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THREE-DIMENSIONAL GRAVITY MODELLING OF EARTH'S CRUST AND UPPER MANTLE IN THE POLISH CARPATHIANS

Grzegorz Bojdys & Marek Lemberger

Międzyresortowy Instytut Geofizyki, Akademia Górniczo-Hutnicza, al. Mickiewicza 30, 30-059 Kraków, Poland

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Abstract: Gravity and other geophysical data suggest that a fragment of oceanic crust is preserved under the eastern part of the Polish Carpathians. Results of gravity modelling are well compatible with the concept of southward subduction of the northern lithospheric plate. Several linear and areal tectonic elements are identified and three-dimensional density model of the crust and upper mantle is presented for the area of the Polish Carpathians.

Key words: gravity modelling, crust, upper mantle, Polish Carpathians.

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INTRODUCTION

Results of two-dimensional gravity modelling of the Earth's crust and upper mantle along two profiles crossing the Polish Carpathians were presented by the authors in earlier papers (Bojdys *et al.*, 1983; Bojdys & Lemberger, in press b). The results of the two-dimensional modelling, after small correction of the earlier results, were extended into a three-dimensional model. The presentation of the model is preceded by general considerations regarding the nature of the crust beneath the Polish Carpathians.

GENERAL REMARKS ON THE NATURE OF THE CRUST AND UPPER MANTLE IN THE CARPATHIANS

The two-dimensional modelling along the Kraków–Zakopane profile (Bojdys *et al.*, 1983) and the Baligród–Radymno profile (Bojdys & Lemberger, in press b) was based mainly on gravity surveys but also on results of deep seismic soundings, magneto-telluric soundings, refraction seismics, density data, and geological information. The resultant curves of gravity effect fit the Δg_B variations measured along the profiles well enough to accept the models.

The structure of the crystalline part of the crust was approximated as consisting of two layers: the upper one of density 2.7 g/cm^3 (called "granitic layer"), and the lower of density 2.9 g/cm^3 (called "basaltic layer"). The main conclusions stemming from the two-dimensional modelling are listed below:

1) Mean density of sedimentary rocks is 2.63 g/cm^3 as was calculated for the Kraków—Zakopane profile and confirmed during the modelling of the sedimentary rocks along the Baligród—Radymno profile (Bojdys & Lemberger, in press a) accordingly with the geological cross-section by K. Żytko (in: Młynarski *et al.*, 1982).

2) Density of the upper mantle decreases southwards from 3.3 g/cm^3 in the north to 3.21 g/cm^3 in the south, due to the underthrusting of the northern plate beneath the southern one in the zone of the Peripienine lineament (*cf.* Bojdys *et al.*, 1983).

3) Crystalline part of the crust is of density 2.9 g/cm^3 throughout its thickness, close to the Baligród—Radymno profile, and this suggests the oceanic nature of this crust and so it is reffered to in the sequel.

4) In the area where the crust is of oceanic nature, the top of the crystalline basement is lowered to the depth between 10 and 20 kilometres and the resultant depression is filled to the depth of 5—10 km with metamorphosed sedimentary rocks of density 2.7 g/cm^3 and of very high electric conductivity in their lower part.

5) The Carpathian gravity depression is due to several superimposed factors and its main source should be in the relief of deep phase boundaries.

6) A deep-seated tectonic fracture runs submeridionally near Nowy Sącz and Krynica (*cf.* Bojdys *et al.*, 1983, fig. 5).

The concepts of plate tectonics have been repeatedly employed to explain the origin of the flysch Carpathians. Many authors postulated a Tertiary subduction zone along the Pieniny Klippen Belt (e.g. Dewey & Bird, 1970; Ney, 1976; Kisłow & Połtowicz, 1976; Książkiewicz, 1977; Sikora, 1976). Prevailing was the concept of oceanic part of the Eurasian plate being subducted beneath the sialic plate of the Inner Carpathians (e.g. Birkenmajer, 1976; Boccaletti *et al.*, 1974; Ney, 1976; Sikora, 1976; Tokarski, 1980). The opposite sense of subduction was suggested by Książkiewicz (1977) who accepted the possibility that the oceanic crust of the Mecsek trench area was underthrusting as far as the flysch basin of the Outer Carpathians. A similar oppinion was accepted by Pospišil (Ádám & Pospišil, 1984). Książkiewicz (1977) and Ney (1976) accepted also the possibility of underthrusting of one sialic block by another, i.e. the kind of subduction postulated by Amstutz (1955).

The results of the authors' modelling conform the opinions on the role of subduction in the Carpathian orogeny. The considerations on the density distribution in the crust (Bojdys *et al.*, 1983) speak in favour of the southerly directed subduction. The results of modelling along the Baligród—Radymno profile suggest also that oceanic crust was present in the underthrusted northern plate. The analogies existing between the results of magneto-telluric soundings and refraction seismics along the Baligród—Radymno profile and the Vth International Deep Seismic Sounding (DSS) Profile (Sollogub, 1978) permit suggestion that also in the latter profile an oceanic crustal fragment is present, albeit it is more restricted in size. Additional modelling of the crust was made along the profiles Jaśliska—Błażowa and Jaśliska—Mielec (location in Fig. 1). The same assumptions on density contrasts and on the

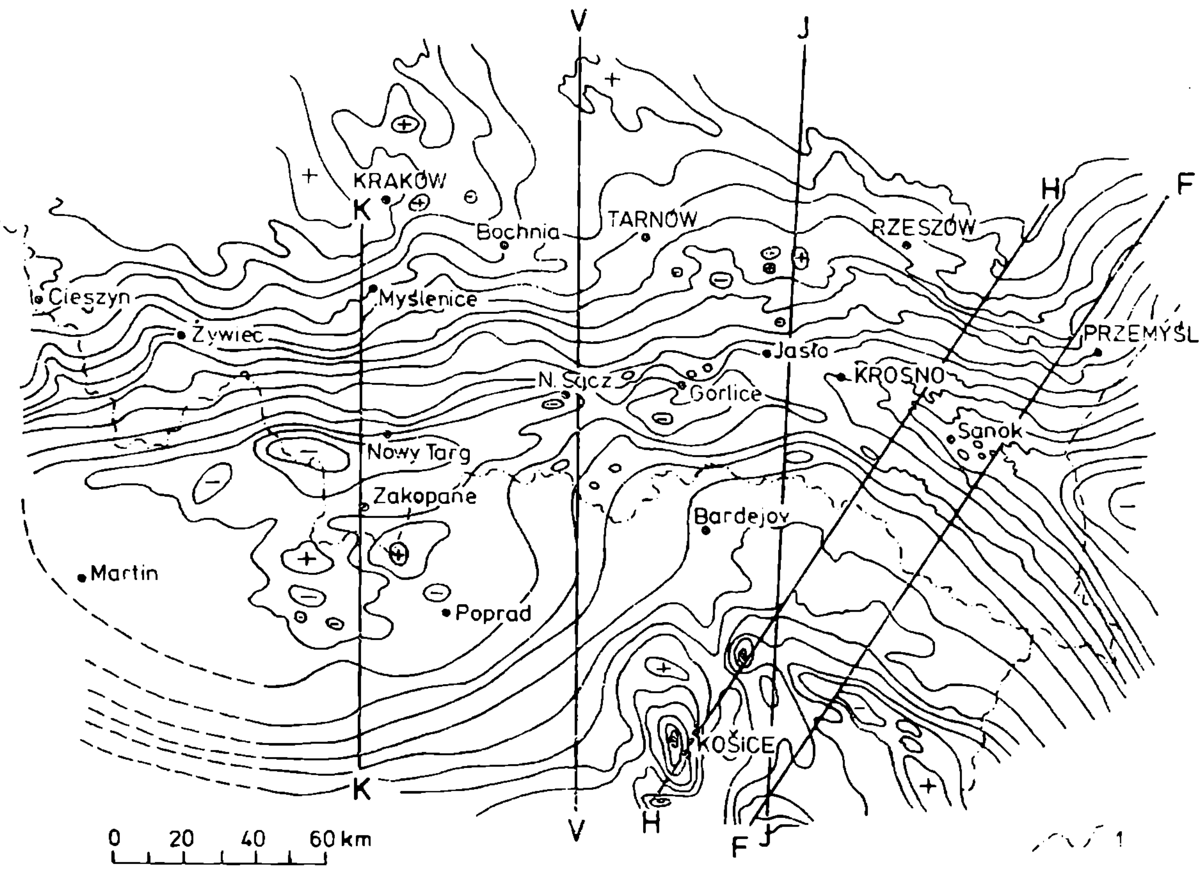

Fig. 1. Map of gravity anomaly after Jamrozik (1965) and Bednař *et al.* (1980). Contour distance 5 milligals. *V—V* — Vth International DSS Profile; *F—F* — Baligród—Radymno profile; *H—H* — Jaśliska—Błażowa profile; *J—J* — Jaśliska—Mielec profile; *K—K* — Kraków—Zakopane profile; *1* — state boundary

general structure of the crust and upper mantle were accepted in order to test the validity of the extrapolation of the results of modelling along the Baligród—Radymno profile as far as the Vth International DSS Profile. The calculated gravity effects of the additional models fit the curves of the measured Δg_B variations (Figs 2 and 3). This corroborates the assumption that the general outline of crustal structure in the vicinity of the additional profiles is the same as along the Baligród—Radymno profile.

The crust of oceanic type beneath the flysch basin was assumed by Rădulescu & Săndulescu (1973) and by Sikora (1976). Especially worth of mention in the context of the results of crustal modelling is the thesis forwarded *int. al.* by Dolenko & Danilović (1976) that the zone of high electric conductivity corresponds to the termination of oceanic crust beneath the flysch basin. Many authors assume that the deposits of the Pieniny Klippen Belt were laid down on oceanic crust (Dewey *et al.*, 1973; Rădulescu & Săndulescu, 1973; Ney, 1976; Grubić, 1974). The opinions diverge, however, on this subject, and Książkiewicz (1977) casts doubts on the oceanic

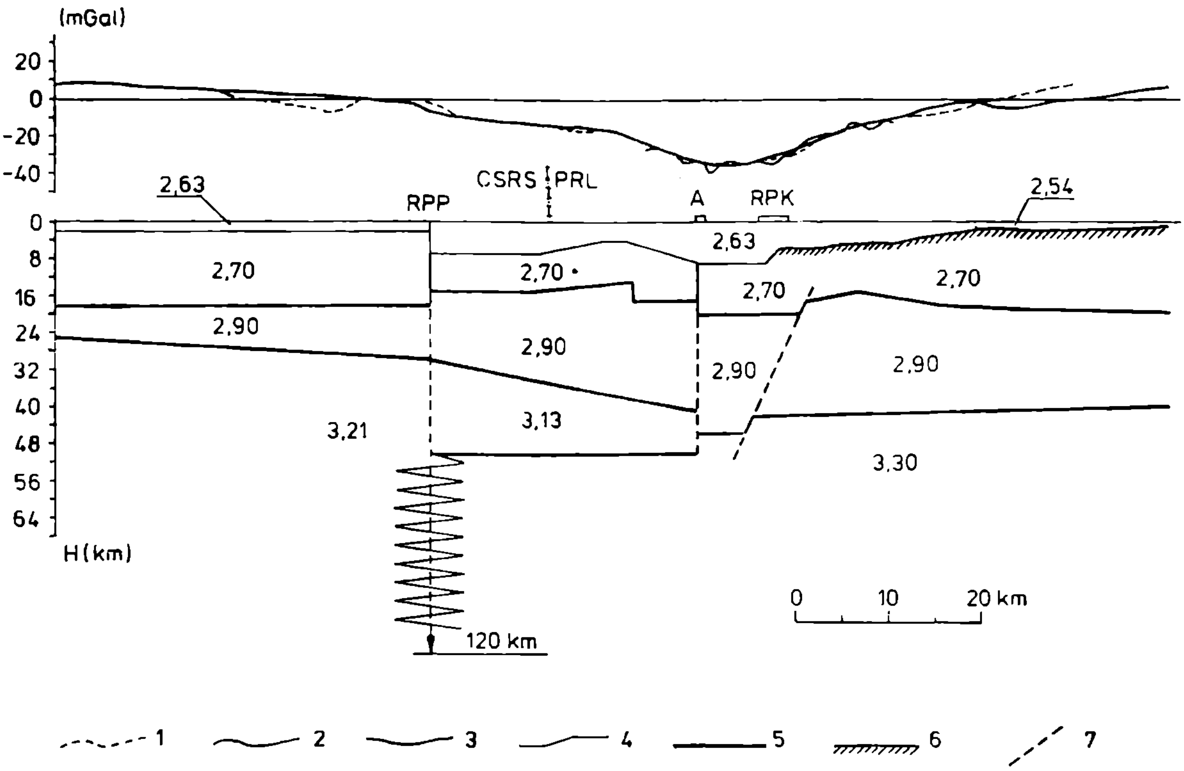

Fig. 2. Model of crust and upper mantle along Jaśliska—Błażowa profile. *1* — curve of observed Δg_B anomaly after regional map by Jamrozik (1965); *2* — curve of observed Δg_B anomaly after regional survey by Maryniak (1951); *3* — curve of gravity effect of the model; *4* — top of sedimentary rocks of density 2.7 g/cm^3; *5* — other density boundaries; *6* — top of crystalline basement after seismic refraction and magnetotelluric soundings; *7* — discontinuity (fracture?) zones in the crust; *RPP* — Peripienine fracture, *RPK* — Pericarpathian fracture. Zig-zag line is the graphic representation of horizontal density gradient in upper mantle

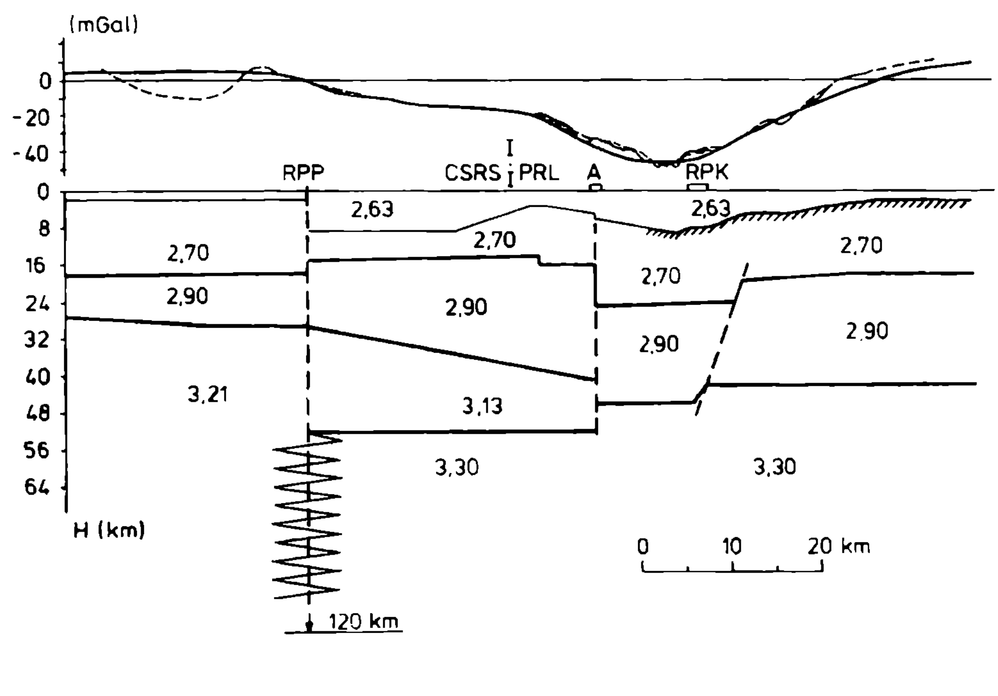

Fig. 3. Model of crust and upper mantle along Jaśliska—Mielec profile. Explanations in Fig. 2

crust in the outer part of the Carpathians. He bases his opinion on the concepts of Hertz & Savu (1974) who proposed the origin of the oceanic crust by spreading within the Inner Carpathians, between the Moldavian platform and Pannonia.

The discussion presented above demonstrates that the results of gravity modelling agree with many geological concepts and in consequence some remarks on crustal and upper mantle structure in the Polish Carpathians are proposed, taking into account the informations obtained from the models (Bojdys & Lemberger, 1983, in press a, b).

The most important tectonic zones, expressed at Moho, are (Fig. 4): (1) the Peripienine fracture zone of Sikora (1976), (2) the W—W and B—B zones of Bojdys

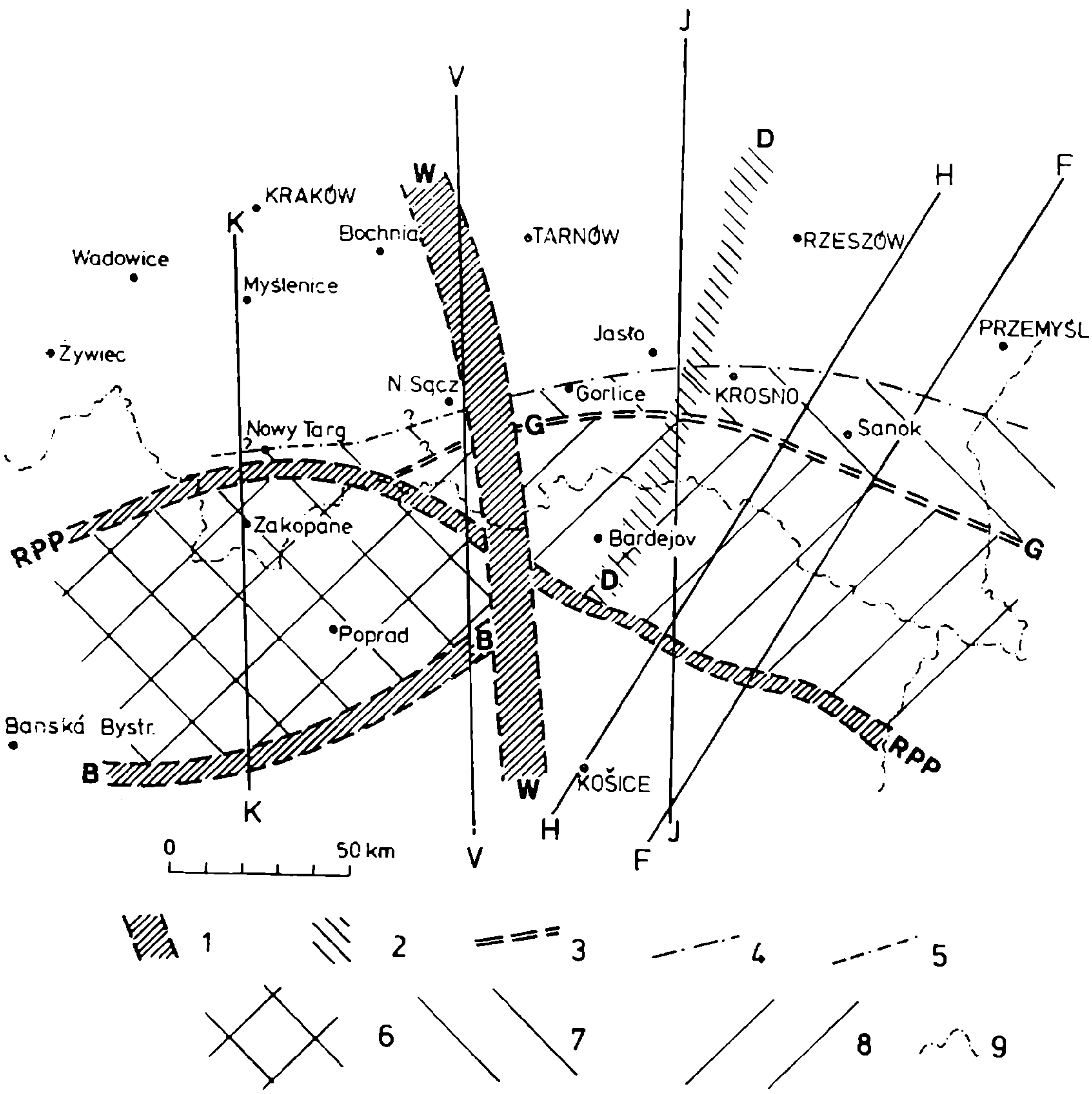

Fig. 4. Tectonic sketch-map of crustal structure in Polish Carpathians. *1* — fracture zones (*RPP* — Peripienine fracture zone); *2* — probable tectonic zones; *3* — *G—G* line — northern boundary of the oceanic crustal fragment in the northern plate; *4* — northern boundary of the lowered fragment of Earth crust; *5* — inferred northern boundary of the lowered fragment of Earth crust; *6* — area of thickened crust in southern plate; *7* — lowered crustal fragment; *8* — area of oceanic crustal fragment in northern plate; *9* — state boundary. *V—V* — Vth International DSS Profile, *F—F* — Baligród—Radymno profile, *H—H* — Jaśliska—Błażowa profile. Profile symbols as in Fig. 1

et al., (1983), (3) the hypothetical D—D zone inferred from contour shapes on Bouger anomaly map.

The most important structural element seems to be the crustal fragment having oceanic characteristics, mentioned above, together with the areally related to it transitional complex between the crust and upper mantle — the zone of phase transitions (shown as having density 3.13 g/cm^3 in Figs 2 and 3; cf. Bojdys & Lemberger, in press b).

The results of modelling along the profiles Baligród—Radymno (Bojdys & Lemberger, in press b), Jaśliska—Błażowa (Fig. 2) and Jaśliska—Mielec (Fig. 3), the results of deep seismic soundings along the IIIrd International DSS Profile (Sollogub, 1978; Bojdys & Lemberger, in press b), and the results of magnetotelluric soundings along the profile F and the Vth International DSS Profile (Pawliszyn—Święcicka, 1980), all permit to draw some conclusions regarding the oceanic crustal fragment beneath the Outer Carpathians:

1 — the zone A^{II}—A^{III}—A^{IV}—A^{I} (line G—G in Fig. 4) is the northern boundary of the oceanic crustal fragment,

2 — the crustal fragment of this type extends between the line G—G and the Peripienine fracture zone,

3 — this crustal fragment extends farther eastwards than the IIIrd International DSS Profile;

4 — results of modelling along the Kraków—Zakopane profile additionally indicate that the discussed crustal fragment is already very thin between this profile and the Vth International DSS Profile, or even the continental fragments of both lithospheric plates have already directly collided with one another in this area.

As there is no information to control the course of the G—G line in Fig. 4 between the profiles we can not exclude a possibility of a rapid change in width of the discussed crustal fragment on tectonic zones D—D and W—W.

The oceanic crustal fragment is probably overlain with metamorphosed sediments of mean density about 2.7 g/cm^3 which in their top part have elastic properties close to those of the so called "granitic layer" and in their lower part have high electric conductivity.

The results of the two-dimensional modelling suggest a possible occurrence of a lowered crustal block of continental type (Fig. 4) extending along the G—G line on its northern side and marked in the Kraków—Zakopane profile by steep, southward dips of the density horizons. Farther to the north the crust is of continental type and simple structure.

The extensive gravity minimum, well visible on the Δg_B map (Fig. 1) in the area of the Tatra Mts and south of them is explained by the authors (Bojdys *et al.*, 1983) by Moho depression on the southern plate, delimited by the tectonic zones B—B, W—W and the Peripienine fracture zone.

The results of modelling indicate that north of the lowered continental crustal block Moho has a low relief and its depth varies from 38 km in the west to ca. 42 km in the east, and is 5—7 km deeper in the lowered area. Within the limits of occurrence of the oceanic crustal fragment the depth of Moho may attain ca. 54 km. Al-though the two-dimensional models are highly simplified in their parts representing the Slovak territory, it may be inferred that south of the Peripienine fracture zone Moho is at depth of 28—30 km and gently rises to the south. The exception is the southern surrounding of the Tatra Mts, where Moho is depressed to ca. 35 km, as was mentioned above.

It may be concluded that the agreement of the basic density and structural assumptions and the good correlation between the neighbouring profiles indicate that the interpretations are valid not only for the close vicinities of the modelled profiles but also for the areas between the profiles and thus permit three-dimensional modelling.

BASIC ASSUMPTIONS OF THREE-DIMENSIONAL MODEL

The three-dimensional model, just as the two-dimensional ones is a layered model defined, in general, by three density boundaries: (a) Moho, (b) the boundary between the "granitic layer" and the "basaltic layer" referred to as "Conrad surface", and (c) a surface which forms the top of the "granitic layer" — referred to as the top of the crystalline basement. It should be also remarked that the prismatic form of the model does not reflect the authors' opinion on the blocky structure of the Carpathians, but results from the prismatic mode of imaging the modelled surfaces.

The model accounts also for the horizontal density gradient in the upper mantle, following the indications from the modelling along the Jaśliska—Mielec, Jaśliska—Błażowa and Baligród—Radymno profiles. The density values accepted for separate materials are those used in the two-dimensional modelling.

The construction of the three-dimensional model was based on:

1) two-dimensional crustal models (Bojdys *et al.*, 1983; Bojdys & Lemberger, in press a, b),

2) results of interpretation of Δg_B map (Bojdys *et al.*, 1983),

3) map of the refraction horizon related to the top of consolidated basement (Przedsiębiorstwo ..., 1977),

4) tectonic sketch map of the Earth's crust in the Polish Carpathians, prepared by the authors,

5) other available geological and geophysical data, partly used in the construction of the two-dimensional models.

The following structural assumptions were considered during the construction of the model:

1) the northern plate plunges under the southern one at the Peripienine fracture zone,

2) there is a subduction-related horizontal density gradient in the upper mantle,

3) there is an oceanic crustal fragment in the eastern part of the Polish Carpathians and a zone of phase transitions in the same area (of density 3.13 g/cm^3),

4) the oceanic crust is overlain by metamorphosed sediments of mean density 2.7 g/cm^3.

Figures 5—7 show models of successive surfaces: Moho (including the horizontal

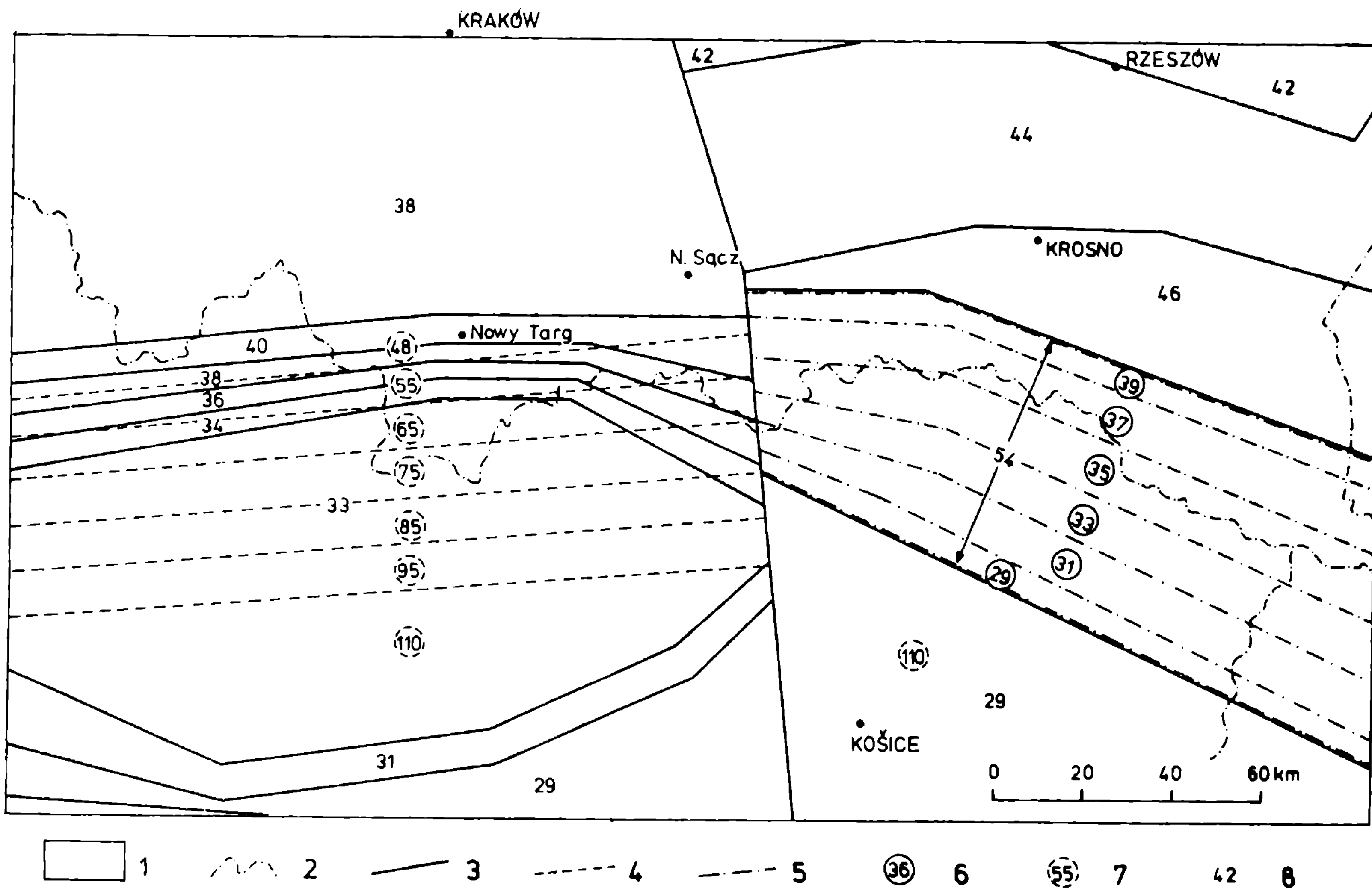

Fig. 5A. Model of Moho, upper mantle and area of phase transitions. Plane projection. *1* — boundaries of the model; *2* — state boundary; *3*—*5* — boundaries of elementary structures approximating: *3* — Moho, *4* — density gradient in upper mantle, *5* — zone of phase transitions; *6*—*8* — depths to tops of elementary structures approximating: *6* — zone of phase transitions, *7* — density gradient in upper mantle, *8* — Moho

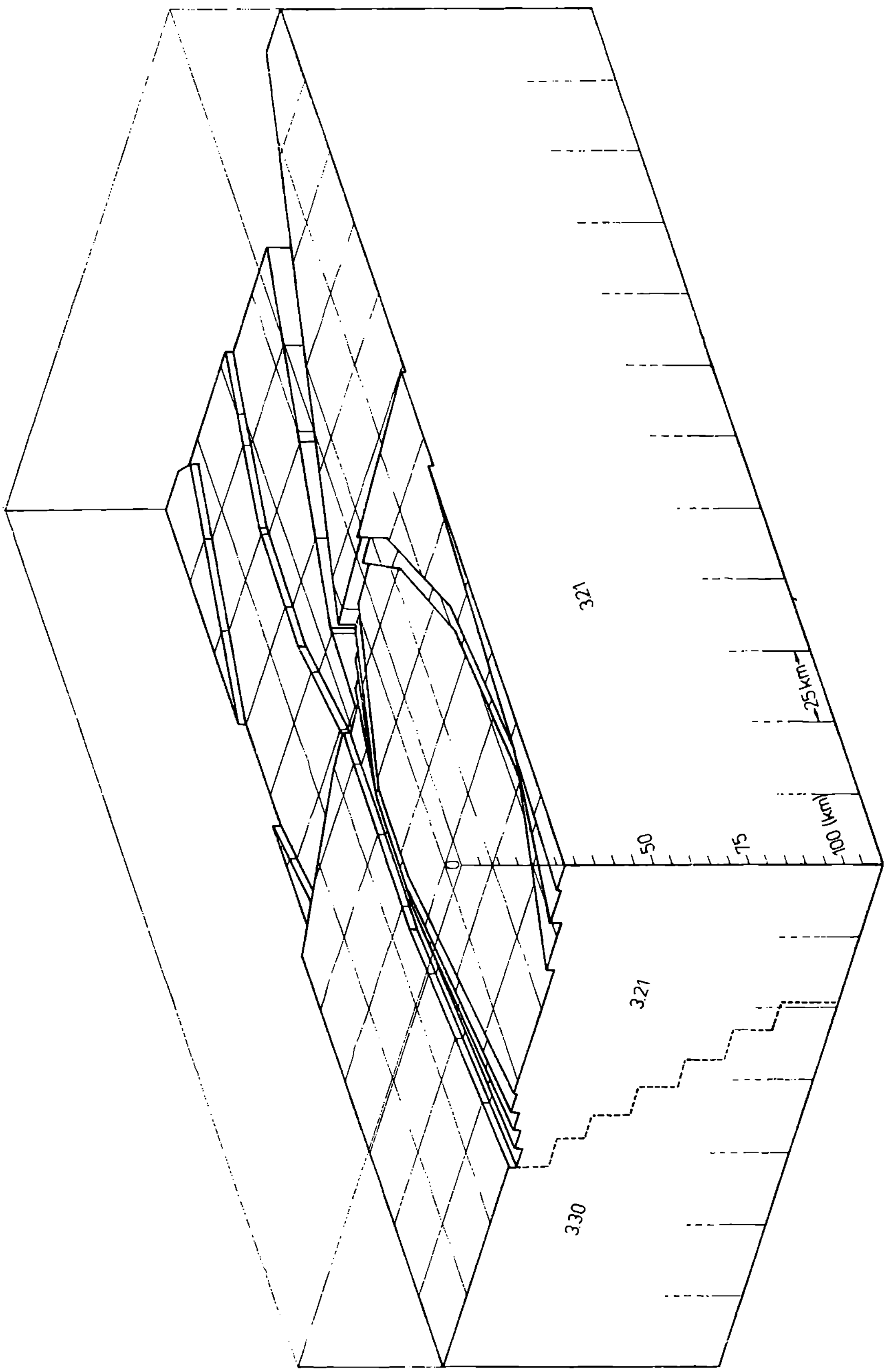

Fig. 5B. Model of Moho, upper mantle and area of phase transitions. Blockdiagram (view from SW) density gradient in the upper mantle and the zone of phase transitions; Fig. 5A, B), "Conrad surface" (Fig. 6A, B), and the top of crystalline basement (Fig. 7A, B). The latter represents the top of the metamorphosed sediments of density 2.7 g/cm^3, in the area where the oceanic crustal fragment occurs. The Peripienine fracture zone (Sikora, 1976) and the W—W zone (Bojdys *et al.*, 1983) are considered first-rank tectonic fractures crossing the whole thickness of the crust and directly reflected in the morphology of the modelled surfaces. For the lack of actual data on the inclination and sense of dip of these zones, they are considered vertical. This simplification is in agreement with the generalized nature of the model. The model represents the area of the Polish and Slovak Carpathians between the meridian of Cieszyn on the west, and that of Przemyśl on the east; between the parallel of Košice on the south and that of Kraków on the north.

MODEL OF MOHO

Model of Moho (Fig. 5A, B) is based on results of the two-dimensional modelling along the Kraków—Zakopane (Bojdys *et al.*, 1983), Baligród—Radymno (Bojdys & Lemberger, in press a, b), Jaśliska—Mielec and Jaśliska—Błażowa (Figs 2 and 3) profiles, results of interpretation of the IIIrd and Vth International DSS Profiles, regional DSS profile LT-3 (Sollogub, 1978), and interpretation of the Δg_B map in the south-western part of the studied area. The relief of Moho is poorly differentiated in the northern and the southern parts, in contrary to the central part which extends along the Pieniny Klippen Belt and widens eastward.

The earlier mentioned, approximately meridional fracture zone W—W disrupts the surface. In the area north of the Pieniny Klippen Belt and west of the W—W zone, Moho lies horizontally at a depth of ca. 38 km. Eastwards of the W—W zone Moho gradually slopes to the south and attains the depth of 46 km. This depression is bordered on the south by the G—G line, which is the northern boundary of the oceanic crustal fragment of the northern plate. Moho is about 29 km deep in the area south of the Pieniny Klippen Belt and east of the W—W zone; it is depressed down to 33 km at the southern margin of the Tatra Mts.

Interpretation of maps of regional Δg_B anomalies (Bojdys *et al.*, 1983) indicated that the depression is limited from the east by the W—W tectonic zone, from the south by the B—B zone, and it narrows and becomes shallower to the west. South of the B—B zone Moho rises to the depth of 27 km.

The depth of Moho is greatest, 54 km, in that area of the northern plate where occurs the oceanic crustal fragment, i.e. between the G—G line and the Peripienine fracture zone. In the same area there occurs a zone of phase transitions, of density 3.13 g/cm^3, delimited from beneath by Moho and from above by a surface separating it from the "basaltic layer" and equivalent to the C—M boundary (see Sollogub 1978, fig. 67). This boundary rises from the depth of 39 km near the G—G line to 29 km near the Peripienine fracture zone.

The model in Fig. 5 includes also the horizontal density gradient in the upper mantle (dashed lines) conforming the results of the two-dimensional modelling.

It should be remembered that the density boundary in the upper mantle is only a representation of the horizontal density gradient from 3.3 g/cm^3 in northern part of the model to 3.21 g/cm^3 in the southern part.

"CONRAD SURFACE"

The model of this surface (Fig. 6A, B) was constructed using the same materials as for the Moho model, supplemented with the results of magnetotelluric soundings along the profile F (Baligród—Radymno) and the Vth International DSS Profile (Pawliszyn-Święcicka, 1980). It should be stressed that the DSS data regarding the "Conrad surface" are much poorer than for Moho. The W—W tectonic zone divides the "Conrad surface" into the eastern and the western parts. North of the line running approximately through Ujsoły—Klikuszowa—Nowy Sącz, and north of the W—W zone, the "Conrad surface" is horizontal, like Moho, and lies at depth of ca. 19 km. Between the Pieniny Klippen Belt and the mentioned line, the "Conrad surface" is steeply inclined to the south and attains the depth of 25 km, and in a small area north of Zakopane even more.

The position of the "Conrad surface" is different in the area east of the W—W zone. At the northern part its depth is about 18—19 km, and south of the line Kobyle Gródek—Frysztak—Węglówka—Kormanice the depth abruptly falls to 22—25 km. The surface forms here a trench 20—40 km wide, with axis running along the line Gorlice—Krosno—Chyrów. The trench margins are steep and may be fracture--controlled. On the south the trench is bounded by the G—G line, the boundary of the oceanic crustal fragment with top at depth of 14—17 km. How the "Conrad surface" rises to this depth, depends on the nature of the contact between the oceanic and continental fragments of the plate. The northern margin of the trench is most probably a fracture zone, as is suggested by the results of interpretation of the IIIrd International DSS Profile (Sollogub, 1978) and the gravity modelling along the Baligród—Radymno (Bojdys & Lemberger, in press b), Jaśliska—Mielec and Jaśliska—Błażowa profiles (Figs 2 and 3). The oceanic crustal fragment extends westwards behind the W—W zone. Its top plunges in this direction to the depth of 25 km near Szczawnica, and farther west it is probably completely consumed in the subduction zone. Along the Peripienine fracture the depth of this surface changes in a non-uniform way. East of the W—W zone the depth increases to 18 km within the southern plate, and west of this zone the surface descends, paralleling Moho, to the depth of 23—24 km in the southern margin of the Tatra Mts, and farther south it rises again to the depth of 18 km, same as in the eastern part.

THE TOP SURFACE OF CRYSTALLINE BASEMENT

This surface, separates sedimentary rocks of mean density 2.63 g/cm^3 from material of density 2.7 g/cm^3. The model of this surface (Fig. 7A, B) is the most differentiated in morphology. The model is based on:

1) map of the horizon attributed to the top of consolidated basement (Przedsiębiorstwo ..., 1977),

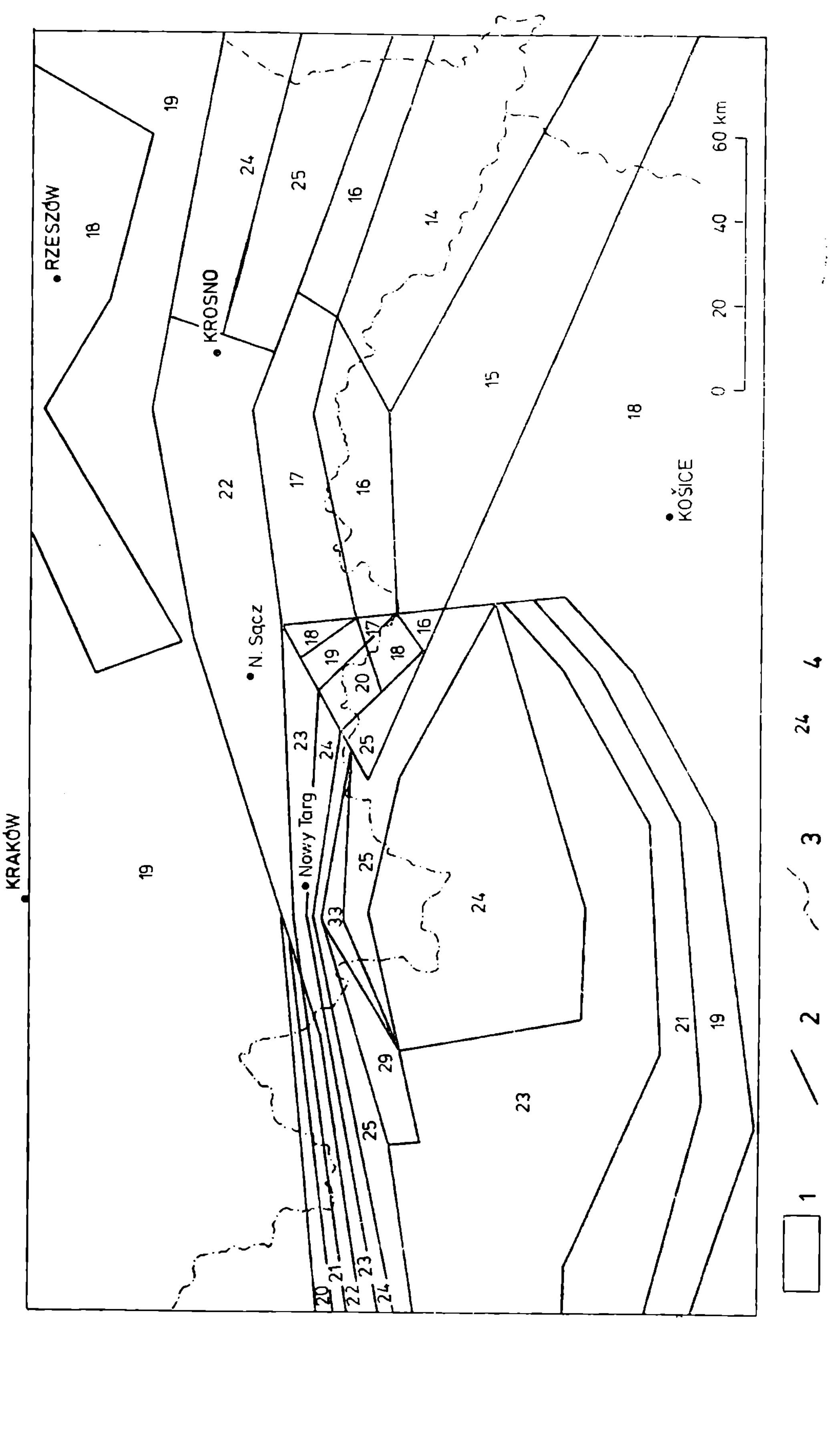

Fig. 6A. Model of "Conrad surface". Plane projection. *1* — boundaries of the model; *2* — boundaries of elementary structures approximating "Conrad surface"; *3* — state boundary; *4* — depths of elementary structures

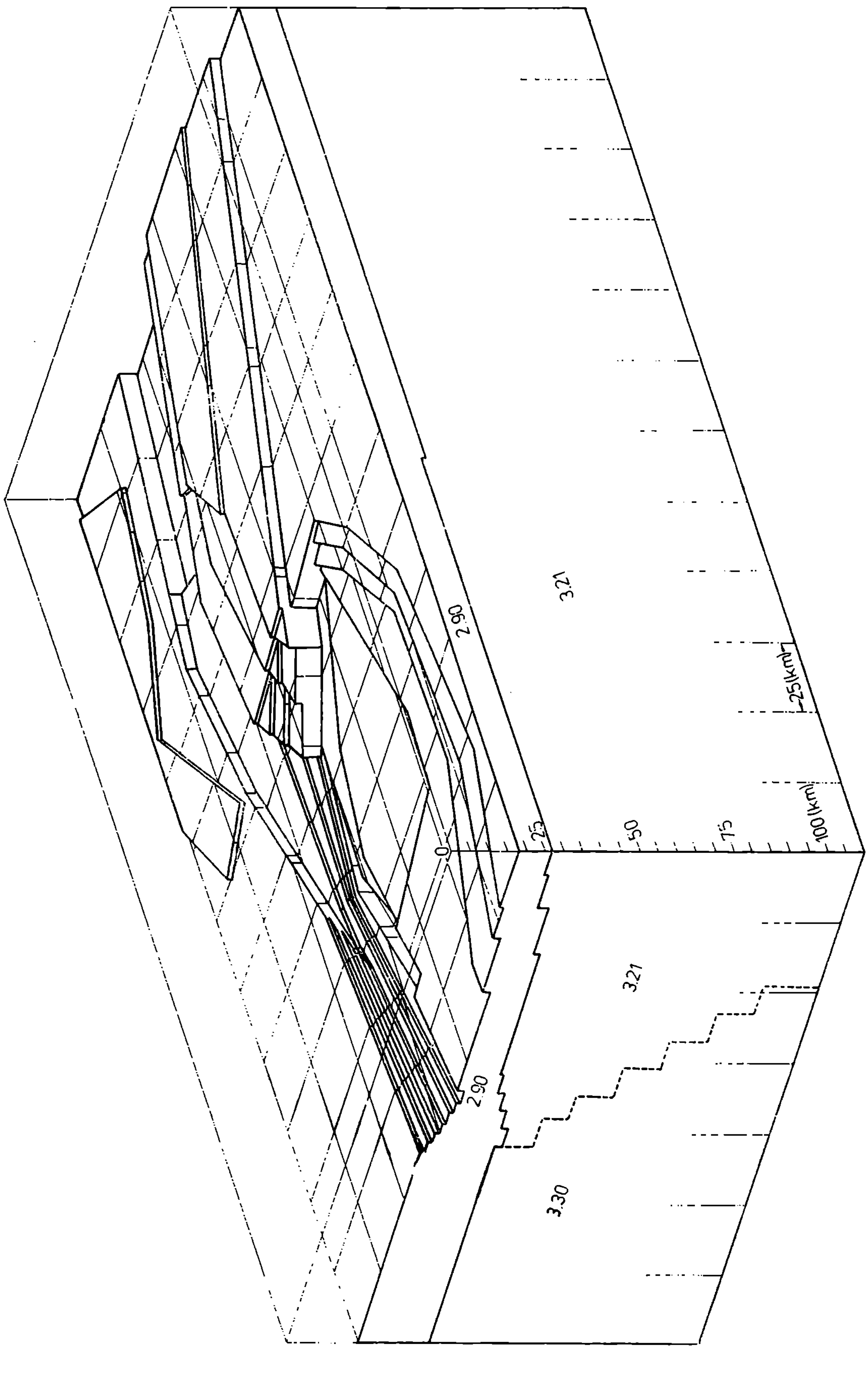

Fig. 6B. Model of "Conrad surface". Blockdiagram (view from SW)

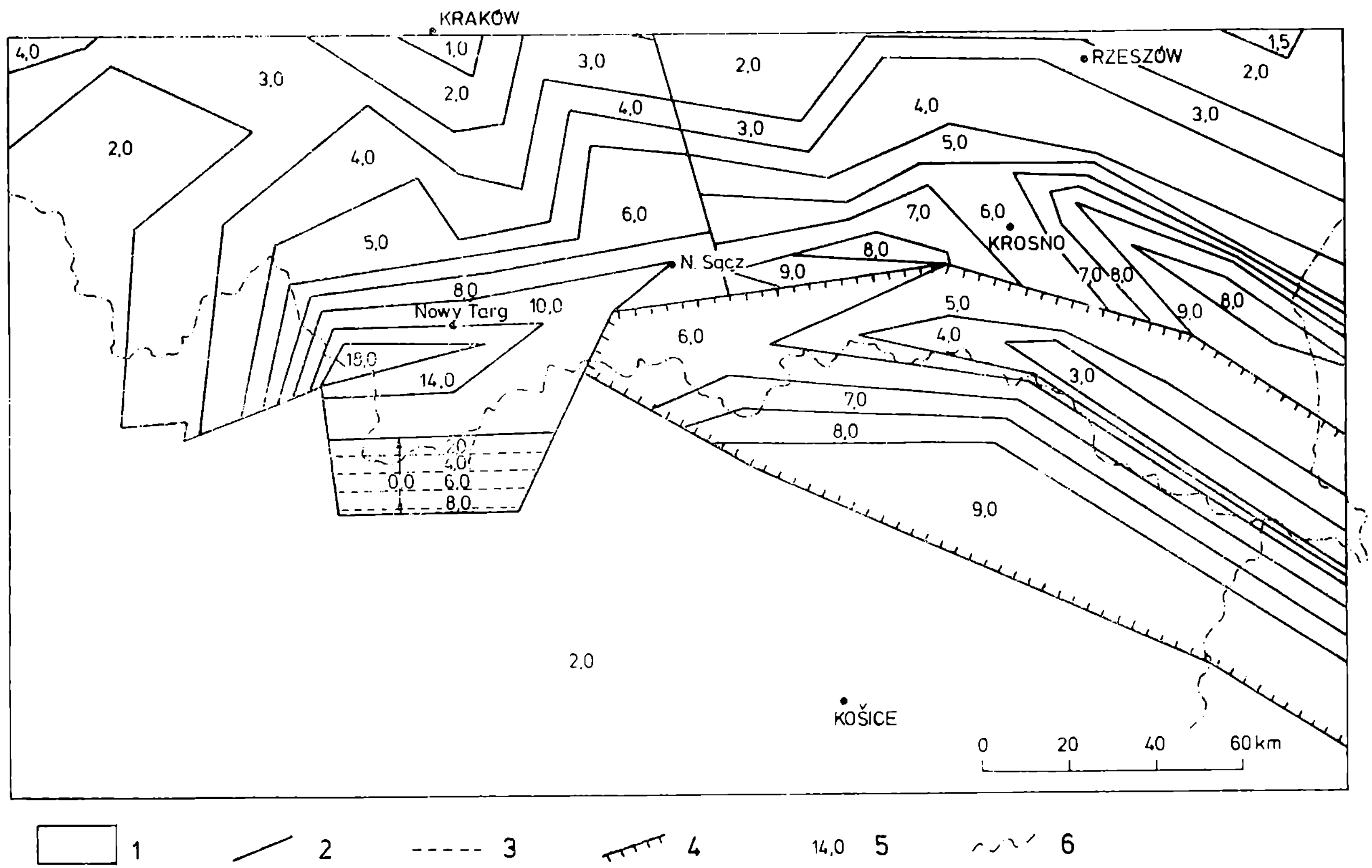

Fig. 7A. Model of the top of crystalline basement. Plane projection. *1* — boundaries of the model; *2* — boundaries of elementary structures approximating the top of crystalline basement; *3* — bottom boundaries of elementary structures approximating the top of crystalline basement; *4* — area of occurrence of sedimentary rocks of density 2.7 g/cm^3; *5* — depths to the top of crystalline basement; *6* — state boundary

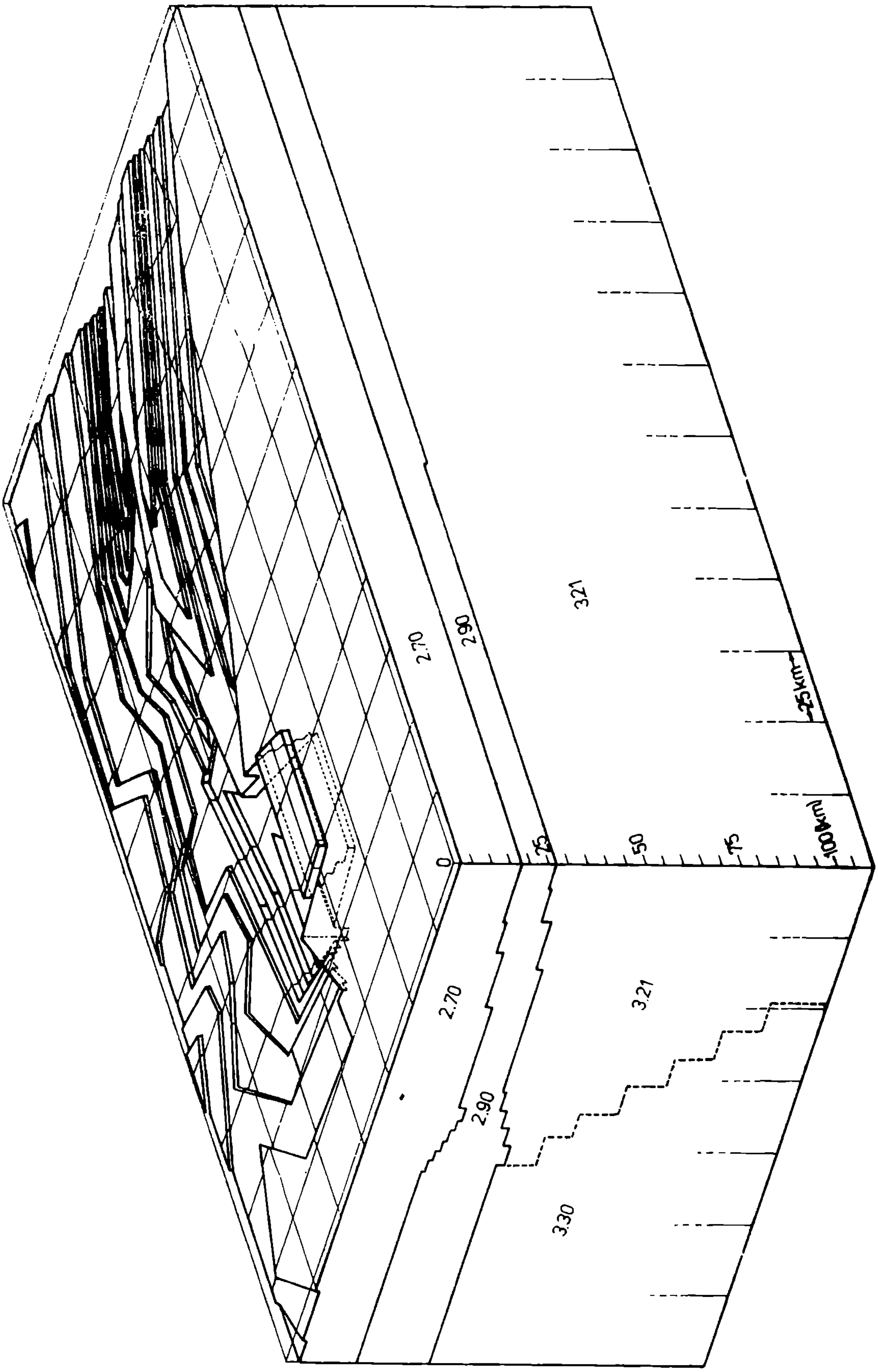

Fig. 7B. Model of the top of crystalline basement. Blockdiagram (view from SW)

2) geological cross-sections by Sikora (in: Sikora *et al.*, 1980) and Żytko (in: Młynarski *et al.*, 1982),

3) results of two-dimensional gravity modelling by the authors,

4) results of magnetotelluric soundings (Pawliszyn-Święcicka, 1980),

5) map of Δg_B anomaly in Bourger's reduction.

The Peripienine fracture zone divides the model into two fundamentally different parts. The northern part has a very differentiated relief; for the southern, lying almost entirely within the Czechoslovak territory, a two-kilometer thick layer of sedimentary rocks of density 2.63 g/cm^3 was accepted as a simplification (except for the Tatra Mts and the Podhale basin). The model of the crystalline basement top in the area of the Tatra Mts and Podhale is very schematic because of the complex geological structure in this area.

The W—W zone and the two other fracture zones reflected clearly in relief of Moho and the "Conrad surface", do not deform significantly the top of crystalline basement. West of the W—W zone in the NW part of the area covered by the model, the latter surface is gradually sinking from a few kilometres in the north to more than 10 km close to the Peripienine fracture zone. The surface is deformed by meridional undulations revealed by seismic surveying.

East of the W—W zone the modelled surface is of complicated character. In the northern part, to the G—G line on the south the model represents the top of the consolidated (crystalline?) basement. Between the line G—G and the Pieniny Klippen Belt, i.e. within the area where the hypothetical oceanic crust occurs, and the "granitic layer" is absent, the model represents the top of the metamorphosed sedimentary rocks of density 2.7 g/cm^3. The presence of the material of this kind is inferred from magnetotelluric soundings and from seismic refraction (*cf.* Bojdys & Lemberger, in press b).

East of the W—W zone the relief of the modelled surface is different than west of this zone. From the north to the south the surface slopes gently from the depth of one to four kilometres and then steeply falls to 9 km, forming a trench, whose axis runs approximately through Nowy Sącz—Gorlice—Krosno—Tyrawa Wołoska. On the south side of the G—G line the surface rises steeply again, and culminates near the Polish-Czechoslovak boundary and then deepens again to the south to the Pieniny Klippen Belt. The trench, mentioned above, has a transversal undulation near Jasło and Krosno, where its bottom rises to the depth of 6 km. In the same area the trench axis shifts by more than 10 kilometres to the north (looking east). West of Nowy Sącz the trench axis continues through the Podhale depression, but in the authors' opinion this is a purely geometrical coincidence.

MAIN FEATURES OF THE THREE-DIMENSIONAL MODEL

All the described density boundaries within the crust and upper mantle constitute a spatial model which reveals several notable elements. These are shown on a map (Fig. 8), which is a modified version of the map showing the main elements of crustal structure as revealed by the two-dimensional modelling (Fig. 4). The most important

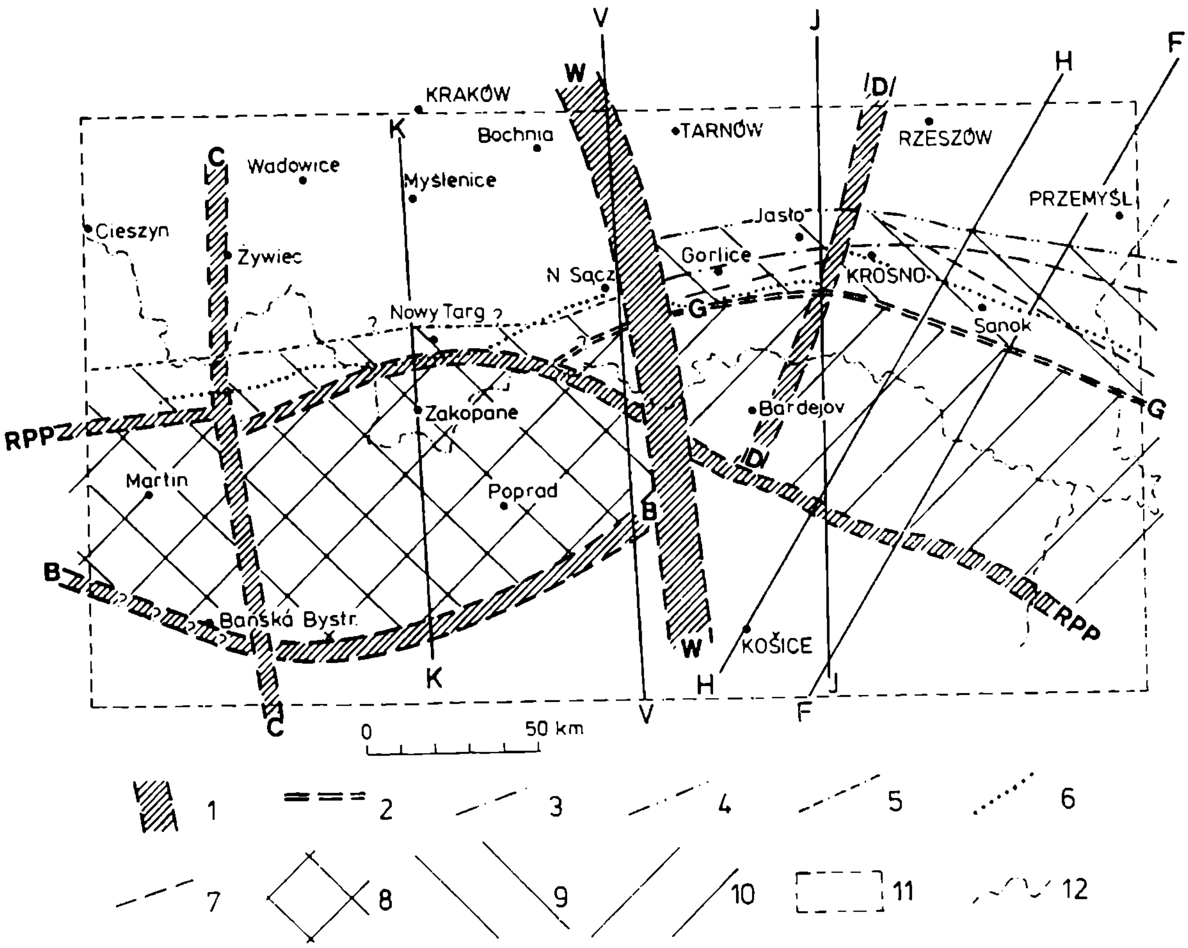

Fig. 8. Tectonic sketch-map showing main crustal elements in the Polish and Slovak Carpathians. *1* — fracture zones (*RPP* — Peripienine fracture zone); *2* — *G—G* line — northern boundary of oceanic crustal fragment in northern plate; *3* — northern boundary of the Moho depression related to the lowered fragment of northern plate; *4* — northern boundary of "Conrad surface" depression related to the lowered fragment of northern plate; *5* — supposed extent of the lowered fragment in northern plate, west of *W— W* fracture zone; *6* — axis of gravity minimum; *7* — axis of depression in the basement of sedimentary rocks of density 2.63 g/cm^3 (according to the model); *8* — area of thickened crust in southern plate; *9* — lowered fragment of northern plate; *10* — area of occurrence of oceanic crustal fragment in northern plate; *11* — boundaries of three-dimensional model; *12* — state boundary. Profile symbols as in Fig. 1

linear elements are the Peripienine fracture zone, the G—G line, and the W—W and B—B fracture zones related to rapid denivelations of Moho and the "Conrad surface" or to significant horizontal changes of physical properties in the crust. The C—C, D—D and E—E zones may also be fracture zones but they have not such an importance in the crustal structure, as have earlier mentioned zones.

The D—D zone, suggested earlier, is expressed by several correlative features on the "Conrad surface" and on the top of crystalline basement:

1) shifts of the trench axis on the top of crystalline basement,

2) transversal denivelation of the trench bottom with amplitude of 3 km,

3) westward wedging out of the elevation at the top of the metamorphosed sedimentary rocks of density 2.7 g/cm^3,

4) westward narrowing of the Moho depression,

5) shallowing in the same direction of the trench on the "Conrad surface".

The D—D zone is manifest in the pattern of regional Δg_B anomaly by separation of the gravity minimum zone, shift of its axis, and changes in gradient value and of the direction of the northern branch of the minimum zone.

The E—E zone delimits from the north the greatest depression of Moho and of the "Conrad surface" in the continental part of the northern lithospheric plate, but it does not pass to the "granitic layer" as is shown by the results of interpretation of the IIIrd International DSS Profile and by the results of the gravity modelling.

The existence of the C—C zone is suggested by the abrupt shift of the Pieniny Klippen Belt and by the pattern of the Δg_B field variations. It is possible that within the sedimentary rocks this zone is a regional tectonic dislocation. Taking into account that, beginning from this zone, the depression of Moho and the "Conrad surface" becomes narrower and shallower to the west, this zone may be a fracture reaching to the deeper crustal layers.

The G—G line is the northern boundary of the hypothetical oceanic crustal fragment and was discussed above. The zones W—W and B—B are discussed by Bojdys *et al.* (1983).

The most complicated is the area between the G—G line and the Peripienine fracture zone. Above Moho, situated at depth of 54 km, there is a zone of phase transitions, of density 3.13 g/cm^3, thickening from 15 km in the north to 25 km in the south. This is in turn overlain by the "basaltic layer" of the oceanic crust, covered with relatively high-density (2.7 g/cm^3) sedimentary rocks of high electric conductivity. The top of these sedimentary rocks is modelled as the top of crystalline basement. This attribution results in a depression of the modelled surface north of the zone of transition from the true top of crystalline basement (in the area of the G—G line) to the top the mentioned sedimentary rocks, which tends to become shallower in the southerly direction. The axis of the depression passes somewhat north of the axis of the gravity minimum and is also shifted, as the latter, in the D—D zone (Fig. 8).

The earlier distingushed, lowered fragment of the continental part of the northern plate is less pronounced in the three-dimensional model. Nevertheless the above described depression of the top of crystalline basement and the significant lowering of the "Conrad surface" in the same area, both permit maintain the concept of the lowered fragment.

South of the Peripienine fracture zone, in the surroundings of the Tatra Mts, the crust is thickened — Moho and the "Conrad surface" form a broad depression delineated by the Peripienine fracture zone and the W—W and B—B zones and on the west shallowing and narrowing, beginning from the C—C zone.

RESULTS OF MODELLING

Gravity effect was calculated for the three-dimensional model presented above. Comparison of the map of the gravity effect of the model (Fig. 9) with the map of regional gravity anomalies, calculated with the Griffin's method for the radius

$R = 5\sqrt{2}$ (Fig. 10), shows that the macroregional pictures agree well enough to consider the model as reflecting the main features of the crustal density structure, though it is not an ideal one.

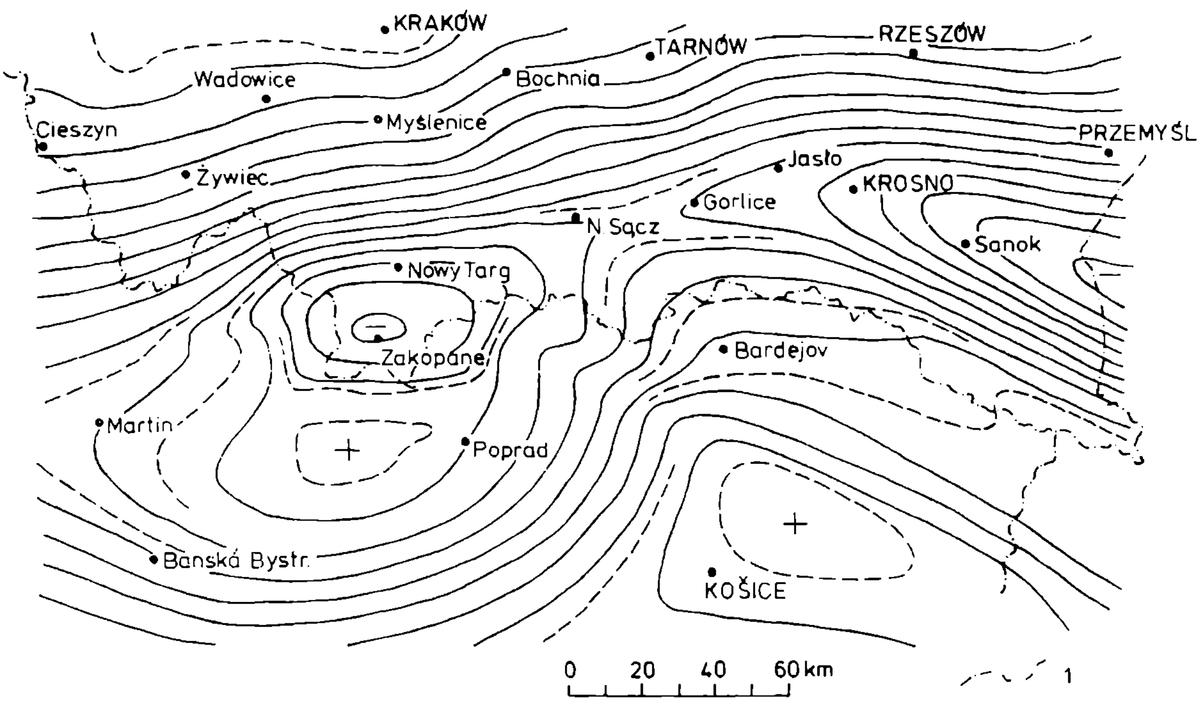

Fig. 9. Map of calculated gravity effect of three-dimensional model. Contour distance — 5 milligals. *1* — state boundary

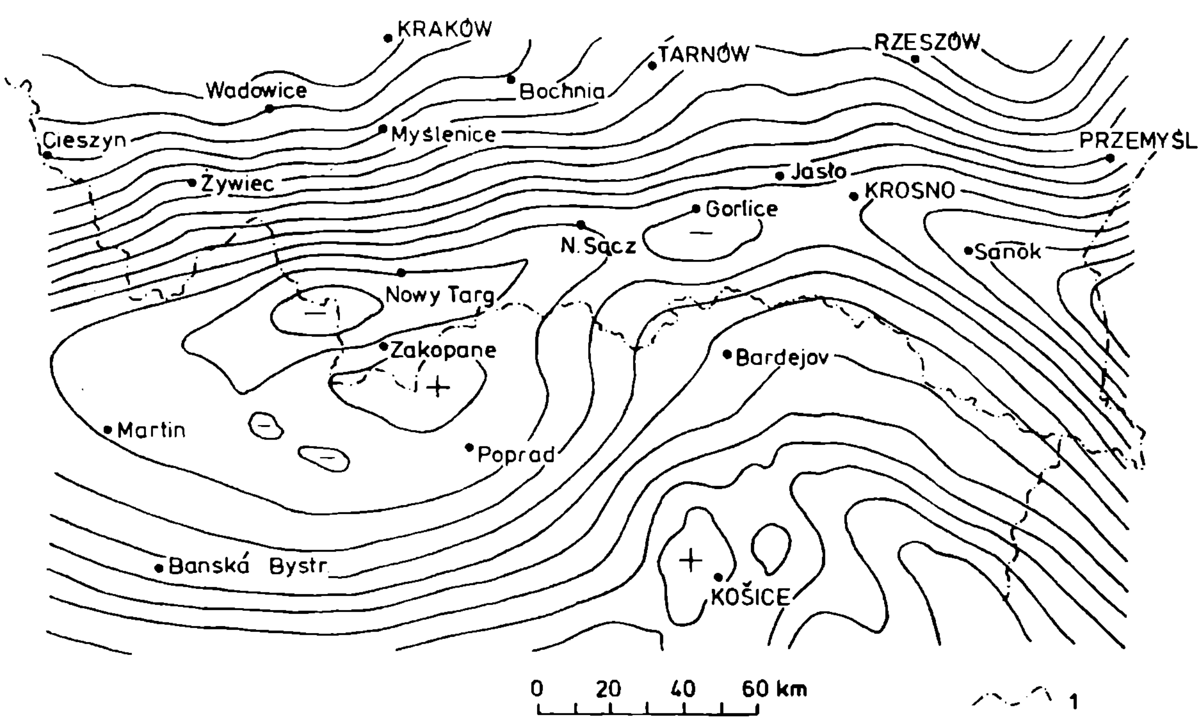

Fig. 10. Map of regional gravity anomalies calculated with Griffin's method for radius $R = 5\sqrt{2}$ km. Contour distance — 5 milligals. *1* — state boundary

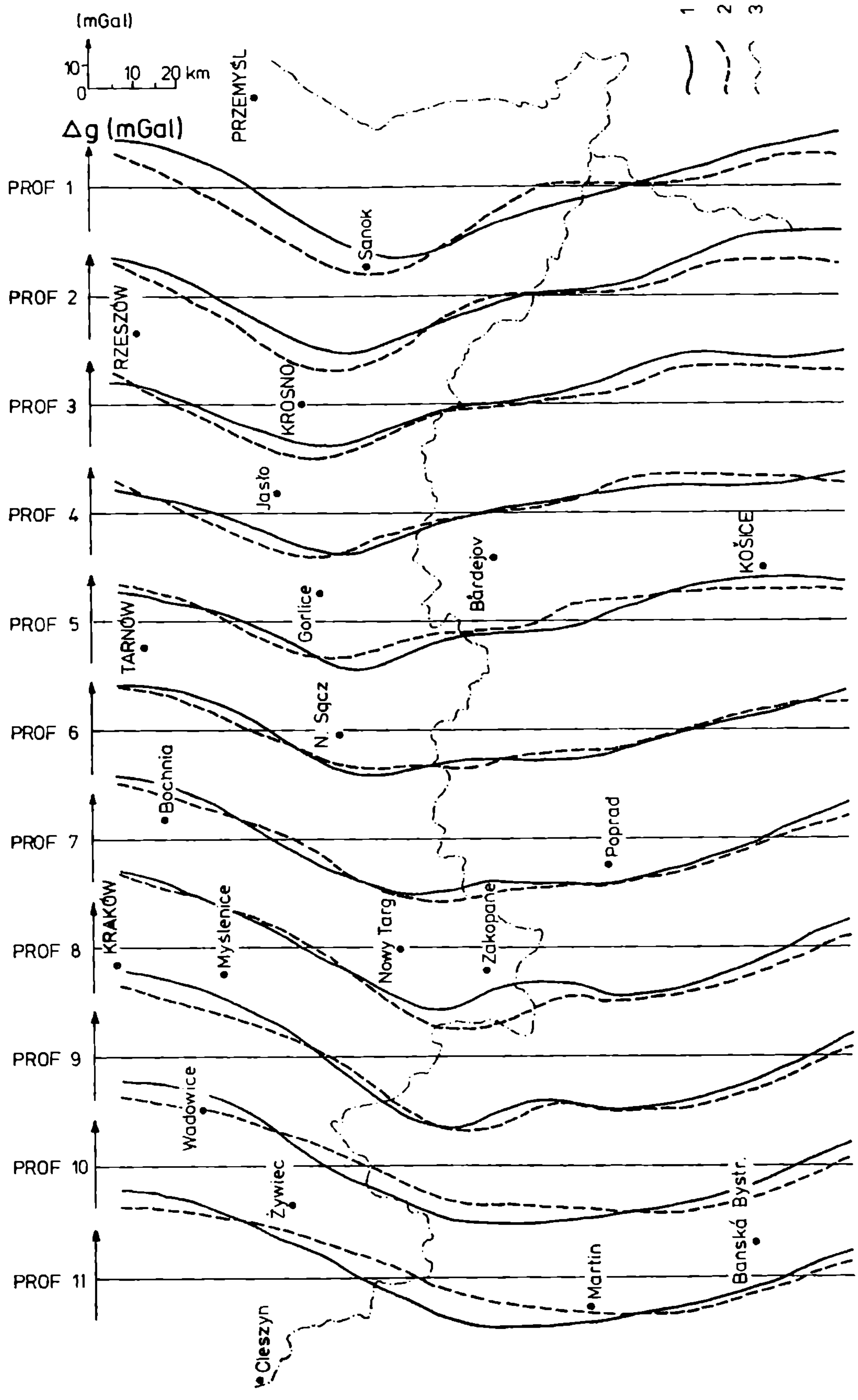

Fig. 11. Comparison of calculated gravity effect of three-dimensional model of crust and upper mantle with regional gravity anomalies calculated with Griffin's method for radius $R = 5\sqrt{2}$ km. *1* — regional anomaly; *2* — gravity effect of the model; *3* — state boundary

Plots of the observed gravity anomalies and gravity effects of the model were compiled along 11 parallel and equidistant profiles to demonstrate the existing differences (Fig. 11). The most important difference is in position of the minima. East of the W—W zone the minimum of the model effect is shifted by 3—7 km to the north relative to its observed position, and west of this zone, by about 5 km to the south. We can conclude that the depression in Moho and the "Conrad surface" is actually situated ca. 5 km to the south from the position accepted in the model. West of the W—W zone the situation is contrary, indicating that horizontal dislocations of crustal elements are along this zone smaller than suggested by the map of Δg anomalies in Bouger's reduction.

Within the broad gravity minimum zone around the Tatra Mts there occur shifts in forms of local extrema, a small mass deficit in the Tatra Mts, and a surplus west of them. Qualitatively the curves agree, indicating that the accepted solution of the regional structure is a correct one. The divergencies result from the simplyfying assumptions accepted earlier during the construction of this very complicated fragment of the model.

Small mass deficits occur at the southern and northern end fragments of the compared profiles; these result largely from the method of calculation of the gravity effect in model margins, namely through horizontal, parallel extrapolation to the infinity of the structures which do not terminate within the model boundaries and density gradient variations in the areas neighbouring the model are not accounted for. The same explanation is valid for the marginal profiles (1 and 11), where the divergencies are the greatest.

Summing up, one may state that the differences between the calculated and observed anomalies do not invalidate either the assumptions accepted for the model construction or the solutions of the geological structure of the area resulting from the two-dimensional and three-dimensional modelling. The existing differences indicate the places and character of corrections which could be introduced to the model to improve its fit with the observed gravity effect.

CONCLUSIONS

1) The macroregional anomaly observed in the studied area is only to a small extent determined by the effect of sedimentary rocks. The great gravity minimum extending along the Carpathians is determined firstly by the morphology of density boundaries deeper than the top of the crystalline basement. The shape of the minimum and its branches reflects the variations in the depth of Moho in the Outer and Inner Carpathians, and the horizontal density gradient in the upper mantle near the Peripienine fracture zone related, in the author's opinion, to the underthrusting of the northern plate below the southern one.

2) In the eastern part of the Polish Carpathians a fragment of the northern plate is of oceanic character. This fragment is limited from the south by the Peripienine lineament, from the north by the G—G line (Fig. 8). This fragment continues to the east beyond the investigated area, and to the west it narrows and probably wedges

out between the Vth International DSS Profile and the meridian of the eastern termination of the Tatra Mts. It is suggested that the oceanic fragment of the northern plate is completely consumed in this traverse and the continental parts of both plates collided with one another. The collision resulted in the uplift of the crystalline core of the Tatras and in thickening and faulting of the southern plate in the vicinity of the Tatras. The oceanic fragment of the northern plate is underlain by an area of phase transitions. Beneath the oceanic crustal fragment there is a zone of phase transitions of density 3.13 g/cm^3.

3) For the sakes of the regional generalizations the sedimentary rocks are considered as a homogeneous material of average effective density 2.63 g/cm^3. This value was determined by modelling along the Kraków—Zakopane profile and was verified on the Baligród—Radymno profile. The results of modelling indicated that above the oceanic fragment of the northern plate and beneath the sedimentary rocks of density 2.63 g/cm^3 there is a zone of material of effective density 2.7 g/cm^3. The authors consider it as metamorphosed sedimentary rocks of high electric conductivity at their bottom part and of elastic parameters close to those of the "granitic layer" at the top. The northern boundary of this zone is accepted schematically along the G—G line, there are however some indications that it could reach somewhat farther north than it is accepted in the model. The bulk of this material would lie south of the G—G line and only a thin wedge would overlie the continental part of the northern plate. It is noteworthy that this zone could be related to the deep--seated (buried) folds zone known farther to the east.

4) The most important tectonic lineaments are: the Peripienine fracture zone, W—W zone and G—G line. The importance of the zone termed Pericarpathian fracture by Sikora (1976) seems much less than suggested by him. The results of modelling indicate that this zone can be a zone of faults lowering the crystalline (consolidated?) basement to the south and can not be considered as a fracture zone *sensu* Sikora (1976).

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Streszczenie

TRÓJWYMIAROWY MODEL SKORUPY ZIEMSKIEJ I GÓRNEGO PŁASZCZA W KARPATACH POLSKICH

Grzegorz Bojdys & Marek Lemberger

Abstrakt: Wyniki modelowania efektu grawitacyjnego sugerują istnienie oceanicznej skorupy we wschodniej części polskich Karpat. Potwierdzają też one słuszność tezy o roli subdukcji w karpackich procesach górotwórczych, podczas których płyta północna podsuwała się pod południową. Wyróżnia się szereg tektonicznych elementów linearnych i powierzchniowych.

Wykonano dwuwymiarowe modelowanie efektu grawitacyjnego wzdłuż czterech profili przecinających poprzecznie polskie Karpaty (Fig. 1). Wyniki modelowania wskazują, że:

1) średnia gęstość skał osadowych wynosi 2,63 g/cm^3;

2) karpacka depresja grawimetryczna wynika z nałożenia się efektu wielu czynników, a jej głównych źródeł należy szukać w morfologii głębokich horyzontów rozdziału gęstości;

3) we wschodniej części polskich Karpat krystaliczna część skorupy ziemskiej ma gęstość 2,9 g/cm^3, co sugeruje jej oceaniczny charakter;

4) w przedziałach występowania skorupy oceanicznej strop krystaliniku zapada na głębokość kilkunastu kilometrów, a depresja wypełniona jest do spągu skał osadowych (5—10 km) zmetamorfizowanymi skałami osadowymi o gęstości 2,7 g/cm^3, w części stropowej mającymi parametry sprężyste zbliżone do tzw. „warstwy granitowej", zaś w części spągowej wykazującymi dobre przewodnictwo elektryczne (Fig. 2 i 3);

5) fragment skorupy oceanicznej podścielony jest kompleksem przejściowym — obszarem zmian fazowych o gęstości 3,13 g/cm^3;

6) gęstość górnego płaszcza zmniejsza się z północy na południe od 3,3 g/cm^3 do 3,21 g/cm^3.

Wyniki modelowań są zgodne z poglądami o roli subdukcji w genezie struktury Karpat, a rozkład gęstości w skorupie jest zgodny z tezą o podsuwaniu się płyty północnej pod południową. Na Figurze 4 autorzy podają szkic tektoniczny Karpat polskich zgodny z tymi wynikami.

Na podstawie tych samych wyników, biorąc pod uwagę kompleksowe dane geofizyczne i geologiczne oraz wspomniany szkic tektoniczny, skonstruowano trójwymiarowy model warstwowy, określony przez trzy powierzchnie: strop krystaliniku, powierzchnię rozdzielającą ośrodki o gęstościach 2,7 g/cm^3 i 2,9 g/cm^3 oraz powierzchnię Moho.

Figury 5—7 przedstawiają kolejne modele wspomnianych wyżej powierzchni rozdziału gęstości, których charakterystyczne cechy zebrane zostały na mapie stanowiącej zmodyfikowany szkic tektoniczny skorupy ziemskiej w Karpatach polskich (Fig. 8). Najważniejszymi linearnymi elementami tektonicznymi są: rozłam perypieniński, linia G—G będąca północną granicą fragmentu oceanicznego skorupy ziemskiej oraz strefy rozłamów W—W i B—B. Strefy C—C, D—D i E—E mogą mieć również charakter rozłamów, lecz ich znaczenie w budowie skorupy ziemskiej jest mniejsze. Obszar pomiędzy linią G—G a rozłamem perypienińskim ma szczególnie skomplikowaną budowę. Powierzchnia Moho zalega tu na głębokości około 54 km, nad nią usytuowany jest obszar zmian fazowych, na którym leży skorupa oceaniczna. Na jej stropie zalegają ciężkie osady zmetamorfizowane, na nich zaś flisz. Osady ciężkie mogą mieć związek z tzw. fałdami wgłębnymi (pogrzebanymi). Autorzy uważają, że na zachód od południka Szczawnicy doszło do całkowitego pochłonięcia fragmentu oceanicznego płyty północnej i do kolizji kontynentalnych części obu płyt, której skutkiem jest wypiętrzenie trzonu krystalicznego Tatr oraz pogrubienie skorupy w ich otoczeniu.

Celem zweryfikowania omówionej wyżej koncepcji modelu gęstościowego obliczono dla niego efekt grawitacyjny (Fig. 9) i porównano z mapą regionalnych anomalii siły ciężkości (Fig. 10). Można stwierdzić, że mapy są wystarczająco zgodne (Fig. 11) by uznać, że model odwzorowuje zasadnicze cechy budowy skorupy ziemskiej.