Recent results of the gravity and magnetotelluric modelling: lithosphere structure in the Polish Carpathians

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*Abstract.*The first studies on lithosphere structure in the Western Carpathians, based on seismic and gravity modelling, indicate that deep crustal rooting could account for the observed gravity low (Bojdys et al., 1983).

During the last few years deep magnetotelluric soundings (MTS) were conducted by the Geophysical Exploration Company and Polish Geological Institute along several profiles in the Polish Carpathians. As a result of MTS interpretation geoelectric cross sections were obtained (Stefaniuk & Klityński, 1999; Klityński & Stefaniuk, 2000). They were the starting points for constructing the structural models of the Earth's crust. For gravity modelling a density distribution was acquired from deep seismic soundings carried out in adjacent countries (Tomek et al., 1989; Kutas et al., 1996; Bezák, 1997; Šantavý et al., 1999). As examples results of gravity modelling for several cross sections are presented, which are typical for the western and eastern segments of the Polish Carpathians (Królikowski et al., 2000).

The bottom of the Palaeozoic-Mesozoic rocks, Miocene molasse and flysch is an irregular surface which is fractured by structures of low resistivity (spurs of flysch ?) descending southwards in the crystalline crust. These structures appear in the gravity minimum zone. The upper crystalline crust is of large thickness and of very complicated structure. It is divided into blocks, which in turn consist of several strata of diversified physical parameters. The lower crust is relatively thin and of simpler structure. In the northern part of profiles lower crust blocks exist of considerably higher resistivity and density. In the whole crystalline crust and even in the lower lithosphere wider or narrower fracture zones occur.

The results of MT and gravity modelling suggest that crustal structures are different in the western and eastern segments of the Polish Carpathians.

Key words: Polish Carpathians, gravity modelling, magnetotelluric modelling, lithosphere structure

Introduction

For many years the geological structure of the Polish Carpathians was studied by a large group of geologists and geophysicists. The synthetic data can be found in numerous publications, on geological maps and cross-sections (for example Geological Atlas of Poland, 1:200 000 scale, 1988-1989).

Over the recent years magnetotelluric survey was conducted by the Enterprise of Geophysical Explorations. Data from three profiles in the western part and four in the eastern part (fig. 1) have been interpreted and geoelectric cross-sections of the crust and upper portion of the lower lithosphere have been compiled (Stefaniuk & Klityński, 1999; Królikowski et al., 2000) providing the basis for preliminary gravity modelling.

In this paper special attention is given to the geological structure of the Carpathian basement.

Geological position of the Polish Carpathians

The western segment

The crystalline basement is built of folded and metamorphozed Proterozoic rocks together with granitoid intrusions and basic effusives. They constitute an extension of the Upper Silesian block and appear directly beneath the Neogene in the Brno-Cieszyn ridge. They are represented by gneisses and migmatites (Beskid Śląski), granitoid belt (E of Bielsko-Biała to the Babia Góra massif) as well as metaargillites (S of the Zawoja-Jordanów line, profile 4). These formations dip northwards under the Cambrian, Devonian, Carboniferous and Triassic sediments which are an extention of the Upper Silesian basin. Futher to the east along the profile lines 5 and 7 the Palaeozoic is overlain by Triassic and Jurassic sediments (Geological Atlas....1988-1989).

The southern sections of profiles 5 and 7 lie in the Inner Carpathians which, in Poland, include the Tatra Mountains and the Podhale area. In the elevated Tatra Mts. exposed are older Pre-Palaeozoic formations and structures which during the Alpine cycle have been covered by Permo-Mesozoic sediments and subsequently folded forming two nappes: the lower called Sub-Tatric and the higher one called Tatric (Książkiewicz, 1972).

The Podhale trough has a simple stucture and is filled with Podhale flysch (Zakopane and Chochołów Beds) overlying the Sub-Tatric unit (Triassic, Jurassic, Cretaceous) at the depth of about 2500 m. The Outer Carpathians are separated from the Podhale trough by the Pieniny

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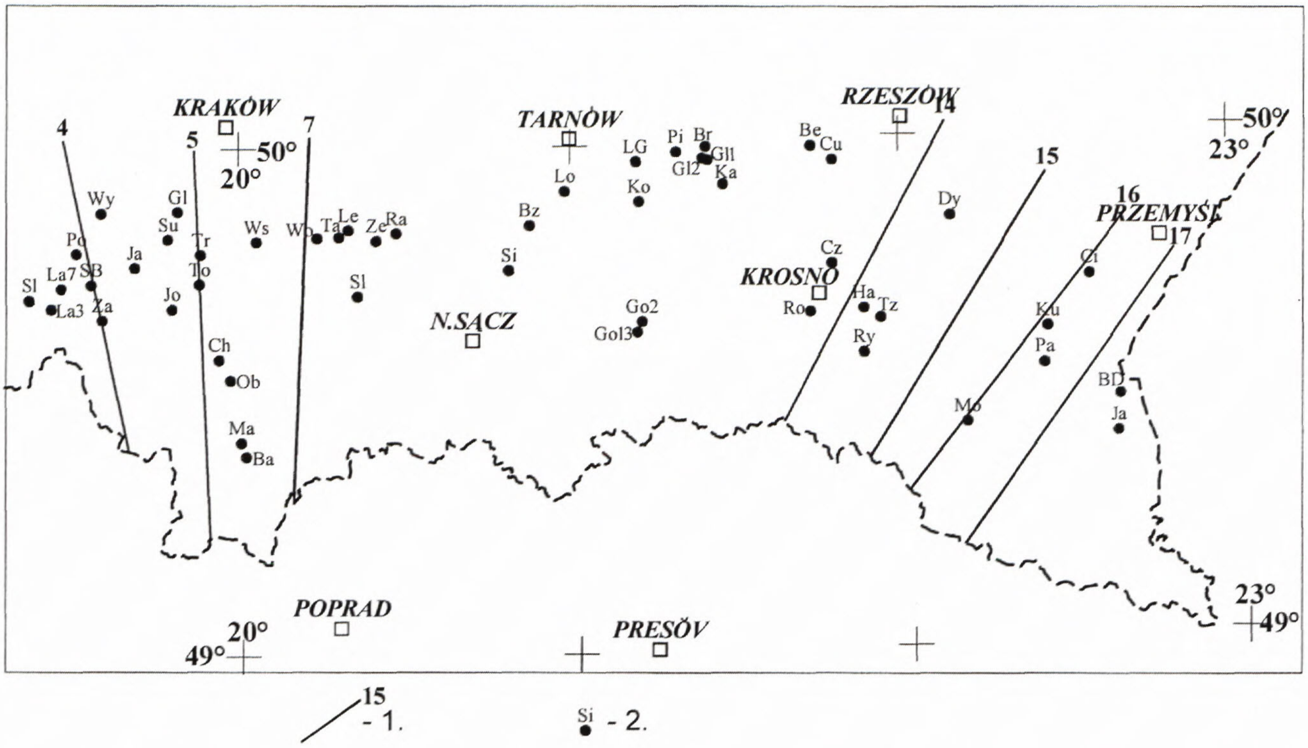

Fig. 1 Location of magnetotelluric soundings profiles (MTS) and boreholes. 1-MTS profile and its number, 2-borehole and its abbreviated name

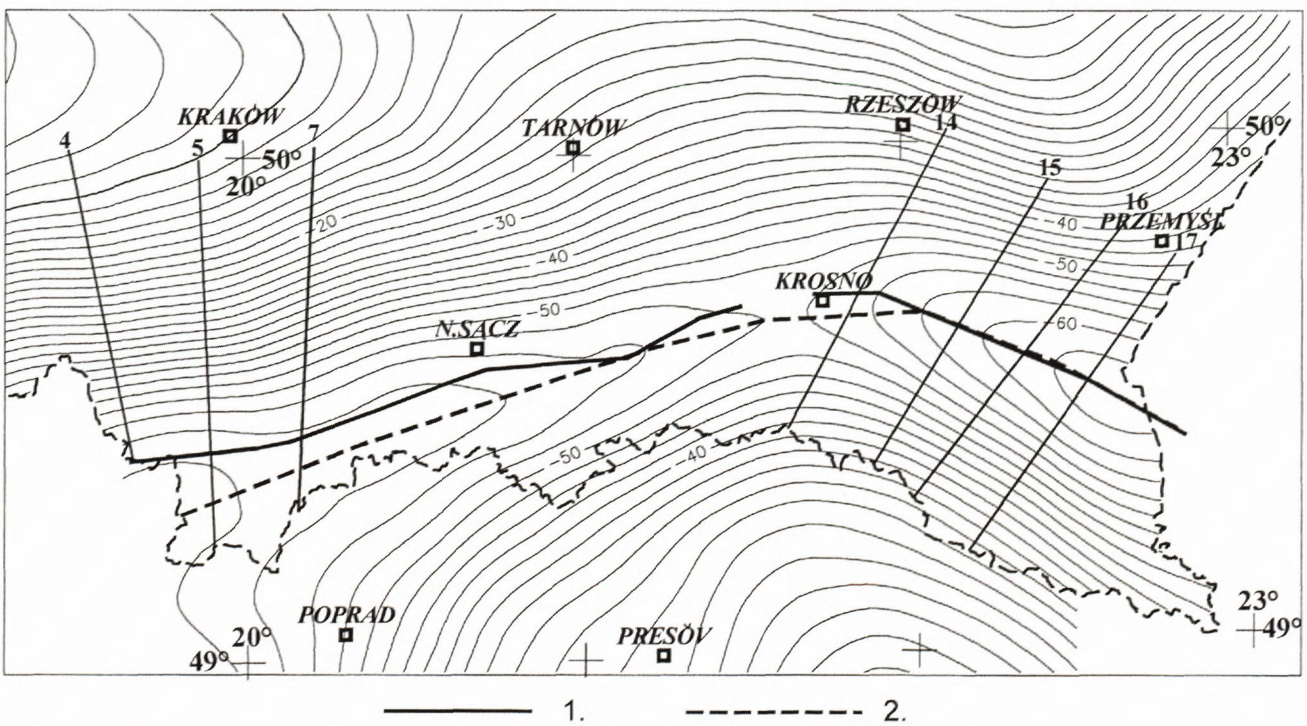

Fig. 2 Gravity minimum axes at the background of the regional anomalies. 1-shallow axis, 2-deep axis; isolines in mGal (10 μms^{-2}); other explanations in fig. 1

Klippen Belt (PPS) built of Jurassic and Cretaceous rocks and exhibiting a fairly complex tectonic structure. According to MT soundings the PPS unit reaches down to the depth of about 10 km and is distinctive by its structure and electrical properties. North of the PPS unit the Magura and Silesia Units occur belonging to the Carpathian Flysch.

The eastern segment

Approximately NE of the Rzeszów- Ustrzyki Dln. line, directly beneath the Tertiary, the crystalline basement occurs built of metamorphozed Baikalian flysch (Geological Atlas....1988-1989). These folded formations belong to the Małopolska massif extending south as far as Dobrudja. Its Fore-Carpathian segment, being a part of the Middle Polish Anticlinorium, elevated at the close of the Cretaceous, is called the San elevation. Due to erosional processes it is devoid of Palaeozoic-Mesozoic sediments. SW of the line mentioned above the massif is lowered and may be covered by Palaeozoic and Mesozoic formations.

Compared with the sediments of the Carpathian Foredeep the sub-flysch Miocene formations show smaller thicknesses. If the Neogene formations of the foreland reach up to 3000 m, they do not exceed 1000 m below the Carpathians (505 m in the Ku 1 hole).

Going from the north the following nappes rest upon the autochtonous basement: Stebnik, Skole, Sub-Silesia, Silesia, Dukla and Magura. The latter enters the Polish territory only west of the Dukla pass.

Previous geophysical knowledge

Up till now deep seismic soundings have been completed on two profiles in the Polish part of the Western Carpathians: profile V (Carpathian) and profile LT-3. According to A. Guterch, the former - also running through Slovakia - is now only of historical value. The latter, whose southern segment runs through the western part of the Polish Carpathians and shot almost 20 years ago shows along the Carpathian segment a very generalized structure of the crust without velocity data (Guterch et al., 1986).

The magnetotelluric surveys have been completed in the seventies and eighties to recognize the deep flysch complexes and their immediate basement. The measuring methods, results and their geological interpretation have been described in detail in numerous reports and publications (among others Ryłko & Tomaś, 1995; Żytko, 1997). The main outcome of this survey was the definition of the top relief of the highly resistant basement related to the so called consolidated Carpathian basement.

The geomagnetic (GM) surveys were conducted by the Institute of Geophysics, Polish Academy of Sciences in the Polish, Slovak and Czech Carpathians. According to the GM and MTS data a body of high conductivity (Carpathian anomaly) was identified in the Carpathians. Its top occurs at the depth of 12 km on the average, its axis approaches the Pieniny Klippen belt and its margin in the Inner Carpathians coincides with the zone of young volcanism evidence (Jankowski et al., 1984, 1991; Żytko, 1997).

The gravimetric survey in the Polish Carpathians is semidetailed, the density of the measuring points being 4 per km^2. The gravimetric pattern of the Carpathians, and of the western part of the Polish Carpathians in particular, was repeatedly transformed and interpreted for various purposes. The gravity modelling described by Bojdys and Lemberger (1986) and Bojdys et al. (1983) revealed a deep rooting of the Polish Carpathians (Cracow-Zakopane profile) inferred from line GSS V while the pattern of gravity anomalies is explained by the changes of Moho depth.

Two vast positive anomalies are clearly visible in the magnetic pattern of the Carpathians: the Jordanów anomaly elongated towards the south and the Nowy Sącz anomaly showing three maxima. Both anomalies have their sources in the crystalline basement. In addition minor magnetic anomalies of amplitudes up to several tens of nT occur in the western part of the Carpathians.

Characteristics and analysis of the gravity field anomalies

The gravity minimum of the Carpathians

The regional Bouguer anomaly in the Polish Carpathians (Królikowski & Petecki, 1995) is part of a vast gravity depression extending, with varying intensity, from Vienna through the Western, Eastern and Southern Carpathians. The lowest gravity values for the Polish part of the Western Carpathians noted on gravity maps occur in the Chyżne area – 80 mGal and in the eastern part E of Ustrzyki Dln. – 75 mGal. These are the lowest gravity values known from the Polish territory.

If the origin of the gravity minimum is related to the structure of the crust and lower lithosphere in their geotectonic evolution, the regional anomalies seem to be more suitable for tracing the run of the minimum. In Fig. 2 are shown two minimum axes against the background of regional anomalies. The first, marked with the solid line, refers to the Bouger anomaly with varying density reduction, the other (broken line) was obtained from regional anomalies with smoothing radius equaling 20 km. In the western part of the Carpathians the „deeper" minimum is shifted considerably towards the south in relation to the „shallower" minimum. This could be explained by the lowering of the crustal structures towards the south.

On the map showing the regional anomalies (20 km radius) the Carpathians are clearly divided into two segments: the eastern one with the minimum in the Ustrzyki Dolne area and the western with the minimum in the Chyżne area. The axes of these anomalies intersect at about 120^o in the Jedlicze village (W of Krosno). The anomaly of the eastern segment is an extention of the deep anomaly of the Eastern Carpathians and its axis direction coincides with the extension of the Eastern Carpathians.

All these differences indicate that the eastern segment is part of the Eastern Carpathians and the western fragment - part of the Western Carpathians.

The gravity discontinuities

Two types of gravity discontinuities have been defined (Fig. 3) using a 1 x 1 km grid of interpolated values on the basis of Bouguer anomalies in the measuring points. Subsequently by smoothing with 5 and 20 km radii

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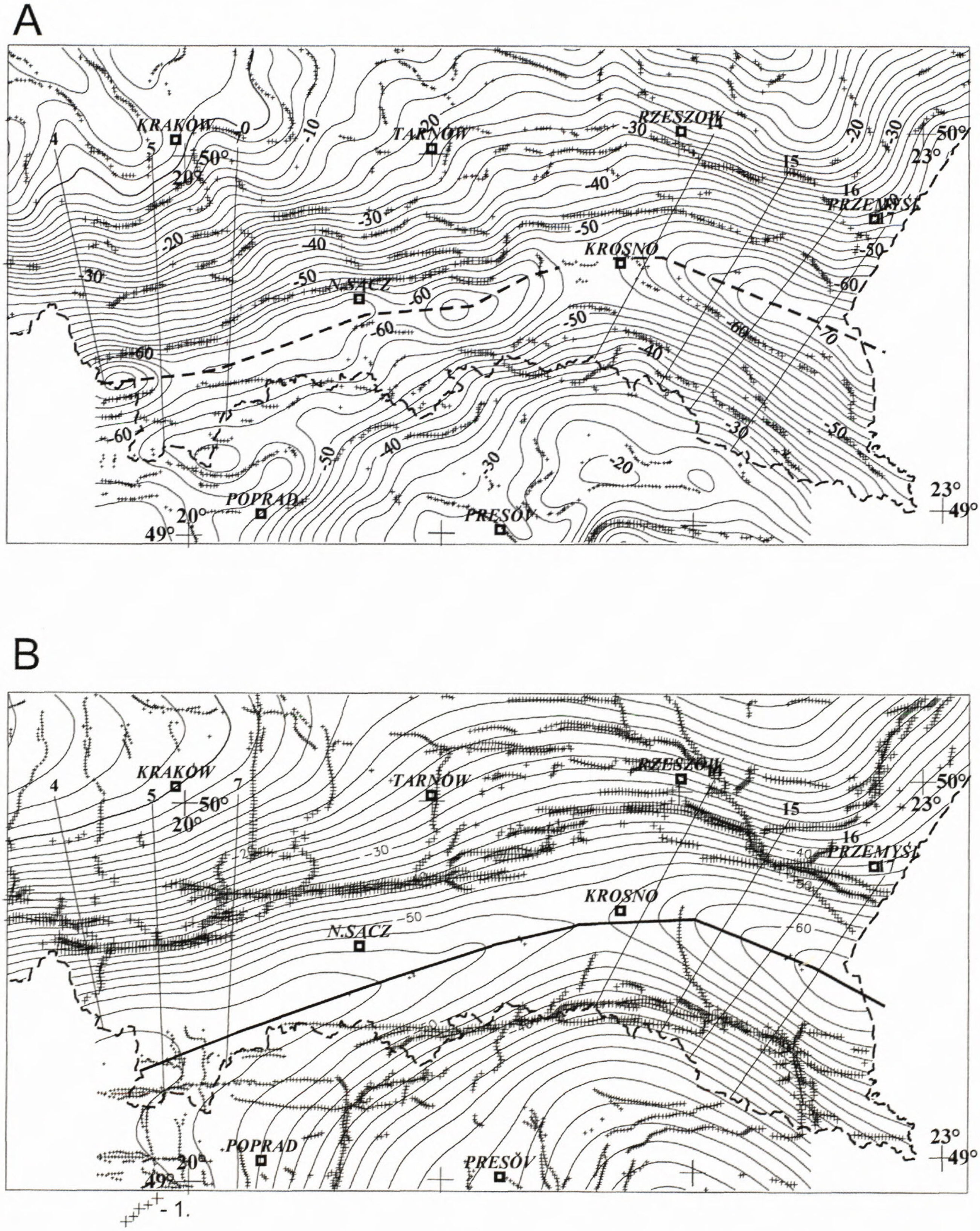

Fig. 3 Trends of gravity discontinuities. a) shallow zone, b) deep zone; 1-gradient axis (maxima of the horizontal gradient modulus); other explanations in fig. 1

two types of regional anomalies have been defined which served as a basis to identify the axis of the maximum horizontal gradient (Cordell et al., 1992). The first type of discontinuities refers to the shallower zone – to the depth of 5 km approximately, the other to the deeper zone – to about 20 km (upper crust).

In general, the four shallow discontinuities are parallel to the flysch structures. In some areas they form an irregular network of lines difficult to correlate. The deep discontinuities form two distinct lineaments on the southern and northern side of the gravity minimum axis. In the western segment part the discontinuity is shifted considerably to the south which could be indicative of transversal discontinuities in this region.

Over the majority of the Polish Carpathian area the former type of discontinuities is distinctive of the flysch, the latter most probably of deep fractures in the crust. Noteworthy is that no transversal discontinuity has been identified which could be interpreted as a boundary between the western and eastern fragment.

Density distribution

The data is derived from two sources: well-logging (85 %) and laboratory tests on drilling cores. The 24 wells were in the vicinity of lines 4, 5 and 7 and 14 wells in the vicinity of lines in the eastern segment. In all boreholes the density of flysch has been defined and has been found to vary considerable with depth and area. The average density in both segments is 2.49 g/cm^3. The definitions of the sub-flysch formations were markedly fewer and mainly for the western segment. The average densities (in g/cm^3) for the sub-flysch formations are as follows:

Autochtonous Miocene –2.55,
Jurassic – 2.52,
Triassic – 2.57,
Carboniferous – 2.54,
Devonian – 2.71,
Cambrian – 2.61,
Precambrian – 2.68.

Constructing the structural and density model of the crystalline basement it has been assumed that in layers or blocks of higher conductivity the density is slightly lower than in surrounding blocks. The reduced resistivity of the rocks can be due to:

- A higher content of minerals of high electron conductivity,
- The presence of mineralized water,
- Partial melting of rocks (at bigger depth).

In the first case density depends on the kind of mineral: heavier ores increase the rock density while with the presence of lighter minerals (for example graphite) the rock density decreases. Both mineralized water and partial melting are responsible for density reduction.

The seismic data for the cystalline basement of the Polish Carpathians which could serve to define densities are lacking. In analogy to the structural models for the Slovak and Czech area (Bezak et al., 1997) and in accordance with the electric sections a bi-layer structure of the crust has been assumed and densities 2.70 –2.75 and 2.90 –2.95 g/cm^3 have been ascribed to the upper and lower layer respectively. The boundary between these layers is not always expressed on the electric sections. It has been defined roughly on the basis of data from the Slovak part of the Carpathians and from the Eastern Carpathians (Kutas et al., 1996). The density changes with depth have been assumed rather than lateral changes resulting from resistivity changes.

Structure and properties of the crust on the basis of magnetotelluric and gravity modelling

The magnetotelluric field and gravity field data served for modelling based on successive approximation. The geoelectric section compiled from MTS data (version I) has been analyzed with respect to gravity anomalies and transformed into version II which served for the proper gravity modelling. Further successive modifications in thickness have been necessary. After magnetotelluric control the III and final version of structural section of the crust and lower lithosphere was obtained.

The following data served to construct the section:

- Two-dimensional geoelectric sections along the profiles,
- Geological sections across the Carpathians,
- The above mentioned data on density distribution in the Carpathian flysch and its basement,
- Geological and geophysical data published in Poland and abroad.

The sections 5 and 16 presented in Figs. 4 and 5 are typical for the western and eastern segment of the Polish Carpathians respectively.

The analysis of gravity modelling on all profiles revealed certain features common for both segments but also substantial differences.

The common regularities are as follows:

- The bottom of the sedimentary formations – flysch, miocene and Mesozoic-Palaeozoic basement – is an irregular surface disrupted by structures dipping to the south, with low resistivities close to these of the flysch and with a bit decreased density; these structures occur in the gravity minimum area,
- The upper crystalline crust has a complex structure. It is cut into blocks which, in turn, consist of layers of differentiated physical parameters,
- The lower crust is relatively thin and has a simple structure. Only in the northern segments of the profiles the rocks of high resistivities and elevated densities occur,
- In addition to the above mentioned structures dipping south, wide and shallow fracture zones have been recognized reaching down to the upper mantle.

The features different in both segments are as follows:

In the western segment:

- No low-resistivity layer has been found beneath the flysch and its sedimentary basement,
- The pattern of gravity discontinuities indicates that faults transversal to the Carpathian arch occur in the crystalline basement,
- The Moho surface is smooth at the depth of 30 – 45 km and shows no evidence of rooting of the crust. The lack of rooting could be indicative of similar structure and evolution of the lithosphere between the area discussed and the Czech and Slovak part of the Western Carpathians (Tomek et al., 1989),

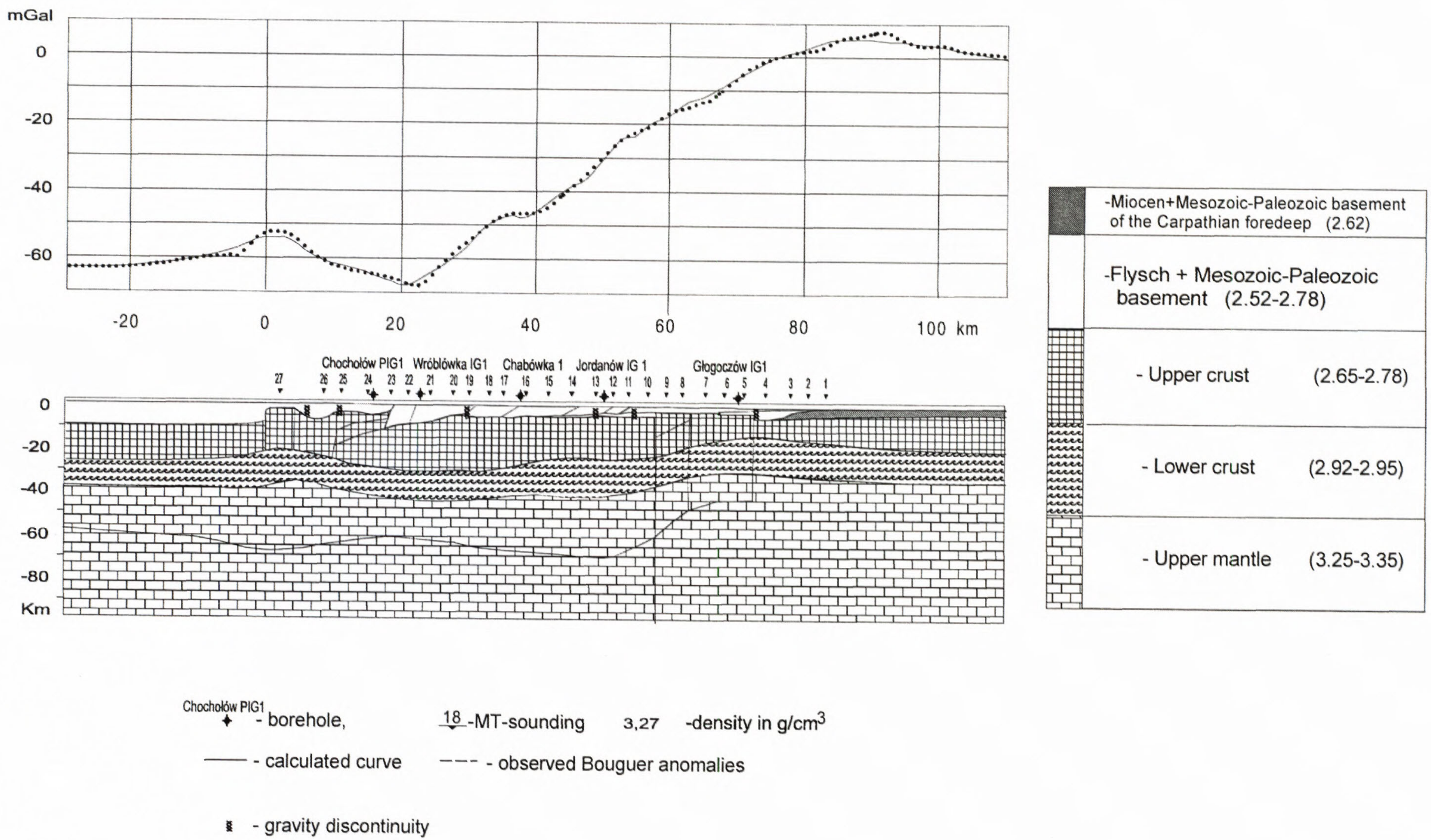

Fig. 4 Structural-density cross-section of the Carpathian lithosphere along profile 5

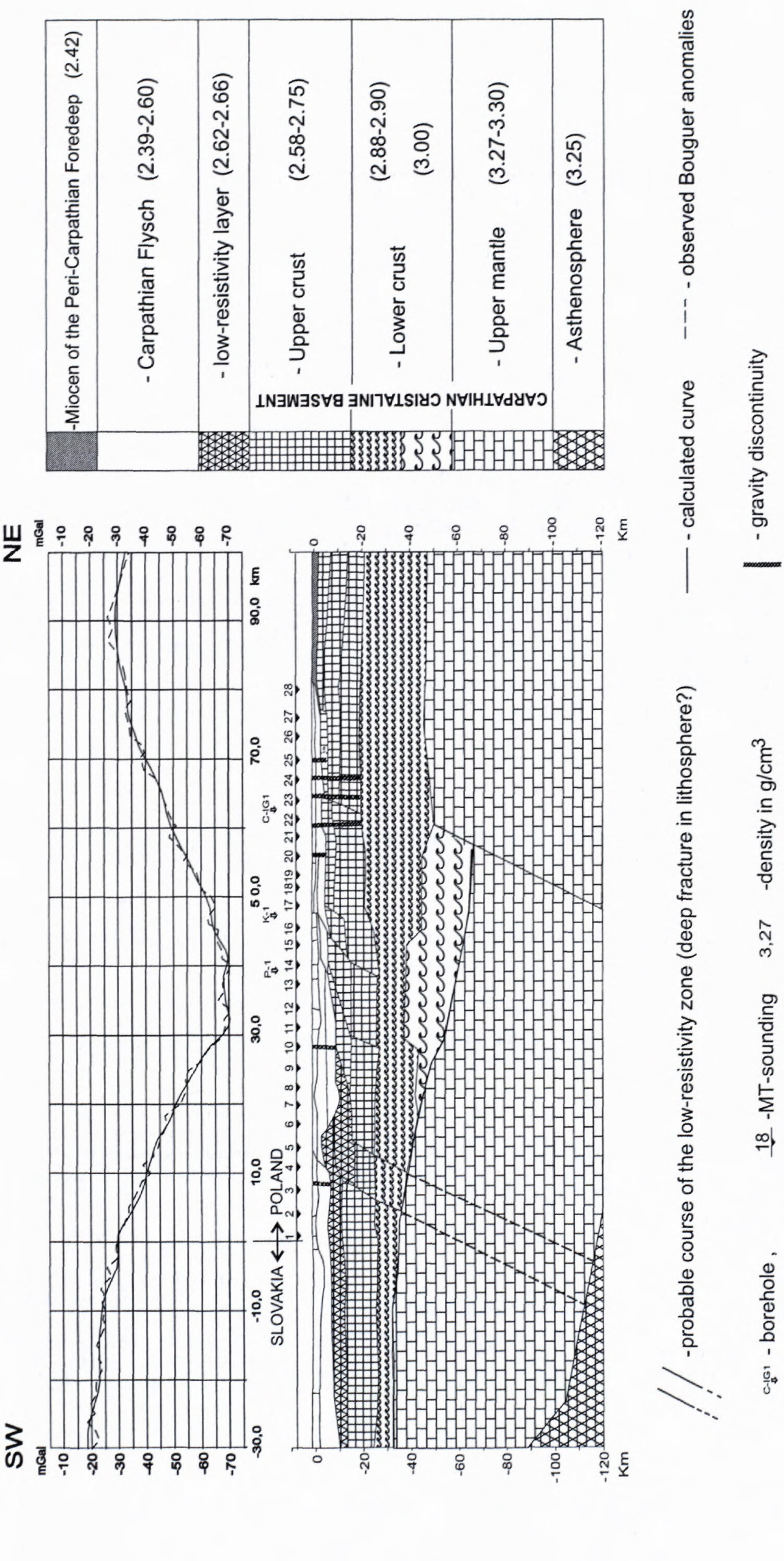

Fig. 5 Structural-density cross-section of the Carpathian lithosphere along profile 16

In the close-to-top part of the lower lithosphere, but only in the southern portions of the profiles, a low-resistivity layer of considerable thickness and reduced density occurs. This could indicate partial melting of rocks in the elevated asthenosphere and petrography different fom the underlying formations,

- The Carpathian gravity minimum is due to increased thickness of the light close-to-surface formations, increased thickness of the lighter upper crust as well as lowering of the Moho surface and density layers within the mantle.

In the eastern segment:

- Beneath the flysch and its Meso-Palaeozoic basement a fairly thick layer of low resistivity has been identified in the southern portions of the profiles. With this layer are the low-resistivity structures dipping to the south and reaching down to the upper mantle are connected,
- On the boundary between the crust and the upper mantle a low-resistivity body has been locally observed. The density value obtained from modelling indicates that this is a transition layer formed in the zone of lithosphere lowering. It is a layer, embedded in the heavier upper mantle formations that could be the source of the gravity low in this segment,
- The depth of the Moho surface is greater in the western segment (40 – 65 km).

A great number of works has been devoted to the evolution of the Carpathian Mountains. Already in the seventies the first applications of plate tectonics (a fairly new concept at that time) to explain the geodynamic evolutin of the Carpathians were attempted (Stegena et al., 1975; Ney, 1976; Sikora, 1976). Now the common opinion is that subduction of the flysch externides under the pushing orogen plate was the basic factor in the geodynamic evolution of the Western Carpathians (Kováč et al., 1997; Plašienka et al., 1997).

The structural difference of both segments of the Polish Carpathians implies a somewhat different evolution or that both segments are now in different phases. According to the interesting hypothesis by Szafián (1999) after the Miocene collision, the subducted lithospheric slab has detached and plunged into the deeper asthenosphere and the process of separation shifted from west to east until it reached the Vrancea zone in the southern fragment of the Eastern Carpathians. Accepting this hypothesis we can assume that the smooth morphology of the Moho zone in the western segment indicates the termination of this process, while it continues in the eastern segment.

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