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GEOLOGICAL FRAMEWORK OF THE VOLHYN COPPER FIELDS WITH A REVIEW OF THE VOLHYN FLOOD BASALT PROVINCE (WESTERN MARGIN OF THE EAST-EUROPEAN CRATON)

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Abstract: Geological structure of the Volhyn Flood Basalt Province has been described. Hydrothermally altered and partly eroded Vendian lava flows and intraflow pyroclastics occur upon an area of about 350,000 km^2 in Belarus, Poland, the Ukraine, and Moldova. They host important native Cu mineralization. The Vendian volcanism developed during four volcanic phases, producing lava and pyroclastics within the Tornquist rift system along the Teisseyre-Tornquist margin. During the last two phases, the Vendian rift was tectonically parted with crust melting. The major volcanic activity occurred in the part superimposed on the deepest part of the older Late Riphean mid-Baltica rift system, which developed across the Tornquist rift. The rifting finished with opening of the Tornquist Ocean. Actually, the Palaeozoic, Mesozoic, and (or) Cainozoic beds cover the trappean volcanic plateau. The Ratne and Rafalovka-Berestovets copper fields are situated in the central part of the Lukow-Ratne swell and along western border of the Ukrainian Shield, respectively. The ore-bearing basalts were partly eroded since the Devonian until the Late Cretaceous.

Key words: East-European Craton, Volhyn, Vendian, Tornquist rifting, flood basalts.

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INTRODUCTION

The Volhyn trapp formations are situated in the western margin of the East-European Craton and present the extraordinary Deccan-size flood basalt province that originated during the Vendian "rejuvenation" of this margin. The flood basalts strike along a distance of 1,150 km from the Mazury High in Poland to the North-Moldovian Monocline in Moldova, following the ancient rift system (Nikishin *et al.*, 1996; Hartz & Torsvik, 2002). Superpositions of the volcanic systems and long-time eruptions resulted in a complex of deposited lava flows, tuffs, and tuffites. These rocks are exposed only at some places along the western borders of Ukrainian Shield and in the Dnister River valley (Fig. 1), whereas at other places they are covered by younger deposits, up to 4,000 m thick.

Małkowski (1929, 1931) published the first data about occurrences of native copper in the Volhyn basalts. He found some small (< 1 kg in weight) nuggets in the bottom of the basalt flow in the village Velykiy Midsk. For the next years, until 1939, the Polish Geological Institute developed prospecting works for copper in the zone Rafalovka-Berestovets (Wojciechowski, 1939; Małkowski, 1951), however, no economic copper concentrations were found. Since 1963 till recent, the Ukrainian Geological Survey periodically resumed the searching, promoted with occasional finding of copper mineralization and nuggets in the basalt open pits (Dovge Pole, Rafalovka, etc.). Of the works, keeping by the Ukrainian State Geological Survey now, prospecting for copper deposits in the Volhyn trappean formations is one of the topical objectives (Pryhodko *et al.*, 1993; Białowolska *et al.*, 2002). Two fields, both at depths of 10–500 m are in prospecting for copper: Ratne and Rafalovka-Berestovets (Fig. 1). The Zhyrychi copper deposit has been found in the Ratne field (Pryhodko *et al.*, 1993). However, because of complicated geological structure, the shape of the economic ore bodies is still obscure. Nevertheless, the numerous finds of high-grade (5–16%) Cu ore make the area potentially economic.

The purpose of this paper is to review geological setting of the perspective fields as a part of the ancient Volhyn Flood Basalt Province. We believe that this work will cork

Fig. 1. Sketch map of the Volhyn flood basalt formations superimposed on the Upper Riphean strata

rect a concept about geological structure of the region, and improve the directions of the ore prospecting.

PRESENT-DAY TECTONIC SETTING

The younger tectonic units divide the ancient flood basalt province. Recently, the volcanic traps have been found in the boreholes in the north-eastern part of the North Moldovian monocline, in the Volhyn Depression, and the Lukow-Ratne Swell, in the eastern part of the Podlasie-Brest Depression, and in the southern slope of the Mazury High (Fig. 1).

Cu-bearing bodies of the Rafalovka-Berestovets field are found within the narrow 300 km^2 zone of the basalt formations, which settles close to the surface in the north-eastern margin of the Volhyn Depression, along the western slope of the Ukrainian Shield. The basalt flows strike along with the 580 Ma swarm of gabbro-dolerite dikes (Semenenko, 1968). These rocks are cutting the Precambrian crystalline rocks, Riphean red-beds, and Volhyn volcanogenic suite. The swarm, 8–10 km wide, strikes NW about 70 km along the marginal fault zone close to the border of the Ukrainian Shield. Westward, in the Volhyn Depression, the trapps dip monoclinally and are thrown down by 3.5–4 km along some regional faults obscured by the younger beds.

The Ratne field is situated in the Ratne High, one of the horst-type highs of the Lukow-Ratne Swell. The swell strikes 350 km E–W in the East-European Craton, from the Ukrainian Shield to the Slavatychsky High in Poland (Semenenko, 1968; Sokołowski, 1970; Garetsky, 1981, 1990; Fig. 1). The adjoining blocks between the highs were downfaulted by submeridional faults. Along the South-Prypyat Fault Zone, the swell abuts on the Volhyn Depression, and southwestwards – on the Lublin-L'viv Basin. Along the South-Prypyat faults, the Precambrian beds are downfaulted by 300, 400, 650, 800 and 1,450 m against the Dubrovitsa, Hoteshov, Ratne, Hotyslav, and Wishnice Highs, respectively. Along the Sarna fault, the Dubrovitsa High borders upon the Ukrainian Shield. The area of flood basalts in the Lukow-Ratne Swell reaches 1,200 km^2.

The swell is poorly recognised structurally. Numerous faults cut the Precambrian beds. Close to the eastern (Dubrovitsa and Hoteshov) highs, the basement is stepwise displaced southwards down by some latitudinal faults. In the Dubrovitsa High, the volcanogenic beds have been found only in the southwestern part. Numerous sublatitudinal faults cut the Hoteshov High. The Precambrian surface of this high is dome-like: in the northern slope the beds dip from 3 to 4° to the north, and in the southern slope – from 6 to 8° to the south. Because of the pre-Cretaceous erosion, the Early Proterozoic basement crops out in the Ratne and Hotyslav palaeohighs, where it recently settles below the Upper Cretaceous beds. Generally, the heavily faulted Upper Proterozoic beds dip 10–15° to the SE and, inbetween the southern faults the dip is even steeper.

Semenenko (1968) and Garetsky (1990) designated the North-Prypyat Fault Zone as the northern border of the Lukow-Ratne High. The vertical displacement of the Precambrian beds down this zone increases from 150 to 300 m westwards, but at some places between the Dubrovitsa and Hotyslav Highs the beds are shifted up, and dip flatly to the north up to the southern faults of the Podlasie-Brest Depression.

REVIEW OF STRATIGRAPHY

The copper fields are located on the tectonically prominent structures, which were periodically eroded between the Early Cambrian and Late Cretaceous. Consequently, in the studied area the sedimentary cover comprises Precambrian, Cambrian, Ordovician and Silurian rocks that are covered by the Upper Cretaceous beds, which, in turn, are locally overlapped by Cainozoic strata (Figs 2, 3). The most complete stratigraphic logs have been found in the boreholes in the western parts of the Podlasie-Brest and Volhyn Depressions, and in the Lublin-L'viv Low (Fig. 2).

The Upper Riphean strata, called Polis'ka series, 170–850 m thick, covers Lower Proterozoic crystalline rocks, which mostly consist of 1.2 Ga gneisses and granitoids containing numerous syenite and 1–1.1 Ga gabbro intrusions (Semenenko, 1968; Velikanov & Korenchuk, 1997). The sedimentary rocks are developed as red-bed sandstones and siltstones intercalated with clays, and comprise four successive sedimentary cycles (Garetsky (Ed.), 1981). The feld-

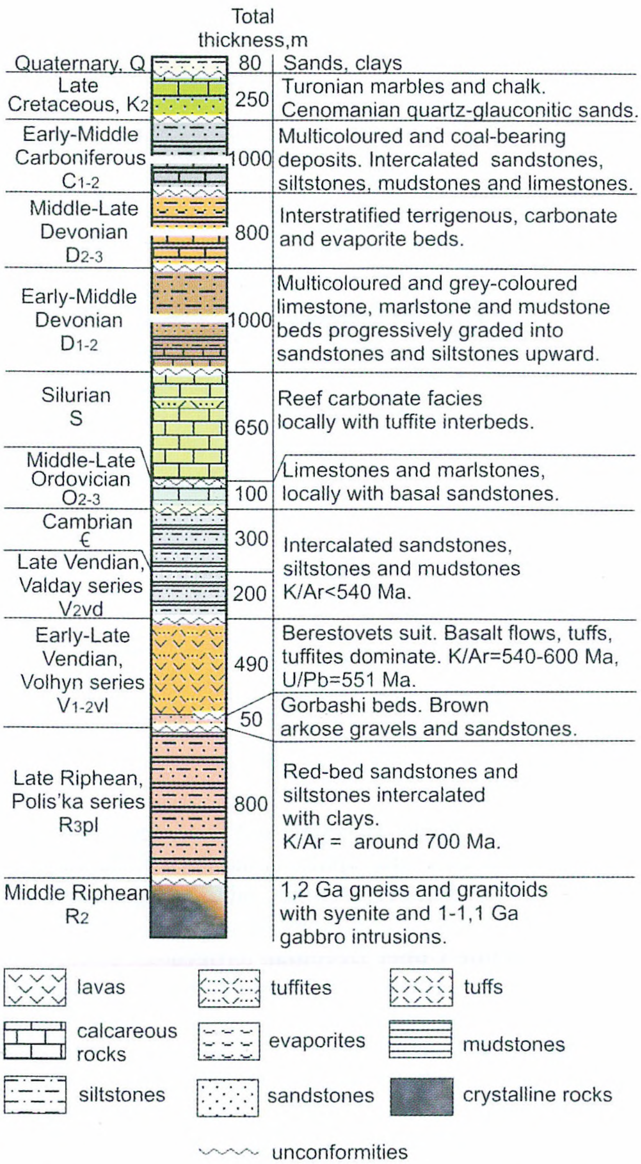

Fig. 2. Stratigraphic log of the Volhynian copper fields and adjacent areas

spar and mica of these sandstones have been K-Ar dated at 770–700 Ma (Semenenko, 1968; Krasheninnikova, 1987). The uppermost beds of the strata contain tillites.

The Upper Riphean strata filled the mid-Baltica rift system (Nikishin *et al.*, 1996), striking from NW and W to E across the present-day Volhyn Depression, Lukow-Ratne Swell, eastern margins of the Podlasie-Brest Depression and Belarus High, Prypyat and Orsha Depressions and Klincovsky High. Northeastwards, across the present-day Velizhsky High, this system abuts on the Mid-Russian – Valday aulakogen. The thickest, about 800 m, red-bed strata have been found in the central part of the Volhyn Depression (Fig.1). In the Lukow-Ratne Swell, their thickness varies from 0 to 300 m on the highs and from 250 to 550 m in the adjacent lows. In the Podlasie-Brest Depression and farther east in the central part of the mid-Baltica, the thickness of these strata reaches 400–450 m.

The Lower Vendian brown and grey-brownish arkose gravelstones and sandstones (Gorbashi beds of the Volhyn Series), 0–50 m thick, overlap the Upper Riphean strata or older crystalline rocks in the outskirts of the already ceased mid-Baltica rift. The clasts are composed of quartz, feldspar, plagioclase, and red sandstones.

The Lower through Upper Vendian flood basalt formations (Berestovets Suite of the Volhyn Series) represent the trappean effusive and pyroclastic deposits which conformably cover the above-described Gorbashi beds, overlap the Upper Riphean strata, and locally rest on the Lower Proterozoic crystalline rocks. Coeval dikes and sills of gabbro-dolerites everywhere cut and intercalate with the Upper Riphean strata and the Volhyn volcanogenic beds. Among pyroclastics, tuffites dominate. They contain many rounded 0.5–30 mm clasts of both basalts and tuffs. Tuffs and tuffites are mostly red, brownish, green-brownish, green or multicoloured. They are hydrothermally affected by epidotization, chloritization, zeolitization, and hematitization. Everywhere basalts include layers of sintered red ashes.

The basalts exposed in the quarries are often columnar or massive. At some places, top massive basalts, 2–3 m thick, are represented by pillow lava flows. Both the colour and structure of the basalts and tuffs testifies to the continental and shallow-marine volcanic environments, characterized by intensive weathering and coastal erosion of the volcanogenic formations.

The thickness of the flood basalt formations reaches 350–450 m in the Volhyn Depression, the central part of the Lukow-Ratne Swell, and the southern part of the Podlasie-Brest Depression (Fig. 1). In these areas, the trapps usually comprise 5–13 basalt flows which are intercalated with tuffs, tuffites, and terrigenous beds. Towards the marginal parts of the basalt province, the volcanogenic formations thin out, but in some places were eroded. Farther eastwards, along the mid-Baltica rift and in the southern margin of the Volhyn Depression, tuffites and terrigenous beds (Fig. 1) laterally displace the trappean formations.

The zircons of the uppermost tuffs have been dated at 551±4 Ma by U/Pb ratio (Compston *et al.*,1995). The K/Ar chronometry shows 600–500 Ma for the Volhyn flood basalts and 660–500 Ma for gabbro-dolerite dikes and sills, although the most common dates range 540–600 Ma (Semenenko, 1968; Krasheninnikova, 1987; Velikanov & Korenchuk, 1997). The last figures estimate the age of the flood basalt plateau. Some older and younger age estimations (Krasheninnikova, 1987; Velikanov & Korenchuk, 1997) relate to the hydrothermally altered rocks.

The Upper Vendian (Valday Series) **and Cambrian** beds unconformably cover the Volhyn volcanogenic formations as cyclically interbedded layers of sandstone, siltstone, and mudstone. The total thickness of the deposits ranges from 300–500 m at the western margins of the Podlasie-Brest and Volhyn Depressions up to 1,500 m in the North Moldovian Monocline. It suggests that the deposition occurred in an opened rift. The boundary between the Vendian and Cambrian beds is ascertained in the top of the so-called Laminarian Horizon, which includes carbon laminae comprised in grey and green-grey claystones.

Semenenko (1968) and Krasheninnikova (1987), basing on K/Ar ratio, dated feldspar and mica of siltstones and

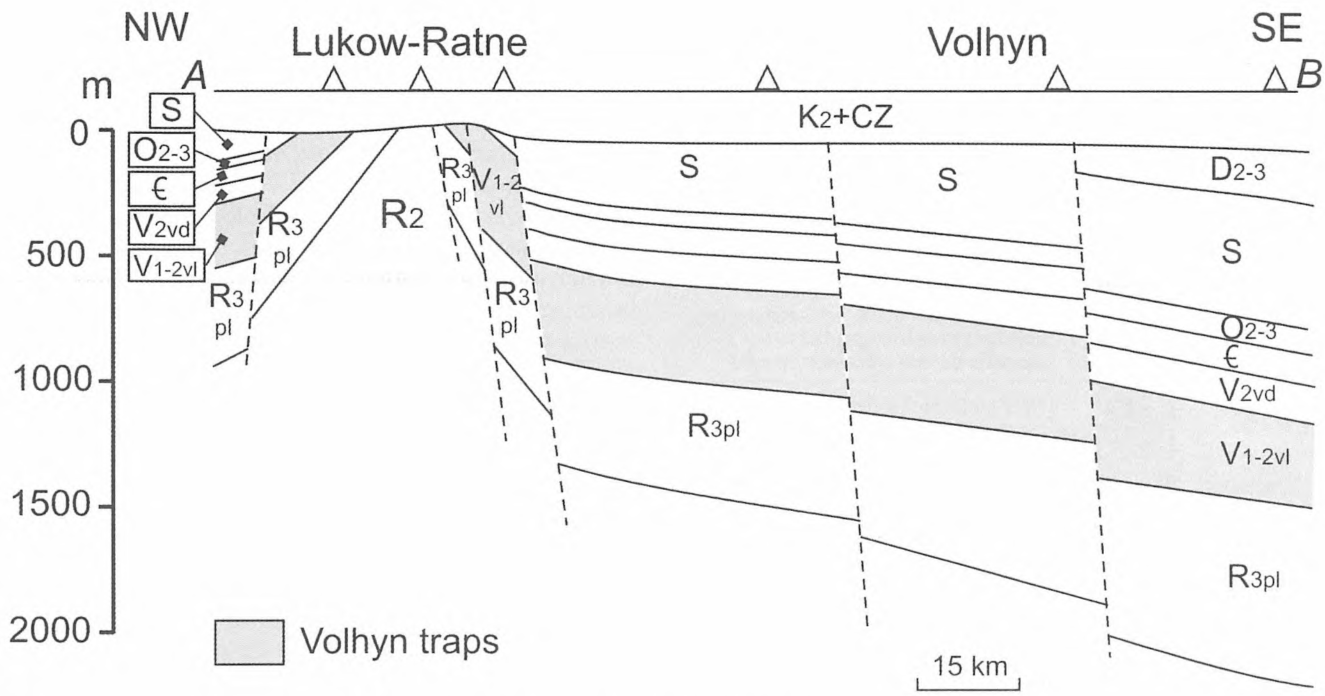

Fig. 3. Geological cross-section through the study area along line A–B on Fig. 1

mudstones of the Valday Series at 540 and 650 Ma, respectively.

The Middle-Upper Ordovician limestones and marlstones unconformably cover the Cambrian units as thin, 45–100-m-thick beds. In the Volhyn Depression, a layer of calcareous sandstone usually settles in the bottom. In the Lukow-Ratne Swell, the Ordovician strata have been found in the Ratne High and farther west.

The Silurian strata are widespread and represent carbonate reef facies. The thickness of the limestones increases from 650 m in the Volhyn Depression to 1,300 m in the Podlasie-Brest Depression. The fore-reef basin opened in the Tornquist Ocean (Garetsky, 1981, 1990; Zabigaylo *et al.*, 1990). The layer of tuffites intercalates the limestones, being coeval with Silurian volcanic activity close to the western margin of the Mazury High. In the Lukow-Ratne Swell these deposits are partly eroded.

The Lower Devonian beds do not occur in the study area. The deposition occurred locally in the Podlasie-Brest Depression, where a bed of multicoloured marlstones and limestones is up to 40 m thick. In the southwestern part of the Volhyn Depression, the marine deposits thicken westwards and reach 1,000 m in the Lublin-Lviv Low. In the bottom, they are represented by intercalating layers of limestones, marls, and mudstones. Higher upwards, the beds become enriched in terrigenous material and grade into siltstones and sandstones. The terrigenous red beds, 1,200 m thick, finished the Early Devonian deposition in the Lublin-Lviv Low (Dnister Series).

During the Early-Middle Devonian, the western margin of the East-European Craton was uplifted and deeply eroded. The maximum of erosion reached 1.5 km in the western part of the Volhyn Depression. In the Lukow-Ratne Swell, the Precambrian crystalline rocks were exposed in the Dubrovitsa, Ratne, Hotyslav, and Wishnice Highs. The adjacent areas were also uplifted, and during Middle-Late Devonian to Carboniferous times subsided again, and the younger sediments covered them outside of the studied area.

The Middle-Upper Devonian terrigenous, calcareous, and evaporitic beds unconformably covered the eroded areas in the southern and western parts of the Volhyn Depression, and in the Lublin-Lviv Low. The narrow strait connected this marine basin with the sea of the Moscow Syneclise (Garetsky, 1990). The thickness of these deposits increases westwards and reaches up to 800 m in the western part of the Volhyn Depression.

The Lower-Middle Carboniferous beds are represented by multicoloured and coal-bearing formations, consisting of intercalating layers of sandstone, siltstone, mudstone, and limestone in the western parts of the Volhyn and Podlasie-Brest Depressions. Farther west, their thickness attains 1,000 m in the Lublin-Lviv Low. In the Lukow-Ratne Swell, these beds rest on the western highs.

The above-described deposits were uplifted during the Early Permian through Late Cretaceous times and deeply eroded, locally down the Precambrian crystalline rocks (Sokolowski, 1970).

During this timespan, the Cu-bearing fields were exposed above the sea level. There are no data pertaining to the intensity of erosional processes, which after the Early Devonian and Early Permian regional inversions were certainly rather weak. Consequently, the deposits of these periods are not described in the present paper, although they were found in the adjacent areas, including the western outskirts of the Lukow-Ratne Swell.

The Upper Cretaceous strata cover the erosional surface that cuts older rocks. The Precambrian magmatic rocks were exposed as the ranges of erosional hills nearby the

Ukrainian Shield and along the Lukow-Ratne Swell. The sediments comprise the Cenomanian quartz-glauconitic sands and sandstones, which are covered by the Turonian chalk and marbles. The thickness of the Upper Cretaceous deposits reaches 200–250 m in the western part of the Lukow-Ratne Swell.

In the copper fields, **Quaternary** sands and clays unconformably overlie the Upper Cretaceous beds. The thickness of these deposits ranges from 0 to 80 m.

GEOLOGICAL PATTERN OF THE VOLHYN FLOOD BASALT PROVINCE

Structure of the trappean plateau

The major volcanogenic strata, 350–450 m thick, occur in the western and central parts of the Volhyn Depression, close to the Ratne, Hoteshov, and Wishnice Highs of the Lukow-Ratne Swell (Fig. 1). Towards the southern margin of the Volhyn Depression, the volcanic beds become thinner and divided into two narrow zones, submeridionally striking along the opposite margins of the North Moldovian Monocline. To the south, these zones contain minimum of pyroclastics and progressively pinch out laterally. Towards the Teisseyre-Tornquist margin, the formations thicken, but their position at the deep levels in the western part of the Volhyn Depression is still unclear. Close to the western border of the East-European Craton, in the southern border of the Wishnice High, the boreholes penetrated 330 m thick trappean formations, but farther west the volcanic beds abruptly disappear. The younger strata rest directly on the crystalline rocks. In the Podlasie-Brest Depression, the Volhyn trapps lie on the Polis'ka strata. Farther north, the volcanogenic beds transgressively cover the Precambrian crystalline rocks and gradually pinch out. To the east, tuffs and tuffites, 150–100 m thick, dominate among volcanogenic rocks. Still farther east the basalt flows disappear, and synchronous tuffite and terrigenous beds fill the shallow deep along the ceased mid-Baltica rift system.

Birulev (1968) proposed a tripartite subdivision of the Berestovets Suite into: the Gorohov (recently Zabolottya) or lower basalt beds, the Babino or mid tuff beds, and the Ratne or upper, predominantly basalt beds. In compliance with the presented reinterpretation (Fig. 4) they do not provide valid information about the structure and development of the basalt plateau. In different parts of the basalt province, the volcanogenic strata have different structure, depending on the number of basalt or tuff-basalt floods, which we referred to successive volcanic phases. The beds of tuffites, containing the layers of tuffs and terrigenous deposits divide them, but usually can not be correctly distinguished as specific eruptive cycles (Juskowiakowa, 1971; Szczepanowski, 1977) or subdivided as independent explosions. In our work, four volcanic phases have been recognized, and called as series A, B, C, and D (Figs 4, 5). They yielded the range of floods which consist of numerous lava flows containing interlayers of pyroclastics.

Phase A produced submeridionally orientated flood basalts, everywhere lying directly on the pre-Berestovets rocks and striking parallel to the Teisseyre-Tornquist margin. In the Volhyn Depression, the basalt flood of phase A is 170 m thick, and contains numerous thin layers of tuffs. Towards the Lukow-Ratne Swell, this flood becomes thinner, but the tuff interlayers pinch out, and the basaltic lava flood, about 60 m thick, strikes NW along the western margin of the Volhyn Basalt Province to the Mazury High. Southwestwards this flood approaches the Teisseyre-Tornquist margin and in the North Moldovian Monocline probably corresponds to the lowermost of two flows, found in the boreholes.

Phase B is observed as three floods, striking eastwards. In series, these floods are located in the Volhyn Depression nearby the Lukow-Ratne Swell, and in the southern and northern slopes of the Podlasie-Brest Depression. They overlap the tuffs, covering flood A or older units. In the Podlasie-Brest Depression, the youngest, southern flood partly covers the older, northern one (Fig. 4c). The thickness of these floods reaches 50–60 m in the zones of major volcanic activity.

Phase C developed following the expansion of the volcanic province. The major basalt flood, 80–100 m thick, bearing numerous interlayers of pyroclastics, was found in the Volhyn Depression. This flood decreases in thickness to 70–80 m in the Lukow-Ratne Swell, where it contains the streaks of ashes and fine-grained tuffs. In the Podlasie-Brest Depression, the phase C produced a basalt flood, 40–80 m thick, almost free of pyroclastics. The flows of andesite and andesite-dacite lavas, 120 m thick, occur on the top of this flood. In the North Moldovian Monocline, the basalt flow of this phase apparently finished the volcanic activity.

The flood basalts of phase C approached the ancient Sarmatian (Ukrainian) Shield and covered both the older floods and pyroclastic units around. The flood strikes in line with the Tornquist margin.

The transitional tuff horizon divides the floods of phases C and D. Phase D produced isolated basalt floods, 20–100 m thick, developed along the Lukow-Ratne Swell, in the southern margin of the Podlasie-Brest Depression, and along the eastern margin of the Volhyn Depression. The numerous interlayers of tuff, tuffites, and conglomerates are observed within this flood. Thus, the phase D was developed during tectonic fragmentation of the basalt plateau with rejuvenation of the volcanic activity in some zones at the end of rifting.

A review of petrochemistry

Many papers have dealt with petrochemistry of the Volhyn effusive rocks (Semenenko, 1967; Szczepanowski, 1977; Korenchuk, 1997; Białowolska *et al.*, 2002). Recently, however, the petrochemical classification of the Volhyn flood formation, especially of dikes and sills, is not clear yet in details. Korenchuk (1997) published the most complete summary of petrochemical composition of the Volhyn effusive rocks. He classified dikes and sills of gabbro-dolerites as K-Na alkaline and subalkaline gabbroids, with low and normal content of alumina. In compliance with this work, the basalts of phase A are K-Na alkaline and subalkaline, and mostly similar with these gab-

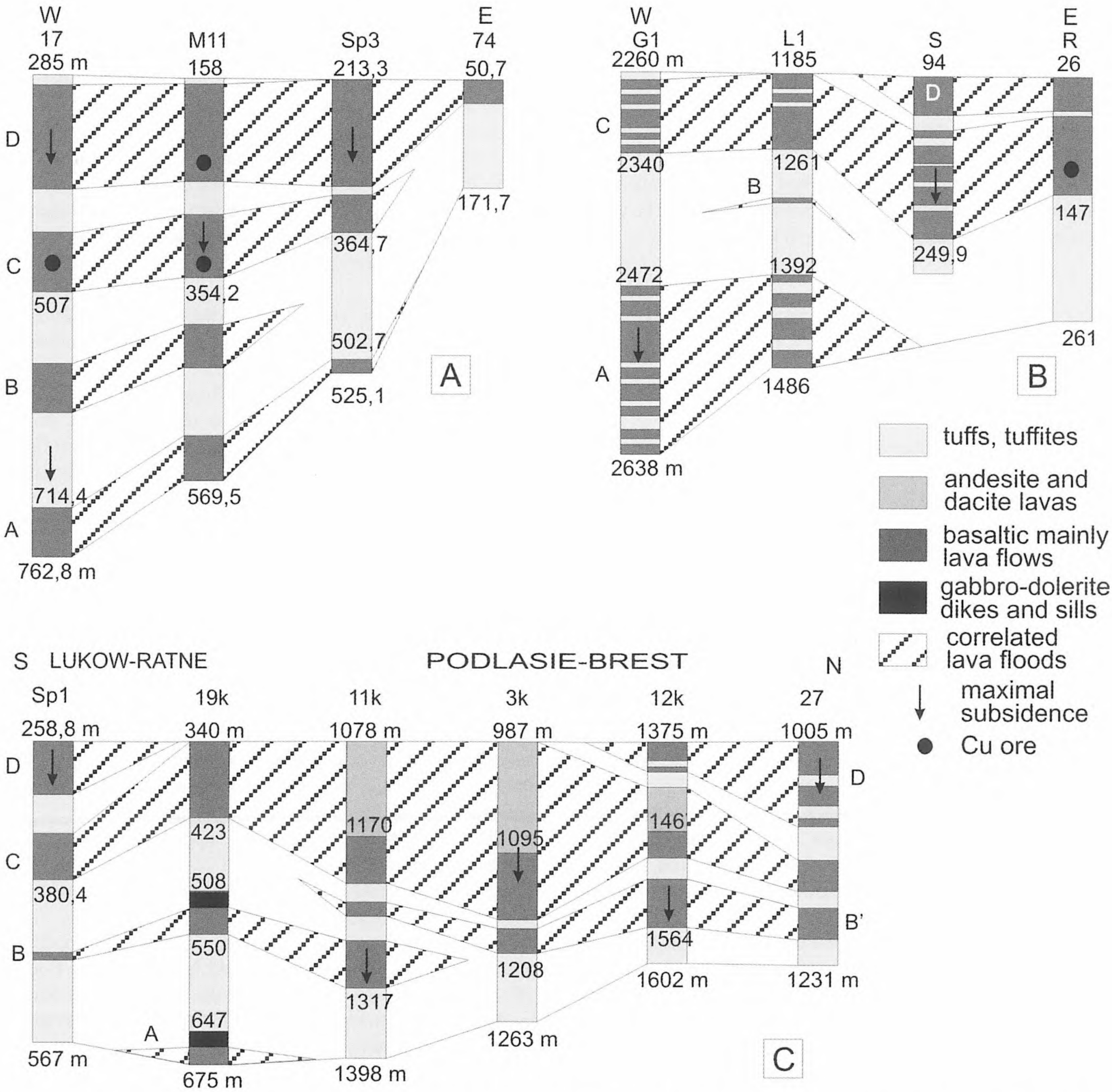

Fig. 4. Correlations of the lava floods between the boreholes (see Fig. 5) drilled in the Volhyn Depression (a), Lukow-Ratne Swell (b, c) and Podl'assky-Brest Depression (c). A, B, C, D – volcanic floods

broids. The normal basalts are uncommon. Basalts of phase B are subalkaline and partly normal with low and normal content of alumina. Subalkaline and normal basalts are distinctly different (Korenchuk, 1997). The basalts of phases C and D have been classified as metaluminous quartz tholeiites (Białowolska *et al.*, 2002) and occur along with normal, subalkaline, and alkaline basalts, andesite-basalts, and trachy-andesites (Korenchuk, 1997) which, in the Podlasie-Brest Depression, are associated with andesites and basalt-andesites (Areń *et al.*, 1979).

Consequently, the volcanism in the Volhyn Flood Basalt Province probably occurred in different tectonic regimes, which controlled different lava compositions during the successive events of the volcanism: phase A – alkaline and subalkaline basalts; phase B – subalkaline and normal basalts; phase C and D – normal and subalkaline basalts, andesite-basalts, trachy-andesites, andesites, and andesite-dacites.

Global tectonic events: a discussion

In compliance with Nikishin *et al.* (1996), the large basalt floods covered the Volhyn Province during rifting which preceded the breakup of Eastern Rodinia, with opening the early Tornquist Sea between Baltica and Amazonia at 551 Ma (Bingen *et al.*, 1998). According to different hypotheses (Hartz & Torsvik, 2002), the Volhyn Basalt Province originated at 570–550 Ma in line with mid-continental

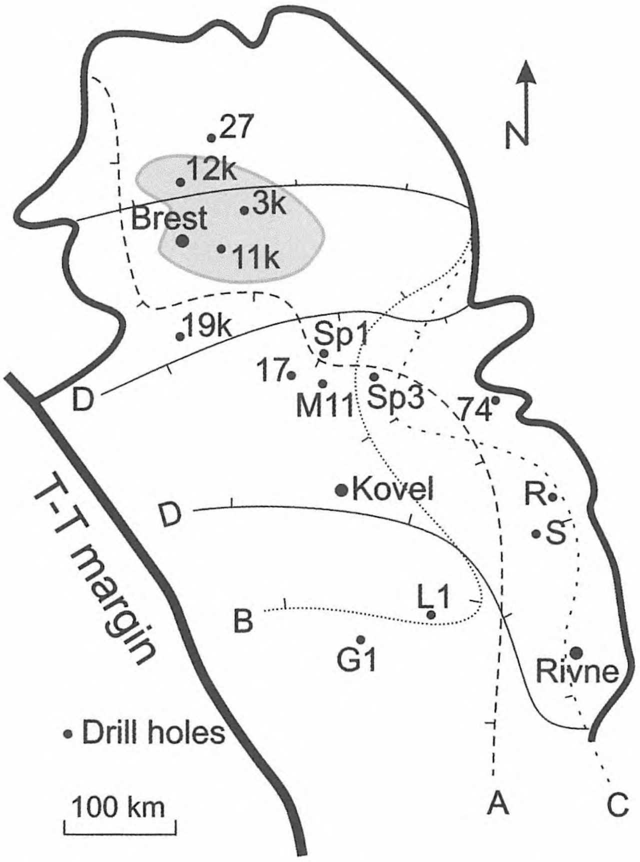

Fig. 5. Sketch map showing spatial distribution of the volcanic floods produced during phases A, B, C, D in the Volhyn Flood Basalt Province

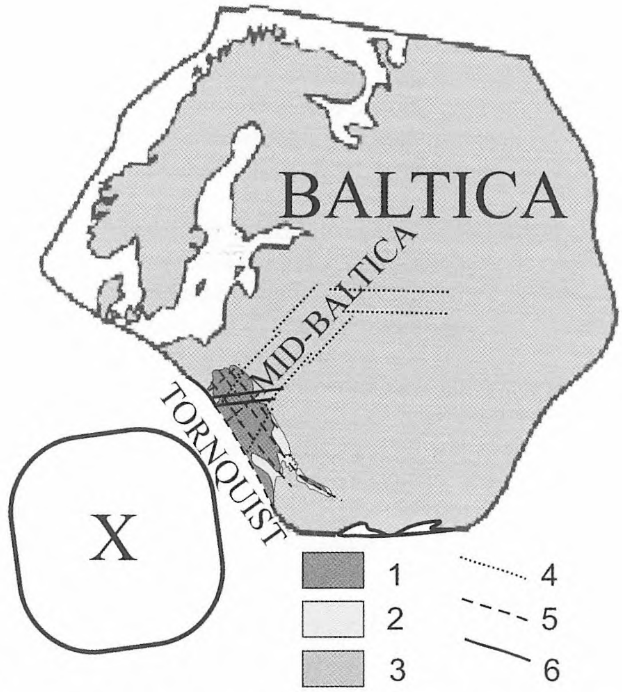

Fig. 6. Sketch of the Tornquist rift which split Baltica and an unknown X-terrain in the Late Vendian. *1* – Volhyn traps; *2* – Volhyn tuffs and tuffites; *3* – present-day land area; faults: *4* – Riphean; *5* – Vendian; *6* – Caledonian-Hercynian

rifting of the pre-Iapetus region (eastern North America) (Cawood *et al.*, 2001) which split Baltica into two plates, along the mid-Baltica rift crosswise the Tornquist margin. The last fit has been developed starting from the palaeomagnetic data, indicating that in 580–550 Ma Baltica independently drifted southwards to Gondwana (Poprawa & Pacześnia, 2002).

The above-described volcanic phases well depict four tectonic events which yielded the volcanism in the ancient rift. The first and third events caused the volcanic activity along the longitudinal faults in concordance with the Teisseyre-Tornquist margin. During these events, the palaeorift invaded transversely the deceased mid-Baltica palaeorifting system. The second event resulted in the lava ejections through the short transversal faults within the rift. During the last two volcanic phases, the rift was tectonically parted because of crust melting, manifested by the ejection of different lavas varying from basalts to andesites and andesite-dacites. The major volcanic activity and lava flows occurred at the place where the younger Tornquist rift crossed the older mid-Baltica (Fig. 6).

Hence, the last idea (Hartz & Torsvik, 2002) is not corroborated with the time when the mid-Baltica developed. The Late Riphean (around 700 Ma) mid-Baltica rifting is now well observed because of preservation of the terrestrial red strata. The thinning bed of the Vendian tuffites, which branches off from the trappean plateau far along the former mid-Baltica rift, suggests that this system developed extremely slowly in comparison to the well-documented 540–600 Ma rifting along the Tornquist line, *i.e.* mid-Baltica formed much earlier than the 570–550 Ma rifting of the pre-Iapetus region (Cawood *et al.*, 2001). During the Vendian, outside the Volhyn basalt plateau, the mid-Baltica relatively inertly responded and was partly melted inside the younger Tornquist rift at the end of the volcanic cycle. Eventually, the mid-Baltica deepening periodically continued much later, in the Cambrian, Ordovician–Early Silurian, and Middle-Late Devonian, but of course was not affected by rifting.

Thus, the Volhyn Flood Basalt Province originated from rifting which split Baltica and an unknown X-continent in the Late Vendian, and opened the Tornquist Ocean (Fig. 6). The opening resulted in slackening along the new passive coast of Baltica, which eventually settled down as marine shelf at the end of the Late Vendian, but later than 540 Ma (Cawood *et al.*, 2001).

REMARKS ON COPPER EMPLACEMENT

At this time, two suppositions are most plausible to explain copper concentrations in the study areas and to improve the ore prospecting.

1) The Ratne and Rafalovka-Berestovets copper fields settle together on the prominent blocks of the East-European Craton. They serve as discharging zones for the ascending fluids, originating in the Upper Riphean oxidized red beds. The basalt and tuffs could reduce them and pre-

cipitate Cu. In this case, the most significant Cu concentrations are supposed to be deposited in the most permeable zones, like tuffs, altered basalts, fracture zones, and in the bottom of the basalt flows, covering the Upper Riphean red beds. This supposition is in concordance with copper deposition in the numerous stratiform red-bed type copper deposits.

2) Hydrothermal magmatic fluids furnished Cu during the last volcanic phases (C and D), developed in the both prospecting fields during tectonic fragmentation of the Tornquist rift and crust melting. If this hypothesis holds true, it can be therefore predicted that the most perspective fields settle in the Podlasie-Brest Depression, where the crust melting occurred most intensively. These ores have to form the telescopically controlled bodies, which should occur as veins and being disseminated along ancient faults, and within the most permeable beds (tuffs, tuffites, amygdaloidal basalts) as strata-bound bodies.

CONCLUSIONS

1. The Volhyn flood basalt plateau developed during rifting which opened the Tornquist Ocean and split the Baltica and an unknown terrain at 540–600 Ma, in the Late Vendian (Fig. 6). After splitting, the detached basalt province served as a marine shelf of the Baltica and eventually continued as a passive margin.

2. The basalt plateau developed during four tectonic events, controlling the major volcanic ejections through the longitudinal and short transversal rifting faults within the Tornquist rift, but most violently inside the deepest part of the transversely orientated Late Riphean mid-Baltica rift (see also Fig. 5).

3. The volcanism ceased together with tectonic fragmentation of the volcanic province and crust melting, manifested by outflowing both basalts and acid lavas.

4. The copper fields are probably situated in tectonically prominent parts of the volcanic plateau which could serve as discharging zones both for thermal magmatic and underground brines which could furnish Cu to the basalt formations and form the ore bodies.

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REFERENCES

Aren, B., Bessonova, V. Y., Brangulis, A. P., Velikanov, V. A., Vlasov, B. I., Keller, B. M., Lendzen, K., Mens, K., Mihnak, P., Kiryanov, V. V., Piskun, L. V., Pirrus, E., Rozanov, A. Y. & Chumakov N. M., 1979. *Stratigraphy of the Late Precambrian and Cambrian deposits of the West of the East-European Craton*. Publ. House Nauka, Moscow, 236 pp.

Białowolska, A., Bakun-Czubarow, N. & Fedoryshyn, Y., 2002. Neoproterozoic flood basalts of the upper beds of the Volhynian Series (East European Craton). *Geological Quarterly*, 46: 37–57.

Bingen, B., Demaiffe, D. & Van Breemen, O. V., 1998. The 616 Ma old Egersund basaltic dike swarm, SW Norway and late Neoproterozoic opening of the Iapetus Ocean. *Journal of Geology*, 106: 565–574.

Birulev, A. E., 1968. On stratigraphy of the Volyn series (Late Precambrian of Ukraine). *Sovetskaya Geologiya*, 3: 23–33.

Compston, W., Sambridge, M. S., Reinfrank, R. F., Moczydlowska, M., Vidal, G. & Cleasson, S., 1995. Numerical ages of volcanic rocks and the earliest faunal zone within the Late Precambrian of East Poland. *Journal of Geological Society*, 152/4: 599–611.

Cawood, P. A., McCausland, P. J. A. & Dunning, G.R., 2001. Opening Iapetus: Constraints from the Laurentian margin in Newfoundland. *Geological Society of America Bulletin*, 113: 443–453.

Garetsky, R. G. (Ed.), 1981. *Geology of the western part of the East-European platform*. Publ. House Nauka i Tehnika, Minsk, 188 pp.

Garetsky, R.G. (Ed.), 1990. *Tectonics of the West of the East-European platform*. Publ. House Nauka i Tehnika, Minsk, 168 pp.

Hartz, E. H. & Torsvik, T. H., 2002. Baltica upside down: A new plate tectonic model for Rodinia and the Iapetus Ocean. *Geology*, 30: 255–258.

Juskowiakowa, M., 1971. Basalts of eastern Poland. *Biuletyn Państwowego Instytutu Geologicznego*, 245: 173–253.

Korenchuk, L. V., 1997. Petrochemistry of Late Precambrian volcanogenic rocks of the western margin of the East-European Platform. *Geologichny Zhurnal*, 3-4: 164–169.

Krasheninnikova, O. V. (Ed.), 1971. *Stratigraphy of USSR. RipheanVendian*. Publ. House Naukova Dumka, Kyiv, 276 pp.

Małkowski, S., 1929. On discovery of the native copper deposit in Volyn. *Biuletyn Państwowego Instytutu Geologicznego*, 24: 16–17.

Małkowski, S., 1931. On native copper deposit in Velykiy Midsk in Volyn. *Sprawozdania Państwowego Instytutu Geologicznego*, 6: brak stron

Małkowski, S., 1951. On the volcanism events between Volinian-Ukrainian Massif and Kujavsky-Pomorsky Swell. *Acta Geologica Polonica*, 2: 491–595.

Nikishin, A. M., Ziegler, P. A., Stephenson, R. A., Cloetingh, S. A. P. L., Furne, A. V., Fokin, P. A., Ershov, A. V., Bolotov, S. N., Korotaev, M. V., Alekseev, A. S., Gorbachev, V. I., Shippilov, E. V., Lankreijer, A., Bembinova, E. Y. & Shalimov, I. V., 1996. Late Precambrian to Triassic history of the eastern European Craton: Dynamics of sedimentary basin evolution. *Tectonophysics*, 268: 23–63.

Poprawa, P. & Pacześnia, J., 2002. Late Neoproteroic to Early Palaeozoic development of a rift at the Lublin-Podlasie slope of the East European Craton – analysis of subsidence and facies record (eastern Poland). *Przegląd Geologiczny*, 50: 49–63.

Pryhodko, V. L., Kosovsky, Y. A. & Ivaniv, I. N., 1993. Perspectives of copper ore of the volcanogenic formations of Volyn series of the Lukow-Ratne horst zone. *Geologichny Zhurnal*, 4: 138–143.

Semenenko, N. P. (Ed.), 1968. *Riphean volcanism and metalliza-*

tion of the western part of the Ukrainian Shield. Publ. House Naukova Dumka, Kiev, 172 pp.

Sokołowski, S. (Ed.), 1970. *Geology of Poland. Volume 1. Stratigraphy. Part 1. Pre-Cambrian and Palaeozoic.* Wydawnictwa Geologiczne, Warsaw, 651 pp.

Szczepanowski, W. J., 1977. Geochemistry of the basalts of the Wishnice series of the eastern Poland. *Biuletyn Instytutu Geologicznego*, 298: 141–208.

Velikanov, V. A. & Korenchuk, L. V., 1997. Phases of magmatism and their relation to the sediment depositions in the Late Precambrian (Riphean – Vendian) of the Volyn-Podolia. *Geologichny Zhurnal*, 1-2: 124–131.

Zabigaylo, V. E., Rizun, B. P., Chyj, E. I. & Shpak, P. F., 1990. Geological formations of the Palaeozoic Formations of the Volyn-Podolia. *Geologichny Zhurnal*, 3: 126–133.

Znamenskaya, T. A., Korenchuk, L. V. & Pryhodko, V. L., 1990. Paleotectonical conditions of the Volyn series formation in the Volyn-Podolye. *Geologichny Zhurnal*, 3: 133–141.

Wojciechowski, J., 1939. Bisherige Ergebnisse der Untersuchungen von kupferführenden Gesteinen im Stromgebiet des Horyn, Volhynien. *Biuletyn Państwowego Instytutu Geologicznego*, 14: 1–10.

Streszczenie

ZARYS BUDOWY GEOLOGICZNEJ WOŁYŃSKIEJ PROWINCJI MIEDZIONŚONEJ (ZACHODNIA KRAWĘDŹ WSCHODNIO-EUROPEJSKIEJ PŁYTY

Alexander Emetz, Adam Piestrzyński & Vasyl Zagnitko

Zainteresowanie bazaltami wołyńskimi datuje się na początek XX wieku (Małkowski, 1929). Rozpoznanie bazaltów prowadzono pod kątem poszukiwań ekonomicznych złóż miedzi. Początkowo badania nie przyniosły spodziewanych rezultatów, pomimo że na powierzchniach erozyjnych bazaltów znaleziono rodzimki miedzi o wadze do 1 kg (Wojciechowski, 1939). Dalsze prace prowadzone były przez ukraińską służbę geologiczną. Przyniosły one rozpoznanie dwóch obszarów prawdopodobnie w kategorii D1–C2, tj. Ratne i Rafałowka-Berestovets. Najbardziej obiecującym obszarem jest złoże Zhyrychi (Ratne), zawierające udokumentowane zawartości Cu do 16 % (Pryhodko *et al.*, 1993). Wskazówkami do poszukiwań złóż miedzi mogą być niewątpliwie koncentracje tego pierwiastka spotykane w dolnych częściach pokryw bazaltowych przykrywających utwory typu *red beds*. Taki układ środowisk jest typowy dla wielu złóż stratoidalnych typu *red beds*.

Bazalty rozciągają się na przestrzeni 780 km od północnej granicy zapadliska podlaskiego do monokliny mołdawskiej na południu wzdłuż linii starego systemu ryftowego (Nikishin *et al.*, 1996; Poprawa & Pacześnia, 2002). Maksymalna grubość formacji trapowych i tufowych sięga 490 m. Wiek bazaltów i tufów ustalony na podstawie badań metodami U/Pb i K/Ar wynosi odpowiednio 551 Ma i 540–600 Ma. Autorzy sugerują obecność czterech faz wulkanicznych, które rozwijały się wzdłuż obecnej linii Teisseyre'a-Tornquista (TESZ). Największa aktywność wulkaniczna datowana jest na ryft wieku wendyjskiego. W centralnej części depresji wołyńskiej bazalty zawierają od 5 do 13 wkładek tufowych i tufitowych. W kierunku południowym pokrywy bazaltowe cienieją i podzielone są południkowo na dwie strefy. Starsze podziały wyróżniające 3 poziomy bazaltowe (Birulev, 1967) w świetle wyników nowych badań nie mogą być zaakceptowane. W pracy wyróżniono cztery fazy wulkaniczne, opisane jako A, B, C i D, które korelują się dobrze z czterema wulkanicznymi cyklami wendyjskimi rozpoznanymi na obszarze Polski (Juskowiakowa, 1971; Szczepanowski, 1977). Największe wulkaniczne erupcje odnotowano w miejscu krzyżowania się starego ryftu "mid-Baltica" utworzonego w późnym ryfeju z ryftem rozwiniętym wzdłuż linii Tornquista (Fig. 6). Otwarcie Oceanu Tornquista spowodowało oddzielenie fragmentu kontynentu "Bałtyckiego".