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Magnetotelluric continuous profiling in recognition of geological structure and lithology differentiation; case studies from Polish Outer Carpathians

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Introduction

The main problems of geological investigations in the Polish Carpathians include recognising of the structure and lithology differentiation of the flysch cover and sub-flysch basement (Stefaniuk et al. 2003). Geological formations building the flysch orogen and upper sedimentary part of the basement are supposed to be hydrocarbon-prospective, so that they have been targets of geophysical and geological surveys. The complex structure of the orogen is a great obstacle to the reflection seismic survey, which is used as a standard method in oil prospecting.

The Outer Carpathians are built of a thick complex of flysch sediments and have the form of an accretion prism (Stefaniuk et al. 2004b). The Carpathian overthrust is built of strongly folded, cut by tectonic zones flysch sediments in which dominate alternating silty-clayey and sandstone layers with varied thickness. The layers are characterized by strong differentiation of elastic parameters. Intense tectonics of the flysch cover generates a complex spatial distribution of elastic parameters and, as a result, a complex wave field pattern that is difficult to interpret. Therefore, the interpretation of geological structures beneath the overthrust is uncertain and wells cannot be reliably located (Górecki et al, 2004).

Under such conditions it is necessary to apply other surface geophysical methods, which can support seismic data interpretation. Of them, the magnetotelluric method is widely applied in the area of the Polish Carpathians. The magnetotelluric method is mainly used for the regional survey, which is intended to recognize the Mesozoic, Paleozoic and Precambrian basement, however semi-detailed and detailed magnetotelluric surveys have been recently made in the Polish Carpathians (Czerwiński and Stefaniuk 2001, Stefaniuk 2001, 2003, Stefaniuk et al. 2004a). The detailed magnetotelluric survey employing the continuous profiling was made along a few seismic reflection lines in the Raciechowice – Stadniki region, southeast of Cracow, and Hermanowa – Strzyżów – Babica area in the Outer Carpathians (Stefaniuk et al. 2003a, b, 2004b).

Miocene complexes and their Mesozoic and Paleozoic sedimentary basement in the outer zone of the Carpathian overthrust are regarded as prospective for oil and gas exploration (Górecki et al. 2004). Numerous gas fields were discovered there in the Carpathians' foreland and beneath the outermost part of the overthrust. A few small oil deposits were also found there. As a result, investigations were extended south where the prospective complexes rest beneath strongly folded flysch cover of the Carpathian overthrust. Over a span of a few dozen years, the area was frequently covered with seismic survey and drilling. However, interpretation of surface seismic data was difficult, mainly because of the above-mentioned complex geology of the Carpathian overthrust and its thickness increasing south.

The magnetotelluric continuous profiling provides a specific modification of the magnetotelluric method. Its characteristic features include such a close sampling of the electric field component parallel to the measurement profile that an electric dipole length is equal to the measurement spacing (Stefaniuk and Czerwiński 2005). As a result, a continuous coverage of the measurement profile with electric dipoles is obtained. Sampling of the magnetic field and the electric field, which is perpendicular to the measurement profile is much poorer. The response of the magnetic field to geological structures is smaller than that of the electric field and therefore the magnetic field is oversampled when the measurement spacing of either field is the same. The electric field measured by means of several dipoles can be referred to the magnetic field measured by a pair of sensors. Since measurement profiles are usually transverse to the geological structures, the variations of the electric component perpendicular to the profile are weaker than those parallel to it.

The foundations of the magnetotelluric continuous profiling were given by Torres-Verdin (1991) as the ElectroMagnetic Array Profiling (EMAP). It was applied to elimination of a so-called static shift of magnetotelluric curve caused by shallow 3D resistivity structures adjacent to a measurement array. The static shift is eliminated with the use of spatial filtering of MT parameters along the profile (Torres-Verdin and Bostick 1992). Since other approaches for static shift elimination for single measurement site were available, the EMAP was mostly applied to relatively shallow investigations.

In Poland, shallow magnetotelluric profiling was applied to recognize zones of thermal water and mineral water filtration in areas of the Sudetes Mts. (Farbisz et al. 2001) and to examine the boundaries of a salt dome in central Poland (Czerwinski and Stefaniuk 2001). In the authors' opinion, the advantages of this method does not confine to the static shift elimination alone. A relative oversampling of magnetotelluric parameters at a low frequency range results in the statistical averaging of the parameters, which is significant for noisy data. Therefore, the MT continuous profiling has been applied to recognize the structure and the lithology of deep- and medium-seated rock complexes in the Outer Carpathians and eastern Pommerania at the Polish Lowland (Stefaniuk et al. 2003).

A few continuous MT profiles were designed in the marginal zone of the Carpathian overthrust to study the structure and lithology of the flysch cover and its basement. The interpretation of resistivity cross-sections gave some details of the flysch structure and allowed the lithology changes reflected in the resistivity distribution to be evaluated. The analysis of resistivity changes of the flysch series was based on well-logging data in relation to the stratigraphy, porosity and pore water salinity.

Outline of Geology

The study area is situated in the Polish Western Carpathians in the extension zone of major structures of the Paleozoic platform, which occurs in front of the Carpathian overthrust (Stefaniuk et al. 2003, Stefaniuk and Ślączka 2003). The geology of the area is complex as a result of intense tectonics and erosional cuttings. Three main structural stages could be distinguished in the area:

- the Sub-Miocene platform-type basement consisting of Precambrian, Paleozoic and Mesozoic formations;

- Miocene mollasses of the Carpathian foredeep;

- the Carpathian overthrust including three tectonic-and-stratigraphic units: the Skole unit, the Silesian unit and the Sub-Silesian unit.

The oldest formation of the platform-type basement consists of magmatic and metamorphic Precambrian rocks, overlain by a thick (up to 2000 m) complex of clastic sediments of Lower Cambrian. Above them, clastic formations of Lower Devonian and carbonate rocks of Middle and Upper Devonian occur. They begin the profile of the post-Caledonian sedimentary cover. Carboniferous sediments are probably absent in the area, however they were observed in the Tarnawa-1 borehole, ca. fifteen kilometres east of the study area. The next complex is formed of clastic sediments of Lower

Jurassic, which fill tectonic and erosion depressions, and sediments of Middle Jurassic. The Upper Jurassic is represented by deeply eroded carbonate measures. Upper Cretaceous sediments were found in the northern part of the area. They occurred in depressions as deeply eroded lobes, with a thickness from several to twenty meters. A strongly tectonically deformed complex of clastic Miocene sediments of different thickness that is overthrust by flysch structures consisting of geosynclinal Mesozoic and Cainozoic formations covers the platform-type basement.

The tectonics of the area was constituted during the latest phases of the Alpine orogenesis. The sub-Miocene basement is cut by two systems of normal faults with directions of strike NW-SE and SW-NE, and divided into several blocks. The reverse faults occur in the area as well. The tectonics of the autochthonous Miocene formations is, in general, conformable with the tectonics of the deeper basement. The thickness of this formation decreases to south to a thin layer, which remained on the Meso-Paleozoic erosion surface as a result of shearing by the thrusting-over Carpathians. The tectonic style of the flysch cover is completely different from the basement tectonics.

Technical and methodological problems of surveys

Magnetotelluric measurements were taken with the use of MT-1 system of Electromagnetic Instruments Incorporation (EMI), Richmond, California, USA. Electric dipoles, X_i, of a standard 100 m length each were oriented along the measurement profiles (Stefaniuk et al. 2003). Electric dipoles, Y_i, were perpendicular to the profiles and spaced every 200-400 meters. Measurements recorded for each 600-m-long section of the profile were referred to a pair of magnetic sensors located near the centre of the section. The time series of MT field components were recorded over a frequency range of 500 – 0.01 Hz. A remote reference site was located at a distance of over 100 km of the study area. Data processing was made with the use of programs included in the MT-1 system. Amplitude and phase sounding curves for each electric dipole, and impedance-tensor skew and polar diagrams for pairs of X_i and Y_i dipoles were results of data processing. 2D resistivity cross-sections were calculated with the use of Bostick algorithm for continuous profiling (EMAP).

Geological interpretation

The magnetotelluric profiling method was applied in the Raciechowice – Stadniki and Hermanowa – Strzyżów – Babica areas in the Outer Carpathians. Results of the investigations enabled the major structures and lithology of the flysch cover and Miocene and sub-Miocene basement to be recognized As a result of magnetotelluric data interpretation, the resistivity differentiation of the basement rocks due to tectonic zones and lithology changes was evaluated. The highest resistivity was probably connected with the crystalline Precambrian rocks overlain by relatively low-resistivity clastic measures of Lower Paleozoic and high-resistivity carbonate sediments of Devonian and Upper Jurassic. Low-resistivity complexes occurring locally between the high-resistivity horizons should be associated with clastic sediments of Lower and Middle Jurassic and, possibly, with Carboniferous. Miocene sediments have low resistivity. The boundary between Miocene complex and the flysch cover is not clear because of low-resistivity rocks building the sub-Silesian Unit that form the lower part of the Carpathian overthrust in the study area. The upper part of the overthrust, the Silesian Unit, is built of thick, high-resistivity, sandstone layers interbedded with low-resistivity shales. Thick sandstone beds can be distinguished in resistivity cross-sections.

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