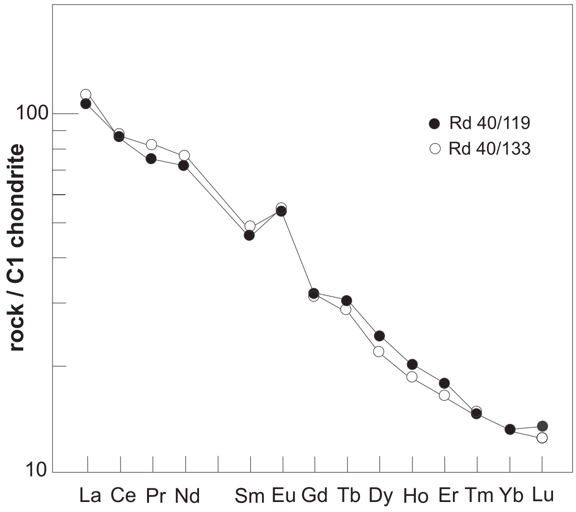

Fig. 5. Chondrite-normalized REE distribution patterns for Riphean dolerites of the Polesie Series. REE contents were normalized to C1 chondrites (EVENSEN *& al.* 1978)

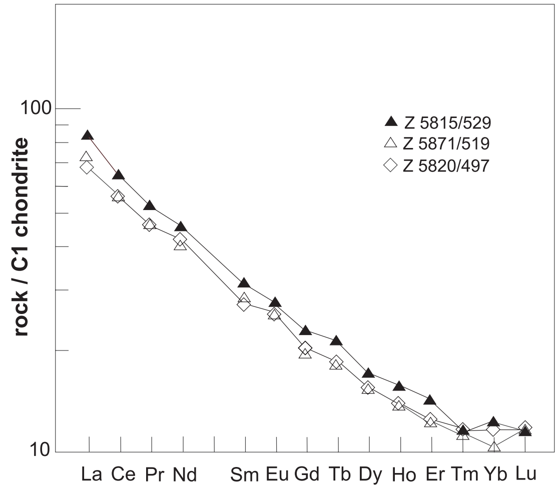

Fig. 6. Chondrite-normalized REE distribution patterns for the basalts of the Zabolottya Beds of the Volhynian Series

anomaly of europium, associated with the predominance of plagioclase of the early generation. The dolerites display a distinct REE fractionation. The La_N/Yb_N ratio is about 8.4. LREE show stronger fractionation than HREE. The Ce_N/Sm_N ratio is about 3.6, and $Dy_N/Lu_N \leq 2$. Both dolerite varieties display a high titanium content (Table 1), which corresponds to relatively high concentrations of ilmenite and titanomagnetite.

Basalts from the Zabolottya Beds

The basalts of the Zabolottya Beds studied herein display relatively high values of magnesium number (69.6-76.5). As compared to the Riphean dolerites, the Zabolottya basalts show higher chromium content (262 - 326 ppm Cr), caused by the presence of the chromium spinel (Table 2). It is worth mentioning that, in sample Z 5815/529, which has the highest copper content (752 ppm Cu; Table 2), trace amounts of silver (0.5 ppm) occur. Since both elements belong to the same subgroup of the periodic table, their co-occurrence may prove their mobilization from the same magmatic source. The same sample also displays the highest strontium content (522 ppm Sr).

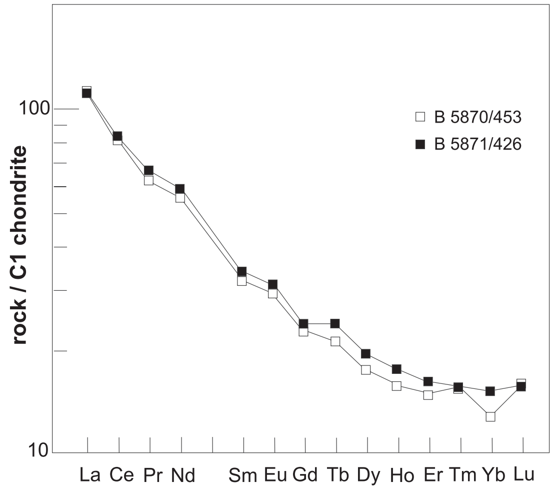

Fig. 7. Chondrite-normalized REE distribution patterns for the basalts of the Babino Beds of the Volhynian Series

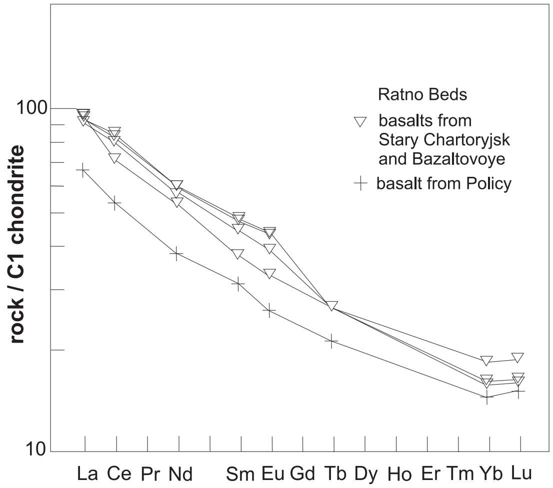

Fig. 8. Chondrite-normalized REE distribution patterns for the basalts of the Ratno Beds of the Volhynian Series (BIAŁOWOLSKA *& al.* 2002)

The basalts from the Zabolottya Beds are uniform in REE content, with values distinctly lower than those of the Riphean dolerites. Also they do not show any europium anomaly (Text-fig. 6). However, they are characterized by distinct REE fractionation, being much stronger in LREE ($Ce_N/Sm_N = 2.5$) than in HREE ($Dy_N/Lu_N = 1.4$).

Basalts from the Babino Beds

The basalts from the Babino Beds are characterized by relatively low magnesium number (*mg* = 57.6 and 56.6). As in the Zabolottya Beds basalts, the sample with the highest copper concentration (B 5871/426 – 1185 ppm) bears trace amounts of silver (0.4 ppm). Their REE concentration is similar to that in the Riphean dolerites, although the latter are richer in the medium REE. The Babino Beds basalts are much richer in REE than those from Zabolottya (Text-figs 6-7), but poorer in the medium REE as compared to the Ratno Beds fresh basalts (Text-fig. 8). They are characterized by a strong fractionation of REE ($La_N/Yb_N \leq 8.8$). This fractionation is more intensive in the LREE group ($Ce_N/Sm_N = 2.6$) than in the HREE group ($Dy_N/Lu_N = 1.1$).

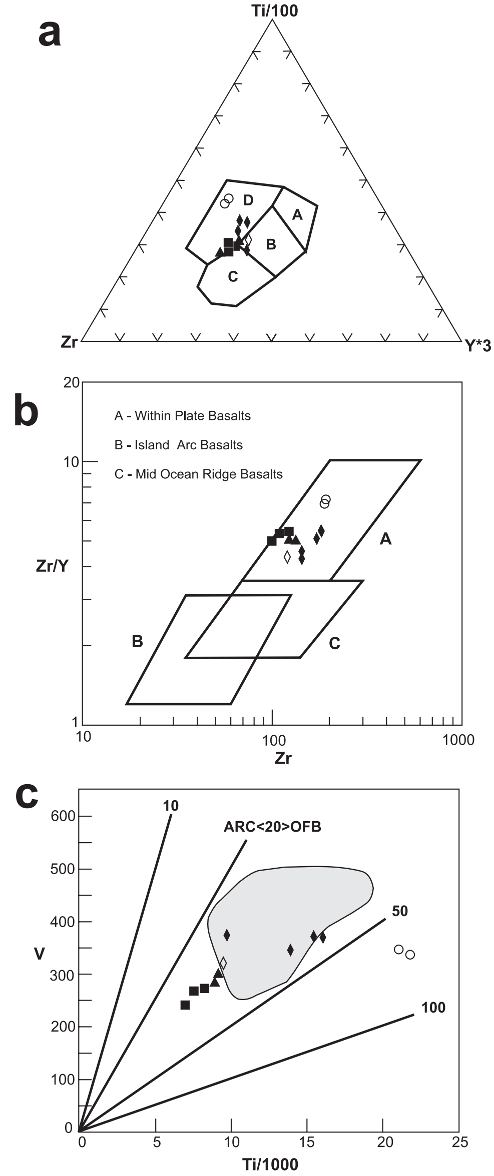

Fig. 9. Discrimination diagrams for the Riphean dolerites of the Polesie Series as well as for the basalts of the Volhynian Series. Open circles stand for the Riphean dolerites, filled squares stand for basalts of the Zabolottya Beds, while filled triangles stand for basalts of the Babino Beds; filled rhombs stand for the fresh basalts of the Ratno Beds and open rhomb stands for the hydrothermally altered Ratno Beds basalt from the Policy quarry; a – the Ti-Zr-Y diagram for basalts according to PEARCE & CANN (1973): A – is the field of island-arc tholeiites, B – is the field of MORB, island-arc tholeiites and calc-alkaline basalts, C – the field of calc-alkaline basalts and D – is the field of within-plate basalts; b – diagram based upon Zr/Y – Zr variations in basalts according to PEARCE & NORRY (1979); c – the Ti–V discrimination diagram for basalts after SHERVAIS (1982), modified by ROLLINSON (1993). Shaded area is the field of continental flood basalts. ARC – is the sector of volcanic arc tholeiites; OFB – stands for the sector of ocean floor basalts, both MORB and back-arc basin basalts as well

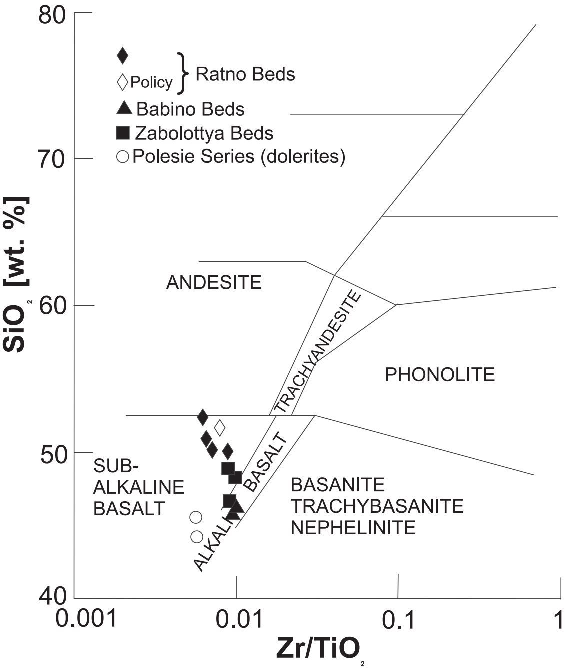

Fig. 10. Riphean dolerites and basalts of the Volhynian series on the SiO_2 – Zr/TiO_2 magma series discrimination diagram, according to WINCHESTER & FLOYD (1977)

For the classification of the studied basalts their normative composition (Table 1) as well as WINCHESTER's & FLOYD's (1977) diagram (Text-fig. 10) have been used. In the diagrams of PEARCE & CANN (1977) and PEARCE & NORRY (1979) as well as SHERVAIS (1982) (Text-fig. 9a-c) these basalts plot largely in the fields of within plate basalts, with a scatter into adjacent fields in some plots (e.g. Text-fig. 9a).

DISCUSSION

The Lower Vendian effusive-tuffogenic complex of the Volhynian Series and the Riphean dolerites cutting the top beds of the Polesie Series, have been known collectively as the Volhynian Trap Formation (LAZARENKO *& al*. 1960; VOLOVNIK 1971; and others). The trap-type igneous activity was initiated in the latest Riphean due to tectonic activity and block movements (VLASOV *& al.* 1972). The main features of the trap formations are as follows: 1) the occurrence within the cratons; 2) the co-occurrence of effusive-tuffogenic and hypabyssal rocks; and 3) negligible lateral variability of the mineral composition. All these features are recognizable in the effusive-tuffogenic and hypabyssal rocks from Volhynia, studied herein.

In the whole sequence of the Volhynian Series studied herein no olivine-rich ultramafic rocks were found, which could be the products of early crystallization. Olivine and chromium spinel have only been observed in the Zabalottya alkali basalts. In the Siberian platform, chromium spinel co-occurs with titanomagnetite and ilmenite only in the picritic variety of basalts (ZOLOTUKHIN & ALMUKHAMEDOV 1991; ZOLOTUKHIN & *al.* 1989). The basalts studied herein (mainly tholeiites,) correspond to the products of the main, short-lived, crystallization stage. During this stage, the main portion of the melt solidifies, resulting in the characteristic ophitic textures (SOBOLEV 1986). The resulting rocks are often referred to as dolerite-basalts, which perfectly describes their character.

The rapid melt crystallization does not allow dissolution of the earliest formed crystals, which leads to the development of porphyritic textures (SOBOLEV 1986). Relics of such primary crystals (both of pyroxenes and plagioclases) are commonly observed in the basalts of the Zabolottya, Babino and Ratno Beds. The textures of these rocks we determined as porphyritic.

If the crystallization process is not rapid, a residual melt is present after the main stage. This melt is enriched in the easily melting and volatile components. This melt either remains in the source rock forming a kind of mesostasis, or it undergoes mobilization and separates from the solids, resulting in diabase pegmatites at later stages of crystallization.

In the Volhynian basalts, the residual melt has formed glass which has been strongly altered into palagonite. It is present in distinct amounts in the basalts from the Ratno Beds, where only occasionally it is recrystallized. It is almost totally recrystallized into post-palagonite chlorite in the basalts from the Zabolottya and Babino Beds.

The next stage is the hydrothermal phase (the influence of hydrothermal solutions on the earlier formed rocks). The hydrothermal solutions might have led to the crystallization of copper in the rocks of the Volhynian Series, resulting in the mineralization observed there. Native copper is present in various concentrations in basalts from all the beds of the Volhynian Series. Such an occurrence has demanded the presence of a reducer, although disproportionation reactions are also possible. Molecular hydrogen – one of the components of the metasomatic mantle fluids (MMF) – being also a component of the volcanic gases, as well as the native iron and graphite dispersed in the rocks (BIAŁOWOLSKA & *al.* 2002), might have acted as the potential reducers required.

With the exception of a single sample, neither native copper nor sulphide mineralization in the Riphean dolerites was found.

The variation in the composition of the pyroxenes is well worth mentioning. Grains of zoned pyroxenes are present in the basalts of both the Zabolottya and Babino Beds. Their rims are richer in ferrosillite than the cores (Text-fig. 4). In the basalts from the Babino Beds, relics of orthopyroxenes have been found, as well as orthopyroxenes forming rims on clinopyroxenes. Such a situation was discussed by DEER & *al.* (1978) and described by SOBOLEV (1986) in basalts from the Siberian Trap Formation. The least variable in composition are the pyroxenes from the Zabolottya Beds, represented mostly by augites and only rarely by ferroaugites. Similarly, the pyroxenes from the Riphean dolerites are weakly variable and plot in the upper part of the augite field and along the augite/diopside boundary (Text-fig. 4). In contrast, pyroxenes in the basalts of the Babino Beds are highly variable in their composition, which plots along a wide band from the augite field, through subcalcic augites, ferroaugites, subcalcic ferroaugites and pigeonites to orthopyroxenes (Text-fig. 4). An even wider range of pyroxene composition is found in the basalts of the Ratno Beds (BIAŁOWOLSKA & *al.* 2002).

A variable composition is also characteristic of the plagioclases in the Volhynian Series basalts, the most variable being those in the basalts of the Zabolottya Beds (ranging from andesine to bytownite). A similar variation is also shown by the plagioclases of the medium-grained variety of the Riphean dolerites. The plagioclases in the basalts of the Babino and Ratno Beds, in turn, are represented by labradorite and bytownite. A labradorite composition is also characteristic of the plagioclases of the fine-grained dolerites. The zoned plagioclases show normal zoning.

The studied basalts of the Zabolottya and Babino Beds differ from those of the Ratno Beds in their higher sum of alkalis and lower silica content, being in these features similar to the Riphean dolerites. The basalts from the Volhynian Series display a consequent enrichment in REE from the bottom to the top of the series.

Analysis of diagrams of the REE distribution patterns (Text-figs 6-8) shows some differences between the basalts of different beds. The basalts of the Zabolottya Beds are the poorest in REE, those of the Babino Beds displaying a higher REE content. The latter are comparable to the basalts of the Ratno Beds, excluding the hydrothermally altered basalt from the Policy quarry. The basalts of the Ratno Beds, however, show a weaker fractionation. A mean value of the fractionation index for these basalts is $La_N/Yb_N = 5.7$. The rock from the Policy quarry have still lower value of this index, namely $La_N/Yb_N = 4.6$.

CONCLUSIONS

The diversity of composition of the Volhynian Series basalts could be caused by several reasons, e.g. upper mantle source heterogeneity, fractional crystallization of parental magma, crustal contamination as well as variable degree of partial melting of mantle source material. However, the overall characteristics of the basalts, the lack of mantle xenoliths, and their extreme paucity in crustal enclaves, suggest a variable degree of partial melting of mantle rocks as the major cause. It can be suggested that the process of formation of the parental magma for the basalts of the Ratno Beds involved a higher degree of melting of the mantle material than for the formation of magmas for the basalts of the two lower beds (the Zabolottya and Babino Beds).

The strongest variation in the pyroxene composition and the Fs-richest pyroxenes are found in the most evolved basalts of the sequence, in the Babino and Ratno Beds. On the one hand this great compositional diversity of pyroxenes is a proof for disequilibrium between the basaltic melt and the solid minerals. On the other hand, the large basalt lava covers are laterally almost homogeneous, probably due to the volumetrically huge effusions of flood basalts.

The majority of the basalts from the Volhynian Series correspond to the continental within-plate tholeiites (Text-fig. 9a-c). Some of the Zabolottya and Babino Beds basalts belong to the alkali basalts (Text-fig. 10). An alkaline character is also exhibited by the Riphean dolerites. The presence of alkali basalts in the volcanogenic Volhynian Series is a proof of the continental character of the effusions. The intensive Late Riphean – Vendian magmatic activity, with mainly linear effusions, in the western margin of the East European Craton, can be correlated with the last stages of rifting and the breakup of the Rodinia supercontinent (DALZIEL 1997).

The Late Mesoproterozoic magmatic activity accompanying the rifting along the Fennoscandia-Sarmatia Suture did not lead to the oceanization of the lithosphere, but terminated at an aulacogen stage (ŻELAŹNIEWICZ 1998). The rejuvenation of the rift structure in a direction concordant with the Orsha-Volhynia aulacogen, following the FSS, i.e. almost perpendicular to the TESZ, took place at the turn of the Riphean, possibly due to the influence of a mantle plume. These structures were migration paths for the magma. The eruption of the tuffogenic material, characteristic of the lower beds of the Volhynian Series, was earlier, the material rich in effusives being erupted later. Most likely, huge effusions of the Volhynian flood basalts may be linked to a mantle plume accompanying the last stages of the Rodinia breakup.

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PLATES 1-4

PLATE 1

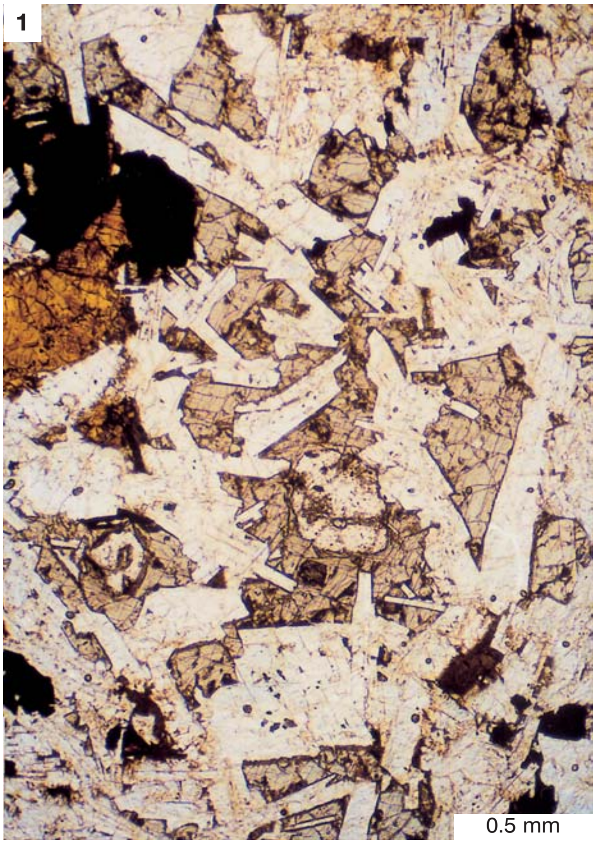
Photomicrographs of thin sections of Riphean dolerites from the Polesie Series

1 – Ophitic-textured, fine-grained dolerite, sample no. Rd 40/133. Black grains of iron-titanium oxides and palagonite (brown) are also visible. One polar.

2 – Medium-grained dolerite showing a variety of ophitic texture with pyroxene aggregates present between plagioclase laths, sample no. Rd 40/119. Apart from plagioclase laths and pyroxene grains, iron-titanium oxide grains are also visible. Oblique polars.

3 – Brown palagonite surrounded by plagioclases, in medium-grained dolerite, sample no. Rd 40/119. One polar.

4 – Chlorite aggregates formed at the expense of palagonite, surrounded by plagioclases and oxides, in fine-grained dolerite, sample no. Rd 40/133. One polar.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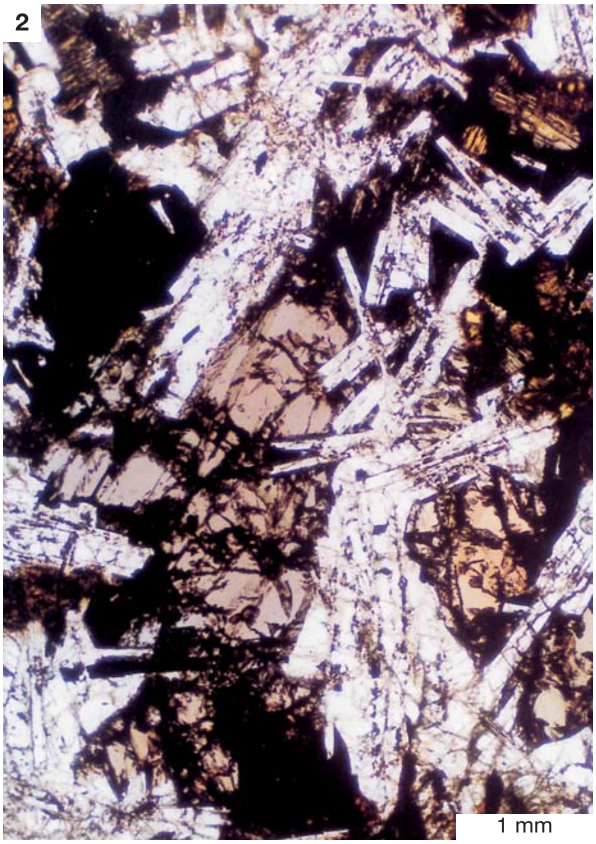
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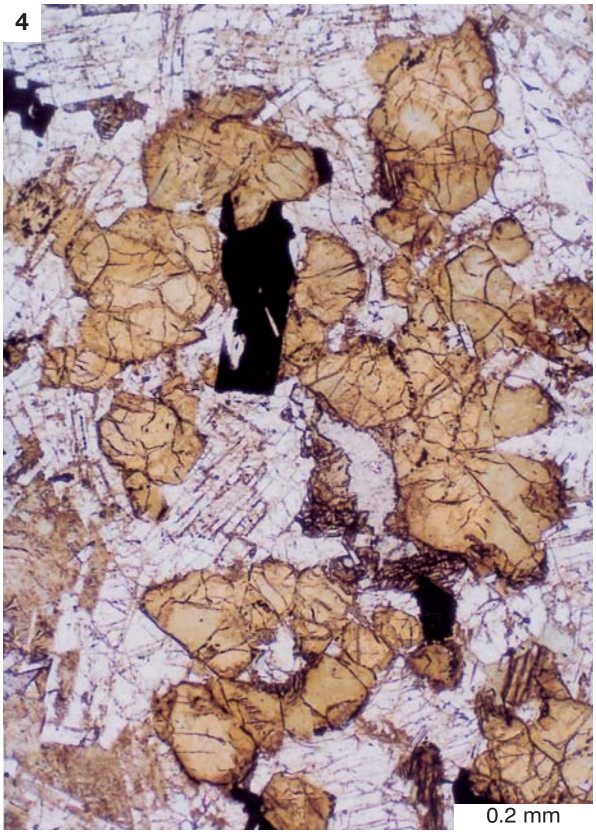
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PLATE 2

Photomicrographs of thin sections of the basalts of the Volhynian Series.

1 – Basalt from the Zabolottya Beds built up of plagioclase laths, light brown pyroxene and greenish brown, mainly interstitial palagonite, surrounded by lighter rims of chlorite, sample no. Z 5870/547. One polar.

2 – Brown palagonite in basalt from the Zabolottya Beds, sample no. Z 5870/542. Rounded exsolutions of acid glass as well as recrystallized zones at the rims of palagonite segregation are visible. One polar.

3 – Basalt from the Zabolottya Beds composed of fine plagioclase laths, pyroxene grains and olivine. Altered, interstitial glass is also present; sample no. Z 5870/541. Crossed polars.

4 – Basalt from the Zabolottya Beds with amygdaloidal texture, sample no. Z 5871/519. Rare, fine grains of pyroxenes and ore minerals occur among the fine laths of plagioclases. The amygdale is filled up with chlorite (mainly) and palagonite (black). Crossed polars.

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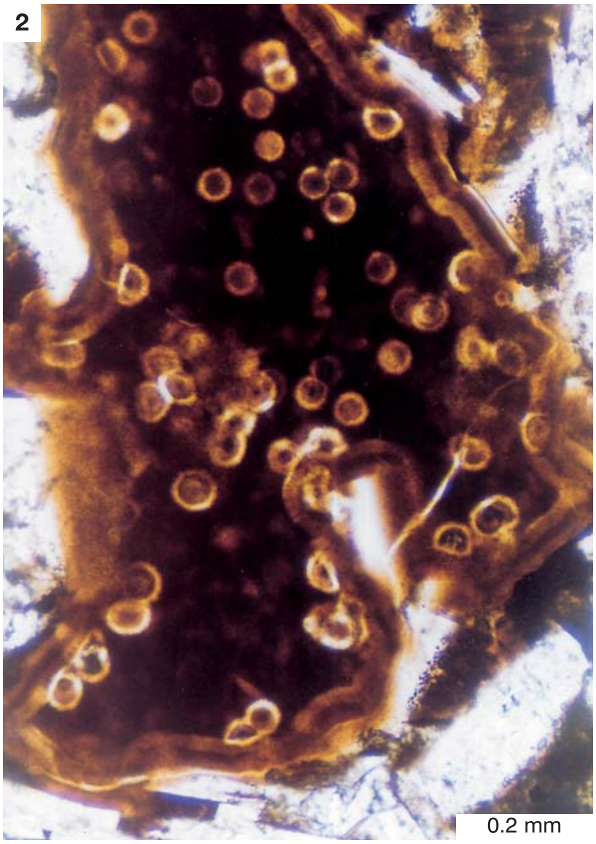

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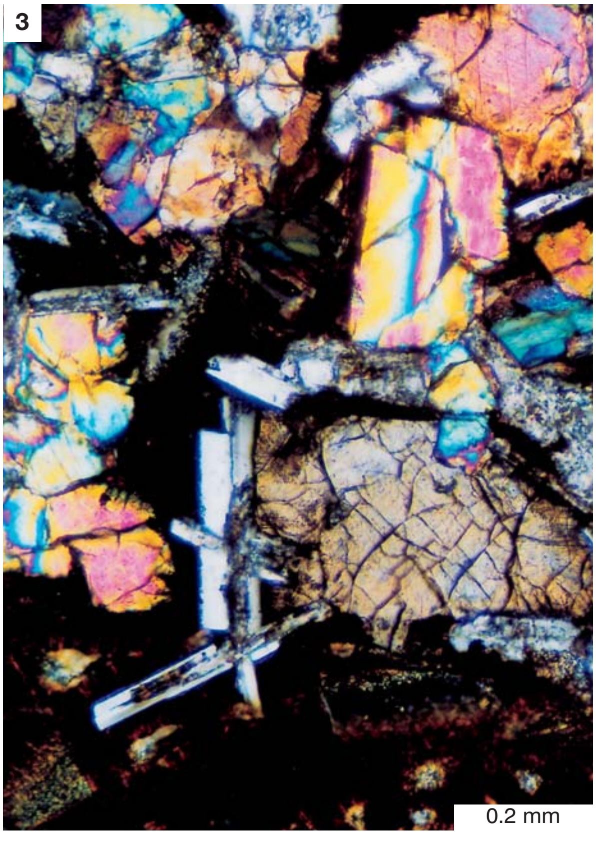

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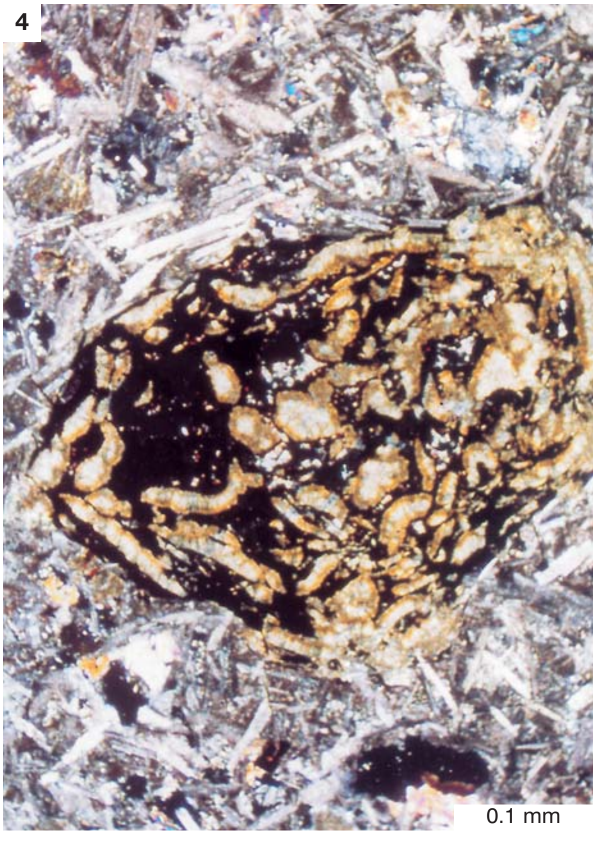
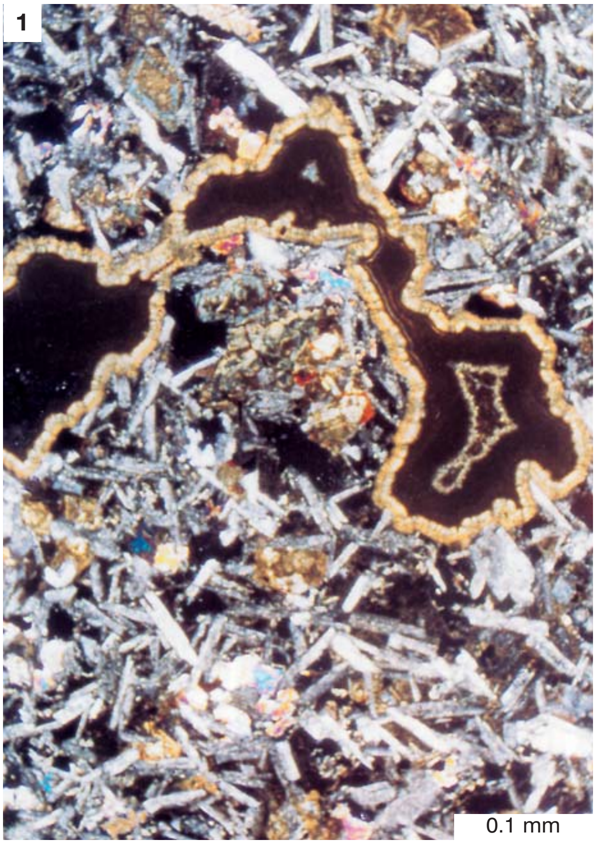


PLATE 3

Photomicrographs of thin sections of the basalts from the Volhynian Series

1 – Basalt from the Zabolottya Beds built up of plagioclase laths and pyroxene grains surrounding fine amygdales filled up with palagonite (black). Sample no. Z 5871/519. Crossed polars.
2 – Basalt from the Babino Beds with ophitic texture, sample no. B 5870/446. Apart from the big pyroxene grains intergrown with plagioclase laths, there also occur fine pseudomorphed orthopyroxenes (?). Crossed polars.
3 – Acid glass segregation, surrounded by chlorite, in basalt from the Babino Beds; sample no. B 5870/451. Crossed polars.
4 – Basalt from the Babino Beds, sample no. B 5870/446. A corroded plagioclase plate belonging to the early generation of phenocrysts can be observed. The plate is surrounded by clinopyroxenes. Crossed polars.

1



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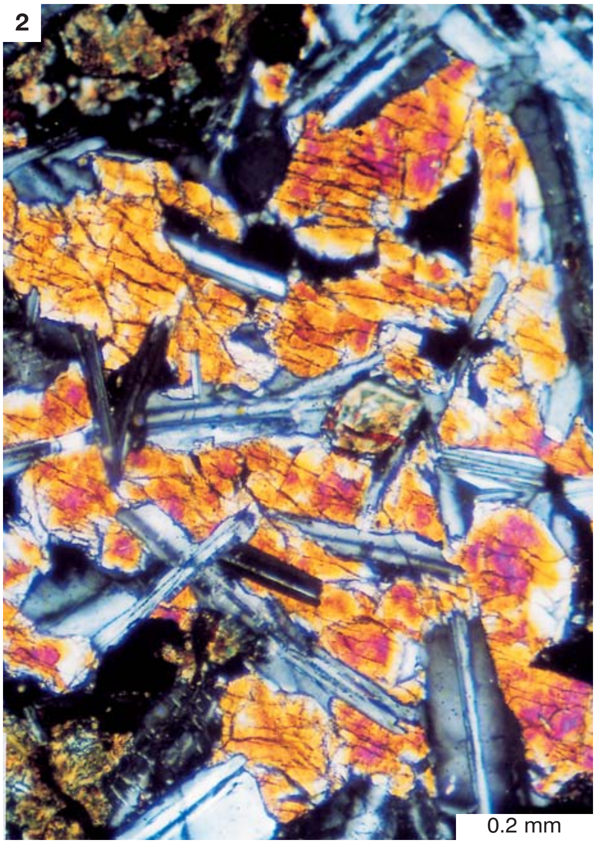

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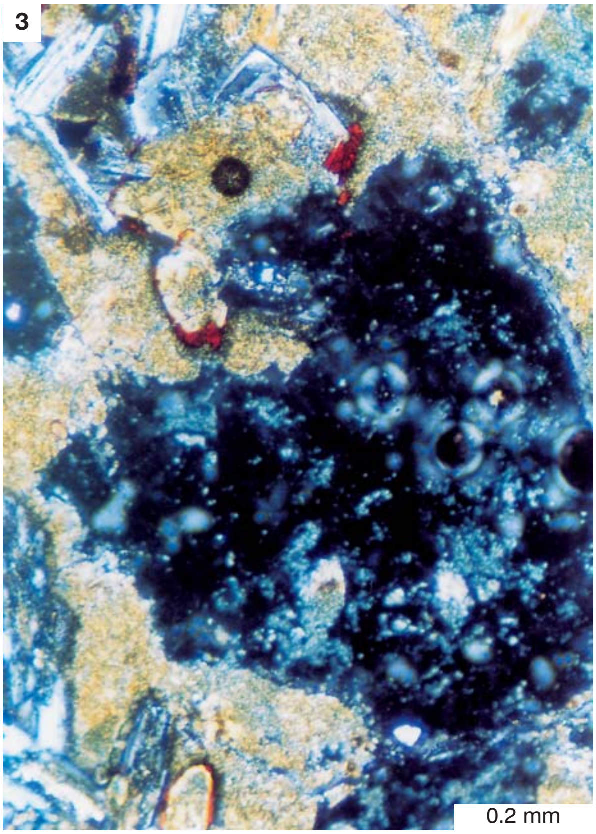

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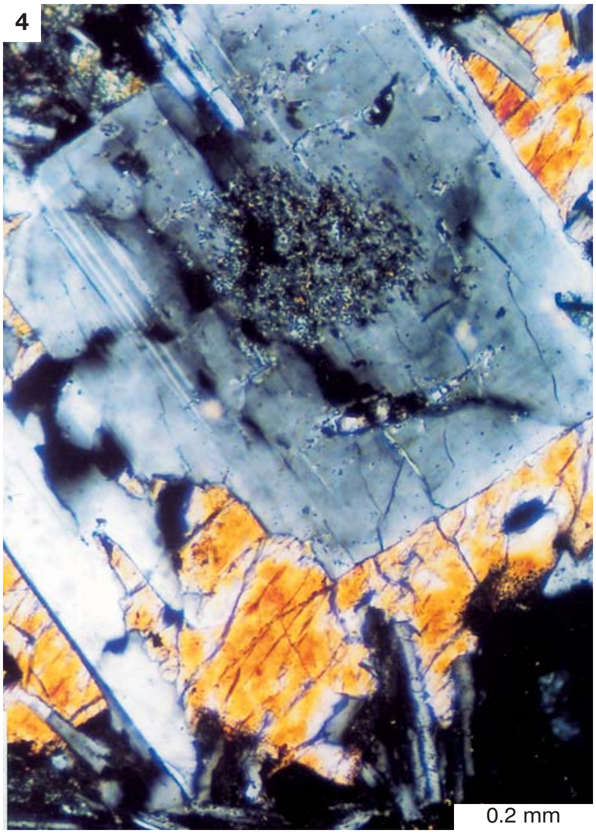

PLATE 4

Photomicrographs of thin sections of the basalts from the Volhynian Series

1 – Plagioclase phenocryst belonging to the early generation, being replaced by the chlorites, in basalt from the Babino Beds, sample no. B 5870/451. Crossed polars.

2 – Segregations of highly birefringent chlorites formed from the alteration of primary minerals (orthopyroxenes) in basalt, sample no. B 5870/451. Oblique polars.

3 – Glomeroporphyritic textured basalt from the Babino Beds, sample no. B 8121/351. The aphyric matrix, aggregates clots of plagioclase and clinopyroxene, intersertal texture. Crossed polars.

4 – Amygdaloidal textured basalt from the Ratno Beds, sample no. R 8121/237. The margin of a big amygdale filled up with chlorite intergrown with ore minerals can be observed. One polar.

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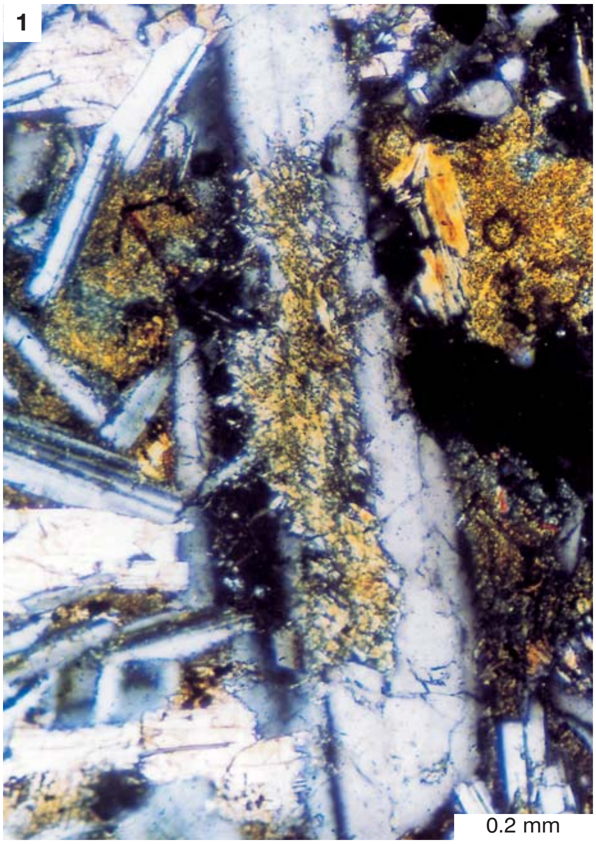

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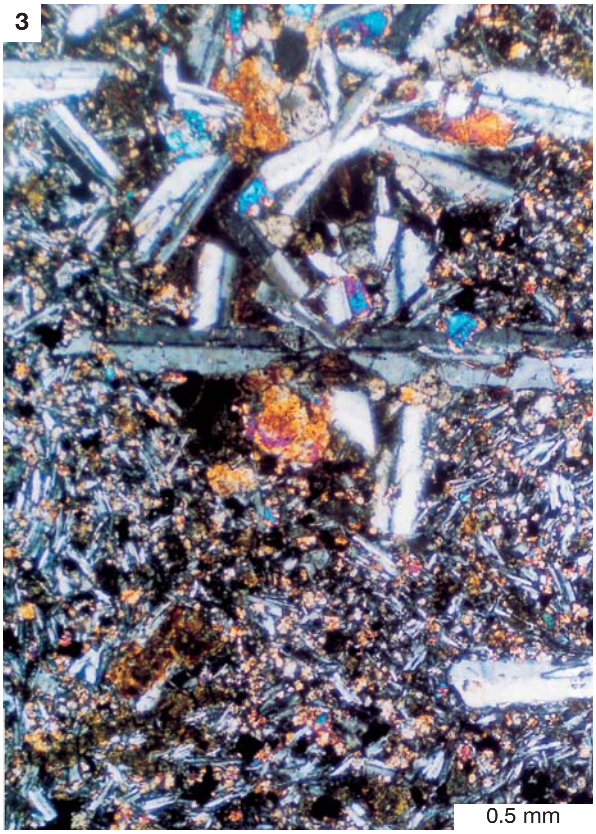

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