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ELECTRICAL CONDUCTIVITY ANOMALY OF THE NORTHERN CARPATHIANS AND THE DEEP STRUCTURE OF THE OROGEN

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Abstract: The Carpathian conductivity anomaly, also called geoelectrical anomaly, is constrained by the presence of high-conductivity rock series at depths of 10 to 25 km, in different segments of the orogen. This paper aims at locating the source of the anomaly in the framework of crustal blocks and at its geological interpretation. The faulted and locally depressed to 20 km surface of the high-resistivity Precambrian basement of the Polish Carpathians is presented basing on the results of magnetotelluric sounding (MTS). The major faults, of Neogene age, are oriented SW–NE in the west and SE–NW in the east, running symmetrically to the Kraśnik–Rzeszów–Rymanów–Debrecen line (ca. 22° E). The high-conductivity layer overlying the crystalline basement is probably composed of metamorphosed Palaeozoic strata, including coal-bearing Carboniferous rocks. The sole presence and extent of these rocks, however, are not sufficient to generate the regional conductivity anomaly whose outline is clearly related to that of the Tertiary Carpathian orogen.

The results of MTS sounding have been compared with those of seismic refraction studies in the Ukrainian Carpathians. Two belts of depressions of variable depth have been distinguished in the basement. The southern belt includes a collision suture, i.e. the contact zone between the lowered Central European block and the blocks of the Central West and East Carpathians. Between Bardejov–Wysowa and the Marmarosh Massif the source of the geoelectrical anomaly is situated close to the northern margin of the southern basement depression. Farther to the south, up to 46° N near Sf. Gheorghe, Romanian geologists place this source on a deep-seated fault that borders the Central East Carpathian block from E.

To the east of the Slovak–Ukrainian border, the southern depression is overlain by folded flysch complexes of the Rakhov, Porkulets, "Black Flysch", and Ceahlau units, interpreted as the infill of the Outer Dacides rift, as well as by the Dukla unit flysch. The rift was situated in the marginal part of the European continent. Its western continuation, presently covered by the Dukla and Magura Nappes, is documented by relics of dark Doggerian and Neocomian flysch strata, as well as by basalts exposed within the Grajcarek Unit, north of the Pieniny Klippen Belt west of Krynica. The farther continuation of this zone can be found in the Penninicum (Piemontais?) of the Alps.

The source of the Carpathian geoelectrical anomaly is situated near the collision suture; however, the structure of the Ukrainian Carpathians basement and a shift of the anomaly source towards the Carpathian Foredeep in the Focşani region, Romania, may indicate a relationship between the anomaly and the lowered, marginal part of the continental crust.

It is suggested that an important factor generating the Carpathian geoelectrical anomaly is graphite originated due to post-Oligocene migration and graphitization of organic substance within deeply buried strata of the Jurassic–Cretaceous rift and within fault zones in the crystalline basement. The near-surface manifestation of this process is the presence of veins bearing hydrothermal mineral association, including authigenic quartz ("Marmarosh diamonds"). This quartz contains inclusions of anthraxolite, a hard bitumen showing traces of incipient graphitization. Such veins are ubiquitous in the Carpathians, close to the axis of the anomaly.

Abstrakt: Karpacka anomalia przewodności zwana też anomalią geoelektryczną wywołana jest obecnością dobrze przewodzących kompleksów skal w głębokości od 10 do 25 km na różnych odcinkach orogenu. Podjęto próbę zlokalizowania źródła anomalii w układzie bloków skorupy oraz próbę wyjaśnienia jego geologicznej natury. Przedstawiono przybliżony obraz zdyslokowanej i obniżonej lokalnie nawet do 20 km powierzchni wysokooporowego fundamentu Karpat polskich (prekambr w oparciu o wyniki sondowań magnetotellurycznych (MTS). Główne pęknięcia powstały w neogenie; układają się one symetrycznie (SW–NE na zachodzie, SE–NW na wschodzie), skośnie w stosunku do linii Kraśnik–Rzeszów–Rymanów–Debreczyn bliskiej południkowi 22. Przedstawiono cechy nadścielającej fundament warstwy dobrze przewodzącej – jest to przypuszczalnie zmetamorfizowany paleozoik z udziałem węglonośnego karbonu. Obecność i zasięg tych utworów nie wystarczają do generowania regionalnej anomalii przewodności, która nawiązuje wyraźnie do trzeciorzędowego zarysu Karpat.

Wyniki badań fundamentu metodą MTS zestawiono z wynikami refrakcyjnych badań podłoża Karpat ukraińskich. Wyznaczono dwa pasy depresji podłoża o zmiennej głębokości. W pasie południowym znajduje się kolizyjny szew czyli strefa kontaktu obniżonego bloku skorupy kontynentu europejskiego i bloków centralnych

Karpat Zachodnich i Wschodnich. Między Bardejovem–Wysową a masywem Marmarosz źródło anomalii geoelektrycznej znajduje się przy północnym brzegu południowego pasa depresji podłoża. Dalej ku południowi, aż po 46 równoleżnik w pobliżu Sf. Gheorghe według rumuńskich geologów źródło to znajduje się przy rozłamie skorupy stanowiącym zewnętrzną granicę bloku centralnych Karpat Wschodnich.

Na wschód od granicy słowacko-ukraińskiej nad depresją południowego pasa znajduje się sfałdowany flisz jednostek rachowskiej, porkuleckiej, Czarnego Fliszu i Ceahlău interpretowany jako wypełnienie ryftu Dacydów zewnętrznych, a także flisz jednostki dukielskiej. Ryft ten zlokalizowany był w brzeżnej strefie kontynentu. Jego zachodnie przedłużenie przykryte płaszczowinami dukielską i magurską dokumentują relikty ciemnego doggerskiego i neokomskiego fliszu oraz bazaltów w jednostce Grajcarka przy północnej granicy pienińskiego pasa skałkowego na zachód od Krynicy. Dalsze przedłużenie znajduje się w Penninicum (Piemontais?) w Alpach.

Strefa źródła karpackiej geoelektrycznej anomalii jest bliska kolizyjnego szwu; budowa fundamentu w Karpatach ukraińskich oraz przesunięcie źródła anomalii do zapadliska w rejon Focşani w Rumunii wskazują na związek anomalii z obniżonym brzeżnym pasem skorupy kontynentalnej.

Istotnym czynnikiem generującym karpacką geoelektryczną anomalię jest przypuszczalnie grafit. Powstał on w wyniku pooligoceńskiej migracji i grafityzacji substancji organicznej w pogrążonych głęboko osadach jurajsko-kredowego ryftu i w strefach pęknięć fundamentu. Przejawem tego procesu przy powierzchni jest obecność żył z asocjacją minerałów hydrotermalnych, w tym autigenicznego kwarcu (diamenty marmaroskie). Obecne są w nim wrostki antraksolitu, twardego bituminu o początkowej grafityzacji. Żyły te są częste w Karpatach w sąsiedztwie epicentrum anomalii.

Key words: geomagnetic sounding, magnetotelluric sounding, high-resistivity basement, high-conductivity layer, orogen, plate boundary, graphitization, mineral veins, anthraxolite, Carpathians, collision.

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INTRODUCTION

Results of geoelectrical sounding point to vertical and lateral differentiation in the conductivity of rocks and(or) enclosed media, both within the near-surface sedimentary cover, and in the whole lithosphere. The studies of geoelectrical effects induced by changes in the geomagnetic field helped to locate a number of regional conductivity anomalies in Europe in the 1970s (Fig. 1; Porstendorfer *et al.*, 1976). Such anomalies are also called geoelectrical anomalies (Jankowski *et al.*, 1984; Petr *et al.*, 1994). The axes of anomalies are indicated by zero value of variation of the Z component of the geomagnetic field, as well as by divergent pattern of the Wiese induction vectors. Vectors detected by magnetic sounding (MV), showing the directions of induction currents, point outwards of the axis of an elongated body of high conductivity which is situated within inhomogeneous complexes of crustal rocks (Rokityansky, 1976; Rokityansky *et al.*, 1976a). The shape of the anomalous field contours is the basis for determination of the maximum depth to the top of the conductive body. The depth of the boundary between rocks of dramatically contrasting conductivity may also be verified by magnetotelluric sounding (MTS; Berdichevski & Dmitriev, 1976).

Geological interpretation of the sources of electrical anomalies, i.e., zones of highly conductive strata, is usually controversial. Both, electrolithic (ionic) conductivity associated with fluids contained within pores and fissures and electronic conductivity, can be taken into account. The latter possibility holds true – on the regional scale – in the case of the presence of biogenic or juvenile graphite. Frost *et al.* (1989) found intergranular graphite forming continuous film around grains in rocks of the lower continental crust, and concluded that graphite originated from CO_2-rich fluids during cooling. The graphite can cause high electrical conductivity of rocks and may be a source of conductivity anomaly. The presence of graphite within cataclastic fractures and related microresistivity anomaly have been documented by the deep KTB borehole near Oberpfalz, Bohemian Massif (Haak, 1993).

An important regional conductivity anomaly is related to the deep zone of the Carpathian orogen (Rokityansky *et al.*, 1976b; Jankowski *et al.*, 1984; Pinna *et al.*, 1992; Petr *et al.*, 1994). It extends from Vienna to the South Carpathians

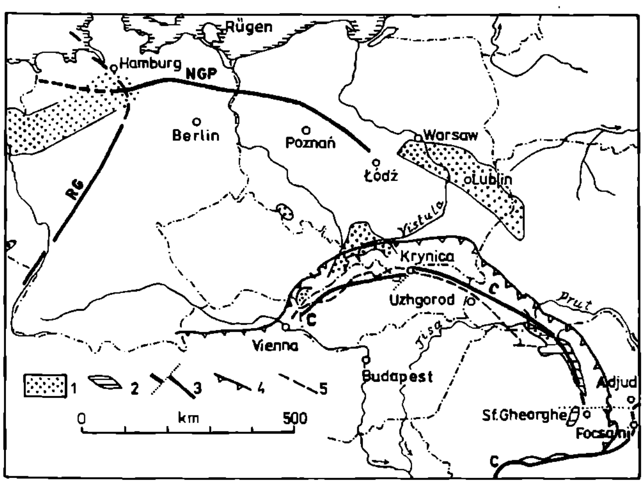

Fig. 1. Map of electrical conductivity anomalies in Central Europe (compiled after Porstendorfer *et al.*, 1976; Rokityansky *et al.*, 1976b; Pinna *et al.*, 1992; coal basins after *Carte Tectonique International de l'Europe*, 1982; Pożaryski & Dembowski, 1984; and Oszczypko *et al.*, 1989). *1* – extent of Upper Carboniferous coal-bearing strata, *2* – Crystalline–Mesozoic zone of the East Carpathians (northern part – Marmarosh massif), *3* – conductivity anomalies (NGP – North German–Polish, C – Carpathian, RG – Upper Rhine Graben–Gottingen), *4* – Carpathian frontal thrust, *5* – Pieniny Klippen Belt

(Fig. 1) at a depth ranging from 10 to 25 km in different segments of the Carpathian arc. Pinna *et al.* (1992) and D. Stanica & M. Stanica (1993) point to a discontinuity of the axis of this anomaly close to the 46 parallel in the Romanian East Carpathians. It has also been found that long-term (>900 s) measurements of geomagnetic induction vectors detect deeply-buried, regular anomalies, whereas short-term measurements reveal highly changeable vector directions and local anomalies (Jankowski *et al.*, 1991). Different geological models explaining the presence of highly conductive rocks or solutions, i.e. the sources of anomalies, have been constructed. The role of altered and(or) fractured rocks, saturated with hot mineral waters, as well as the proximity of anomaly sources to boundaries of different crustal blocks, including that between the Carpathians and the adjacent platforms, have been taken into account (Ádám & Pospišil, 1984; Jankowski *et al.*, 1984, 1991; Oszczypko & Ślączka, 1985; Pinna *et al.*, 1992; Petr *et al.*, 1994).

Most of the authors reject the idea of graphite schists as a possible source of the geoelectrical anomaly. However, Tomek (1988) is inclined to accept Stanley's opinion (*pers. comm.*, 1986) that graphite associated with buried subduction zones is the most probable source of conductivity anomalies.

In this paper, a possible connection between the Carpathian anomaly and the presence of metamorphosed coal-bearing Carboniferous strata beneath the orogen is discussed; nevertheless, the author's opinion is that the source of the anomaly should be related to graphitized rocks occurring close to the boundaries of crustal blocks. The pattern of the latter is analyzed below, basing on the results of magnetotelluric sounding (MTS) conducted in the Polish Carpathians by the State Geological Institute in 1978–79 and 1986–90 (Molek & Oraczewski, 1988; Molek & Klimkowski, 1991), as well as on published data on the Ukrainian, Slovak and Romanian Carpathians.

COAL-BEARING AND BITUMINOUS FORMATIONS AS POSSIBLE SOURCES OF THE CONDUCTIVITY ANOMALY IN CENTRAL EUROPE

Dortman and Toporec (1984) report on very low electrical resistivity of metamorphosed coals present in well logs of the Sakhalin and Donbas basins (Fig. 2). The specific resistivity of these coals decreases with increasing coalification, attaining less than 1 Omm in anthracites. Similar properties may have metamorphosed claystones rich in plankton-derived organic substance.

The northern, German–Polish anomaly, occurs in the platform area between Hamburg and Łódź (Fig. 1). In a model elaborated by Porstendorfer *et al.* (1976) for the area south of Rugen, low-resistivity layers (6 and 25 Omm, rarely <5 Omm) are found between highly resistive Zechstein salts and the crystalline basement, at a depth of 5–7 km. Highly conductive layers also occur in the supra-Zechstein sedimentary cover, as well as in the lower crust and upper mantle. The studies carried out by ERCEUGT–Group (1992) along the Alps–Baltic Sea profile, located the discussed anomaly between the Rhine and the Elbe. Low resistivity of the topmost part of sediments has been related to electrolites (brines), whereas the low resistivity of rocks at depths between 5 and 15 km is thought to have been induced by an electronic conductor, probably biogenic meta-anthracite/graphite within the horizon of Early Palaeozoic black shales.

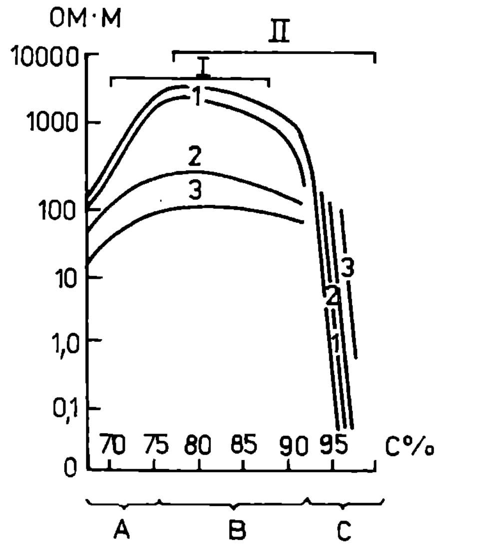

Fig. 2. Relationship between electrical resistivity and degree of coalification, based on well logs (after Dortman & Toporec, 1984). 1 – coal of low ash content, 2 – coal of high ash content, 3 – coal-bearing shale. Coalification: A – brown coal, B – black coal, C – anthracite. Coal basins: I – Sakhalin, II – Donbas

Taking into account the vertical resistivity distribution in the Porstendorfer's *et al.* (1976) model, one can also consider coal seams and carbonaceous Carboniferous shales of the Variscides' foreland as a source of the German–Polish anomaly (Fig. 1). These strata, if present in the area in question, should be thermally metamorphosed by the Early Permian volcanism, which extended as far east as Poznań–Łódź region (Ryka & Pokorski, 1978). Basing on geomagnetic and magnetotelluric sounding, Jankowski *et al.* (1991) concluded about the presence of a deep graben filled with highly conductive formations in the basement of the Northern Carpathians; porous rocks infilling the graben, saturated by hot mineral waters, have been considered the principal source of the Carpathian conductivity anomaly. In relation to the above discussion on geological setting of the German–Polish anomaly, it seems necessary to analyze the possible occurrence of rocks showing electronic conductivity in the Carpathian basement and their location in the deep structure of the orogen.

MAGNETOTELLURIC SOUNDING (MTS) OF THE POLISH CARPATHIAN BASEMENT: RELIABILITY OF THE RESULTS

Magnetotelluric sounding has been performed with the aim of locating the source of the Carpathian geoelectrical anomaly (Jankowski *et al.*, 1984). In 1975, a survey of the top of the high-resistivity Carpathian basement was initiated (W. Bachan, J. Święcicka-Pawliszyn & M. Molek, in Młynarski *et al.*, 1982). This survey detected a depression in the basement at a depth of 17 km near Baligród, as well as the overlying low-resistivity layer (0.4–5 Omm). These results led to further sounding in the years of 1986–90, throughout the Polish Carpathians.

The sounding was conducted every 4–6 km, along profiles perpendicular to the strike of the orogen. The data obtained include depths to the high-resistivity basement, the distribution and properties of the low-resistivity layer. To the west and south of Krynica and NE of Wysowa, the MTS resistivity curves are particularly strongly disturbed. A few soundings between Rymanów and Łupków are characterised by uninterpretable curves. Some of the results have already been published by Doktór *et al.* (1990), Kuśmierek (1990) and Ryłko & Tomaś (1995). The results of MTS sounding have been used to construct a map of conductivity, as well as resistivity models of the two transversal Carpathian profiles (Jankowski *et al.*, 1991).

Figure 3 shows data concerning the depth to the high-resistivity horizon. In the zones of high density of sounding, only representative values have been shown. These results are confronted with well-log data. The location of selected wells which reached crystalline basement under the sedimentary cover and overthrust flysch nappes (Fig. 3) is also presented. The high-resistivity basement rocks SW of Wadowice include Precambrian gneisses, migmatites and granitoids of the Upper Silesian massif; those drilled SE of Kraków are crystalline schists, gneisses and amphibolites of the Rzeszotary block, whereas east of that block numerous wells reached poorly metamorphosed flysch strata of the Cadomian Małopolska–Central Dobrogea orogen. This Vendian–(?)Lower Cambrian flysch represents the marginal Carpathian basement south of Tarnów (Zakliczyn–Brzozowa) and between Rzeszów–Przemyśl and Kuźmina in the south. It should be noted that the flysch nature of this series was established by the present author in the cores from the Kuźmina 1 borehole in the depth interval 7421–7541 m.

It has been found that the high-resistivity horizon drilled in marginal part of the Carpathians is associated with the above listed crystalline Precambrian rocks in the basement. Their resistivity is a few hundred Omm; much higher than that of the overlying sedimentary rocks.

The reliability of the MTS sounding data is a matter of debate. In some cases, they are compatible with well-log data (*e.g.*, Kuźmina 1), in other cases they are not. The borehole Zawoja 1, south of Sucha, indicates that the crystalline basement lies deeper than suggested by MTS data; the error exceeds 15%. In the vicinity of Gorlice (boreholes G 11, G 13), Oligocene flysch strata extend at least 300–400 m deeper than the high-resistivity horizon indicated by MTS

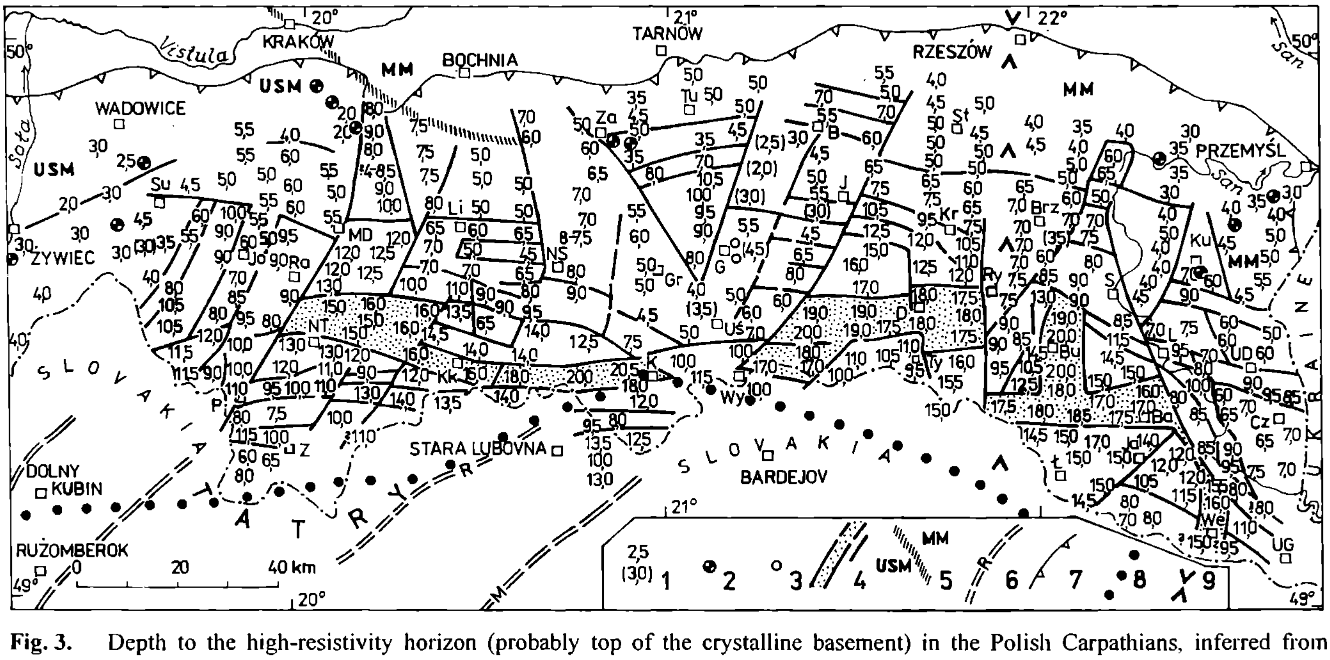

Fig. 3. Depth to the high-resistivity horizon (probably top of the crystalline basement) in the Polish Carpathians, inferred from magnetotelluric sounding (MTS). Dots mark the deepest zone. Boundary between foreland massifs redrawn from Jachowicz & Moryc (1995). *1* – depth in km, values in brackets refer to sounding data that are inconsistent with well description data or doubtful, *2* – wells that drilled crystalline Precambrian rocks, *3* – wells documenting greater depths to the basement than those indicated by MTS data from the neighbouring areas, *4* – boundaries between blocks of comparable depth to the high-resistivity horizon (most probably faults and erosional scarps on top of the basement), *5* – boundary of the Upper Silesia Massif (USM) and Małopolski (Little Poland) Massif (MM) beneath the Carpathian Foredeep and marginal part of the Carpathians, *6* – principal near-surface faults in the Central Carpathians (R – Ružbachy, M – Muraň), *7* – Carpathian frontal thrust, *8* – axial zone of the electrical conductivity anomaly, *9* – symmetry axis of the pattern of Neogene faults in the substratum. B – Brzostek, Ba – Baligród, Brz – Brzozów, BU – Bukowsko, Cz – Czarna, D – Dukla, G – Gorlice, Gr – Grybów, J – Jasło, Ja – Jabłonki, Jo – Jordanów, K – Krynica, Kk – Krościenko, Kr – Krosno, Ku – Kuźmina, L – Lesko, Li – Limanowa, Ł – Łupków, MD – Mszana Dolna, NS – Nowy Sącz, NT – Nowy Targ, P – Podczerwone, Ra – Rabka, Ry – Rymanów, S – Sanok, St – Strzyżów, Su – Sucha, Tu – Tuchów, Ty – Tylawa, UD – Ustrzyki Dolne, UG – Ustrzyki Górne, Uś – Uście Gorlickie, We – Wetlina, Wy – Wysowa, Z – Zakopane, Za – Zakliczyn

sounding. Taking into account these examples, the sounding data distinctly too low as compared to well-log data or those of dubious quality are shown in brackets in Fig. 3. It appears that the relative differences among depths of individual blocks and their boundaries are generally reliable, although not every MTS sounding value shown in Fig. 3 can be interpreted as reflecting the actual depth to the crystalline basement.

Approximate depth and main features of the surface of high-resistivity basement of the Polish Carpathians

The overthrust Carpathian nappes are underlain by the European platform, composed of crystalline basement rocks and overlying, differentiated Palaeozoic–Mesozoic sedimentary rocks and Miocene molasses. These elements form together the Carpathian basement. The results of seismic refraction studies of the relief of the Carpathian crystalline basement have been presented by Ślączka (1975); the MTS sounding, however, brings numerous changes to this picture. Data concerning approximate depths to the high-resistivity horizon (Fig. 3) make it possible to detect supposed boundaries between areas showing comparable depths to the crystalline basement. These boundaries usually follow different faults and erosional scarps of canyons. Regular depth changes detected along certain sounding profiles, particularly to the west and SW of Krosno and south of Sanok, point to the presence of tectonically-tilted and/or erosional surfaces of basement blocks.

The variations in the depth of the high-resistivity horizon permit one to distinguish several depth levels in the top of the crystalline basement (Fig. 3). The upper level is a continuation of the top of the Carpathian Foredeep basement beneath the overthrust flysch nappes. It is a differentiated surface occurring at depths of 4–8 km, averaging at 5–7 km. Extensive basement blocks whose surfaces represent this upper level extend far beneath the Carpathians, as far as Żywiec, farther west into the Upper Vistula drainage basin (Doktór *et al.*, 1990), as well as southwards of Przemyśl, as far as Ustrzyki Dolne area. The southernmost extent of the upper level is marked by the Sucha–Mszana Dolna–Krynica fault system. South of Rzeszów, an equivalent of this boundary lies closer to the Carpathian front. It is represented by the Jasło–Krosno–Lesko faults which border on the north the subsided basement blocks, extending between the Wysowa–Jasło and Sanok–Lesko–Ustrzyki Górne faults.

Close to the upper level are relatively small areas where the top of the basement occurs at depths of 8 to 10 km, averaging at 9 km (Fig. 3). They are incorporated into the upper level NE of Mszana Dolna, south of Nowy Sącz, NW of Gorlice, and close to Krosno and Sanok; they also form large grabens to the north and east of Lesko. The top of the basement, occurring at 9 km depth, is also represented by a large crustal block, extending between Sucha and Rabka and including an additional horst close to Jordanów, by subsided fragments of the upper level between Krynica and Wysowa and east of Baligród, and by the Rymanów horst. The last horst marks a distinct salient of the upper level in the south, similarly to a small horst occurring NE of Krościenko and another one close to Czarna, near Ustrzyki Dolne in the east.

The areas showing lower-situated top of the high-resistivity basement occur south of the Mszana Dolna–Krynica and Jasło–Krosno–Lesko lines (Fig. 3). In the west, they are represented by a vast Nowy Targ–Krynica depression, where the top of the basement occurs at a depth of 12–14 km. This level is dissected by a minor graben (dotted area in Fig. 3), wherein the high-resistivity horizon has been detected at depths 15–16 km and in the eastern part even at 18–20 km. Farther to the east, within the bi-partite Dukla–Baligród depression, the high-resistivity horizon occurs at depths ranging from 15–16 km to 18–20 km. The depression is subdivided in two parts by the Rymanów salient.

The southern margin of the two above depressions only partly lies in Poland and only there it was sounded. Differentiated depths to the basement, a general shallowing and the presence of blocks whose top occurs at 7–9.5 km, have been detected near Gronków SE of Nowy Targ, south of Krynica (Muszyna) and Dukla (Tylawa), as well as between Łupków and Wetlina (Roztoki Górne).

The Nowy Targ–Krynica and Dukla–Baligród depressions form a subparallel belt which is bordered by the Podczerwone–Mszana Dolna fault on the west and the Sanok–Lesko–Ustrzyki Górne fault on the east. The depression belt is also cut by the already mentioned Wysowa–Jasło fault, whose southern continuation in the Central Carpathians (according to the tri-partite subdivision of the West Carpathians into Outer, Central and Inner Carpathians; *cf.* Mahel, 1986) is the near-surface, post-Palaeogene Muraň fault (Pospišil *et al.*, 1989). The Podczerwone–Mszana Dolna fault does also have its southern continuation in post-Palaeogene faults that subdivide the Velka Fatra and Nizke Tatry blocks and mark the western boundary of the Stare Hory massif (*vide* Mahel *et al.*, 1967).

Leaving aside a detailed analysis of this young-Alpine system of faults in the basement, one should take notice of a peculiar symmetric pattern, whose axis is marked by a line extending between Kraśnik in the Carpathian foreland, via Rzeszów–Rymanów towards Zemplin and Debrecen in the Pannonian Basin in the south (Fig. 3). In this pattern, the Wysowa–Jasło fault is paired by a conjugate Sanok–Lesko–Ustrzyki Górne fault, both of them being reverse faults. Some 75–80 km away of these faults, two conjugate fault systems can be detected: in the Carpathian basement between Ružomberok–Mszana Dolna–Jordanów in the west, and in the Carpathian Foredeep basement between Krakovets–Stryy–Gorodok in the east (see Figs. 3 and 5 for location). This Neogene pattern of a complementary set of shears is followed by the extent of the Miocene Carpathian Foredeep and, arranged symmetrically to this axis, Little Pannonian Basin and Transylvanian Depression.

Properties of the highly conductive layer in the basement of the Polish Carpathians

The MTS sounding have confirmed the presence of the highly-conductive layer, frequently called the low-resistivity layer, at different depths above the high-resistivity horizon in the southern part of the Polish Carpathians. This layer is absent in the northern part of the orogen, and in the San drainage basin, far in the south (Fig. 4). It has already been

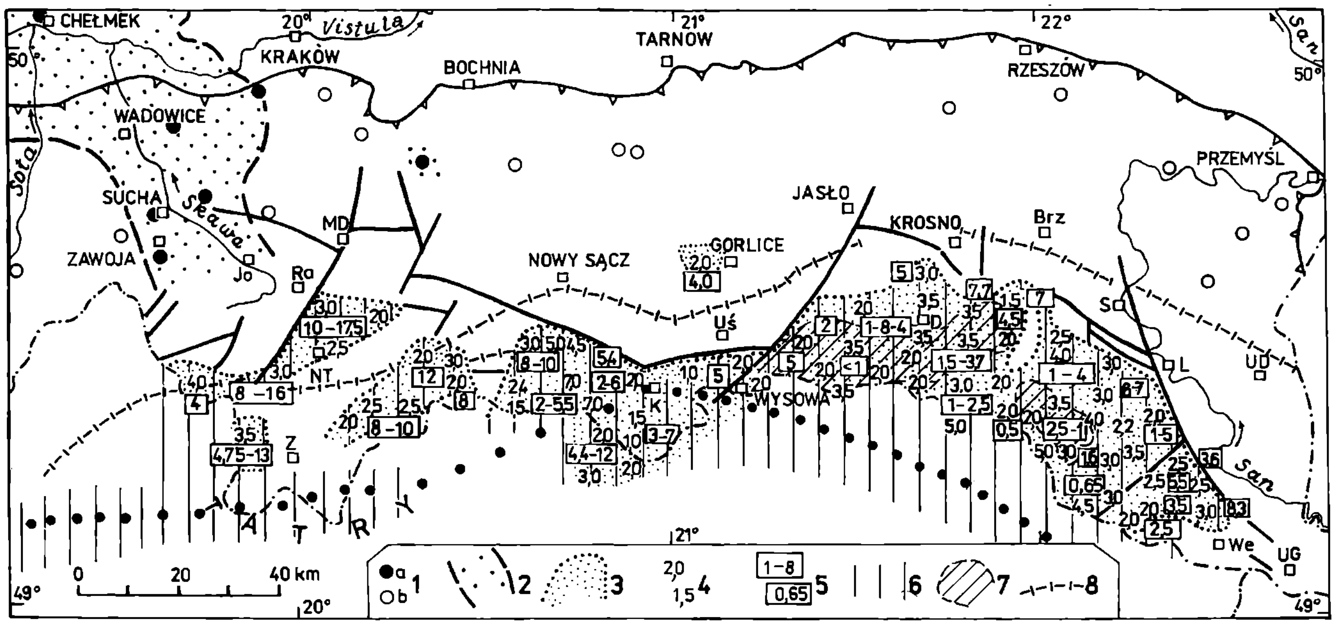

Fig. 4. Location and properties of high-conductivity rocks in the substratum of the Polish Carpathians inferred from magnetotelluric sounding (MTS). *1* – selected wells which proved the presence (*a*) and lack (*b*) of coal-bearing Upper Carboniferous rocks, *2* – extent of proven coal-bearing Carboniferous strata in the basement of the Carpathians and Carpathian Foredeep, *3* – extent of high-conductivity rocks found by MTS sounding in the Polish Carpathians, *4* – approximate thickness (in km) of the high-conductivity complex overlying high-resistivity basement, *5* – resistivity of high-conductivity rocks in Omm, *6* – extent of high-conductivity rocks in the Carpathian basement, detected by geomagnetic (MV) and magnetotelluric (MTS) sounding, *7* – areas where resistivity of rocks overlying high-conductivity complex is lower than 10 Omm, *8* – axial zones of segments of the Carpathian gravity low. For other explanations – see Fig. 3

detected by previous MV and MTS studies (Jankowski *et al.*, 1984) which marked the Carpathian conductivity anomaly (Figs. 1, 4). Basing on geoelectrical data, Lefeld and Jankowski (1985) concluded about the allochthonous nature of the Tatra massif, being underlain by sedimentary rocks. Between Zakopane and Nowy Targ, as well as SW of Nowy Sącz there are areas where the highly-conductive layer has not been found. Further to the east, the layer extends continuously over a large area, with a minor interruption near Rymanów.

The low resistivity of the layer, its most important characteristic, is changeable throughout the study area (Fig. 4). West of Krynica meridian, the resistivity ranges between a few and 13 Omm, exceptionally attaining 17.5 Omm. East of Krynica, however, these values do not exceed 6–8 Omm and, locally in the southern part of the area, they drop even below 1 Omm.

The high-conductivity layer is overlain by rocks of resistivity ranging between 20 and 300–400 Omm, rarely attaining 500 Omm. East of Wysowa–Jasło line, in the zone of the maximum depression of the high-resistivity basement (Fig. 3), the resistivity of rocks overlying the highly-conductive layer diminishes to *ca.* 10 Omm and even 3 Omm (Fig. 4). These are the areas where the resistivity of the underlying highly-conductive layer drops below 1 Omm.

The MTS sounding have also supplied a wealth of information on the thickness of the low-resistivity layer that covers the consolidated basement (Fig. 4). This thickness usually ranges between 2.0 and 3.5 km; some measurements suggest 1.5 km and – in exceptional cases (south of Nowy Sącz and near Łupków) – even 4.5–7.0 km. Depths to the low-resistivity layer are conformable with differentiated depths to the top of the high-resistivity basement (*cf.* Figs. 3 and 4).

An analysis of nearly 400 MT sounding performed by J. Pawliszyn (in Jankowski *et al.*, 1991, Fig. 6) clearly shows that the longitudinal electrical conductivity in the Polish Carpathians increases SE of Nowy Sącz. The highest values have been found near Krynica, in a zone of a basement high south of Dukla, and in the Baligród depression. The influence of regional basement lows, i.e., the Dukla and Baligród depressions, upon the increase in conductivity is notable.

Geological interpretation of the highly conductive layer in the Polish Carpathians basement

A possibility, resulting from the Porstendorfer's *et al.* (1976) model, that highly conductive layer in the German–Polish anomaly zone comprises Palaeozoic and, particularly, metamorphosed coal-bearing Carboniferous strata should be taken into account when discussing the Carpathian anomaly. The West Carpathian foreland includes the Upper Silesia Coal Basin whose Upper Carboniferous coal measures are overlain in the south by Miocene molasses of the Carpathian Foredeep and overthrust flysch nappes of the Carpathian margin (see Oszczypko *et al.*, 1989). These measures have been drilled as far south as in basement depressions south of Ostrava and in the Skawa river drainage basin (Figs. 1, 4). The southernmost borehole Zawoja 1 drilled Carboniferous coal-bearing strata in a depth interval of 4858 m to 5023 m (Jawor, 1989; Karnkowski, 1989). These rocks are also known from the basement of the Moravian Carpathians NW of Hodonin, where they have been drilled by Nemčičky 1 borehole at a depth of 4000–

4500 m (see Oszczypko *et al.*, 1989).

Data presented in Figs. 3 and 4 clearly show that the highly conductive layer detected by MTS sounding in the Carpathian basement could represent a continuation of coal-bearing Carboniferous rocks of the Skawa drainage basin, documented by boreholes Sucha IG-1, Jachówka 1 and Zawoja 1 (Fig. 4), and lowered by a few to even more than 10 km. The total thickness of the coal-bearing Upper Carboniferous strata, drilled by a borehole near Chełmek, attains 2.1 km (Jureczka & Kotas, 1986), approaching that of the geophysically detected highly conductive layer. Such a relationship suggests that the highly conductive layer in the Carpathian basement south of Rabka is also composed of Upper Carboniferous strata.

The abnormally high thicknesses of this layer south of Nowy Sącz and near Łupków may result from tectonic coupling or steeply dipping of strata, whereas the eastward decrease in resistivity could be associated with the increasing depth, and an additional decrease east of Wysowa – with dynamometamorphism and thermal influence of the Slovakian Tertiary volcanic centres.

It should be also taken into account that between the top of the high-resistivity basement and the low-resistivity coal-bearing sequence, may occur older Palaeozoic, Devonian and Lower Carboniferous siliciclastic and carbonate rocks, saturated with mineral waters. Such strata are known from the basement of the marginal part of the Carpathians where their thickness is 600 m like, for instance, in boreholes near Lachowice, SW of Sucha (Karnkowski, 1989), or greater. These strata have not been distinguished in the interpretion of the MTS curves (Molek & Oraczewski, 1988; Molek & Klimkowski, 1991; Jankowski *et al.*, 1991). This, however, does not contradict a concept which ascribes the high-resistivity horizon in the Polish Carpathians to the top of Precambrian rocks, and the overlying highly-conductive layer to metamorphosed coal-bearing Carboniferous strata.

The data presented in Figs. 3 and 4 suggest that the highly-conductive layer occurs both within the major basement depressions and in the southward-located, uplifted blocks of Muszyna, Tylawa and Roztoki Górne. This points to the relation between the Palaeozoic infill of the depressions and uplifts in the basement. SE of Rabka, near Krościenko–Krynica and close to Rymanów (Fig. 3), the highly-conductive layer has also been found on the high southern margin of the platform. Similarly as the Carboniferous strata, documented in the Skawa drainage basin (Fig. 4), this may indicate initial proximity of the platform and the lowered crustal blocks in the Carpathian basement, although tectonic shortening between these regions cannot be excluded. Thermobaric conditions associated with a lowering of crustal blocks in the Krynica–Dukla–Baligród zone caused increase in the conductivity of the lower part of their sedimentary cover.

One should also take notice of the fact that variously metamorphosed coal-bearing Carboniferous strata are known in outcrops in the Central West Carpathians, namely in Slovenske Rudohorie and farther east, near Zemplin (Mahel *et al.*, 1967), i.e. south of the conductivity anomaly axis. Metamorphosed Carboniferous rocks, *ca.* 250 m thick, have also been found in NW part of the Marmarosh (Romanian Maramureş) Massif (Zhukov, 1968), emerged within the East Carpathian flysch (Fig. 1).

The above data indicate that extensive, highly-conductive layers found by MTS sounding within the lowered zone of the Northern Carpathian basement are probably represented by metamorphosed, coal-bearing Carboniferous strata. However, neither the belt of basement depressions filled with these deposits, nor the tectonic graben filled with coal-bearing Carboniferous strata within the platform basement of the Carpathians in the Skawa drainage basin, do generate the changes in the orientation of the Wiese induction vectors. The axis of the Carpathian geoelectrical anomaly, located with a precision of a few kilometres (Praus & Pěčova, 1991), occurs farther south (Figs. 3 and 4), and it is there where one should look for geological explanation of this anomaly. Hence, let us review the crustal properties of the anomaly zone.

MAJOR CRUSTAL BLOCKS OF THE NORTHERN CARPATHIANS

The basement of the Carpathian Foredeep and, as follows from the above mentioned magnetotelluric sounding, of the Outer Carpathians as well, is represented by crustal blocks that belong to the Central European Platform. These blocks are overlain by overthrust flysch nappes of an accretionary prism. South of the Pieniny Klippen Belt, the Slovak, *i.e.*, Central West Carpathian block, extends from the Vienna Basin to the Uzhgorod area (Fig. 1). Further eastwards lies an obliquely oriented block of the Central East Carpathians that crops out from beneath flysch strata NE of the Pieniny Klippen Belt as the Marmarosh Massif. Both these Central Carpathian blocks are tectonically compressed and uplifted; they also differ from one another in the age of the main folding. The blocks consist of nappes which comprise, apart from mostly carbonate Mesozoic strata, pre-Alpine rocks, including crystalline ones. Post-collisional lithospheric suture between the subsided platform blocks and the uplifted Central Carpathian blocks originated in a subduction zone of the primary basement of flysch nappes and the Pieniny Klippen Belt.

East Carpathians – Ukrainian and N-Romanian sector

To characterise crustal blocks of the Northern Carpathians in greater detail, the results of MTS sounding of the Polish Carpathian basement (Fig. 3) have been compared with those of the seismic refraction studies, including deep sounding, in the Ukrainian Carpathians. The latter have been confronted with well-log data and reinterpreted to show features of the autochthonous, Palaeozoic–Mesozoic basement, called "sub-flysch substratum" by Burov *et al.* (1986) and Glushko & Kruglov (1986). Despite different methods (MTS, seismic refraction) of various precision, a general picture of basement highs and lows has been obtained for a large segment of the Carpathians (Fig. 5). The names of the tectonic elements are introduced by the present author.

It is evident from this picture that a belt of depressions in the Polish Carpathians (Nowy Targ–Krynica–Dukla–Baligród) has its continuation to the east in the Skole depression, 13–14 km deep, showing longitudinal fractures in its axial and southern parts. The SW-shifted continuation of this depression can be found east of Rakhov, within the upper reaches of the Black and White Cheremosh rivers. Further to the SE, in Câmpulung Moldovenesc, Romanian Carpathians (see Figs 5 and 6 for location purposes), the top of the basement of this depression occurs at a depth of 14 km, as shown by MTS data (Stanica *et al.*, 1986).

The Baligród and Skole depressions are separated by a transversal Czarna high (depth to the basement *ca.* 7 km), south of Ustrzyki Dolne. The values of magnetic Z component (see Żytko, 1985) suggest that this high is a salient of the platform that constitutes the basement of the Carpathian Foredeep, similarly as the already mentioned Rymanów salient (horst). NE of Rakhov, another shallowing of the depression belt to *ca.* 9 km, as well as the transversal Shopurka fault can be seen.

The uplifted Tylawa and Roztoki Górne blocks that surround the depression on the south have their continuation in the seismic refraction pattern in the Ukrainian East Carpathians. It is the longitudinal Uzhok–Ust' Chorna uplift of variable height which rises to the SE, from –14 km near Uzhok to –7 km north of Rakhov. Farther to the SE, in Romanian Carpathians, the top of this uplift between Vatra Dornei and Câmpulung Moldovenesc (*cf.* Figs. 5 and 6) lowers again to *ca.* –11 km (Stanica *et al.*, 1986).

SW of this belt of basement highs, within the "sub-flysch substratum" of the Porkulets and Dukla nappes and the Fore-Dukla zone, a deep depression has been found (Glushko & Kruglov, 1986), called the Chernogolova–Krasna depression. It shallows towards SE, from –17 km in the Uh river valley to –11 km NW of Rakhov.

MTS sounding performed at "Rakhov" locality have shown that the top of the highly-conductive layer lies at a depth of *ca.* –16 km (Rokityansky *et al.*, 1976b); it was supposed that this depression is filled with altered flysch sediments underlain by high-resistivity rocks. This may indicate a lowering of the continuation of the southern basement depression under the overthrust Marmarosh massif, east of the Shopurka transversal fault.

An analysis of seismic refraction profiles has shown that the Chernogolova–Krasna depression has a complex structure. To the west of Rakhov it is cut by a longitudinal fault of downthrown southern side. This fault continues through Mezhgorye–Volovets towards Zboj in eastern Slovakia (Fig. 5). It is this fault which is followed by the axis of

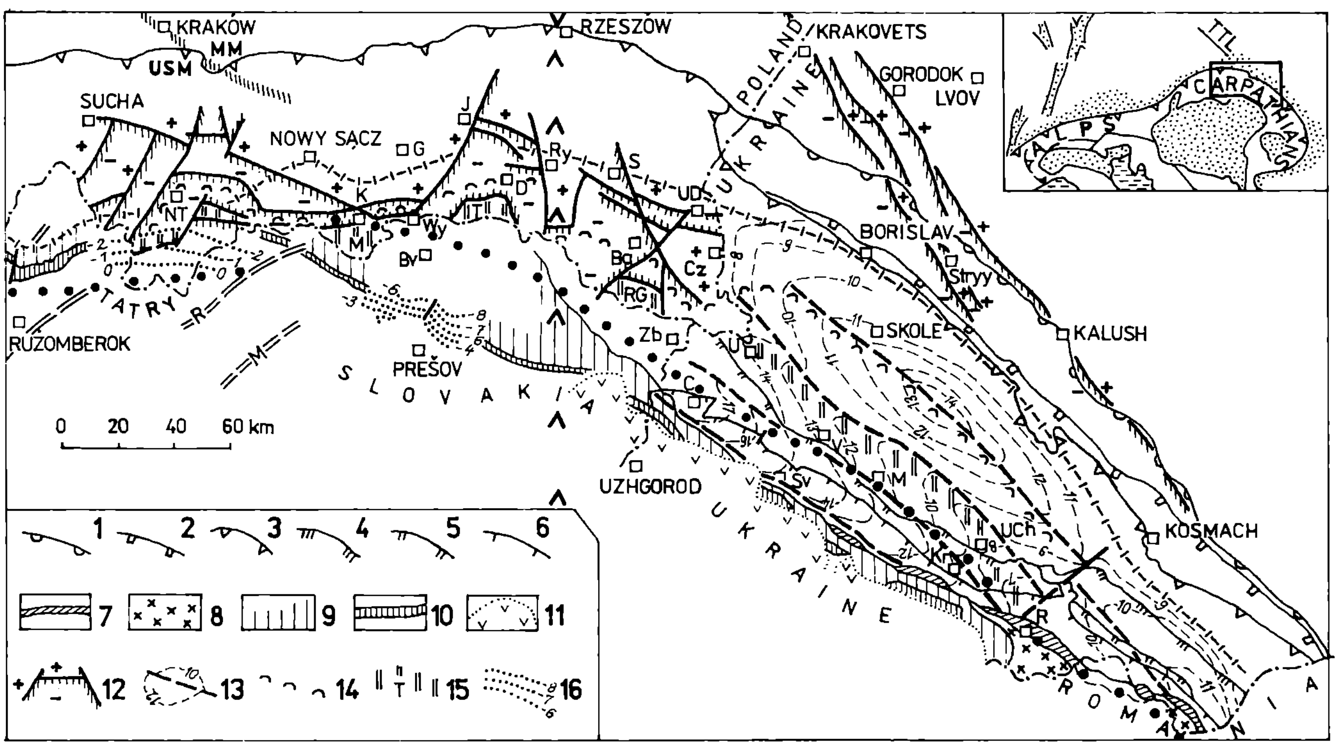

Fig. 5. Map of the top of high-resistivity basement of the Polish Carpathians. concordant with Fig. 3, supplemented by the pattern of seismic refraction-studied basement of the Ukrainian Carpathians (based on Glushko & Kruglov, 1986). Selected surficial geological boundaries shown for location purposes. *1–6* – northern extent of the East Carpathian nappes (*1* – Stebnik–Sambor, *2* – Borislav–Pokutie, *3* – Skiba; further to the west – sub-Silesian and Skole frontal thrusts, *4* – Chernohora, *5* – Dukla, *6* – Porkulets), *7* – Rakhov Unit, *8* – Marmarosh massif (Crystalline–Mesozoic zone of the East Carpathians), *9* – Magura Nappe (its outer part in the west has been omitted), *10* – Pieniny Klippen Belt (segments near Nowy Targ and Prešov have been omitted), *11* – young-Alpine volcanic rocks, *12* – boundaries of uplifted (+) and subsided (–) basement blocks, *13* – depth contours (in km) and faults in the flysch substratum, *14* – boundary between the margin of the Central European Platform and the subsided crustal slab, *15* – basement high within the subsided crustal slab (M – Muszyna, T – Tylawa, RG – Roztoki Górne), *16* – depth contours (in km) of the sub-Palaeogene surface of Triassic dolomites in the Central West Carpathians. Bv – Bardejov, C – Chernogolova, Kr – Krasna, M – Mezhgorye, R – Rakhov, Sv – Svalava, U – Uzhok, UCh – Ust' Chorna, V – Volovets, Zb – Zboj. For other explanations see Figs. 3 and 4

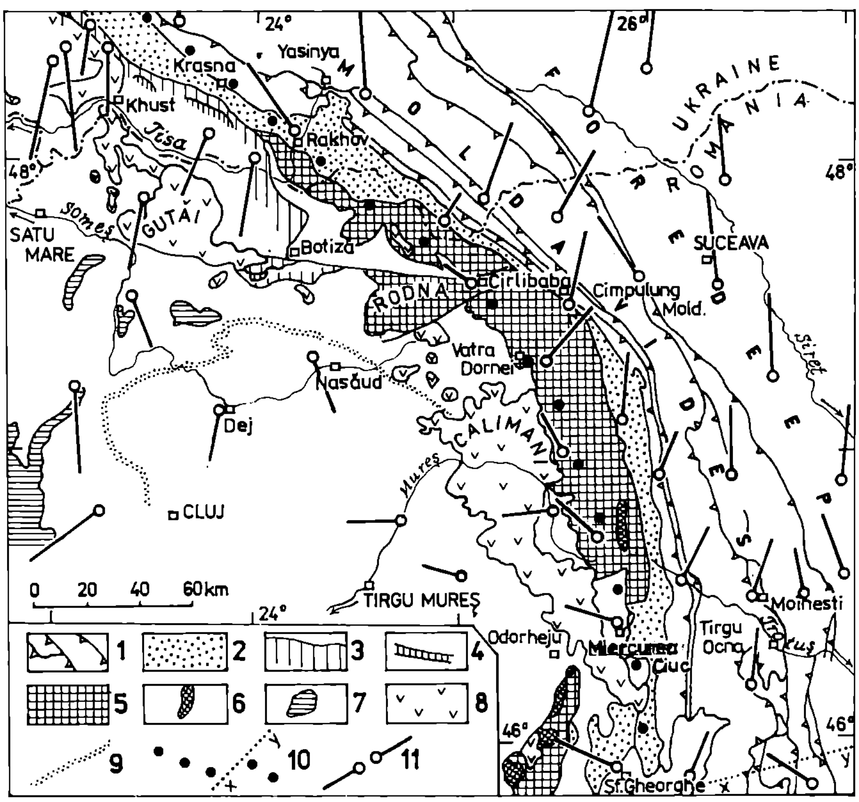

Fig. 6. Relation between geoelectrical anomaly and tectonic elements of the East Carpathians (vectors compiled after Rokityansky *et al.*, 1976b and Pinna *et al.*, 1992; geology based on Săndulescu *et al.*, 1978; Săndulescu, 1984; Glushko & Kruglov, 1986). *1* – major thrusts of the Moldavides, *2* – inner flysch units (Outer Dacides): Rakhov, Porkulets, "Black Flysch", Ceahlău; *3* – Magura Unit (Monastyrets, Petrova and Botizei flysch zones, as well as "Wildflysch"), *4* – Pieniny Klippen Belt and Poiana Botizei klippes, *5* – Crystalline–Mesozoic zone of the East Carpathians (Middle Dacides), *6* – Transylvanian nappes, *7* – pre-Tertiary rocks of the hinterland, *8* – young-Alpine volcanic rocks, *9* – northern extent of Neogene sediments in the Transylvanian Basin, *10* – axis of geoelectrical anomaly and X–Y displacement, *11* – Wiese vectors

geoelectrical anomaly. The Chernogolova–Krasna depression is bordered on the SW by the longitudinal Svalava fault, beneath the inner part of the Porkulets unit (Glushko & Kruglov, 1986). The fault probably forms the NW continuation of the outer boundary of the Marmarosh massif, *i.e.* the Central East Carpathians.

The SE continuation of the Svalava fault is a deep (down to Moho) crustal fault in the Romanian Carpathians near Vatra Dornei (Stanica *et al.*, 1986). The fault-related depression is, however, very narrow; a possible continuation of the graben occurring within the deepest part of the Chernogolova–Krasna depression, between Svalava and Zboj–Mezhgorye faults, is here buried beneath the block of Crystalline–Mesozoic units of the Central East Carpathians that are thrust upon flysch units. Stanica *et al.* (1986) and D. Stanica & M. Stanica (1993) report on the presence of a deep-seated fault also further south, close to Miercurea Ciuc, in a MTS profile between Odorhei and Târgu Ocna (*cf.* Fig. 6). Crystalline platform basement of the Flysch Carpathians outwards of the fault forms there a vast depression of poorly differentiated bottom, whose depth attains –10 km.

Pinna *et al.* (1992) accept that the crustal fault between Vatra Dornei and Miercurea Ciuc continues as far as 46° parallel near Sf. Gheorghe and that it is associated – geographically – with the Carpathian electrical conductivity anomaly, induced by the presence of highly conductive rocks close to the fault.

Geoelectrical anomaly is disrupted close to 46° parallel and appears again *ca.* 100 km to the east, near Focşani, from where it continues to the SW and west into the Carpathian Foredeep (Fig. 1). This disruption approaches as well a left-lateral shift of the axis of regional gravity low by about 25 km along the Trotuş river valley; the shift occurs in the western continuation of the northern boundary of the Cimmerian orogen of Northern Dobrogea–Crimea (Visarion *et al.*, 1988).

West Carpathians – Polish and E-Slovak sector

Data presented in Fig. 5 point to the presence in the sub-flysch basement of the Ukrainian Carpathians of two belts of orogen-parallel depressions. It is possible that the Chernogolova–Krasna–Rakhov depression continues to the NW under flysch units of the Slovak Carpathians, as indicated by data from the Prešov–Dukla region.

MTS sounding south of Dukla detected a basement high (–10 km), called the Tylawa horst (Figs. 3, 5). Seismically-detected (Mořkovsky *et al.*, 1992) surface of Triassic dolomites of the Central West Carpathians, covered by Palaeogene flysch strata, dips to the north under the Pieniny Klippen Belt and the inner part of flysch nappes, at least to a depth of –8 km (Fig. 5). Well-log data collected by the State Geological Institute between the Tatras and the Pieniny Klippen Belt, close to Nowy Targ, do also reveal a similar feature. One can infer, therefore, the presence of a basement depression between the Tylawa and Roztoki Górne horsts in the north and the northern slope of the Central Carpathians in the south. Hence, the Chernogolova–Krasna–Rakhov depression probably continues towards NW, from the Uh drainage basin to Bardejov.

It has already been mentioned that the deep basement of the northern belt of depressions between Nowy Targ and Baligród, together with the horsts which surround them on the south, probably represents a lowered part of the Central European Platform. Taking into account magnetic properties (ΔZ) of the Czarna high, south of Ustrzyki Dolne, one can suppose as well that the Skole depression and the sur-

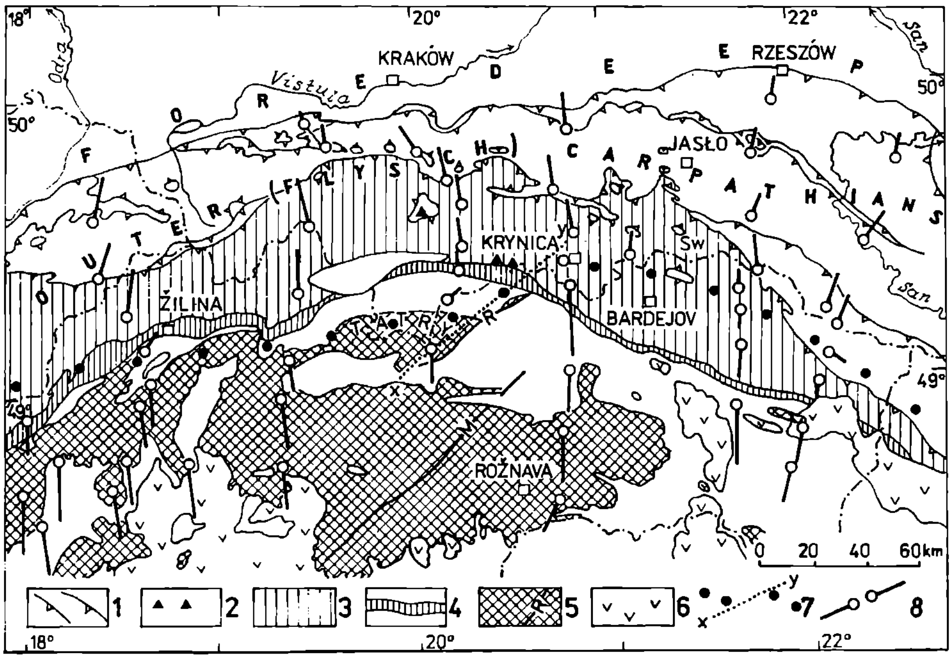

Fig. 7. Geoelectrical anomaly in relation to tectonic elements of the West Carpathians (vectors compiled after Jankowski *et al.*, 1984; Lefeld & Jankowski, 1985; geology based on Książkiewicz, 1962; Mahel *et al.*, 1967). *1* – major thrusts of the Outer Carpathians (SW – Świątkowa), *2* – zone of probable occurrence of slices composed of the black Neocomian flysch (possible continuation of the Outer Dacides), *3* – Magura Unit, *4* – Pieniny Klippen Belt, *5* – pre-Tertiary units of the Central West Carpathians, *6* – young-Alpine volcanic rocks, *7* – axis of geoelectrical anomaly and the possible X–Y displacement, *8* – Wiese vectors. R – Ružbachy fault, M – Muraň – Wysowa – Jasło fault

rounding Uzhok–Ust' Chorna high could also represent a lowered, marginal part of the Central European Platform. This conjecture is additionally supported by similarities between the boundaries of the subsided and uplifted parts of the crust, particularly to the east of the Wysowa–Jasło fault. The Rymanów and Czarna salients, belonging to the uplifted part, face recesses in the southern belt of basement highs (Fig. 5).

The above mentioned two Central Carpathian crustal blocks occur SW of the Bardejov–Chernogolova– Krasna–Rakhov depression and Vatra Dornei–Miercurea Ciuc fault.

CARPATHIAN GEOELECTRICAL AND GRAVITY ANOMALIES VERSUS SURFICIAL AND DEEP STRUCTURE OF THE NORTHERN CARPATHIANS

It should be stressed that east of Nowy Targ the axis of the gravity low lies north of the outer belt of basement depressions and it is related to the Neogene pattern of symmetry (see Figs. 4, 5). The basement depressions do not show up in the pattern of the gravity field. Between the Tatras and Žilina region, the axis of the anomaly is situated within the Central Carpathians. Further to the west it cuts the Pieniny Klippen Belt, and then proceeds along the flysch nappes towards Vienna (Figs. 1, 7). Similarly, to the east of the Tatras, the anomaly axis protrudes into the flysch Carpathians. The arrangement of Wiese induction vectors (Fig. 7) indicates a disruption of a generally linear trend of the anomaly between the Tatras and Krynica, probably due to the presence of the Ružbachy and Muraň–Wysowa–Jasło fault system. Lefeld and Jankowski (1985) hypothesized about the overthrust of the Tatra crystalline massif upon a series of sedimentary and/or metamorphic rocks that are the carrier of a ionic source of the anomaly.

East of Krynica, the anomaly axis occurs within the Magura Nappe area and then within rocks of the structurally lower Dukla nappe and even Fore-Dukla zone. SE of Krasna, even up to Sf. Gheorghe (Fig. 6), the axis of the electrical anomaly appears to be associated with the Outer Dacides flysch sequences (Porkulets, Rakhov, "Black Flysch", Ceahlău Nappes) that are overlain, to a large extent, by overthrust units of the Central East Carpathians (Pinna *et al.*, 1992). It is a feature similar to that inferred for the West Carpathians in the Tatra region.

To explain the relation between the basement and the overlying sedimentary rocks of the accretionary prism in the geoelectrical anomaly zone, the area near the Marmarosh massif of the Central East Carpathians near Rakhov (Fig. 5) should be taken as the best example. The depth to the top of the highly-conductive layer under the Rakhov and Porkulets flysch units is about 16 km (Rokityansky *et al.*, 1976b). An association of grey and black flysch strata, together with mafic eruptive rocks within these units (Rakhov, Belaya Tisa, Burkut Formations), alongside with their Romanian counterparts in the "Black Flysch" and Ceahlău Units (Sinaia and Bistra Formations) represents sedimentary infill of the Jurassic–Early Cretaceous palaeorift of the Outer Dacides (*vide* Săndulescu, 1984, 1989). This rift, originally situated in a marginal zone of the European continent, has been compared to the Afar–Red Sea rift, and considered to be an equivalent of Valais, an outer rift in the Alpine Penninicum zone. It is likely that the Outer Dacides rift, whose very concept is based on an analysis of allochthonous orogenic complexes, is associated with the Chernogolova–Krasna–Rakhov basement depression and its continuations, both towards Bardejov and Vatra Dornei.

The uplifted Marmarosh massif and the regional shallowing of the Carpathian basement NE of Rakhov (Fig. 5), as well as the proximity of the anomaly axis to the Zboj–Mezhgorye fault in the northern margin of the basement depression, all point to a possibility of a causal relationship between the geoelectrical anomaly and the Outer Dacides' rift, or – directly – its NE boundary. A shift of the anomaly axis into the flysch of the Dukla Nappe towards NW and the position of the northern boundary of the Porkulets Unit at the surface in respect to basement depression (Fig. 5) do not necessarily testify to the lack of initial interrelationship existing between the depression and Porkulets flysch. Such a situation appears to be similar to the "fan idea" discussed by Andrusov (1968), namely the occurrence of post-Palaeogene, south-vergent folds and slices in the inner part of the Magura Unit, Pieniny Klippen Belt or even Central Carpathians (e.g. the south-vergent Tatra mega-anticline). Backthrusting Laramian and Savian movements have also been accepted by Birkenmajer (1986) for the Grajcarek Unit. Such features are also documented by detailed geological maps of the Magura Unit in East Slovakia (Matějka *et al.*, 1964) and the N-dipping top of Mesozoic strata of the Central Carpathians (Fig. 5). Backthrusts occur as well in the Fore-Dukla zone in the San river drainage basin (see Żytko, in: Młynarski *et al.*, 1982; Fig. 6). Hence, there is a bulk of evidence pertaining to subduction and shortening of the basement within the Bardejov–Chernogolova depression, as well as pointing to a shift of allochthonous elements towards SW in relation to the southern boundary of the depression. Starting from Krynica, this depression is placed south of the Muszyna high and continues further west under the overthrust Tatra massif, following the centre of the geoelectrical anomaly.

ON POSSIBLE PRESENCE AND LOCATION OF THE JURASSIC–CRETACEOUS RIFT OF THE OUTER DACIDES IN THE POLISH CARPATHIANS

The Carpathian geoelectrical anomaly coincides both with the Zboj–Mezhgorye basement fault in the northern part of the Chernogolova–Krasna depression, and with the Rakhov, Porkulets, "Black Flysch" and Ceahlau inner flysch units of the East Carpathian allochthon. These units are composed of the infill of the Outer Dacides' palaeorift, situated outwards of the Pieniny Klippen Belt, Magura flysch and Marmarosh Massif (Figs. 5, 6). The Porkulets unit flysch is known both from the surface and the Chernogolova deep borehole, close to the Slovak/Ukrainian boundary. These strata plunge towards NW under the Magura Nappe (Fig. 5), and their traces can probably be found farther west. One should also take into account the affiliation of Oligocene strata of the Porkulets and Dukla Units (Dusina, Turitsa and Malyy Vyzhen Formations) to the Menilite–Krosno rather than Magura flysch lithofacies (Burov *et al.*, 1986).

In the 1960s, W. Sikora expressed an opinion about the presence of Lower Cretaceous black flysch strata, called the Sztolnia Beds, within a separate zone distinguished between the Magura Unit and the Pieniny Klippen Belt. This zone is also called the Hulina Unit or Grajcarek Unit (see Sikora, 1971; Birkenmajer, 1986). Birkenmajer and Myczyński (1977) documented a Middle Jurassic age of these dark, micaceous Sztolnia Beds and renamed them as the Szlachtowa Formation.

Nevertheless, there appeared new data on the presence of Lower Cretaceous dark flysch deposits between the Pieniny Klippen Belt and the Dukla Unit. Birkenmajer *et al.* (1979) described dark, Hauterivian–Albian flysch strata, *ca.* 200 m thick, from the Grajcarek unit (well PD9 at Szczawnica) and called them the Bryjarka Formation. These strata are overlain by Cenomanian–Turonian variegated shales and sandy Upper Senonian Jarmuta Formation. The same unit comprises as well black and green shales of the Wronine Formation of Albian age, also containing variegated shales at the top (Birkenmajer & Dudziak, 1987). The proximity of Tithonian–Neocomian pelitic, chert-bearing limestones indicates that the unit is characterised by two different Neocomian facies, *i.e.* flysch and limestones.

Golonka and Rączkowski (1984) described from Szczawnica dark flysch strata containing Early Cretaceous foraminifer assemblages (*det.* J. Blaicher) and upheld the name Sztolnia Beds for these deposits. According to B. Olszewska (*pers. comm.*), the assemblage comprises, among others, the species *Ammobaculoides carpathicus* Geroch, indicative of Neocomian age.

In Biała Woda, in the same zone, a block of basalts (olistholite?) has been found, whose age has been determined at 140 ±8 Ma, *i.e.* Jurassic/Cretaceous transition (Arakelyants, in Birkenmajer & Wieser, 1990). Numerous clasts of mafic, spilitic rocks have also been found in Senonian conglomerates.

Further to the north, in the margin of the Mszana Dolna tectonic window, dark Albian–Cenomanian flysch strata of the Lgota Beds occur within a series that overlies the Dukla and Grybów units (Burtan & Łydka, 1978; Burtan *et al.*, 1992). Close to these beds occurs a complex of alternating siliceous sandstones and black clayey shales lacking in foraminifers; they also comprise an interlayer of extrusive rocks (Burtan *et al.*, 1978, p. 27). The strata in question have been assigned to the Magura Nappe series, although strong tectonization makes such an assignment problematic. Some of the Lgota Beds have been associated with the Grybów Unit (Mastella, 1988). Both the Wronine Formation strata of the Grajcarek unit, and the "Lgota Beds" close to Mszana Dolna are impregnated with copper mineralization.

The above data on the Hauterivian–Albian age of the Bryjarka Fm, as well as the presence of Neocomian foraminifers within the Sztolnia Beds near Szczawnica (*cf.* Golonka & Rączkowski, 1984) point to a possibility of deposition of flysch strata and volcanic rocks (basalts from Biała Woda) in an Early Cretaceous anoxic basin north of the Pieniny Klippen basin (Fig. 7). Such a basin could have existed already in Doggerian times (Szlachtowa Formation), as accepted by Birkenmajer (1986). This basin might have been a continuation of the Outer Dacides' rift and, strictly speaking, the "Black Flysch" Unit. Most of its sedimentary infill has been tectonically reduced; its relics are visible in the Grajcarek Unit.

It should be added that both, the Cretaceous and Palaeogene strata of the Pieniny Klippen Belt and the Central Carpathian and Magura flysch, comprise abundant detritus of ultramafic rocks, particularly chromium spinels (Starobova, 1962; Mišik *et al.*, 1980; Winkler & Ślączka, 1992, 1994). They indicate the presence of ophiolitic complexes of oceanic crust or, at least, continental rift ophiolites, within source areas. The original position of such areas is difficult to reconstruct and raises many controversies. Palaeotransport indicators reconstructed for the Magura basin during the Late Cretaceous and Palaeogene reveal, apart from basin-parallel, also southerly, northerly, and north-easterly directions (Książkiewicz ed., 1962). Some of the material could have been derived from an obducted part of the rift in question; that including mafic and ultramafic extrusive rocks. The position of the Magura furrow infilled with Upper Cretaceous–Palaeogene flysch strata which include, at least locally, Neocomian carbonates (Moravian localities Hluk, Četechovice and Kurovice; *cf.* Buday *et al.*, 1967) in respect to the graben filled by dark, Jurassic–Neocomian flysch, remains uncertain. More precisely, we do not know whether the original basement of the future Magura Nappe was composed of Jurassic–Cretaceous rocks, incorporated later into the Pieniny Klippen Belt, or was it made up of flysch and extrusive rift infill.

The base of the outer part of the Magura Nappe, close to its contact with the flysch strata of the Grybów Unit (Ropa–Pisarzowa) in the Świątkowa tectonic window (Fig. 7), contains blocks of tectonically brecciated limestones of unspecified age (up to 120 60 cm in size; Kozikowski, 1956). The presence of blocks of chert-bearing limestones and their tectonic position, all indicate that they must have been transported by the Magura Nappe from the area of the future Pieniny Klippen Belt. The rigid Upper Cretaceous–Palaeogene flysch complex of the nappe could then represent a "scalp" torn off that presently narrow zone. This process, initiated in Eocene times, lasted until the Early Miocene, as indicated by deposits of that age drilled at 3050–3100 m depth interval by the Nowy Targ PIG 1 borehole (Paul & Poprawa, 1992), immediately in front of the Pieniny Klippen Belt. Hence, the belt is probably composed of Jurassic–Cretaceous rocks of the substratum of the Magura flysch. If this is true, the Grajcarek Unit, a postulated continuation of the Outer Dacides' flysch, is exposed in Szcza-wnica in a tectonic window.

Birkenmajer (1986) hypothesized about the presence of two belts of oceanic crust in the Magura and Pieniny furrows, in the Middle Jurassic–Early Cretaceous time-span. Moreover, Dercourt *et al.* (1990) also inferred two parallel belts of crustal accretion, separated by the Czorsztyn–Poiana Botizei ridge, in the Middle and Late Jurassic. The northern "Magura" belt should pass westward into the outer Ybbsitz–Valais palaeorift; whereas the connection with the Outer Dacides (Ceahlău) rift remains unexplained. If we accept the relation between the Carpathian geoelectrical anomaly and the Outer Dacides' rift, whose supposed presence west of Krynica (Fig. 7) is documented by relics of Doggerian and Neocomian flysch in the Grajcarek Unit, we should conclude that the bulk of flysch deposits of that rift, at least its crustal scar, is now deeply buried under the Central Carpathians. Birkenmajer (1986) postulated southward-directed Laramian subduction in this zone. Hence, the idea of possible connection of one of the Penninicum grabens with the Outer Dacides' graben (Săndulescu, 1984, 1989) becomes more likely.

The postulated southern zone of oceanic crust (Vahicum, Kysuca) is being placed in the zone of the future Pieniny Klippen Belt (Mahel, 1983; Birkenmajer, 1986; Dercourt *et al.*, 1990; Winkler & Ślączka, 1994). However, palaeogeographic reconstructions of the Northern Carpathians and their correlations with the Alps should also consider the presence of both the teschenite-bearing flysch graben of the future Silesian unit in the Early Cretaceous, and the Meliata zone of oceanic crust in the Triassic and Jurassic.

An attempt at correlating the Carpathian and Alpine sectors of the rifts may be based on the timing of the appearance of deep-water troughs, related to their northward migration. The trough of the Outer Dacides and the Grajcarek unit, in which flysch sediments were being laid down already in Doggerian time (Szlachtowa Formation) is probably a prolongation of the Southern Penninicum (Piemontais). The Silesian trench in which flysch (Cieszyn Formation) appeared at the end of Jurassic, may correspond to the Valais trough. The Silesian Cordillera between the troughs (Książkiewicz ed. 1962) would thus correspond to the Brianconnais in the Alps, and to the Peri-Moldavian Cordillera (Săndulescu, 1984) in the East Carpathians. Such a correlation rises a question of the existence of the Vahicum–Kysuca Trough while the presence of the oceanic crust of Meliata is well documented.

LOCATION OF THE SOURCE OF THE CARPATHIAN GEOELECTRICAL ANOMALY

The Nowy Targ and Dukla–Baligród–Skole basement depressions (Fig. 5), containing highly-conductive layers in the Polish Carpathians, do not generate geoelectrical anomalies. The only exception is the Krynica–Wysowa region, possibly due to a fault zone (Fig. 3) and consequent NW plunging of the eastern crustal block. Moreover, the anomaly shows no relation to the regional gravity low zone (Fig. 5), except the Carpathian Foredeep south of Trotuş (Visarion *et al.*, 1988).

Between Chernogolova and Rakhov (Fig. 5), and farther south, up to Vatra Dornei (Fig. 6), the anomaly is associated with the Zboj–Mezhgorye fault, *i.e.* the northern tectonic boundary of the southern basement depression. The depression probably continues westwards to Bardejov–Wysowa region and plunges under the Tatra Massif. To the east, up to Sf. Gheorghe area, the anomaly is linked with the boundary between the foreland platform and the Central Carpathian crustal block, but relief of the buried platform basement is not differentiated.

The Zboj–Mezhgorye fault that separates subsided crustal blocks is situated outwards of the boundary of the overthrust Central East Carpathian block, represented by the Svalava–Vatra Dornei–Miercurea Ciuc fault. This fact, together with the position of the geoelectrical anomaly in the East and South Carpathian Foredeep, south of Focşani (Pinna *et al.*, 1992), indicates a relationship between the anomaly and the lowered, marginal part of the continental crust. This zone is close to the collision suture. Immediately above the anomaly's source or in its vicinity the Outer Dacides' flysch units occur, represented by the Rakhov, Porkulets, "Black Flysch", Ceahlău units (Săndulescu, 1984, 1989) and their western extension (i.e. Grajcarek unit). The units are partly covered by blocks of the Central West (Tatra massif) and East Carpathians (the Marmarosh Massif and its southern continuation).

It has been shown that the anomaly is associated with a certain boundary or geotectonic zone, nevertheless, one should also look for an additional factor, *i.e.* good electrical conductor that could generate magnetic field inducing divergent induction currents, following requirements accepted in theoretical models (Rokityansky *et al.*, 1976a). Such a factor can be found in the Marmarosh massif and surrounding flysch strata. There occur metamorphosed, coal-bearing Carboniferous strata, uplifted from beneath the orogen (Zhukov, 1968), close to the anomaly centre. The results of MTS sounding in the Polish Carpathians do not confirm, however, the relationship between the anomaly and the Carboniferous rocks in the basement. Moreover, the Carpathian anomaly is closely related to the Tertiary framework of the Carpathian orogen and not to the Hercynian structural grain.

GRAPHITIZED ROCKS CLOSE TO CONVERGENT PLATE BOUNDARY AS A POSSIBLE SOURCE OF THE CARPATHIAN GEOELECTRICAL ANOMALY

NW part of the Marmarosh massif comprises graphite schists, as well as "graphite" lenses, layers and nests (Tokarski *et al.*, 1934). These rocks show specific resistivity in the ranges of 0.19 to 0.61 Om cm. Their carbon content is from 9.76 to 96.95%, the amount of ash being variable; the C/H coefficient ranges from 20 to 72, exceptionally 140 and 245. The X-ray studies make it possible to assign this substance to meta-anthracites, in rare cases to black coals (Vulchin *et al.*, 1967) or fine-crystalline graphites and shungites (Gabinet *et al.*, 1977).

These rocks are exposed among different varieties of crystalline schists, and in carbonate rocks included in the metamorphic sequence of the massif. Their age has been determined as Carboniferous (Zhukov, 1968) and Early Palaeozoic (*e.g.*, "Boyerovska svita" of (?)Cambrian age; *cf.* Gabinet *et al.*, 1976, 1977). It is interesting that nests, lenses and veins of such coaly substance have also been found within Cretaceous flysch strata, close to their contacts with the overthrust units of the massif (Tokarski *et al.*, 1934; p. 225, 293; Fig. 9). Pelitic rocks of the Tithonian–Neocomian flysch (Obnuj Fm) of the "Black Flysch" Unit, Outer Dacides in the Romanian Marmarosh Massif, are also rich in graphite (see Săndulescu, 1984). In the zone of the overthrust of metamorphosed Palaeozoic rocks upon Cretaceous flysch at Kobyletska Polana near Rakhov, graphitized and quartz-enriched brecciated rocks are exposed at the surface, forming a belt of 15–20 m 500–600 m in area. There occur lenses and layers of the coaly substance. Such "graphite" layers lie conformably within Cretaceous strata (Gabinet *et al.*, 1977; p. 186).

Tokarski *et al.* (1934) hypothesized about "erosional-sedimentary" or tectonic transport of the coaly substance from older rocks into flysch strata. Vulchin *et al.* (1967) suggest that all occurrences of the metamorphosed coaly substance are of sedimentary origin. This opinion raises some doubts, since both the Polish and Ukrainian flysch sequences, particularly their inner parts, as well as flysch covers of the Central West Carpathians and the Marmarosh massif are cut by open tectonic fractures and veins which contain hydrothermal mineral associations, including calcite, quartz ("Marmarosh diamonds"), black hard bitumen substances, rarely ore minerals. This association is of post-Oligocene age. Some of these minerals, and particularly inclusions contained within authigenic quartz crystals, are a subject of intensive studies (see Karwowski & Dorda, 1986; Dudok, 1990; Lomov, 1991).

According to Lomov (1991), who studied Ukrainian Carpathian flysch rocks collected near Mezhgorye, hard organic substance occurs both between quartz and calcite crystals, and as inclusions in quartz. The substance contains 89.57% C; and has C/H ratio of 18.31 (shown in % of standard organic matter). This is low-grade metamorphosed anthraxolite of moderately ordered fabric, as shown by X-ray studies. The substance does not melt even at 500°C. Inclusions in "Marmarosh diamonds", contain liquid and volatile hydrocarbons (mostly methane). One should add, however, that the frequency of occurrence of "Marmarosh diamonds" increases markedly south of the belt of oil deposits within flysch strata of the Borislav–Pokutie Unit in the Ukraine and its continuation into the Polish Carpathians. These deposits cluster close to the axis of the Carpathian regional gravity low, between Nowy Sącz and Kosmach (*cf.* Fig. 5).

Features described from the Carpathian realm are comparable to the formation of hard bitumen veins ("asphaltites"). Parnell and Carey (1995) described such veins from a zone of Late Miocene folding in the sub-Andean Neuquen province, western Argentina. Jurassic and Cretaceous strata are there cut by 1–3 m, rarely 5 m thick, veins built up of hard bitumens of the impsonite–gilsonite group. This substance is accompanied by dolomite, calcite, gypsum and – rarely – authigenic quartz crystals, comprising inclusions of hard bitumens. There also occur traces of hydrothermal ore mineralisation (V, Ni, Cu). This association is a polyphase one; the veins were formed both in Eocene–Oligocene times, before the main phase of oil generation, and before the main phase of thrusting. The bitumens occur close to their parent rocks; migration occurred over short vertical distance and was controlled by high fluid pressure.

The above results indicate that similar mechanisms of coaly substance mobilization from source rocks to overlying strata, could occur also in the Carpathians. We do not know whether the "meta-anthracite" occurrences described from the Marmarosh massif are genetically associated with anthraxolite, ubiquitous in veins and open fractures which contain "Marmarosh diamonds" in the Northern Carpathian flysch strata, although such a hypothesis is probable. The coaly substance occurring close to the axis of the geoelectrical anomaly is epigenetic and it is probably associated with deeply-buried organic substance derived, perhaps, from coal-bearing Carboniferous strata. Under thermobaric conditions existing deep in the orogen, close to the plate boundaries and in a subduction zone, large occurrences of this substance could well be metamorphosed into graphite, a suitable conductor necessary to generate the geoelectrical anomaly. The frequency of occurrence and the large extent of anthraxolite migrating in a certain phase of hydrothermal processes, as well as "graphitization" of the tectonic boundary of the Marmarosh massif indicate that young graphite occurrences deep inside the orogen could generate the Carpathian geoelectrical anomaly. This idea agrees with the already mentioned Stanley's opinion, quoted by Tomek (1988), that the source of the anomaly could be represented by graphite, associated with a fossil subduction zone. The closeness of the anomaly and plate collision suture is evident, although geophysical setting of the Zboj–Mezhgorye region (Fig. 5) and areas situated south of Focşani (Fig. 1) suggest that the anomaly appears to be related to the boundary between blocks of subsided, marginal part of the continent.

CONCLUSIONS

1. Geomagnetic (MV) and magnetotelluric (MTS) studies enable one to conclude about deep structure of the Northern Carpathian orogen. The surface of the crystalline, high-resistivity basement (Fig. 3), and the extent and properties of the overlying highly-conductive layer (Fig. 4) have been well constrained. A symmetrical pattern was observed in young Alpine conjugate fractures in the crystalline basement of the Carpathians and their Foredeep. The axis of symmetry of this pattern runs from Kraśnik through Rzeszów– Rymanów towards Zemplin and Debrecen (Figs. 3 and 5).

2. From topographic point of view, it is possible to relate the MTS-detected highly-conductive layer in the Carpathian basement to proven coal-bearing Carboniferous strata beneath the Skawa river drainage basin (Fig. 4). The geoelectrical anomaly, however, does not continue west of Krynica towards Nowy Targ and upper Skawa drainage basin; instead, it passes beneath the Tatras into the Central Carpathian area (Fig. 7).

3. Two belts of orogen-parallel basement depressions have been detected by seismic and MTS sounding (Fig. 5). Depressions of the northern belt (Nowy Targ–Skole) do not generate a separate deep geoelectrical anomaly, despite high depths (15–20 km) to the basement with the highly conductive layer. Nevertheless, a relatively shallow, SSW–NNE oriented anomaly, has been found between Dukla and Rymanów (Jankowski *et al.*, 1991).

4. The southern belt of the basement depressions (Bardejov–Chernogolova–Krasna–Rakhov) is bordered on the south by blocks of the Central West and East Carpathians (Figs. 5, 6). To the east of the Slovak/Ukrainian boundary, the depressions of that belt are overlain by folded flysch sequences of the Rakhov, Porkulets, "Black Flysch" and Ceahlău Units, interpreted as an infill of the Outer Dacides' rift of the East Carpathians, as well as by Dukla Unit flysch strata. To the west of this boundary, as far as Bardejov–Wysowa region, the basement depression is overlain by the Dukla and Magura flysch units; whereas data pertaining to the deep basement are lacking.

5. The slices of Doggerian and Neocomian flysch rocks, together with basalts dated to the Jurassic/Cretaceous boundary, described from the Grajcarek Unit close to the boundary of the Pieniny Klippen Belt and Magura Nappe near Szczawnica, probably represent a continuation of the Outer Dacides' rift into the West Carpathians. The further westerly continuation can be found within the Penninicum (Piemontais?) in the Alps.

6. The source of the geoelectrical anomaly appears to be associated with the northern tectonic boundary of the southern belt of basement depressions. This zone is close to the Carpathians collision suture. Some segments of the orogen, however, like those near Zboj–Mezhgorye or south of Focşani, point to the link of the anomaly with the lowered, marginal part of continental crust. Immediately above or close to the source of the anomaly, flysch sequences of inner units (Rakhov, Porkulets, "Black Flysch", Ceahlău and its western continuation, *i.e.* Grajcarek unit) occur. The position of the anomaly indicates that the blocks of the Central West (Tatras) and East Carpathians (the Marmarosh Massif and its southern continuation) are thrust upon flysch strata of the Outer Dacides and their western continuation.

7. The pattern of Wiese induction vectors shows a tectonic discontinuity of the anomaly-generating zone between the Tatras and Krynica (Fig. 6). This discontinuity is, however, much smaller than that occurring near Sf. Gheorghe–Focşani in Romania (Fig. 1).

8. Graphite is an important factor in the origin of the Carpathian geoelectrical anomaly. It formed by post-Oligocene migration and graphitization of organic substance within deeply-buried strata of a Jurassic–Cretaceous rift, particularly in deep-reaching fault zones. This process is reflected by the presence of veins bearing hydrothermal mineral association, including the so-called "Marmarosh diamonds", accompanied by anthraxolite, occurring close to the anomaly centre.

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Streszczenie

ANOMALIA PRZEWODNOŚCI ELEKTRYCZNEJ KARPAT PÓŁNOCNYCH A WGŁĘBNA BUDOWA OROGENU

Kazimierz Żytko

Sondowania geomagnetyczne (MV) i magnetotelluryczne (MTS) ujawniły istnienie pionowego i lateralnego zróżnicowania elektrycznej przewodności skał skorupy ziemi. W centralnej Europie wykryto kilka regionalnych anomalii przewodności zwanych też anomaliami geoelektrycznymi (Fig. 1). Związane są one z obecnością w skorupie wydłużonych stref z kompleksami dobrze przewodzących skał. Prostopadle i rozbieżnie w stosunku do osi tych przewodzących ciał czyli osi anomalii indukowane są prądy rejestrowane jako geomagnetyczne wektory Wiese'go. Rozważane są różne geologiczne źródła anomalii i przyczyny dobrej przewodności. Często brana jest pod uwagę przewodność elektrolityczna (jonowa) związana z solankami w porach i szczelinach skał. Przewodność elektronowa, w naturalnych warunkach skorupy związana jest tylko z grafitem. Spotykany jest on jako powłoka międzyziarnowa w skałach dolnej skorupy kontynentalnej (Frost *et al.*, 1989). W strefie północnej niemiecko-polskiej anomalii jako źródło rozpatrywane są łupki wczesnego paleozoiku bogate w biogeniczny meta-antracyt/grafit (ERCEUGT–Group, 1992). Dobrą przewodność wykazują też zmetamorfizowane węgle (Fig. 2).

W pracy tej podjęto próbę wyjaśnienia genezy anomalii karpackiej, której źródło według MV i MTS znajduje się na głębokości do 10 do 25 km na różnych odcinkach orogenu. W tym celu zanalizowano problem obecności węglonośnego karbonu w głębokim podłożu i układ bloków skorupy orogenu Karpat północnych w oparciu o dane MTS i sejsmiczne dane refrakcyjne.

Przybliżona głębokość i główne rysy powierzchni wysokooporowego podłoża Karpat polskich

Wyniki MTS w Karpatach polskich przedstawiają przybliżone rysy horyzontu wysokooporowego (Fig. 3). Z porównania tych danych z profilami głębokich otworów w brzeżnej strefie Karpat wynika, że horyzont ten wiąże się ze stropem krystalicznych skał prekambru. Na zachodzie są to skały masywu Górnego Śląska i bloku Rzeszotar, na wschód od Krakowa słabo zmetamorfizowane klastyczne skały masywu małopolskiego (*vide* Jachowicz & Moryc, 1955). Te ostatnie to flisz kadomskiego orogenu, który ciągnie się pod płaszczowinami Karpat aż do Dobrudży Centralnej (*vide* Săndulescu, 1984).

Znane są przykłady przybliżonej zgodności danych MTS z profilami otworów (np. Zakliczyn 1 i Brzozowa 1, Kuźmina 1), jak i przykłady dużych – nawet ponad 15% – różnic między nimi (np. Zawoja 1, Gorlice 11 i 13). Wydaje się, że przybliżony wynik sondowań, względna różnica głębokości stropu bloków podłoża i lokalizacja granic między blokami mogą być brane pod uwagę, nie można jednak traktować prezentowanych wyników MTS jako bezwzględnych głębokości krystalicznego podłoża. Granice między blokami różniącymi się przybliżoną głębokością stropu wysokooporowego podłoża mogą być rozpatrywane jako różnego typu uskoki i skarpy erozyjne. W oparciu o dane MTS (Fig. 3) wyróżnić można kilka zróżnicowanych dodatkowo poziomów stropu podłoża krystalicznego. Poziom górny, o przeciętnej głębokości 5–7 km, z odchyleniami do 3–4 oraz 8 kilometrów, jest przedłużeniem podłoża zapadliska przedkarpackiego pod nasunięty flisz. Sięga daleko ku południowi w rejony Żywca, Grybowa –Uścia Gorlickiego i Ustrzyk Dolnych. Południową granicę tego poziomu na zachodzie wyznaczają uskoki wzdłuż linii Sucha–Mszana Dolna–Krynica a na wschodzie uskoki wzdłuż linii Jasło–Krosno–Lesko.

Na południe od wymienionych linii znajdują się obszary o głębokim położeniu stropu podłoża wysokooporowego. Wyróżnić można poziom około 9–10 km, poziom około 12–14 km oraz najgłębsze obniżenia sięgające od 15 do 20 km. Te ostatnie wyznaczają depresję Nowy Targ–Krynica i dwudzielną depresję Dukla–Baligród rozdzieloną horstem Rymanowa. Południowe obrzeżenie obu depresji tworzą podniesione bloki: na SE od Nowego Targu (Gronków), na S od Krynicy (Muszyna) i Dukli (Tylawa) oraz na E od Łupkowa (Roztoki Górne). Strop krystalicznego podłoża w tych blokach znajduje się w głębokości 7–9,5 km.

Powierzchnia podłoża Karpat przecięta jest parą sprzężonych odwróconych uskoków Wysowa–Jasło i Sanok–Lesko–Ustrzyki Górne (Fig. 3). Uskok Wysowa–Jasło jest przedłużeniem trzeciorzędowego systemu uskoków Murania w Karpatach Centralnych (*vide* Pospišil *et al.*, 1989). Około 75–80 km ku NW i NE od obu wymienionych uskoków zaczynają się następne, przypuszczalnie również sprzężone systemy równoległych pęknięć podłoża. Na zachodzie najważniejszym z nich jest uskok Podczerwone–Mszana Dolna, na wschodzie, już w zapadlisku przedkarpackim środkowo-mioceński uskok Krakowiec–Stryj (Fig. 5). Zarysowuje się symetryczny układ, którego oś stanowi linia biegnąca od rejonu Kraśnika na przedpolu Karpat przez Rzeszów–Rymanów w kierunku Zemplina i Debreczyna w depresji pannońskiej (Fig. 3, 5). Do tego komplementarnego neogeńskiego zespołu ścięć nawiązują zewnętrzne granice mioceńskiego basenu zapadliska przedkarpackiego i symetrycznie w stosunku do osi rozmieszczone Mała Depresja Pannońska i Depresja Transylwańska.

Warstwa dobrze przewodząca w podłożu Karpat polskich

Na południu, ponad wysokooporowym podłożem znajduje się warstwa dobrze przewodząca wykryta badaniami MV i MTS (*vide*

Jankowski *et al.*, 1984, 1991). W oparciu o dane MTS (Molek & Oraczewski, 1988; Molek & Klimkowski, 1991) wyznaczono zasięg, orientacyjną grubość i oporność tej warstwy (Fig. 4). Z zestawienia danych na Fig. 3 i 4 wynika, że warstwa ta o miąższości przeważnie 2–3 km, znajduje się w głównych depresjach wysokooporowego podłoża i na wyniesieniach obrzeżających je od południa. Lokalnie, w rejonie Krościenka, Krynicy i Rymanowa warstwa dobrze przewodząca znajduje się również na północ od maksimum depresji. Ta wspólna pokrywa wskazuje pierwotną bliskość tych bloków podłoża i ich związek z platformą centralnej Europy.

Południowe przedłużenie górnośląskiego zagłębia węglowego stwierdzono pod nasuniętymi Karpatami w otworach Sucha IG-1, Jachówka 1, Zawoja 1 w dorzeczu Skawy (Fig. 1, 4) oraz na południe od Ostravy (Czechy). Węglonośny karbon znany jest też z podłoża Karpat morawskich (otwór Nemčičky 1 kolo Hodonina) jak i z masywu Marmarosz w Karpatach Wschodnich (Żukov, 1968). Rozległe, dobrze przewodzące warstwy wykryte MTS w obniżonej strefie podłoża Karpat polskich są więc prawdopodobnie obniżonymi o kilka, a nawet o więcej niż 10 km zmetamorfizowanymi utworami paleozoiku z udziałem węglonośnego karbonu. Wskazuje na to zwłaszcza sytuacja między Zawoją a Nowym Targiem (Fig. 4).

Ani pas depresji podłoża między Nowym Targiem a Baligrodem wypełnionych dobrze przewodzącą warstwą ani rów tektoniczny z węglonośnym karbonem w platformowym podłożu Karpat w dorzeczu Skawy nie generują zmian kierunku indukcyjnych wektorów Wiesego. Wyznaczona dokładnie oś karpackiej anomalii geoelektrycznej znajduje się dalej na południu (Fig. 3, 4) i tam trzeba szukać jej źródła.

Główne bloki skorupy Karpat północnych a karpacka anomalia geoelektryczna

Podłoże zapadliska przedkarpackiego, a zgodnie z przytoczonymi danymi MTS również Karpat fliszowych, reprezentowane jest przez bloki skorupy platformy środkowoeuropejskiej. Na południe od pienińskiego pasa skałkowego (PPS) między basenem wiedeńskim a rejonem Użgorodu znajdują się Centralne Karpaty Zachodnie zwane też blokiem słowackim. Dalej ku wschodowi znajduje się ukośnie do rozciągłości orogenu ustawiony blok Centralnych Karpat Wschodnich wynurzający się wśród fliszu na zewnątrz od PPS jako masyw Marmarosz. Oba centralnokarpackie bloki skorupy są tektonicznie zwężone i wydźwignięte, różnią się czasem głównej fazy fałdowań. Składają się z płaszczowin, w budowie których obok mezozoiku o dużym udziale formacji węglanowych uczestniczą utwory prealpejskie ze skałami krystalicznymi włącznie. Pokolizyjny, litosferyczny szew między obniżonymi blokami platformy i wydźwigniętymi blokami Centralnych Karpat powstał w miejscu subdukcji pierwotnego podłoża płaszczowin fliszowych i PPS.

Wyniki badań krystalicznego podłoża Karpat polskich metodą MTS (Fig. 3) zestawiono na Fig. 5 z wynikami refrakcyjnych badań podfliszowego podłoża Karpat Ukraińskich (Burov *et al.*, 1986; Gluszko & Kruglov, 1986). Mimo odmiennych metod i różnego stopnia dokładności uzyskano ogólny obraz obniżeń i podniesień stropu podłoża dużego odcinka Karpat. W pracy omówiono też wyniki badań podłoża rumuńskich Karpat Wschodnich metodą MTS (Stanica *et al.*, 1986).

Zarysowują się dwa pasy depresji w podłożu Karpat. Zewnętrzny pas (depresje Nowego Targu–Krynicy i Dukli–Baligrodu) ma przedłużenie w postaci depresji Skolego (maksymalna głębokość 14 km). Przez dorzecze górnego Czeremoszu (głębokość 11 km) kontynuuje się po Cimpulung Moldovenesc (lokalizacja na Fig. 6), gdzie ponownie osiąga głębokość 14 km (dane MTS, Stanica *et al.*, 1986). Depresje tego zewnętrznego pasa rozdzielone są, obok wspomnianych już obszarów płytkiego podłoża w rejonie Żywca, Uścia Gorlickiego i Ustrzyk Dolnych–Czarnej, również przez występ (horst) Rymanowa i podniesienie podłoża koło rozłamu Szopurki między Rachovem a Kosmaczem (Fig. 5). Podkreślić trzeba, że na wschód od Nowego Targu oś grawimetrycznego minimum Karpat znajduje się na N od zewnętrznego pasa depresji i nawiązuje do wspomnianego neogeńskiego planu symetrii.

Pas wgłębnych, podfliszowych wyniesień Gronkowa–Muszyny–Tylawy i Roztok Górnych ma przedłużenie w postaci wyniesienia Użok–Ust' Czorna w podłożu Karpat ukraińskich. Dalej ku SE jego przedłużeniem może być wyniesienie o szczycie na głębokości 11 km stwierdzone na profilu MTS między Vatra Dornei a Cimpulung Moldovenesc (porównaj Fig. 5 i 6 dla lokalizacji).

Na SW od powyższego pasa wyniesień sygnalizowana jest refrakcyjnie wewnętrzna depresja podłoża spłycająca się ku SE między Czernogołową (głębokość 17 km) – Krasną (11 km) – Rachowem (> 16 km według MTS, Rokityansky *et al.*, 1976 b). Brak przedłużenia tej depresji na profilach MTS w Karpatach rumuńskich koło Vatra Dornei i Miercurea Ciuc (Stanica *et al.*, 1986). Natomiast na Słowacji między Preszowem a Bardejowem wykryto sejsmicznie (Mořkovsky *et al.*, 1992) zanurzanie się ku NE powierzchni centralnokarpackich, triasowych dolomitów do głębokości 8 km pod PPS i flisz (Fig. 5). Wynik ten wskazuje, że na południe od wyniesienia Tylawy, w rejonie Bardejova, znajduje się obniżenie podłoża – przypuszczalnie przedłużenie ku NW depresji Czernogołowy–Krasnej.

Południową granicę depresji Czernogołowy–Krasnej–Rachowa stanowi rozłam Swalawy (Fig. 5), przypuszczalnie przedłużenie zewnętrznej granicy zanurzonego masywu Marmarosz. W północnym zboczu tej depresji według danych refrakcyjnych znajduje się rozłam ciągnący się od doliny Użu, blisko Zboja na Słowacji, przez Wołowiec–Mieżgorie w kierunku Rachowa. Z lokalizacji wynika, że z tym właśnie rozłamem może być związane źródło anomalii geoelektrycznej (Fig. 5, 6).

Obniżony blok podłoża między rozłamami Zboja–Mieżgoria i Swalawy przypuszczalnie zwęża się ku SE i zanurza pod blok krystaliczno-mezozoicznych jednostek Centralnych Karpat Wschodnich gdyż w okolicy Vatra Dornei wykryto tylko jeden rozłam (Stanica *et al.*, 1986). Pinna *et al.*, 1992 przyjmują, że ten rozłam skorupy wykryty metodą MTS między Vatra Dornei a Miercurea Ciuc dochodzi do 46. równoleżnika w okolicy Sf. Gheorghe. Rozłam ten jest granicą skorupy Karpat Centralnych i podsuniętej skorupy platformowej, wiąże się z nim geoelektryczna anomalia wywołana obecnością dobrze przewodzących warstw w sąsiedztwie rozłamu. Anomalia przerwana jest w sąsiedztwie 46. równoleżnika (Fig. 6) i pojawia się znowu około 100 km ku E w okolicy Focşani skąd kontynuuje się ku SW i W w zapadlisku przedkarpackim (Fig. 1) zgodnie z osią minimum grawimetrycznego. Nieciągłość anomalii zlokalizowana jest w strefie lewostronnego przesunięcia osi tego minimum o około 25 km w sąsiedztwie doliny Trotuş. Nieciągłości te znajdują się na zachodnim przedłużeniu północnej granicy kimeryjskiego orogenu Północnej Dobrudży–Krymu (Săndulescu *et al.*, 1978; Visarion *et al.*, 1988).

W wewnętrznej depresji podłoża między Bardejowem–Czernogołową–Rachowem, pod spiętrzonym fliszem znajduje się kolizyjny szew obniżonej brzeżnej części platformy środkowoeuropejskiej i obu bloków centralno-karpackich. Przy północnym skłonie tej depresji, na zewnątrz od pienińskiego pasa skałkowego, biegnie oś anomalii geoelektrycznej. Dalej na zachodzie, między Tatrami a Żyliną (Fig. 1, 7) oraz na wschodzie między Rachowem a Miercurea Ciuc (Fig. 1, 6) anomalia znajduje się na obszarze bloków Centralnych Karpat Zachodnich i Wschodnich ale jej źródło znajduje się pod tymi blokami.

Na zachód od Żyliny oraz począwszy od okolic Krynicy ku wschodowi oś anomalii geoelektrycznej znajduje się na obszarze płaszczowiny magurskiej a następnie na wynurzających się spod niej utworach płaszczowiny dukielskiej (Fig. 7); w rejonie Wołowca–Mieżgoria ta oś dochodzi do strefy przeddukielskiej (Fig. 5). Na SE od Krasnej, aż po okolice Sf. Gheorghe oś anomalii wykazuje lokalizacyjny związek z fliszem Dacydów zewnętrznych (płaszczowiny porkulecka, rachowska, czarnego fliszu i Ceahlău) przykrytych na znacznym obszarze jednostkami Centralnych Karpat Wschodnich (Fig. 7; Săndulescu *et al.*, 1978; Pinna *et al.*, 1992). Dacydy zewnętrzne to asocjacja szarego i czarnego fliszu oraz zasadowych skał eruptywnych reprezentujących utwory jurajsko–wczesnokredowego ryftu (*vide* Săndulescu, 1984, 1989). Ryft ten usytuowany był w brzeżnej strefie kontynentu europejskiego i porównywany jest z ryftem Afar–Morze Czerwone. Uważany był dotąd za odpowiednik Valais, zewnętrznego ryftu w strefie Penninicum Alp. Płaszczowiny Dacydów zewnętrznych znane są na powierzchni aż po rejon Czernogołowy (Fig. 5; Gluszko & Krugłov, 1986), ku zachodowi zanurzają się pod płaszczowinę magurską.

Jest możliwe, że utwory ryftu Dacydów zewnętrznych mają związek z depresją podłoża Czernogołowa–Rachow i jej postulowanym przedłużeniem tak w stronę Bardejowa jak i w stronę Vatra Dornei, a tym samym ze źródłem anomalii geoelektrycznej. Przyjęcie tego związku wymaga akceptacji przesunięcia utworów jednostki dukielskiej ku południowemu zachodowi w stosunku do aktualnych granic depresji podłoża; zjawisko wstecznych nasunięć w tej strefie orogenu jest jednak znane (idea „wachlarza", Andrusov, 1968). Dodać ponadto trzeba, że oligoceńskie utwory jednostki dukielskiej i zaliczonej do Dacydów zewnętrznych jednostki porkuleckiej należą do tej samej litofacji menilitowo-krośnieńskiej (Burov *et al.*, 1986). Rzuca to dodatkowe światło na problem granicy obu tych jednostek.

Problem obecności i lokalizacji jurajsko-kredowego ryftu w polskich Karpatach zewnętrznych

Idea związku anomalii geoelektrycznej z ryftem wewnętrznych jednostek fliszowych czyli Dacydów zewnętrznych stawia pytanie o obecność tego ryftu w Karpatach zachodnich, a zwłaszcza na zachód od Krynicy. Autor zestawia informacje o obecności łusek ciemnego neokomskiego fliszu (formacja z Bryjarki, część warstw ze Sztolni) i wulkanitów tego wieku zachowanych między pienińskim pasem skałkowym a utworami płaszczowiny magurskiej w jednostce Grajcarka (Fig. 7). Utwory te być może są obecne także w obrzeżeniu okna Mszany Dolnej. Z przytoczonych danych wynika możliwość istnienia we wczesnej kredzie na zewnątrz od obszaru przyszłego pienińskiego pasa skałkowego, basenu o redukcyjnym środowisku i zasadowych wylewach. Ten basen fliszowy istniał w tej strefie już w doggerze (formacja ze Szlachtowej – Birkenmajer, 1986). Mógł on być przedłużeniem ryftu Dacydów zewnętrznych Karpat Wschodnich. Większość jego osadów uległa tektonicznej redukcji a ich ślady widoczne są w jednostce Grajcarka.

Detrytus skał ultramaficznych (np. spinele chromowe) stwierdzono w kredowych i paleogeńskich formacjach pienińskiego pasa skałkowego a także w centralnokarpackim i magurskim fliszu (Starobova, 1962; Mišik *et al.*, 1980; Winkler & Ślączka, 1992, 1994). Wskaźniki paleotransportu we fliszu magurskim obok układu wzdłuż osi basenu wskazują na dostawę materiału tak z południa jak i z północnego obrzeżenia basenu (Książkiewicz, ed., 1962). Znaczna część materiału może więc pochodzić z obdukowanej ku północy części utworów rozważanego ryftu. W Karpatach Wschodnich obok fliszowych utworów wypełniających basen Dacydów zewnętrznych znajdują się zasadowe skały ekstruzywne (*vide* Săndulescu, 1984).

Pieniński pas skałkowy utworzony jest przypuszczalnie z kredowo–jurajskiego podłoża górnokredowo–paleogeńskiego fliszu magurskiego. Flisz ten odkłuty jest i przesunięty ku północy ponad postulowanym przedłużeniem rowu Dacydów zewnętrznych, których fragment ukazuje się w oknie tektonicznym Szczawnicy jako część utworów jednostki Grajcarka. Jeśli przyjąć związek geoelektrycznej anomalii z ryftowym rowem Dacydów zewnętrznych, główna masa osadów tego rowu wciągnięta jest obecnie głęboko pod wewnętrzne jednostki fliszowe i Karpaty Centralne. Idea połączenia rowu Dacydów zewnętrznych Karpat Wschodnich i Pennicum (Valais) Alp (Săndulescu, 1984, 1989) jest realna, ale autor sugeruje jednak związek z Piemontais.

Zgrafityzowane skały w sąsiedztwie kolizyjnej granicy płyt źródłem anomalii geoelektrycznej

Strefa generacji anomalii geoelektrycznej (jej źródło) związana jest z północną, tektoniczną granicą południowego czyli wewnętrznego pasa depresji w podłożu orogenu. Strefa ta jest bliska kolizyjnego szwu Karpat. Istnieją odcinki (Zboj–Mieżgorie, obszar na S i SW od Focşani) wskazujące na związek anomalii z obniżonym brzeżnym pasem skorupy kontynentalnej. Na północ od Sf. Gheorghe (Fig. 1) ponad źródłem anomalii lub w jego bliskim sąsiedztwie znajdują się utwory wewnętrznych jednostek fliszowych częściowo przykryte nasuniętymi blokami Centralnych Karpat Zachodnich i Wschodnich. Niezależnie od rozległego obszaru z warstwą dobrze przewodzącą – Fig. 4 (przypuszczalnie zmetamorfizowany paleozoik) dla wyjaśnienia genezy anomalii musi istnieć dodatkowy czynnik – dobry przewodnik prądu związany z określoną granicą czy strefą geotektoniczną.

Dane z masywu Marmarosz i sąsiedniego fliszu wskazują na grafityzację substancji węglistej w głębokiej strefie orogenu Karpat. Proces ten objął formację węglonośnego karbonu. Ponadto w strefach stektonizowanych utworzyły się nagromadzenia „metaantracytu" (Tokarski *et al.*, 1934; Vulczin *et al.*, 1967; Gabinet *et al.*, 1976, 1977). Obserwacje geologiczne wskazują na epigenetyczne pochodzenie części tych nagromadzeń.

W sąsiedztwie osi anomalii geoelektrycznej w różnych jednostkach Karpat północnych występują pooligoceńskie asocjacje hydrotermalnych minerałów tworzące żyły i wypełnienia otwartych szczelin. Ich wyznacznikiem są autigeniczne kryształy kwarcu – „diamenty marmaroskie". Tak w inkluzjach w kryształach kwarcu jak i między kryształami stwierdzono obecność antraksolitu o niskim stopniu metamorfizmu (Lomov, 1991). Ta twarda węglista substancja wykazuje pewne uporządkowanie struktury a więc początek grafityzacji. Jej powszechność tak na powierzchni jak i w głębokich otworach wskazuje na możliwość istnienia w głębi orogenu młodych skupień grafitu generujących anomalię geoelektryczną.