Annales Societatis Geologorum Poloniae (2003), vol. 73: 219–231.

STRUCTURAL INTERPRETATION OF SEMI-DETAILED MAGNETOTELLURIC SURVEY IN KAMIENICA DOLNA–GOGOŁÓW AREA IN THE POLISH OUTER CARPATHIANS

Michał STEFANIUK[1, 3] & Andrzej ŚLĄCZKA[2]

[1] *Department of General and Mathematical Geology, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, e-mail: stefan@geolog.geol.agh.edu.pl*

[2] *Institute of Geological Sciences, Jagiellonian University, ul. Oleandry 2a, 30-063 Kraków, e-mail: slaczka@geos.ing.uj.edu.pl*

[3] *Geophysical Exploration Company, 03-301 Warszawa, ul. Jagiellońska 76*

Stefaniuk, M. & Ślączka, A., 2003. Structural interpretation of semi-detailed magnetotelluric survey in Kamienica Dolna–Gogołów area in the Polish Outer Carpathians. *Annales Societatis Geologorum Poloniae*, 73: 219–231.

Abstract: Semi-detailed magnetotelluric survey was carried out in the area between Kamienica Dolna, Gogołów and Łopuchowa in the Polish Outer Carpathians. Magnetotelluric soundings were made along three lines located in a zone of the tectonic loop in the Carpathians' basement, which is reflected by the distribution of flysch outcrops. The sounding sites along profiles were ca 1.5 km apart. Magnetotelluric data were measured with the use of MT-1 system. To eliminate the effects of electromagnetic noise, the magnetic field remote reference was applied. Measurement data were processed using standard procedures of remote reference processing. Quantitative data interpretation was made with the use of 1D LSQ inversion. Initial geoelectric models were constructed basing on geological cross-sections obtained from surface and borehole data. 2D resistivity cross-sections, obtained from MT data interpretation, allowed the general structure of the flysch cover and its basement to be identified. Two major high-resistivity horizons were related to the top of Meso-Palaeozoic and Precambrian basement. A low-resistivity layer, related to the Lower Palaeozoic sediments, was interpreted.

Key words: Outer Carpathians, magnetotelluric sounding, structural interpretation.

Manuscript received 6 August 2003, acctepted 17 December 2003

INTRODUCTION

The Geophysical Exploration Company carried out a semi-detailed magnetotelluric survey at Kamienica Dolna–Gogołów area in the central part of the Polish Outer Carpathians during the years 1997–1998. The measurements were made with the use of MT-1 measurement and interpretation system (produced by Electromagnetic Instruments Inc.) along three lines running over a zone of the tectonic loop, which is reflected by the flysch outcrop pattern and residual gravity anomaly pattern (Fig. 1). Generally, the goal of the survey was to recognize the structure of the Carpathians and their basement. An integrated analysis of magnetotelluric, gravity and seismic data made earlier (Miecznik *et al.*, 1993, 1997) allowed the specific arrangement of gravity anomalies generated by the sub-Miocene basement elevations to be identified. Therefore, the main objective of the investigations was to prove the occurrence of elevated basement structures that were considered to be prospective for hydrocarbon accumulations. In particular, the MT data interpretation aimed at:

– delimiting the prospective zones in the Palaeozoic and Mesozoic formations,

– determination of the extent of individual Palaeozoic and Mesozoic complexes,

– recognition of the Carpathian orogen structure,

– evaluation of the thickness of the Carpathian orogen,

– identification of the contact zones between major tectono-stratigraphic units.

The results of investigations show a significant differentiation in resistivity and prove the intense tectonic engagement of the area. The flysch cover and the basement form a complex tectonic loop with at least two systems of faults recognized by MT data interpretation and change of the vertical structural plan. The MT data interpretation, integrated with surface and borehole geological data, resulted in construction of geological cross-sections along the measurement lines.

Fig. 1. Study area. Location of magnetotelluric soundings at measurement lines

GEOLOGICAL SETTING

Two major structural stages can be identified in the study area: the Outer Carpathian flysch nappes overlain by transgressive Miocene deposits and alluvial Quaternary sediments, and underlying North European Platform built up of Precambrian and Meso-Palaeozoic formations covered by autochthonous and allochthonous (Zgłobice Unit) Miocene.

OUTER CARPATHIAN NAPPES

The study area is built up of three tectono-stratigraphic units: Skole Nappe, Sub-Silesian Nappe and Silesian Nappe (Fig. 1).

The Skole Nappe covers the northern part of the study area between places of Pilzno, Kamienica Dolna, Wiśniowa and Wielopole Skrzyńskie. This nappe is built up of about 2,700 m thick Early Cretaceous–Early Miocene flysch beds and is irregularly folded with several thrust folds dipping towards the south. The marginal part is uplifted and built up of the Late Cretaceous–Paleogene Inoceramian beds, Siliceous Marls (Hołownia Marls), and variegated shales with the Late Cretaceous Spass shales in the cores of anticlines. Zones with transgressive sediments of Middle Miocene age are preserved there, forming the so-called Pilzno Bay. These are parautochthonous molasse-type beds covering the folded and partly eroded flysch (Geological Atlas 1988-1989; Połtowicz, 1991). The Pilzno Bay and the marginal anticlinorium are separated from the Strzyżów Synclinorium by a transverse elevation of Kamienica Dolna. The Strzyżów Synclinorium, filled with the Oligocene–Early Miocene Krosno beds and situated in the inner part of the Skole Nappe, is an important feature of the Skole Unit (Książkiewicz, 1972). The Skole Nappe is detached from pre-Early Cretaceous basement and it is overthrust on the Miocene cover of the Platform.

The Sub-Silesian Nappe builds central part of the study area near Kamienica Górna. Characteristic elements of this unit are Late Cretaceous variegated Węglówka Marls and Paleocene–Eocene variegated shales. They are underlain by Cenomanian red and green shales and Early Cretacoeus flysch (Gaize/Lgota beds, Veřovice Shales, Grodziszcze Sandstones, and Upper Cieszyn Shales). The Sub-Silesian Nappe is thrust over the inner part of the Skole Nappe.

The Silesian Nappe is situated south of the sub-Silesian Nappe. It is built up of flysch formations of Early Cretaceous to Oligocene–Early Miocene age. The Upper Cieszyn Shales and Veřovice Shales, as well as Grodziszcze sandstones and Lgota beds (Valanginian–Cenomanian) are distinguished there. They are covered by red shales and the Godula sandstones, which pass laterally into variegated shales (Cenomanian–Senonian) towards the north. The Senonian and Paleocene are represented mainly by thick-bedded sandstones of Istebna beds covered by Ciężkowice Sandstones, Hieroglyphic beds (Eocene), Menilite beds, and Krosno beds with thick-bedded sandstones (Oligocene). The total thickness of the sediments reaches ca 3–4 km.

The Silesian Nappe is built up of several folds and thrust folds overthrust on the Sub-Silesian Nappe and probably also directly on the North European Platform. Significant changes in the pattern of Silesian Nappe folds are observed near the Wisłoka River. They include the half-window of Brzostek – Kamienica Dolna, the Lower Cretaceous uplift within the Brzanka–Liwocz fold west of Kołaczyce, and the Z-shaped turn of this fold.

THE BASEMENT OF THE FLYSCH COVER

The allochthonous Zgłobice Unit and North European Platform covered by autochthonous Miocene represent the basement of flysch nappes.

The Zgłobice Unit is built up of refolded and tectonized Middle Miocene clays and sandstones, and it is overthrust on the autochthonous Miocene deposits of the Carpathian Foredeep. Its thickness in the Pilzno–Dębica area reaches 200–400 m. The depth of its burial is 3,000 m in the Głobikowa-1 well and some 3,700 m in Kowalowy-1 well located southwest of the study area.

The Carpathian basement is identified up to the line made by boreholes Zalasowa-1, Zalasowa-2, Kowalowy-1 and Szufnarowa-1. In the outer part of the study area it is represented by platform-type Mesozoic sediments of the extension of the Miechów Trough with autochthonous molasse cover of Middle Miocene age (Geological Atlas, 1988–1989; Połtowicz, 1991). However, it cannot be excluded that farther to the south Lower Miocene sediments can be preserved as well. Seismic survey and drillings, reaching down to about 4,000 m, identified the roof of the sub-Miocene basement, dipping south (Moryc, 1992, 1996, 1997). The foundation of the platform is built up of poorly metamorphosed folded shales and sandstones of Upper Precambrian (Riphey ?) – Lower Cambrian age (Cadomian meta-flysch). The roof of this complex was drilled at a depth of 3,300 m in Zalasowa-1 and Zalasowa-2 boreholes, at 3,015 m by Dębica-2 well, and at 3,634 m in Zagórzyce-1 well.

Between boreholes Stawiska-1, Zalasowa-1 and Zalasowa-2 (south) and Dębica-2, Zagórzyce-1, Zagórzyce-6, and Będzienica-2 (north) there runs a strip of Ordovician dolomites and limestones, 140 m thick, which turns farther east into thin graptolitic shales. Silurian graptolitic shales occur in the same area with the maximum thickness of 206 m in borehole Pilzno-40. The Devonian has not been observed in the area. Clastic and carbonate formations of Lower Carboniferous (Tournaisian) age were found only in borehole Dębica-10K. The overlying carbonate complex of Visean age with the thickness up to 200 m extends from Podgórska Wola near Pilzno to Zagórzyce and Nawsie to the east. Formations of Upper Visean, Upper Carboniferous and Permian have not been found there.

North of boreholes Stawiska-1, Zalasowa-1 and Zalasowa-2, along a line Podgórska Wola – Łęki Górne – Pilzno, there is a narrow trough with W-S strike filled with a complex of Lower Triassic sandstones, conglomerates and shales up to 600 m in thickness (Moryc, 1996). The beds of the same age with their thickness reduced to a few dozen meters (occasionally 125 m) were observed in boreholes in the area of Zagórzyce, Nawsie and Będzienica.

The Jurassic formations are bipartite. The lower complex of Middle Jurassic is built up of dark clays and silts intercalated with sandstones and sometimes conglomerates. The upper complex is formed of limestones observed over the entire area, although they can be eroded between Łęki Górne and Zalasowa (Moryc, 1996). The maximum thickness of the complex was observed in boreholes Nawsie-1 (1339 m), Zagórzyce-1 (1297 m) and Zagórzyce-6 (1187 m). The recent thickness and the extent of Jurassic limestones are a result of the block tectonics and erosion, mainly post-Laramide but pre-Cenomanian as well. The roof of the complex dips to the south. The maximum depth of burial was found in Szufnarowa-1 well (Moryc, 1996).

The platform-type Lower Cretaceous sediments were found in boreholes Pilzno-20, Pilzno-21, Stasiówka-1, Zagórzyce-6, and Nawsie-1 (Moryc, 1997). The sediments have the form of isolated lobes of limestones intercalated with silts and their thickness ranges from several to a few dozen meters. The platform-type Upper Cretaceous sediments are divided into two sedimentary covers (Cenomanian–Coniacian and Santonian–Mastrichtian) by local gaps and disconformities. Locally pinching out, the Cenomanian sediments are built up of sandstones whose thickness ranges from several to a few dozen meters. Turonian–Mastrichtian sediments are represented by carbonates: limestones and marls of the total thickness of 220–270 m near Dębica. Platform-type Cretaceous sediments have not been found in Stawiska-1, Zalasowa-1, Zalasowa-2, Głobikowa-2 and Szufnarowa-1 boreholes. This is a result of post-Laramide erosion.

Terrestrial sediments of Palaeogene are not observed in the study area. In the Palaeogene and Early Miocene strong erosion took place, palaeovalleys were formed; they were reached by boreholes Podgórska Wola-15, Łęki Górne-1, Pilzno-41 and Łączki Kucharskie-1. The palaeovalleys dip to the south and are filled with Middle Miocene sediments that create the autochthonous cover in the roof of the subflysch basement. The boundary between the cover and the overthrust molasses of Zgłobice Unit, which are of the same age, is hardly noticeable in borehole logs. The thickness of the cover changes from 1,100–1,200 m in palaeovalleys through 300 m off them to the complete reduction. The occurrence of Lower Miocene sediments in the Carpathian basement is considered both as an extension of the Zgłobice/Stebnik Unit and the autochthon.

METHODOLOGY OF MAGNETOTELLURIC INVESTIGATIONS

The magnetotelluric survey was carried out over the area with complex geology and rough morphology. Magnetotelluric sounding sites were distributed along three measurement lines: two of them (no 11 and 11b) were transverse to the strike of major flysch structures and the third one (no 11a) linked the two others (Fig. 1). The azimuths of the measurement array were the same as those of the measurement lines. Magnetotelluric sounding sites were ca 1.5 km apart. Measurements were made over a frequency range of 500–0.001 Hz with the use of MT-1 system. To evaluate the influence of near-surface non-homogeneities (the static shift), short, four-site continuous profiling of electric components referred to magnetic components was carried out (Stefaniuk *et al.*, 1998a, b, c). The basic measurement array consisted of four pairs of mutually perpendicular electric dipoles E_{xi}, E_{yi} and one pair of magnetic sensors located near the centre of electric dipole spacing. In general, the length of the electric dipole was 100 m, however, sometimes it was shorter due to terrain conditions. A remote magnetic field reference was applied to reduce the effects of electromagnetic noise.

The standard remote reference processing was applied to electromagnetic field time series in order to compute amplitude and phase curves, skew, and impedance polar diagrams, which were further interpreted. Qualitative and quantitative MT data interpretation was performed. In qualitative interpretation, parameters describing general characteristics of a geoelectric medium were analysed. Based on results of quantitative interpretation of MT sounding data, resistivity distribution in the geoelectric medium was evaluated and geoelectric layers were assigned to geological complexes. 1D automatic LSQ inversion was applied and, additionally, Bostick inversion was also used (Anderson, 1979; Bostick, 1977; MT-1 Operation Manual) (Fig. 2). TE-mode curves were used in inversion because they were less sensitive to horizontal variability of resistivity distribution in a geological medium. The program for 1D LSQ inversion is based on the least-square minimization algorithm by Marquardt (Anderson, 1979; Oldenburg, 1990; Pedersen & Hermance, 1986). An initial model for the inversion was constructed basing on 1D Bostick inversion (Bostick, 1977) and provisional geological cross-sections and results of parametric sounding data interpretation. Parametric soundings were made near boreholes. Well-logging data were used to construct initial models for interpretation of parametric sounding data. This enabled for the differentiation of geoelectric medium to be evaluated and verified the quantitative interpretation results, and tied geological, lithological or stratigraphic complexes with interpreted geoelectric layers.

The construction of final 2D geoelectric models as well as geological interpretation of MT sounding data were based on 1D LSQ inversion. Geoelectrical cross-sections were made basing on the correlation of resistivity layers along profiles. The position of resistivity horizons was extrapolated in near-fault zones to avoid disturbances caused by real geoelectric environment, which is not 1D. In interpretation of the fault zones, disturbances of MT sounding curves and rapid depth changes of interpreted horizons were taken into account. The interpretation of geoelectric boundaries in flysch complexes was adjusted to the general idea of its structure presented in geological cross-sections (Figs 3, 5, 7).

RESULTS OF INTERPRETATION

The survey was made in a zone of a specific tectonic loop. The complex geology of the area can be seen when analysing the surface geological map. The geology is re-

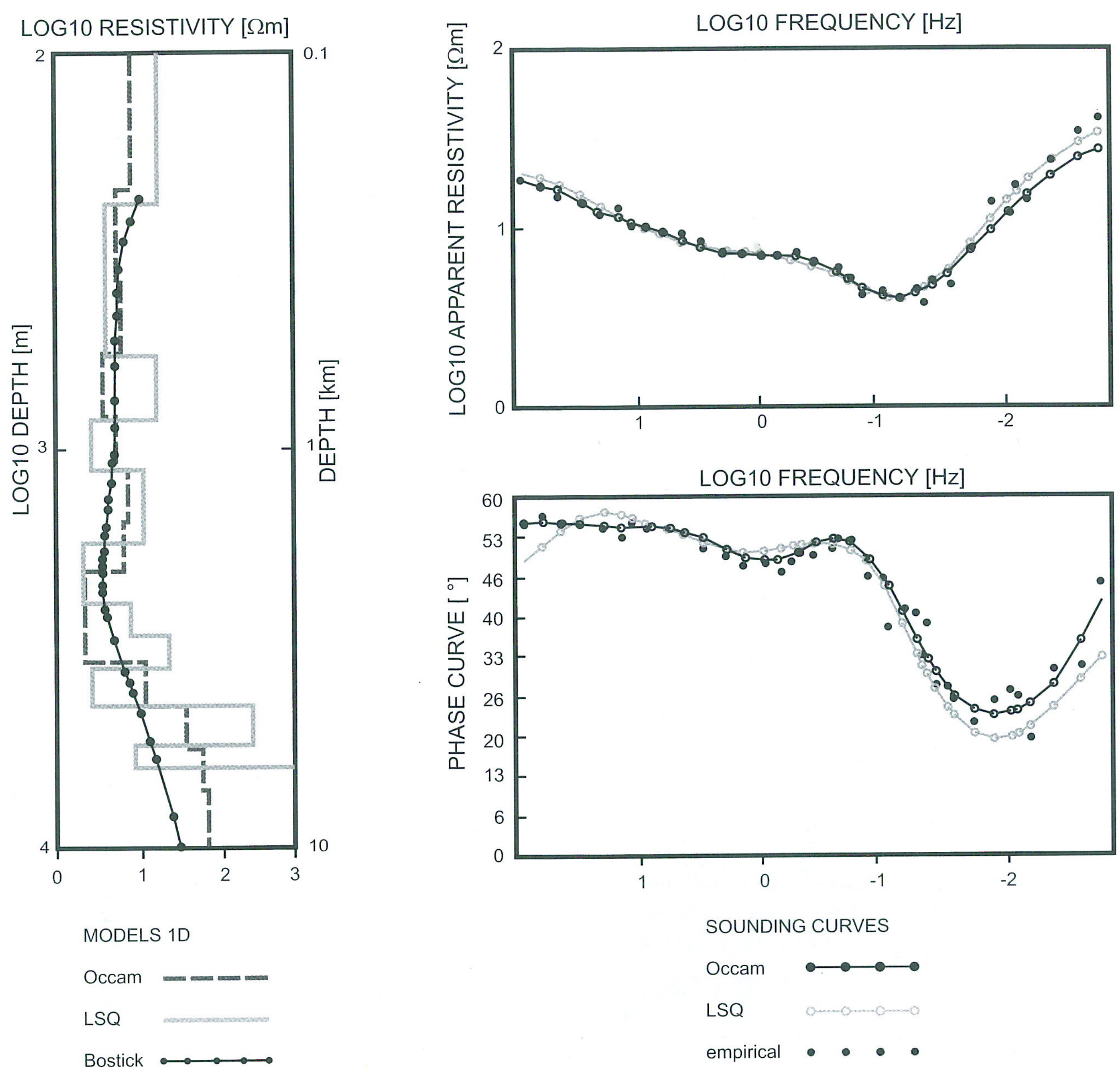

Fig. 2. Example of 1D automatic inversion. Sounding No 25, profile Sieklówka–Latoszyn

flected in the distribution of geophysical parameters and geophysical fields. The qualitative analysis of impedance polar diagrams and skew allows three structural plans (i.e., levels of different orientation of the main axis of geolectric medium) to be separated (Stefaniuk *et al.*, 1999). Also, the azimuth of the main geoelectric axis was variable along measurement lines, irrespective of the structural levels. It can be concluded that the structural arrangement changes both vertically and along the cross-sections of the flysch cover and its basement. 2D automatic inversion is not applicable to such complex 3D geoeletric medium.

Geological cross-sections along the MT measurement lines (Figs 3, 5, 7) were applied to construct initial interpretation models. Results of data interpretation are shown in 2D geoelectric cross-sections (Figs 4, 6, 8).

A characteristic feature of the geoelectric medium in the study area is a bipartite resistivity distribution. The upper part of the medium is associated with the flysch cover and autochthonous and para-autochthonous Miocene sediments. It is characterized by relatively low values of resistivity (occasionally exceeding 50 Ω m) and strong resistivity differentiation (Figs 3–8). Resistivities of the lower part of the medium are higher and range from a few hundred to a few thousand Ω m. The roof of the sub-Miocene basement, built up of Mesozoic and Palaeozoic formations forms the sharp resistivity boundary, which first of all could be associated with Jurassic limestones. That boundary is not so distinct when Cretaceous beds occur in the roof of the sub-Miocene basement and in zones where deep-seated low-resistivity complexes had been erosionally exposed.

A layer of 1 km thickness and low resistivity of 6–20 Ω m occurs below the high-resistivity (100–500 Ω m) layer in the upper part of the sub-Miocene basement, which probably is built up of shales, silts, and sandstones of Lower

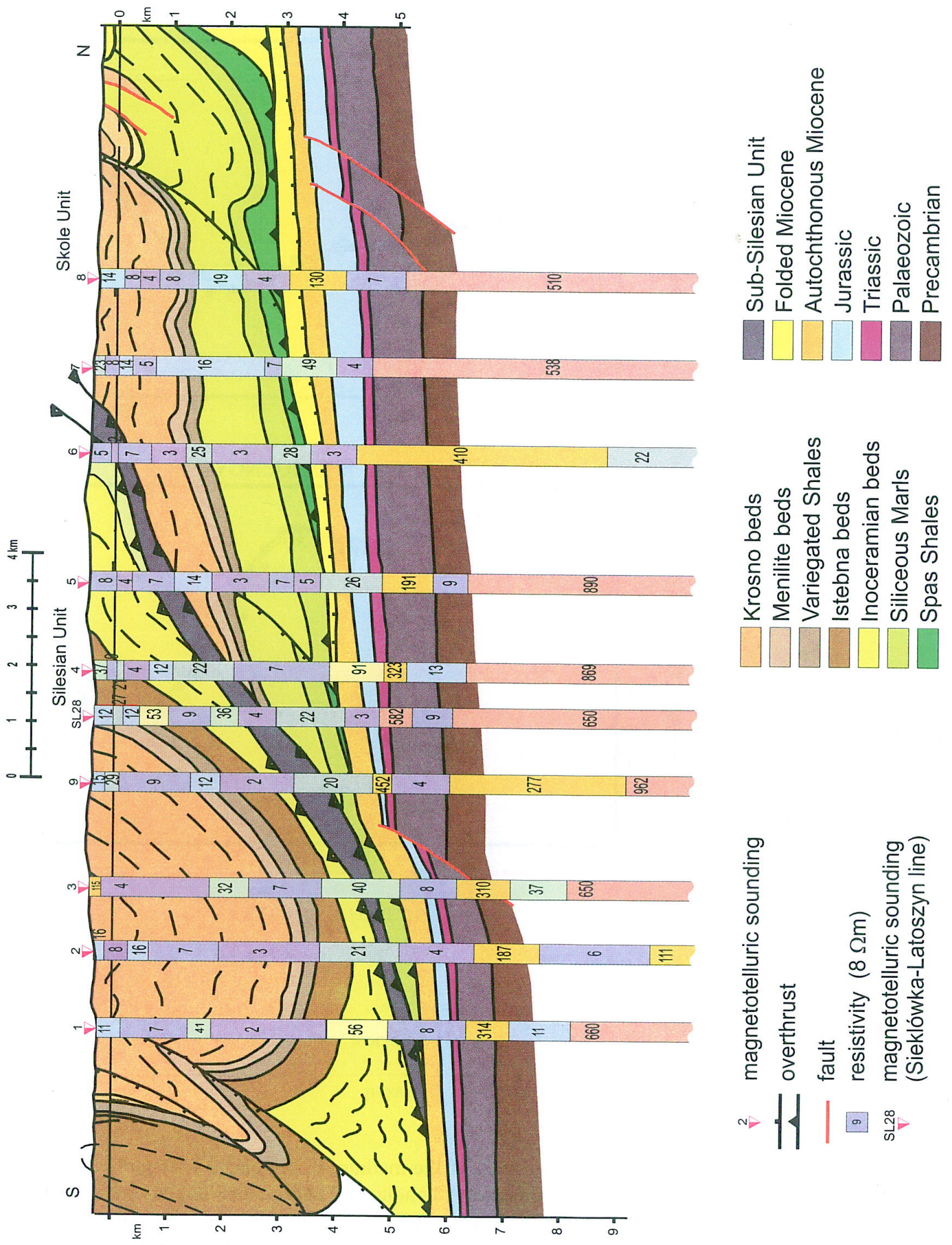

Fig. 3. Results of 1D inversion and geological cross-section. Profile 11b: Sieklówka–Brzeziny. TE mode, YX

Palaeozoic age. This layer is visible in cross-sections Sieklówka–Brzeziny (11b, Figs 3, 4) and Sieklówka–Latoszyn (11a, Figs 7, 8), but it is not interpretable in the Kamienica Dolna – Łopuchowa cross-section (11, Figs 5, 6). The possible reason of this is that the measurement line runs over the structural elevation in the roof of Mesozoic and crystalline basement. The structural elevation caused either reduction of thickness, so the layer could not be visible for MT method, or facies changes, which could increase measured values of resistivity. Beneath the low-resisitivity layer, there occur a high-resistivity complex that is probably built up of the crystalline Precambrian rocks.

Zones of tectonic discontinuity in the sub-Miocene basement were interpreted basing on the resistivity distribution and characteristic disturbances of MT sounding curves. These zones correlate well with zones of strong gradients of residual gravity anomalies (Stefaniuk *et al.*, 1999).

Diverse lithology and strong tectonic deformations of the flysch beds result in complex and ambiguous resistivity distribution. Generally, single structures and lithological

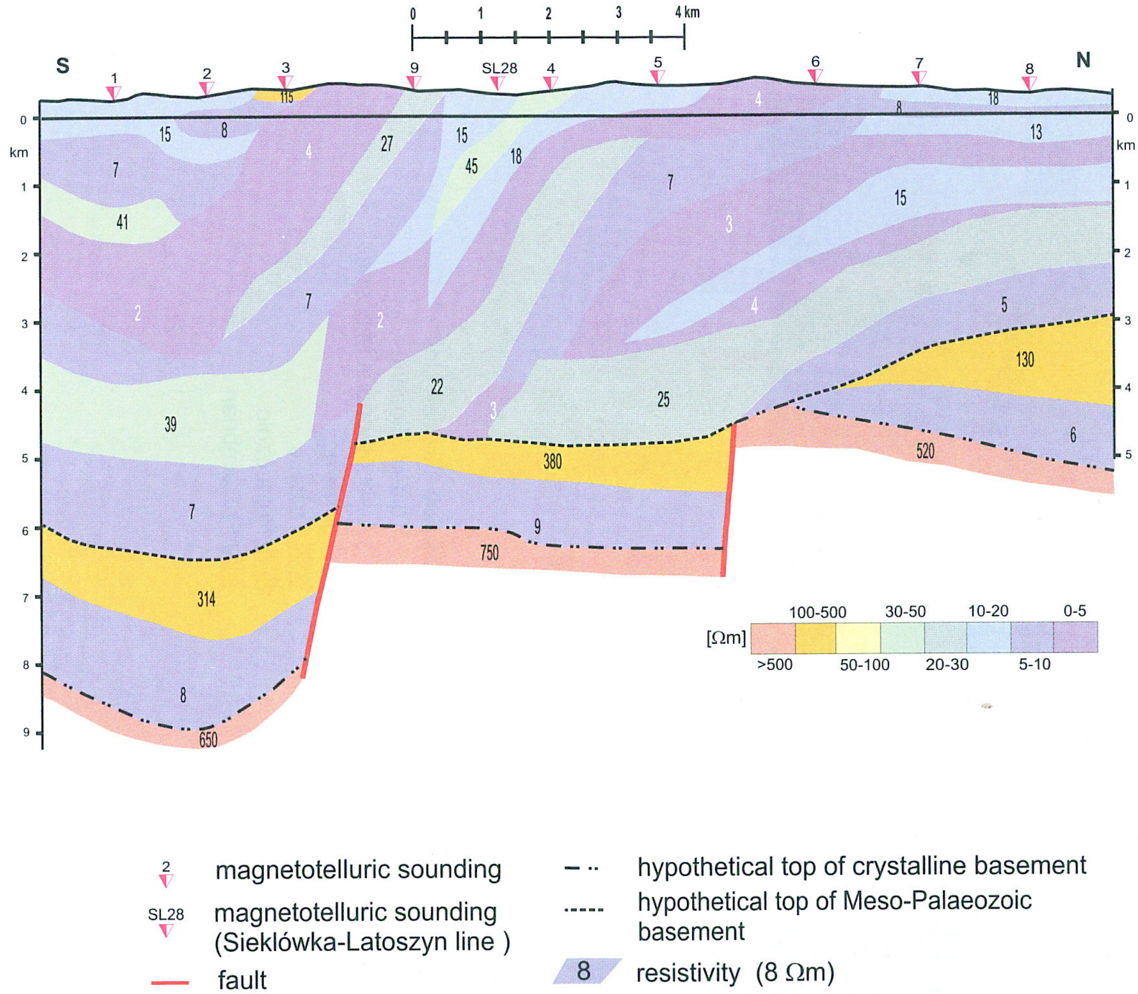

Fig. 4. 2D geoelectric cross-section 11b: Sieklówka–Brzeziny

complexes are reflected by resistivity changes. Yet, the quantitative interpretation is not quite reliable because the structures are built up of thin layers showing different lithology and resistivity and the volume proportion of each lithotype determines the equivalent resistivity. Tectonic surfaces, such as faults and overthrusts do not show as distinct resistivity boundaries and this reduces the accuracy of interpretation. Some parts of the flysch cover with distinct resistivity contrast can be visible in each cross-section. An example is given by high-resistivity portions of the central part of the Kamienica Dolna – Łopuchowa and Sieklówka–Brzeziny sections.

Cross-section no 11b: Sieklówka–Brzeziny

The Sieklówka–Brzeziny profile is oriented meridionally (Fig. 1). The roof of the high-resistivity horizon rests at a depth of 3 km at the northern edge of the section and dips steeply to the south. The fault with the roof displacement of ca 2 km to S is observed between MTS9 and MTS3 (Figs 3, 4). The stratigraphic and lithological identification of geoelectric layers is difficult because there are no boreholes in the neighbourhood (Stefaniuk *et al.*, 1999). The high-resistivity horizon is probably associated with the roof of Jurassic carbonates and sandstones (Fig. 3). Lower resistivities in the northern part of the cross-section can be attributed to Cretaceous sediments. A layer with resistivity of ca 10 Ω m and thickness of 1 km occurs beneath. The layer overlies a high-resistivity complex, probably built up of crystalline rocks. In the zone of steep sloping sub-Miocene basement roof, a high-resistivity layer pinches out, so that the low-resistivity layer and the crystalline basement occur directly at tbhe top of the sub-Miocene basement roof. Two normal faults divide the sub-Miocene basement into blocks forming a steep step system descending to the south (Fig. 4).

Resistivities of the upper part of the medium range from 5 to 20 Ω m, occasionally exceeding 50 Ω m (Figs 3, 4). In the northern part of the section, geolectric layers rest flat and gradually dip to the south. A great synclinal structure, probably modified by secondary folding, is clearly visible in the southern part of the section. Geoelectric layers dip steeply in the central part of the cross-section and their resistivities are variable. The zone is related to the Silesian and sub-Silesian overthrusts.

The upper part of the sub-flysch basement is built up of a thin complex of autochthonous Miocene sediments. The Miocene sediments of the northern part join with Lower Cretaceous flysch sediments forming a layer with 5 Ω m resistivity. In the central part of the cross-section, auto-

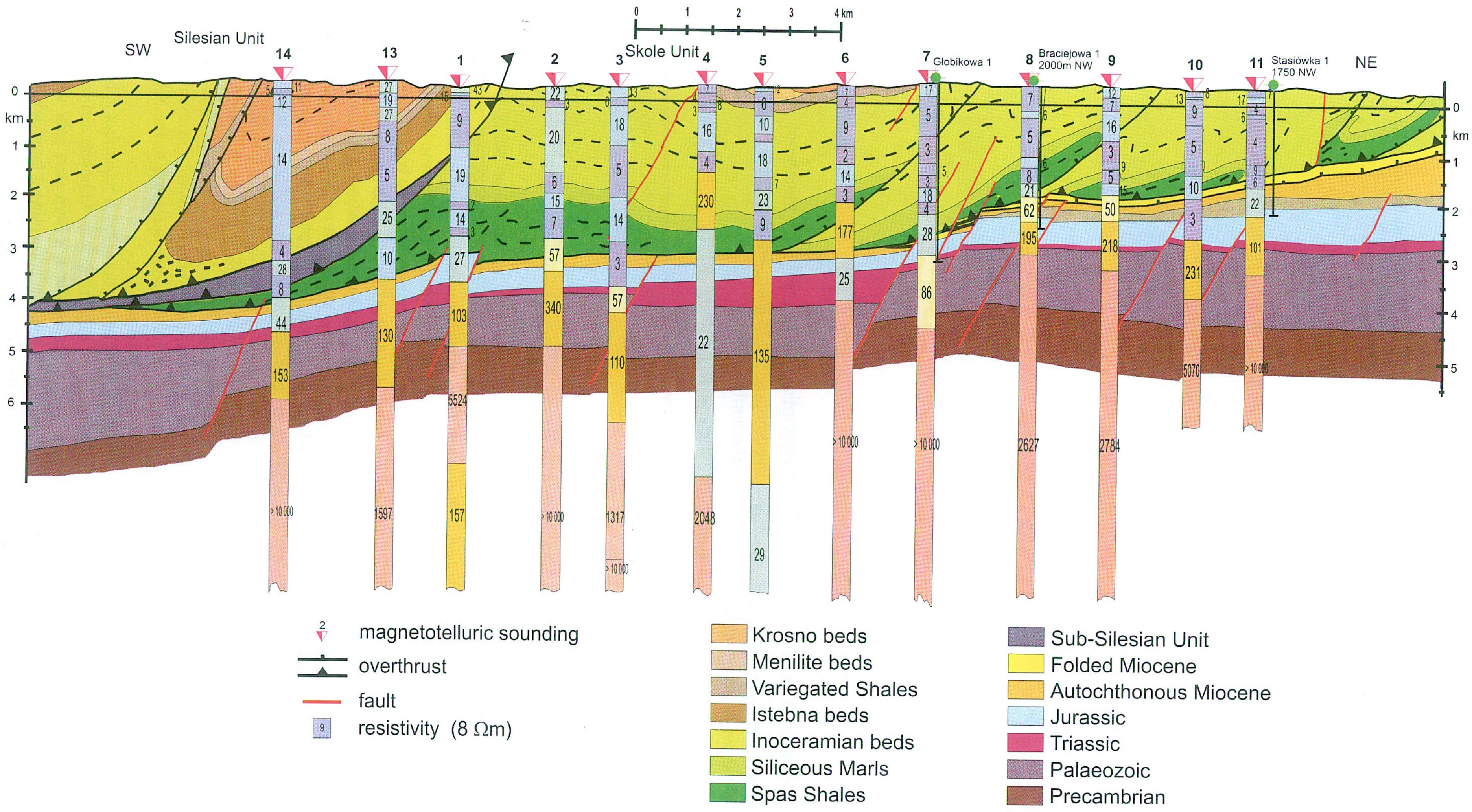

Fig. 5. Results of 1D inversion and geological cross-section. Profile 11: Kamienica Dolna – Łopuchowa. TE mode, YX

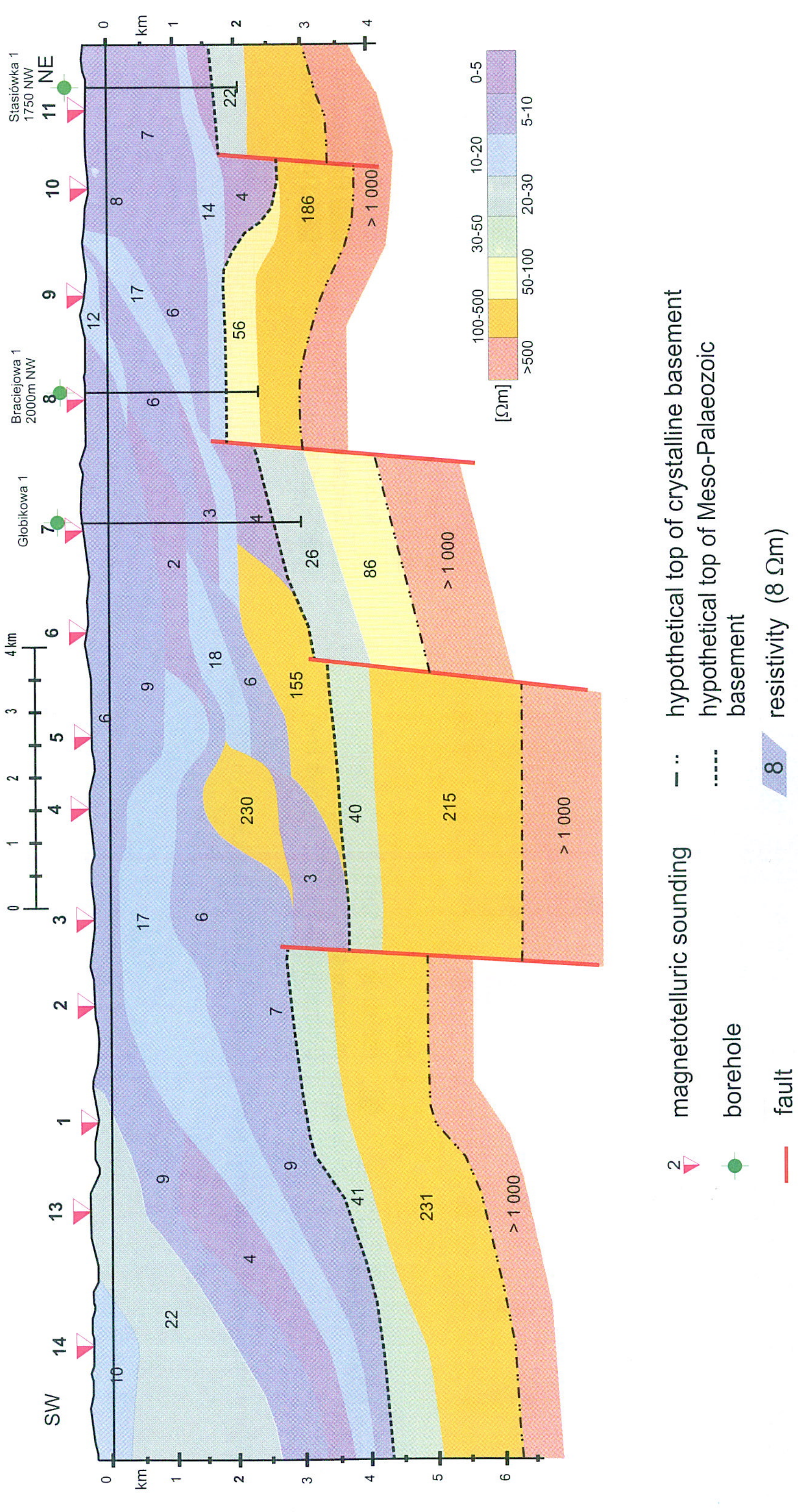

Fig. 6. 2D geoelectric cross-section 11: Kamienica Dolna – Łopuchowa

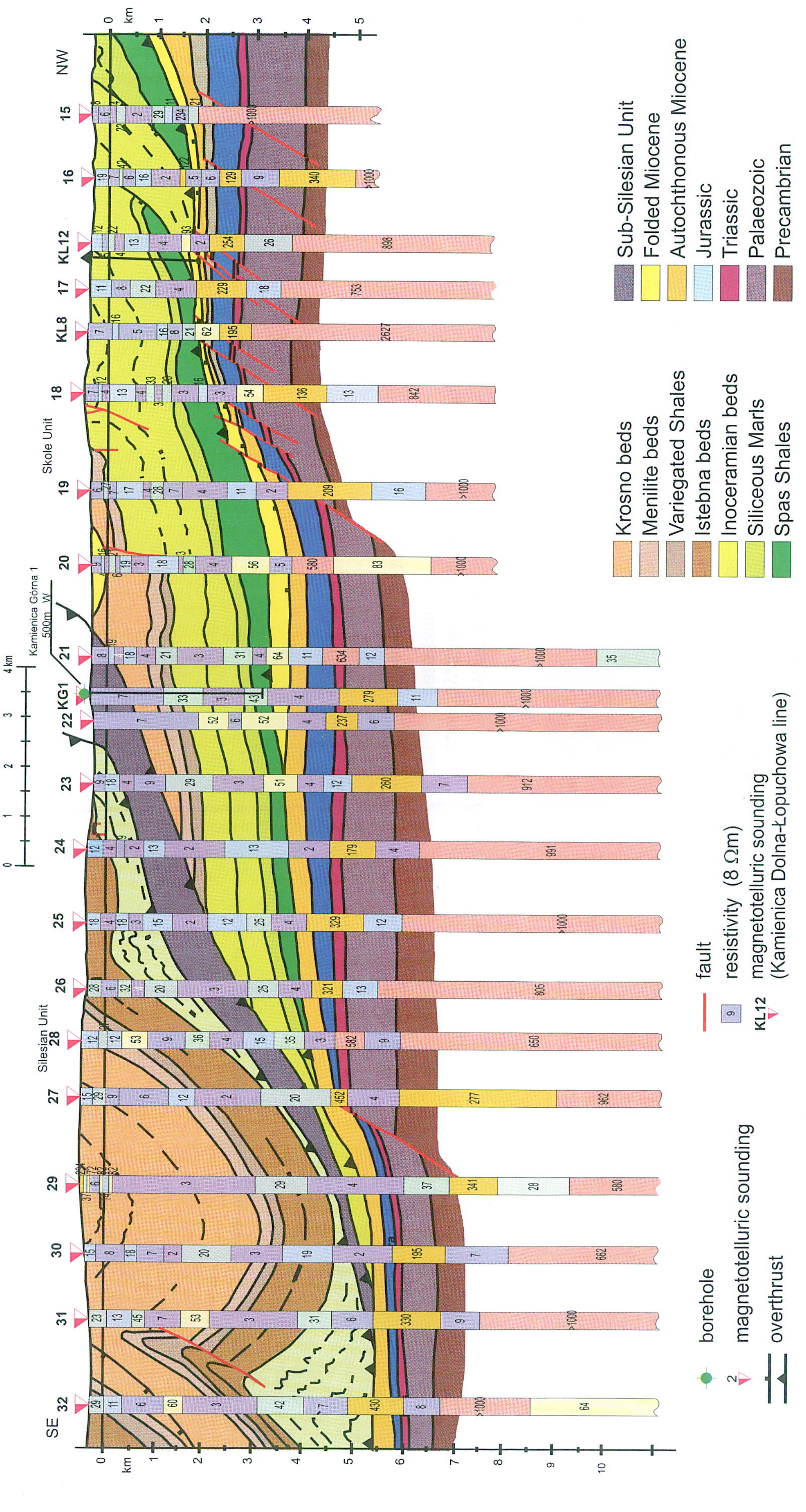

Fig. 7. Results of 1D inversion and geological cross-section. Profile 11a: Sieklówka–Latoszyn. TE mode, YX

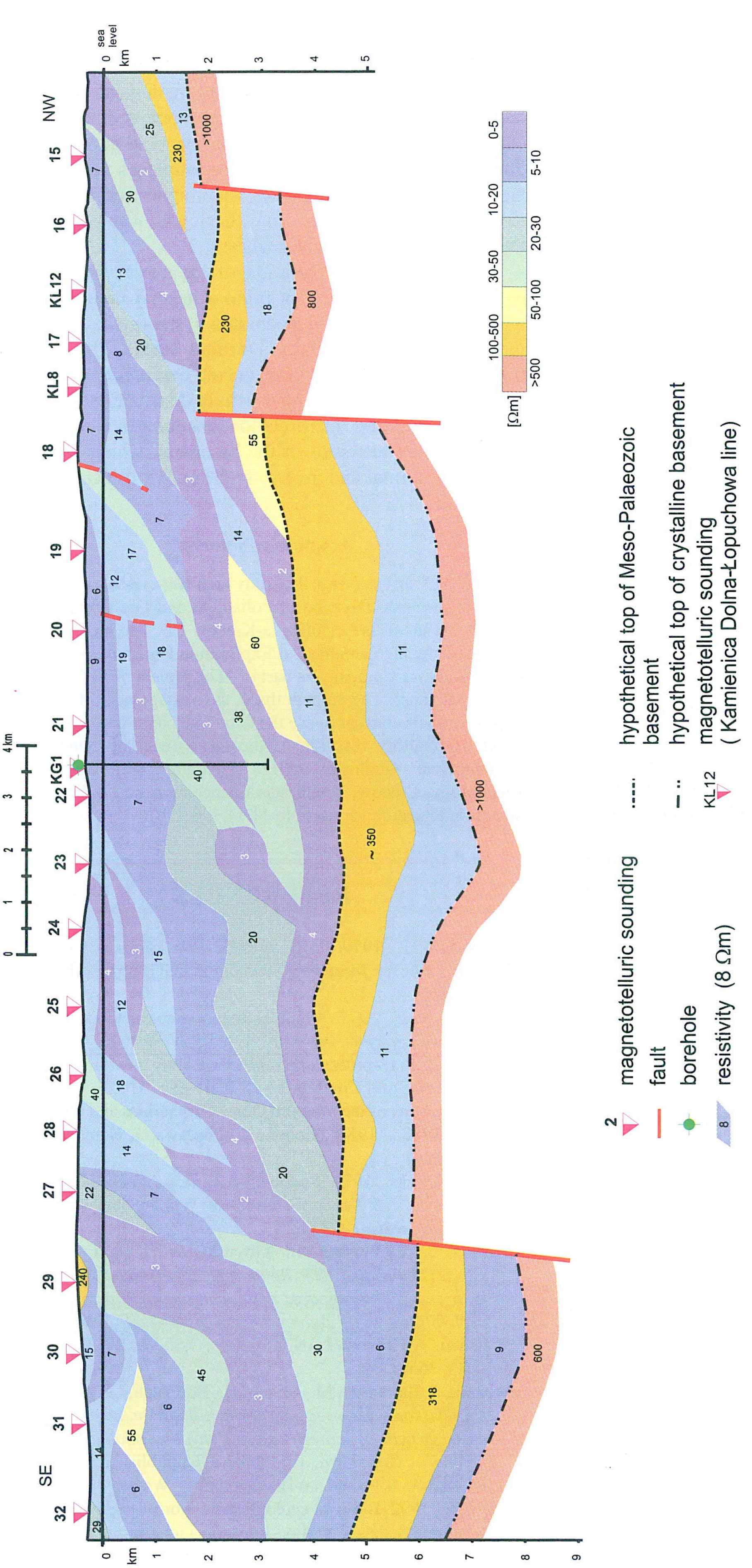

Fig. 8. 2D geoelectric cross-section 11a: Sieklówka–Latoszyn

chthonous Miocene sediments and Lower Cretaceous flysch are too thin to be distinguished in the geoelectric profile or the flysch cover lies directly over the roof of Meso-Palaeozoic basement. Low-resistivity beds of the southern part of the section, representing probably Lower Cretaceous flysch of Silesian and sub-Silesian units and autochthonous Miocene, form a 1 km thick complex.

Cross-section no 11: Kamienica Dolna – Łopuchowa

The line Kamienica Dolna – Łopuchowa is located in NW part of the study area (Fig. 1). The low-resistivity upper complex is fairly homogeneous in the central and NE parts of the section (Figs 5, 6). Somewhat higher resistivities are observed in SW part of the section, in the Silesian Unit. The surfaces of the overthrusts of the Silesian and sub-Silesian Units and minor overthrusts of the Skole Unit are rather clearly visible. The Carpathian overthrust onto autochthonous Miocene sediments in NE part of the section is evident, as well (Stefaniuk *et al.*, 1998c).

Three geoelectric layers can be distinguished in the sub-Miocene basement. Resistivities of the uppermost layer are rather low (20–30 Ω m) and the layer is probably built up of Cretaceous sediments. The medium layer with resistivity of 80–250 Ω m is composed of Middle Jurassic rocks and sedimentary complex of the Palaeozoic. The lowermost layer has high resistivity (exceeding 1000 Ω m) and is probably associated with crystalline Precambrian rocks.

Based on analysis of magnetotelluric and geological data, it is supposed that a system of faults divides the basement into five blocks (Fig. 6). Two blocks occur in the basement alone, while the other three are visible in the overlying complexes. A deep and narrow depression filled with low-resistivity sediments occurs in the basement roof in the northern part of the cross-section. That is probably an erosional form, which developed on the tectonic zone and was filled with younger sediments.

Cross-section no 11a: Sieklówka–Latoszyn

The Sieklówka–Latoszyn line runs across the study area and connects two other lines. Three fault zones divide the basement into separate blocks that dip steeply to SE (Fig. 8). Resistivity distribution in NW part of the cross-section is similar to that in NE part of the Kamienica Dolna – Łopuchowa section, however, it correlates well with SE part of the Sieklówka–Brzeziny section (Figs 7, 8).

CONCLUSIONS

The Meso-Palaeozoic basement of the Carpathians is cut at least by two systems of faults, which divide the Kamienica Dolna – Gogołów area into several blocks with different geological structure. Two main resistivity horizons are related to the roof of Meso-Palaeozoic and Precambrian basement. The upper high-resistivity layer of the basement is built up of carbonate and sandy sediments of Jurassic and Upper Palaeozoic age. It is locally overlain by Cretaceous formations of rather low resistivity (20–60 Ω m). Between the two high-resistivity complexes, there occurs a low-resistivity layer (5–15 Ω m) built up of Lower Palaeozoic sediments. That complex is not observed in the Kamienica Dolna – Łopuchowa section in NW part of the study area.

Resistivities of the upper part of geological profile related to the flysch cover and autochthonous or para-autochthonous Miocene sediments are low, seldom exceeding 50 Ω m. Resistivities of the flysch complexes are variable. Generally, younger complexes have higher resistivity, e.g. Lower Cretaceous rocks have the lowest values whereas Oligocene sediments – the highest.

The tectonic interpretation of the sub-Miocene basement was made bearing in mind a general conception of normal faults creating a steep step system, which divided the basement into regularly stratified blocks. The undulations in the roof of Meso-Palaeozoic basement are a result of erosion. The analysis of resistiviy distribution, obtained from MT sounding interpretation, encourages a concept of more complex tectonics of the basement, which had been formed by normal and inverse faults or overthrusts.

Acknowledgements

The MT surveys over the study area were initiated by Zenon Borys of the Jasło Division of Polish Oil and Gas Company and Henryk Trygar of the Geofizyka-Kraków Co. The measurements were made by the Geophysical Exploration Company for the Polish Oil and Gas Company as part of 'The project of MT survey in the Carpathians'. The authors thank the management of the companies for their consent to use the data. The paper was written as a result of statutory research of the Department of General and Mathematical Geology, AGH University of Science and Technology, Cracow, which was financed by the Committee for Scientific Research (project No 11.11.140.808).

REFERENCES

Anderson, W. L., 1979. *Program IMSL PW: Marquardt inversion of plane-wave frequency soundings.* USGS open-file report: 79–586.

Bostick, F. X. Jr., 1977. A simple almost exact method of magnetotelluric analysis. In: Ward S. (ed.), *Workshop of Electrical Methods in Geothermal Exploration.* Univ. of Utah Res. Inst., US Geol. Surv. Contract 14-08-0001-g: 1–319.

Geological Atlas of the Western Outer Carpathians and their Foreland, 1988 – 1989. (Coord.: D. Poprawa, J. Nemčok), PIG, Warszawa.

Książkiewicz, M., 1972. *Budowa geologiczna Polski. T. IV. Tektonika, część 3. Karpaty.* (In Polosh) Wydawnictwa Geologiczne War- szawa, 228 pp.

Miecznik, J., Stefaniuk, M., Klityński, W., Trygar, H., Maćkowski, T. *et al.*, 1993. *Reinterpretacja sondowań magnetotellurycznych w obszarze dodatnich anomalii grawimetrycznych Strzyżowa – Babicy i Gogołowa* (In Polish). Unpublished. Archiwum PGNiG S.A. – Ośrodek BG Geonafta – Jasło, 36 pp.

Miecznik, J., Stefaniuk, M., Trygar, H., Borczuch, M., *et al.*, 1997. *Projekt kompleksowej interpretacji badań magnetotellurycznych, grawimetrycznych i sejsmicznych w rejonie Kamienicy Dolnej – Gogołowa.* (in Polish). Unpublished. Archiwum PGNiG S. A. – Oddział BG Geonafta – Warszawa, 30 pp.

Moryc, W., 1992. Budowa geologiczna utworów podłoża miocenu w rejonie Sędziszów Młp.- Rzeszów i ich perspektywiczność. lin Polish, English summary). *Nafta* 9-10: 205–223.

Moryc, W., 1996. Budowa geologiczna podłoża miocenu w rejonie Pilzno – Dębica –Sędziszów Młp. (in Polish, English summary). *Nafta - Gaz*, 12: 522–550.

Moryc, W., 1997. The Lower Cretaceous in the pre-Miocene substratum of the southern part of the Carpathian Foredeep in Poland. *Annales Societatis Geologorum Poloniae*, 67: 287–296.

MT-1 Magnetotelluric System Operation Manual, version 3.2, 1996. EMI Inc., Richmond, Ca., USA, 235 pp.

Oldenburg, D., 1990. Inversion of electromagnetic data: an overview of new techniques. *Surveys in Geophysics*, 11: 231–270.

Pedersen, J. & Hermance, J. F., 1986. Least-squares inversion of one-dimensional magnetotelluric data: an assessment of procedures employed by Brown University. *Surveys in Geophysics*, 8: 187–231.

Połtowicz, S., 1991. Miocen strefy karpackiej między Wieliczką a Dębicą. (In Polish, English summary). *Kwartalnik AGH, Kraków*, 17 z. 3: 19–57.

Stefaniuk, M., Czerwiński, T., Wajda, A. & Mrzygłód T., 1998a. First results of high-frequency magnetotelluric investigations in Poland. In: *Book of Abstracts, the 14th Workshop on Electromagnetic Induction in the Earth, Sinaia*: 172–173.

Stefaniuk, M., Czerwiński, T., Wajda, A. & Mrzygłód, T., 1998b. Perspektywy i problemy wykorzystania badań magnetotellurycznych do rozpoznawania utworów fliszowych na przykładzie przekroju Zawoja-Potrójna. (In Polish). In: *Materiały konferencyjne XIX Konferencji Terenowej Sekcji Tektonicznej PTG – Magura '98*: 42–43.

Stefaniuk, M., Miecznik, J., Pepel, A., Wajda, A., Mrzygłód, T., Klityński, W., Pałka-Zielińska, E., 1998c. *Dokumentacja badań magnetotellurycznych wzdłuż profili Zawoja - Potrójna i Kamienica Dolna - Łopuchowa 1997 - 1998. Opracowanie przejściowe*. (In Polish). Unpublished. Archiwum PBG Warszawa, 78 pp.

Stefaniuk, M., Miecznik, J., Pepel, A., Wajda, A., Mrzygłód, T., Klityński, W., Pałka-Zielińska E., 1999. *Dokumentacja badań magnetotellurycznych w obszarze Kamienica Dolna - Gogołów 1998 - 1999*. (In Polish). Unpublished. Archiwum PBG Warszawa, 76 pp.

Streszczenie

STRUKTURALNA INTERPRETACJA PÓŁSZCZEGÓŁOWYCH BADAŃ MAGNETOTELLURYCZNYCH W REJONIE KAMIENICY DOLNEJ – GOGOŁOWA, POLSKIE KARPATY ZEWNĘTRZNE

Michał Stefaniuk & Andrzej Ślączka

W latach 1997–1998 Przedsiębiorstwo Badań Geofizycznych w Warszawie wykonało badania magnetotelluryczne w centralnej części polskich Karpat zewnętrznych w rejonie Kamienicy Dolnej – Gogołowa. Wykonane zostały one na trzech profilach zlokalizowanych w strefie specyficznego węzła tektonicznego zaznaczającego się w intersekcyjnym obrazie powierzchniowym (Fig. 1) oraz w rozkładzie anomalii grawimetrycznych. Celem geologicznym badań było rozpoznanie strukturalne orogenu karpackiego i jego podłoża. Wykonana wcześniej kompleksowa analiza danych magnetotellurycznych, grawimetrycznych i sejsmicznych pozwoliła na stwierdzenie obecności charakterystycznego układu anomalii grawimetrycznych w tym obszarze, związanych prawdopodobnie z elewacjami podłoża podmioceńskiego. Głównym zadaniem prezentowanych badań było potwierdzenie obecności wyniesionych struktur podłoża, które uważane są za perspektywiczne dla prospekcji węglowodorów. W szczególności celem interpretacji było wyznaczenie stref perspektywicznych w utworach paleozoiku i mezozoiku, wyznaczenie zasięgu poszczególnych serii mezozoiku i paleozoiku, rozpoznanie budowy strukturalnej orogenu fliszowego, określenie jego miąższości i stref kontaktu wielkich jednostek tektoniczno-stratygraficznych.

Punkty sondowań magnetotellurycznych rozmieszczone były co 1,5 km. Pomiary wykonano za pomocą systemu MT-1 produkcji Electromagnetic Instruments Inc. z Richmond, USA. Zastosowano tzw. zdalne odniesienie magnetyczne (*magnetic field remote reference*) w celu eliminacji wpływu zakłóceń elektromagnetycznych. Wyniki pomiarów opracowano wykorzystując standardowy processing referencyjny. W interpretacji ilościowej zastosowano 1D automatyczną inwersję LSQ (Fig. 2). Początkowe modele geoelektryczne przyjmowano bazując na przekrojach geologicznych skonstruowanych na podstawie danych powierzchniowych i otworowych (Fig. 3, 5, 7). W wyniku interpretacji 1D uzyskano pionowe modele rozkładu oporności w ośrodku geologicznym w punktach sondowań. Przekroje opornościowe wzdłuż profili magnetotellurycznych (Fig. 4, 6, 8) skonstruowane zostały na podstawie wyników interpretacji 1D przy uwzględnieniu ogólnego modelu geologicznego rejonu oraz danych z otworów wiertniczych.

Rezultaty badań wskazują na duże zróżnicowanie oporności oraz intensywne zaangażowanie tektoniczne utworów fliszowych, i ich podłoża. Zarówno pokrywa fliszowa jak i podłoże tworzą skomplikowany węzeł tektoniczny, charakteryzujący się obecnością przynajmniej dwu systemów przecinających się uskoków w podłożu, wyinterpretowanych na podstawie badań magnetotellurycznych, oraz zmianą planu strukturalnego w pionie. 2D przekroje oporności, otrzymane z interpretacji danych magnetotellurycznych, pozwoliły na określenie generalnej budowy pokrywy fliszu i jego podłoża. W podłożu podmioceńskim wyinterpretowane zostały trzy główne kompleksy opornościowe:

– stropowy wysokooporowy (100–500 Ω m), związany z węglanowymi i klastycznymi skałami mezozoiku i górnego paleozoiku;

– pośredni niskooporowy (3–20 Ω m), odpowiadający prawdopodobnie ilasto-mułowcowym utworom dolnego paleozoiku;

– dolny wysokooporowy (500–2000 Ω m), odpowiadający skałom krystalicznym.

Interpretacja litologiczna i stratygraficzna pokrywy fliszowej jest utrudniona wobec dużej zmienności litologicznej i facjalnej fliszu (a zatem jego oporności) oraz stosunkowo słabych kontrastów opornościowych i płynnych przejść pomiędzy kompleksami stratygraficznymi.