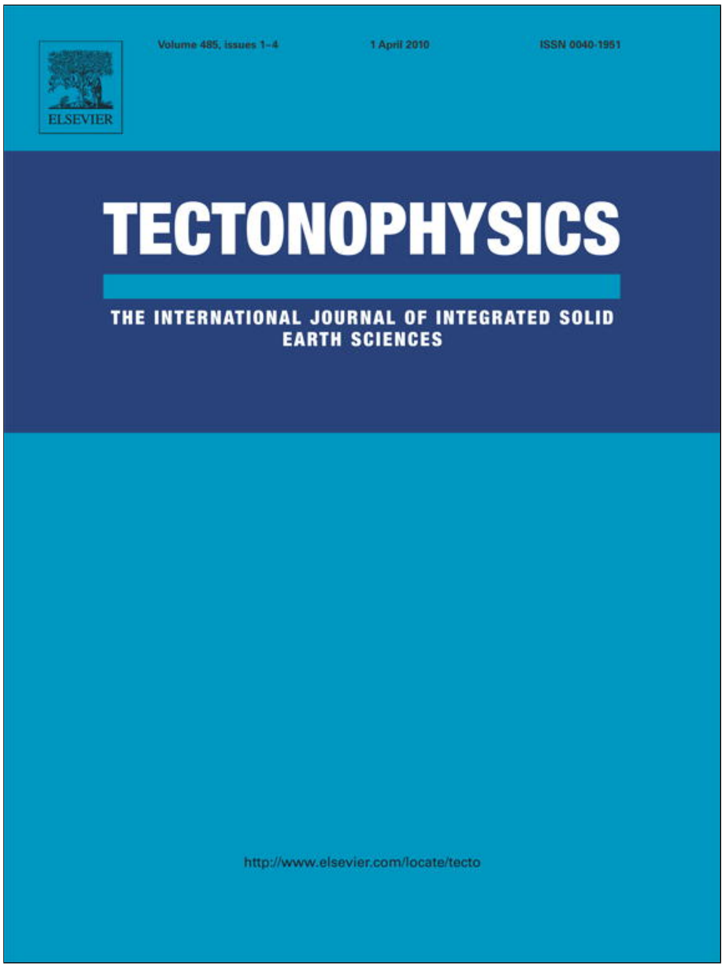
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Lithosphere structure at the contact of the Adriatic microplate and the Pannonian segment based on the gravity modelling

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ABSTRACT

Two-dimensional gravity modelling is applied to the contact of the Dinarides and the Pannonian basin as a contribution to solving structural and tectonic relations in the area characterised by very complex relations. An interpretation procedure, which improves the resolution of gravity modelling by the use of seismic refraction data, has been developed. On the Alp07 profile, which is set up in the framework of the ALP 2002 seismic experiment and stretches in Croatia from Istra over the Dinarides to the Drava River, seismic modelling was performed in order to determine the structure of the lithosphere. A 2-D gravity modelling was also carried out on the profile to obtain calibrated rock densities using interfaces from the seismic model.

Calibrated densities were applied to other profiles set up in the study area for the purpose of determining the structural relations. The structural units determined on the Alp07 profile (Pannonian crust, Transition zone and Dinaridic crust) can be easily followed on all other profiles. The Transition zone, which separates the Pannonian and the Dinaridic crusts, is very wide and characterised by lateral and vertical changes in velocities and densities. It corresponds with the ophiolite zones in more recent tectonic maps. The Tisia block can be compared with the Pannonian crust, whereas the Dinaridic crust would relate to the structural unites of the Adriatic. However, the NE boundary of the Transition zone is located much further north than the boundary of the Tisia block in published tectonic maps. Due to a marked 2-D structure, the obtained results enabled the development of a 3-D structural map of the Mohorovičić discontinuity. The main fault in the upper mantle, which was defined on the basis of geometrical relations, indicates a subduction of the Adriatic microplate beneath the Pannonian segment in the NE wing of the Dinarides.

1. Introduction

The Dinarides and the Pannonian basin are located within the framework of complex structural and tectonic relations in an area, which also includes the Alps and the Carpathian range. The structural and tectonic relations are explained by the generally accepted theory of plate tectonics. Although there are numerous published works dealing with this subject, all structural and tectonic relations have not yet been fully explained. A contribution to a better understanding of these issues is also offered by the ALP 2002 deep refraction experiment (Brückl et al., 2003; Brückl et al., 2007). However, the contact between the Dinarides and the Pannonian basin, which is dealt with in this paper, is only covered by the ALP 2002 project in the west marginal part (Šumanovac et al., 2009). The new insights into the structural units obtained on the Alp07 profile, which was defined in the ALP 2002 project and stretches in the WSW–ENE direction from Istra to the Croatian–Hungarian border, were applied to a significantly wider area in order to obtain a more comprehensive definition of the contact between the Dinarides and the Pannonian basin (Fig. 1).

Active seismic explorations achieve significantly greater resolutions than other geophysical methods used for deep investigations of the lithosphere, such as gravity method and magnetotellurics, but they are technically demanding and significantly more expensive. On the other hand, gravity data have been available for a long time and gravity method is a very cheap method for investigations of structural and tectonic relations, which is why seismic and gravity interpretations were simultaneously performed on the Alp07 profile. To this purpose, interpretation procedure and methodology were developed, which significantly improve the resolution of gravity interpretation. Thus, in the greater study area, it was possible to define the structural and tectonic relations more accurately.

It was possible to follow all structural units, defined on the Alp07 profile, very easily by means of density models of the profiles set up in the study area, so the boundaries of individual units were determined. Density models enabled the definition of the 3-D surface of the Mohorovičić discontinuity and the type of contact between the Adriatic microplate and the Pannonian segment.

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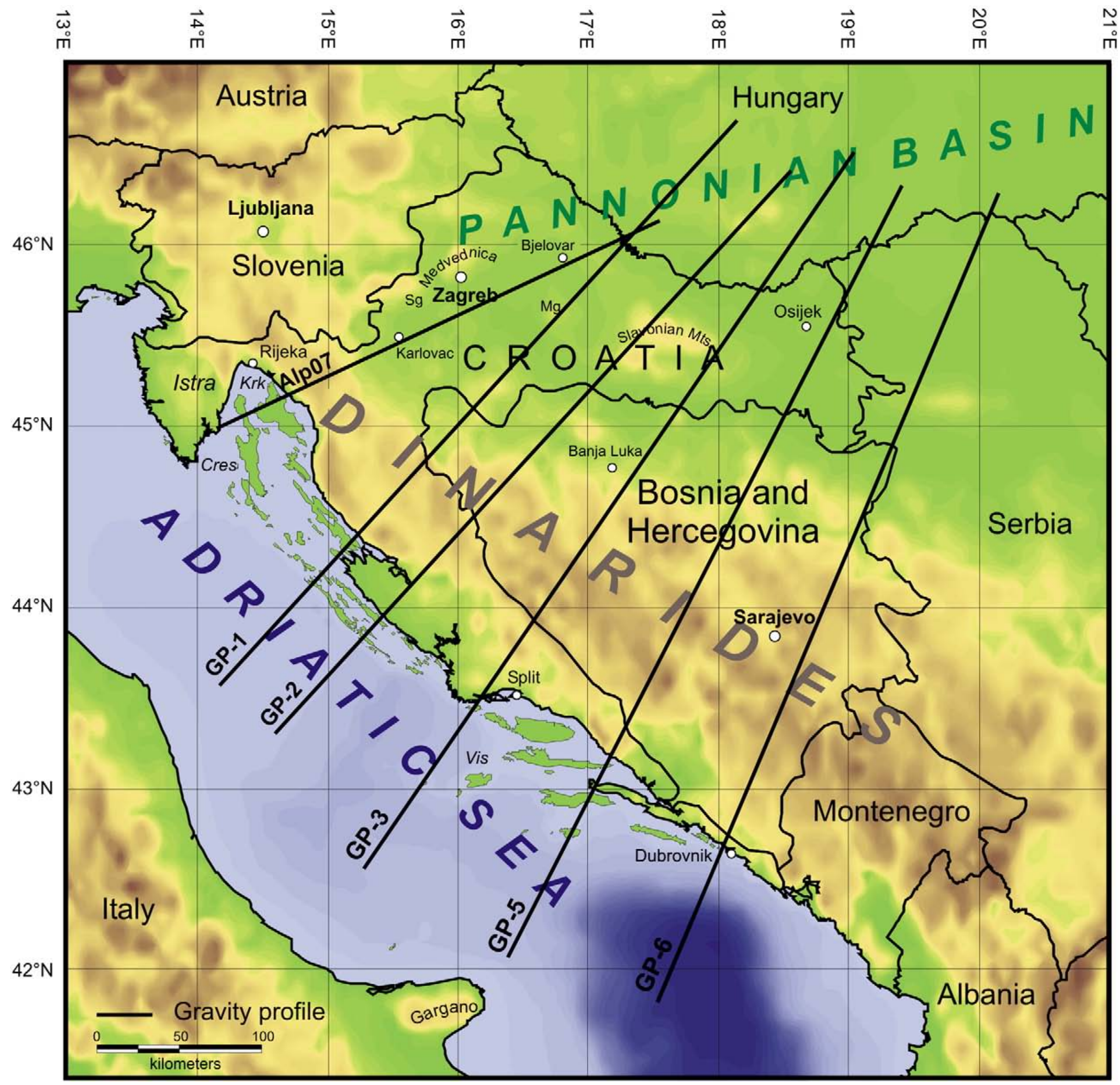

Fig. 1. Positions of profiles used for covering the study area (Sg—Samoborsko gorje, Mg—Moslavačka gora).

2. The study area and regional settings

The study area covers Croatia and Bosnia–Herzegovina and the marginal areas of Hungary, Slovenia and Vojvodina in Serbia (Fig. 1). It is located in the boundary zone between the African and Eurasian plates that includes the Dinarides and the Pannonian basin, thereby encompassing several different geotectonic units (Fig. 2). There is a contact between the Adriatic microplate as part of the African plate and the Pannonian segment as part of the European plate. The Pannonian basin is characterised by extending structures (Posgay et al., 1995), while subduction is the main dynamic process in the Dinarides (Herak, 1986; Moretti and Royden, 1988).

Explorations were carried out along six profiles set up nearly perpendicularly to the direction of the main tectonic units (Fig. 2). On the first profile, Alp07 profile, which is set up in the framework of the ALP 2002 project and stretches across the western boundary of the study area, seismic and gravity modellings were performed in order to determine the structure of the lithosphere. Thereafter five profiles, labelled GP-1 to GP-6, were set up in the remaining study area, where 2-D gravity modelling was carried out. Thus the entire study area was evenly covered.

The profile Alp07 stretches from the edge of the Adriatic microplate through the northern part of the External Dinarides and a very narrow belt of the Internal Dinarides. Towards the Pannonian basin, the profile crosses a wide ophiolite zone (Schmid et al., 2008), which is divided into the narrow Dinaridic ophiolite zone and much wider Sava–Vardar zone (Fig. 2). The ophiolites of these two zones differ in their origin, structure and age (Pamić et al., 2002). The profile terminates at the eastern part of the Tisia block in the Pannonian basin. Similarly, the GP-1, GP-2, GP-3 and GP-5 profiles stretch across the same units, although they cover longer distances in the Tisia block and in the Dinaridic area. The easternmost GP-6 profile, set up at Dubrovnik, stretches across the central part over the wide areas labelled Adria derived thrust sheets in the tectonic map (Fig. 2).

The study area is characterised by compression and movement of the Adriatic microplate in NNE direction (Grenerczy et al., 2005) with clockwise rotations (Anderson and Jackson, 1987). This motion is nearly perpendicular to the trends of exposed tectonic structures. According to more recent insights based on seismic activity, the Adriatic microplate is not a single coherent feature and consists of at least two major fragments (Favali et al., 1990; Oldow et al., 2002; Ivančić et al., 2006). The boundary runs approximately from Gargano

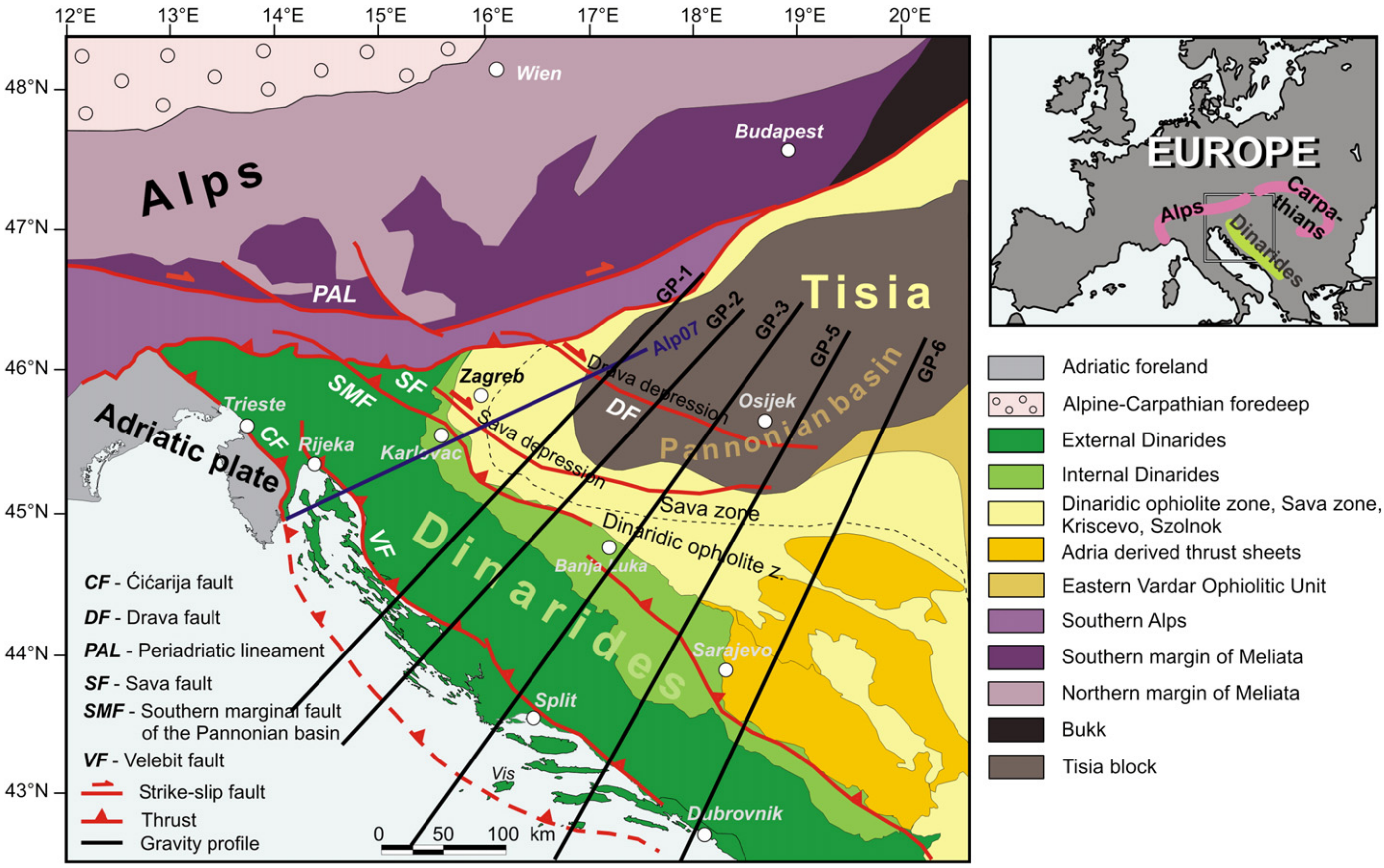

Fig. 2. Generalized tectonic map of the study area with gravity profiles (Alp07 and GP-1 to GP-6), generalized according to Schmid et al. (2008) and Tomljenović (2002).

(in south-eastern Italy) towards Dubrovnik. The southern fragment is rotating counter clockwise, opposite to northern fragment (Favali et al., 1990). As result of the push exerted by the African plate, the Adriatic microplate is under thrusting the European plate, causing the formation of the Alpine–Dinaridic orogenic belt. Tectonic movements during the Palaeogene caused compression in north-eastern direction, whose consequence is the final formation of the Dinarides. In the coastal part of Croatia, the Adriatic microplate is under thrusting the Dinarides (Herak, 1986; Moretti and Royden, 1988), which is observed in seismicity as a north-eastern subduction (Kuk et al., 2000).

3. Geological setting

According to Vrabec and Fodor (2006) subduction of the Adriatic microplate under the external Dinarides caused the appearance of the steep reverse faults of NW–SE direction and a belt stretching from the NE coast of Istra towards the North Adriatic islands. There are two significant reverse faults in the northern Dinarides. At the very beginning of the profile Alp07, there is a fault at the edge of the External Dinarides, known as the Trst-Učka-Dugi Otok or Ćićarija fault (*CF* in Fig. 2). Its location at the mainland is very well defined. In the Adriatic Sea, however, its direction is not accurately defined, and according to some authors, it extends as far as the island Vis (Fig. 2) in the southern Adriatic. The other significant reverse fault parallel to the Dinarides is the Velebit fault (*VF* in Fig. 2). These faults are part of a zone of reverse and thrust faulting southeast of Trieste that lies along the Adriatic coast and is considered by some authors as the main discontinuity between the External Dinarides and the Adriatic microplate (Aljinović et al., 1984). However, recent studies show that there is a continuous structural transition between Adriatic microplate and External Dinarides, which consists of a series of folds with smaller southwest-directed thrusts (Poljak and Rižnar, 1996).

In a geological sense, two main areas can be distinguished: the Dinaridic area and the Pannonian basin. Mesozoic carbonates (limestones, dolomites, breccias, etc.) are dominant in the Dinarides. Palaeogene rocks (carbonates, clastics and flysch layers) can be also found, especially in Istra and the coastal part of Croatia, but also in some inland karst fields (Geologic Map of SFRY, 1970). Smaller flakes of Palaeozoic and older rocks can be found in this area as well. Between Sarajevo and Banja Luka in Bosnia, there is a tectonostratigraphic unit called the “Bosnian Flysch” (“flysch bosniaque”), which is a passive continental margin carbonate-clastic unit. This large tectonostratigraphic unit of the central Dinarides consists of the Jurassic to Late Cretaceous sequences, up to 4000–5000 m thick, which were deposited at the continental slope of the Adriatic–Dinaridic carbonate platform (Pamić et al., 1998).

The southern marginal fault of the Pannonian basin (Fella-Sava-Karlovac; *SMF* in Fig. 2) is considered to be the boundary between the Dinarides and the Pannonian basin (Prelogović et al., 1998). The Pannonian basin and its origin are most frequently considered in relation to the Carpathian range in terms of a “back-arc” basin (Stegena et al., 1975; Royden et al., 1983). However, marginal areas of the southern Pannonian basin are influenced by events in the Dinarides (Pamić, 1993; Tari and Pamić, 1998). The Neogene and Quaternary sediments are predominant in the SW part of the Pannonian basin, which is bordered by the Southern Alps in the east and the Dinarides in the south. There are also depressions filled with Neogene deposits that vary in their dimensions and depths. The largest and deepest depressions in this part of the Pannonian basin are the Sava and Drava depressions, whose geological sedimentary fill is well known due to petroleum exploration (Lučić et al., 2001; Saftić et al., 2003). Pannonian basin is characterised by significant hydrocarbon potential and the main hydrocarbon reservoirs in the SW part of the Pannonian basin are in the Sava and Drava depressions. There are 35 oil and 13 gas fields discovered. The Sava depression is located along the very south-western edge of the Pannonian basin, whereas the Drava depression is further to the north (Fig. 2). Both depressions are of asymmetrical shape, with steeper southern limbs that are elongated in NW–SE direction. The main boundary fault of the Drava depression is a dextral transcurrent fault of NW–SE direction. According to Prelogović et al. (1998), the Drava fault continues to the Periadriatic lineament (PAL) and is called the Periadriatic–Drava fault (DF). The Neogene deposits are the deepest, about 7 km, in the Drava depression (Velić et al., 2002), reaching to about 5 km in the area of the GP-2 profile. There are also several smaller depressions in the survey area: the Slavonia–Srijem depression, the Bjelovar sag, the Karlovac depression, etc. The Neogene–Quaternary deposits of the depressions generally consist of a few lithostratigraphic units. Above the bedrock formed by Mesozoic and Palaeozoic rocks, the lower strata are breccias, conglomerates and limestones that are overlain by mostly sandstones, shales and marls. The shallowest deposits are sands, clays and gravels.

The Slavonian mountains and the Moslavačka gora (Mg in Fig. 1) are located between the Sava and the Drava depressions and consist of Palaeozoic–Mesozoic rocks. The Medvednica and the Samoborsko gorje mountains (Sg in Fig. 1), where outcrops of ophiolites have been discovered, are located at the northern margin of the Sava depression (Pamić and Tomljenović, 1998).

4. Previous geophysical investigations

A gravity map of the study area was developed in the 1950s at a scale of 1:500,000 (Gravity map of SFR Yugoslavia, 1972). Bouguer corrections were done with a density of 2.67 g cm^{-3}. According to the Explanation for the Gravity map of SFRY-Bouguer Anomalies (Bilibajkić et al., 1979) measurement density was greater in the Pannonian part and lower in the Dinarides. Measurement density in Croatia is between 6.1 stations per km^2 (in some plain regions) and less than 1 station per 10 km^2 in the southern part of the Adriatic Sea where measurements were done mainly on islands. In the vicinity of the profile Alp07, measurement density is in the range 0.94 to 6.1 stations per km^2, with an average density of 2.7 stations per km^2.

Measurement density in the study area was between 1 station per 10 km^2 and 9 stations per 1 km^2 (Fig. 3). In general, measurement density was greater in the Pannonian basin and lower in the area of higher mountains as well as in the area of the Adriatic. Errors for the Bouguer corrections were calculated separately for three regions. The first region is the Pannonian basin with RMS error of Bouguer anomalies ± 0.08 mGal. The second region is transition zone between Pannonian basin and Dinarides with RMS error ± 0.23 mGal. The third region includes central parts of Dinarides and other high mountains where Bouguer anomalies have less accuracy with RMS error ± 0.51 mGal. It can be concluded that this precision and measurement density satisfy requirements for regional scale gravity research. A

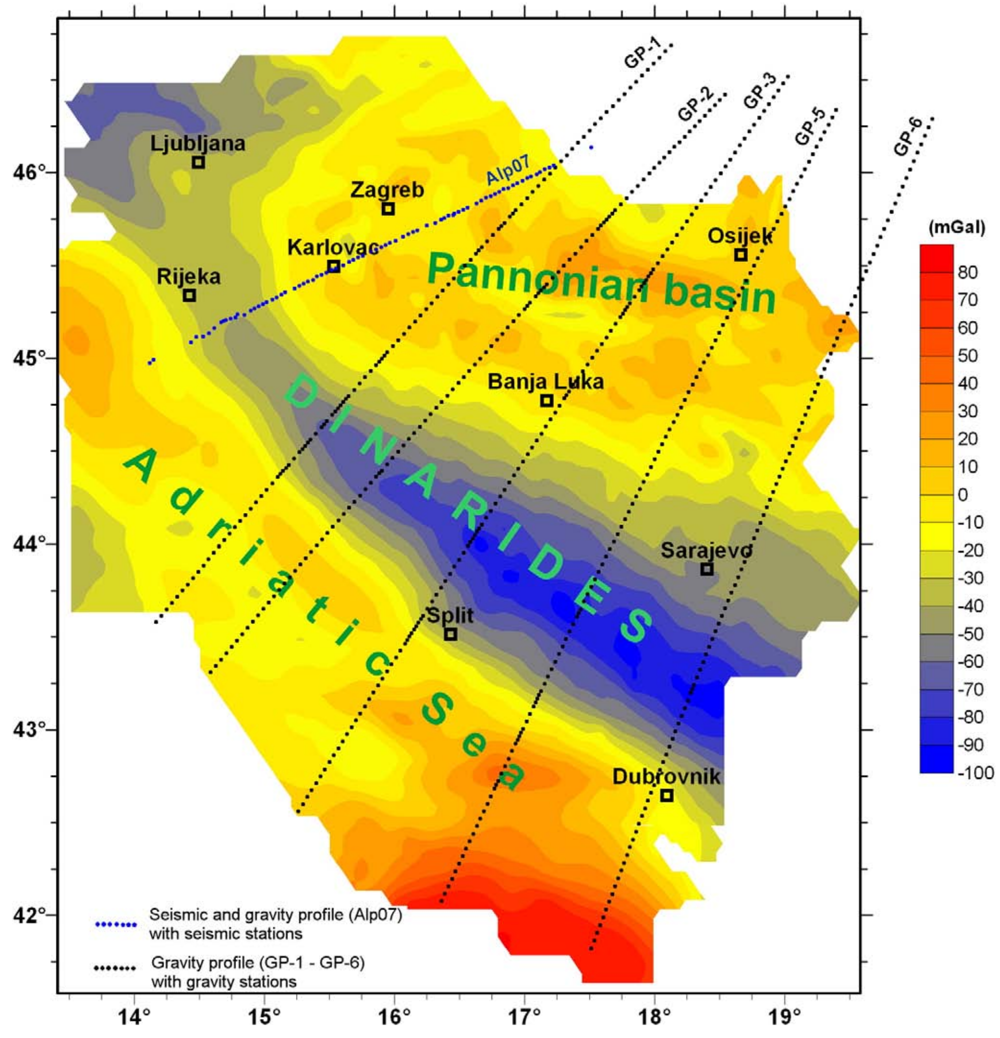

Fig. 3. Generalized gravity map of the study area with gravity profiles (GP-1 to GP-6) and seismic and gravity profile Alp07 (the data for 2-D gravity modelling were extracted in gravity stations from the Gravity map of the SFRY, 1972).

good accuracy of the measured data was also confirmed during gravity modelling along the Alp07 profile. This gravity profile shows a very sharp negative anomaly in the vicinity of Karlovac (close to SMF fault in Fig. 4). At first sight the anomaly seemed like an error in measured data. Applying thicknesses of sediments in the Karlovac depression from the literature (Saftić et al., 2003) the density model could not fit the measured data. Calculated and observed data could be well fitted only by modelling a narrower and deeper Karlovac depression. Additional verification of recent borehole data in this area has confirmed that the depression is narrower and deeper than considered in the literature.

Regional gravity anomalies (between −70 and +30 mGal) mostly express the depth of the Mohorovičić discontinuity (Mohorovičić, 1910) as the main density contrast in the lithosphere (Fig. 3). Local anomalies originate from shallower structures, showing geological relations in the near surface parts of the crust, and are thus most frequently targeted in petroleum exploration, thermal and mineral water exploration and other geological research.

The lowest gravity in the study area stretches in NW–SE direction below the Dinarides; therefore, the deepest Mohorovičić discontinuity is expected here. The highest gravity values of this minimum are noticed at Rijeka, in the NW part of the area. On the Alp07 profile, it reaches −40 mGal, with over −90 mGal on the GP-5 and GP-6 profiles. Because of the local minimum caused by a very deep karst field, the value on the GP-3 profile is −100 mGal. High gravity values are located in the Pannonian basin area, and in the Adriatic region as well (around the island Cres and Istra, Fig. 1), and therefore, a thinner crust can be expected in these areas. Highest values, ranging up to even 80 mGal, are observed in the southern Dalmatia, in the Adriatic Sea at Dubrovnik.

In the Pannonian part, there is also a series of local anomalies, which originate from depressions or other shallow geological structures. The main minima in the Pannonian basin are caused by the Sava and Drava depressions, located at the end of the profile. Between these basins, a local maximum is located, caused by a shallow depression (Figs. 2 and 4).

Previous deep lithosphere research was performed as part of a research program that covered Slovenia, Croatia and Bosnia–Herzegovina. This research program included both deep electrical sounding (Kovačević, 1966) and deep seismic sounding (DSS method), using refraction surveying. Two basic discontinuities were mapped, the Mohorovičić discontinuity and the basement beneath the sedimentary cover, and results were published in numerous publications: Andrić and Zeljko (1971), Joksović and Andrić (1982; 1983), Zeljko (1972), Aljinović et al. (1981), Dragašević and Andrić (1982), Aljinović and Blašković (1984), and Skoko et al. (1987).

In the recent times, a refraction seismic experiment ALP 2002, “Seismic Exploration of the Alpine Lithosphere” (Brückl et al., 2003), was carried out as part of a wide network of seismic projects in the Central Europe: POLONAISE 97, CELEBRATION 2000 and SUDETES 2003 (Guterch et al., 2003). The ALP 2002 project was a big international seismic experiment whose primary goal was to obtaining fundamental data on deep structures in the lithosphere in the area of the Eastern Alps, the NW Dinarides, the eastern part of the Pannonian basin and western part of the Bohemian massif. The participants of the ALP 2002 experiment include researchers from the European countries (Austria, Czech Republic, Croatia, Denmark, Finland, Hungary, Poland and Slovenia) as well as from Canada and the USA.

5. Methodology of interpretation

When applying gravity modelling, it is necessary to take into account ambiguity of gravity interpretation. Namely, the process of inversion of gravity data does not lead to a unique solution. For a given gravity anomaly, a series of density models can be identified, which can fit the measured data. It is, therefore, necessary to have available data from other sources as well to reduce the number of possible solutions down to a usable level. It can be further stated that the resolution of gravity method is relatively low in comparison with seismic methods, which particularly refers to great exploration depths. Seismic methods are aimed at discovering subhorizontal discontinuities in rocks, whereas, on the other hand, those discontinuities are determined only with great difficulty with the application of gravity method.

Therefore, the method used for defining the main discontinuities, the Mohorovičić discontinuity and the crust discontinuities, was seismic refraction, whereas gravity method was used to define in more detail the attributes of layers in the lithosphere. The procedure of interpretation consists of the three main steps:

1. seismic modelling was applied on the Alp07 profile to determine the structure of the crust and the upper mantle;
2. gravity modelling was applied on the Alp07 profile to constrain interpretation ambiguity, while interfaces from the seismic model were used to obtain calibrated densities;
3. calibrated densities were used in the wider area, on the other profiles, to determine structural relations, such as lateral boundaries and vertical interfaces.

On the Alp07 profile, by means of seismic modelling of active seismic data, the main discontinuities and the lateral changes of velocities in individual layers were relatively accurately defined (Šumanovac et al., 2009). The discontinuities along the depth, the Mohorovičić and Conrad discontinuities, were fixed during gravity modelling, they were not changed, while rock densities in individual layers and lateral zones were changed to obtain the model of densities, which fits the measured values. In this manner, gravity data were calibrated by means of seismic data. Assuming that density properties will not significantly change laterally, calibrated density data were used for determination of discontinuities in the wider area of the Dinarides and the Pannonian basin.

Based on the gravity map of the area of Slovenia, Croatia and Bosnia–Herzegovina, a conclusion can be drawn about typical 2-D structures characterised by constant lateral properties (Fig. 3), which fully justifies the application of 2-D gravity modelling. Densities of individual lateral and vertical zones determined on the Alp07 profile were transferred to all other profiles (GP-1 to GP-6, Fig. 1). The only changes were in terms of depths of interfaces and widths of lateral zones to obtain the final models of densities. A very good matching of theoretical and measured gravity data was obtained on all profiles. 2-D gravity models of the profiles were then used in the definition of a 3-D model of the Mohorovičić discontinuity in the entire study area, which particularly indicates structural and tectonic relations between the Adriatic microplate and the Pannonian segment of the Eurasian plate.

6. Geophysical interpretation of the Alp07 profile

Two techniques were used in the 2-D seismic interpretation of the Alp07 profile (Šumanovac et al., 2009): seismic tomography inversion (Hole, 1992) and ray tracing modelling (Červený and Pšenčík, 1983). Following seismic modelling, 2-D gravity modelling was performed to determine the densities in the lithosphere (Fig. 4). Gravity modelling was performed by using the software based on the Talwani method (Talwani et al., 1959).

On the basis of both data sets, three types of crust can be defined: Dinaridic, Transition zone and Pannonian (Fig. 4). The Dinaridic crust is comprised of two parts, the lower and the upper crust, whereas the Pannonian crust is virtually single layered. The Dinaridic upper crust is characterised by low seismic velocities (about 6 km s^{-1}) and lower densities (2.70 and 2.78 g cm^{-3}), while the lower crust has high seismic velocities (6.5–7.1 km s^{-1}) and high density (2.89 g cm^{-3}). The

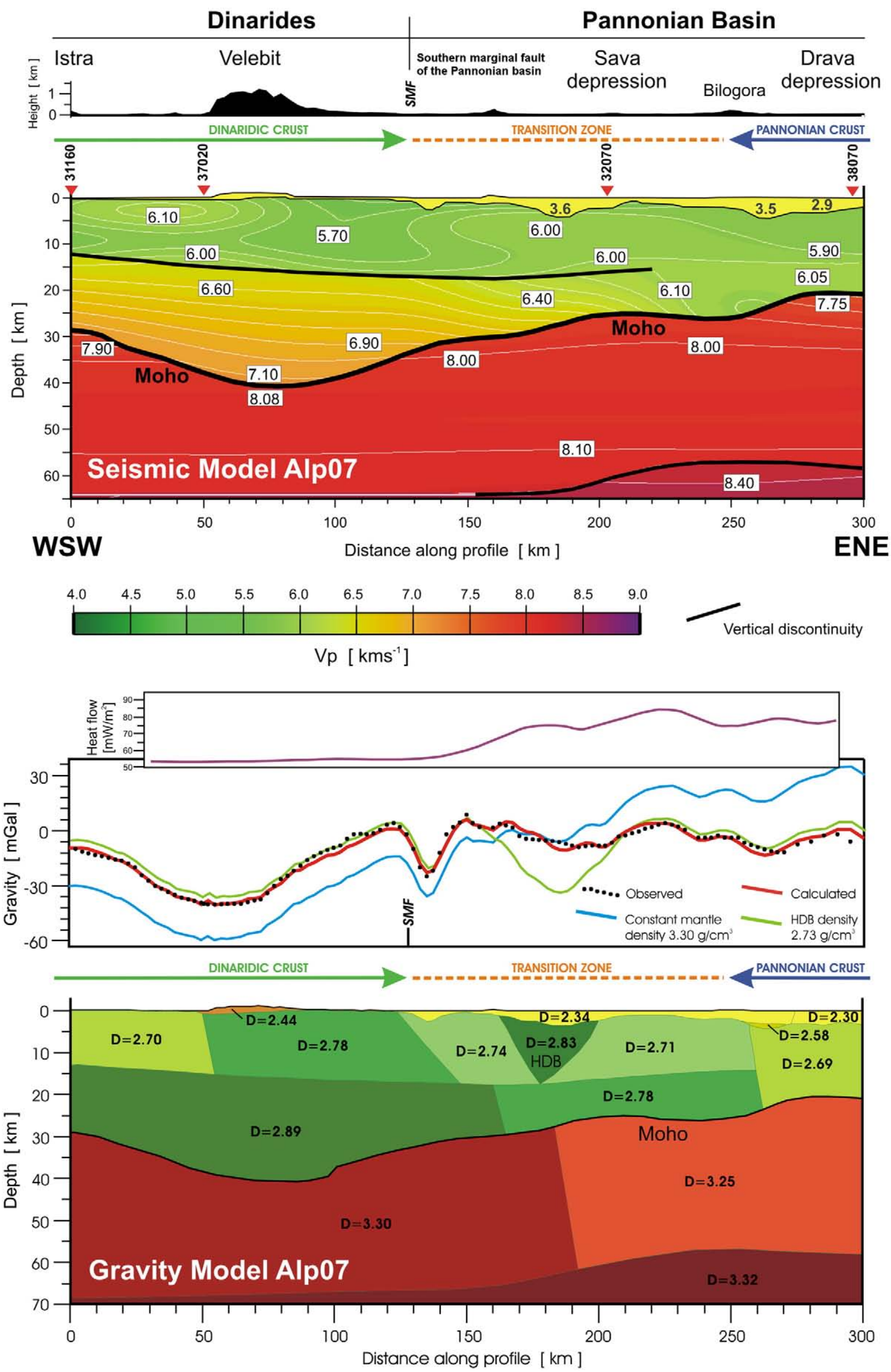

Fig. 4. Seismic and gravity models along the Alp07 profile. Forward ray tracing modelling was used for designation of the seismic model (V_p — P-wave seismic velocity, D — densities in g cm^{-3}), Šumanovac et al., 2009.

Pannonian crust is characterised by similar seismic velocities as the upper Dinaridic crust and very low density (2.69 g cm^{-3}). The strongest lateral changes in seismic velocities and densities were found on the margin of the Pannonian basin and in the area of the Sava depression and the Bjelovar sag. Thus a wide Transition zone splitting up these units was defined. The southern boundary of this zone corresponds with the southern marginal fault of the Pannonian basin, and the northern boundary with the Drava fault (Fig. 2).

The steps in the Moho were obtained by seismic forward modelling, and were also confirmed by gravity modelling (Fig. 4). They may indicate deep faults or shear zones in the crust and uppermost mantle. The correlation of these features with the depressions in the Pannonian basin indicates that they might relate to major upper crustal features such as the Sava and the Drava depressions. Based on geometric relations and the fact that the Adriatic microplate is being squeezed against the Eurasian plate as confirmed by the data from geodetic and geodynamic measurements (Grenerczy et al., 2005), it seems that the Adriatic microplate at the level of the Mohorovičić discontinuity is at least locally being thrust beneath the Pannonian region. Similar conclusions were also drawn from the interpretation of the Alp01 and Alp02 profiles (Brückl et al., 2007). The lower crust under the Dinarides is relatively dense and main surface faults in the area of the Dinarides cannot be correlated to features at the Moho level. On the other side, the density model shows in the Pannonian basin that surface fault zone can be followed through the crust. For example, the main Velebit fault has no influence, even at the lower crustal level. Unlike the fault below the Drava depression can be followed through the entire crust.

7. Gravity modelling

The data for 2-D gravity modelling were extracted from the gravity map of the SFR Yugoslavia (Fig. 3; Gravity map of SFRY, 1972), while the ends of the profiles were extracted from the Gravity Map of Transdanubia in scale 1:1,000,000 (Kovacsvölgyi, 2000). The densities in individual layers for initial gravity model of the Alp07 profile were determined on the basis of seismic velocities, mostly by using Gardner's formula (Gardner et al., 1974), and formulas proposed by Christensen and Mooney (1995), as well as the classic Nafe–Drake curve (Ludwig et al., 1970). Table 1 shows the velocities from the seismic model, densities calculated from seismic velocities by using different empirical formulas, and the final densities obtained for Alp07 profile in gravity modelling.

Gardner's formula is of the form:

$$\rho = 1.74V_p^{0.25}, \tag{1}$$

where ρ is density in g cm^{-3}, and V_p is P-wave velocity in km s^{-1}. It was obtained by analysing a large number of laboratory and field data for different sedimentary rocks, and is most often applied in petroleum exploration. Gardner's formula gives mean density values of sediment rocks (with the exception of evaporates), thus the values obtained from this formula were used in the shallowest part of the initial density model.

For crystalline crustal rocks, the linear density–velocity relationship of Christensen and Mooney (1995) was used:

$$\rho = 0.541 + 0.3601V_p. \tag{2}$$

They developed this formula based on velocity values from a large number of seismic refraction profiles and comparison with laboratory measurements of seismic velocities under high pressure on a large number of rock samples.

Crustal densities were also calculated by a formula derived by Brocher (2005) from the Nafe–Drake curve by the application of polynomial regression. Thus, this is, in fact, the Nafe–Drake empirical curve in the form of an equation:

$$\rho = 1.6612V_p - 0.4721V_p^2 + 0.0671V_p^3 - 0.0043V_p^4 + 0.000106V_p^5, \tag{3}$$

defined for velocities between 1.5 and 8.5 km s^{-1}.

Considering that the seismic data had higher spatial resolution then gravity data, the boundaries of individual layers and lateral boundaries of the initial gravity model of the Alp07 profile were taken from the ray tracing seismic model (Fig. 4). It was expected that gravity modelling of the Alp07 profile would assist in the definition of the density characteristics of individual layers and anomalous zones determined by seismic modelling. However, some features of the seismic model attained a new meaning during the gravity modelling, especially the zone of higher velocities beneath the Sava depression and width of the transition zone, so the gravity modelling was particularly valuable to integrated geophysical and geological interpretations.

The densities calculated by Gardner's formula for sedimentary rocks corresponded very well with the final densities in the gravity model. In order to achieve an acceptable fit between measured and calculated Bouguer anomalies, densities within the layers in the model were varied within the ranges of the predicted by the velocity–density relationships with the exception of two regions in the upper crust. One of these exceptions was the need for higher density body in the distance range of 150–200 km that can be explained by the presence of ophiolites that crop out near the profile, in the area of Medvednica and Samoborsko gorje (Figs. 1 and 4). It is obvious that there is a great discrepancy between the measured and calculated gravity data, if this High Density Body is not included in the model (Fig. 4). The other area was the region of low seismic velocities in the upper crust between 80 and 130 km where relatively high density of 2.78 g cm^{-3} was required. Higher density below mountains, which continues to the SMF fault, points to the complex geological relations in this area characterised also by very active seismicity. In the beginning of the profile slightly higher velocities at the surface correspond to the Istrian carbonate platform, which can also explain lower average density of 2.7 g cm^{-3} for that part of the upper crust.

The increase in the depth of the Moho, a trough in the Moho at a distance about 245 km was also confirmed by gravity modelling because attempts to even out this interface lead to discrepancies between measured and calculated values. Already the seismic model showed the existence of a Transition zone (distance 130–255 km), but it is much more evident in the density model. The density values in the Transition zone range from 2.71 to 2.83 g cm^{-3}. Two densities were derived in the upper mantle, which can better satisfy gravity data. In the first part of the profile, the density is higher (3.3 g cm^{-3}) while at the end part of the profile it is lower (3.25 g cm^{-3}). This density distribution is compliant with heat flow data in the survey area. Heat flow and temperature gradients are higher in the Pannonian basin than in the area of Dinarides

Table 1
P-wave seismic velocities and corresponding densities.

Structural unit	P-wave velocity (km s^{-1})	Density (g cm^{-3})			
		Nafe–Drake	Christensen and Mooney	Gardner	Used (final)
Sediments	2.5–4.0	2.09–2.39	–	2.18–2.46	2.24–2.42
Dinaridic upper crust	5.8–6.1	2.68–2.74	2.63–2.74	2.70–2.73	2.70–2.78
Dinaridic lower crust	6.4–7.1	2.81–3.00	2.85–3.10	–	2.89
Pannonian crust	5.7–6.1	2.66–2.74	2.59–2.74	2.68–2.73	2.69
Transition zone	5.6–6.4	2.64–2.81	2.56–2.85	–	2.73–2.78
Mantle	7.75–8.3	3.20–3.40	–	–	3.25–3.32

(Jelić et al., 1995). The surface heat flow in the Dinarides is very low and has values about 55 mWm^{-2}, while in the Pannonian basin has values between 70 and 85 mWm^{-2} (Fig. 4). Therefore, higher velocities and densities in the upper mantle should be expected in the Dinarides than in the Pannonian basin. These calibrated densities were applied on all other profiles (GP-1 to GP-6, Fig. 5).

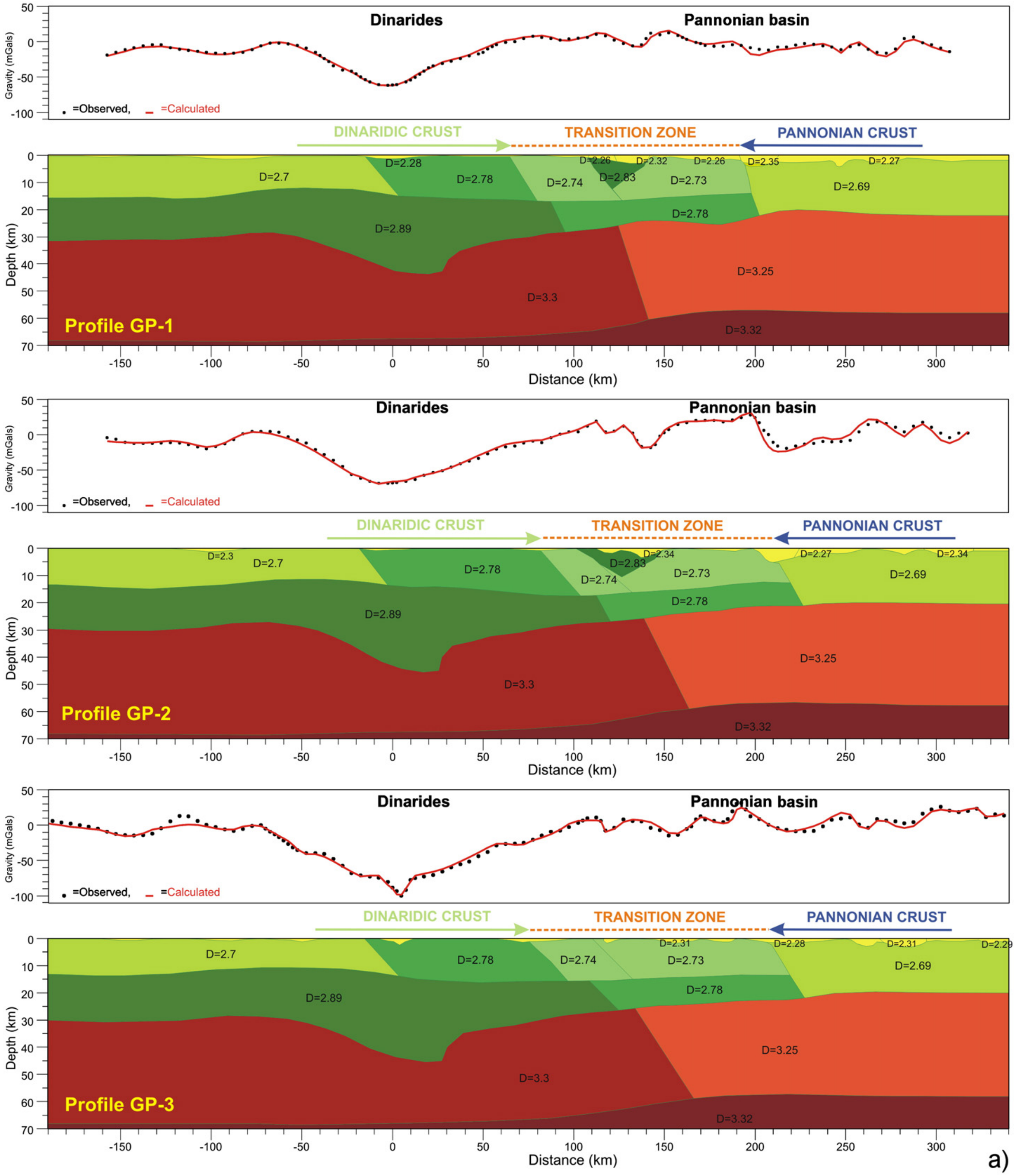

Fig. 5. a) Two-dimensional gravity models of the GP-1 to GP-3 profiles obtained by the use of calibrated densities (D — densities in g cm^{-3}). b) Two-dimensional gravity models of the GP-5 and GP-6 profiles obtained by the use of calibrated densities (D — densities in g cm^{-3}).

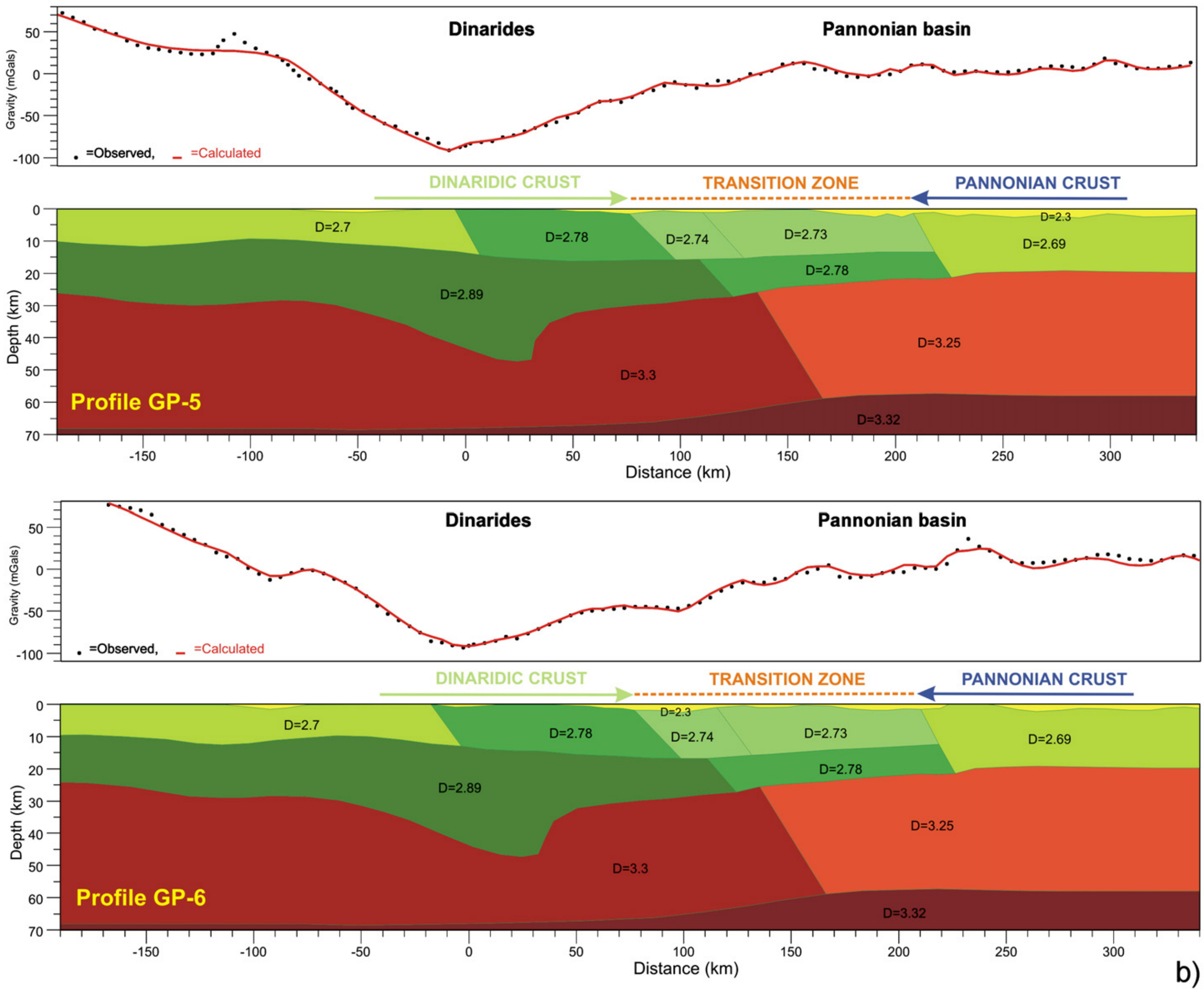

Fig. 5 (*continued*).

All structural units defined on the Alp07 profile can be very easily followed, in order to comply with the measured gravity values, on all other profiles, from GP-1 to GP-6, as well (Fig. 5). The depth of the Mohorovičić discontinuity strongly increases on the GP-1 profile, and the flanks are much steeper than on the Alp07 profile. An even steeper dip and greater depths are observed on the GP-2 profile, whereas on the other profiles depths and dips are similar, and there are no significant changes among the profiles. A slight depression in the Mohorovičić discontinuity below the Transition zone is seen only on the GP-1 profile, while it is very poorly observable on the other profiles and located on the boundary between the Pannonian crust and the Transition zone. The zone of high densities, interpreted as ophiolite rocks, which is clearly observed on the Alp07 profile, can be also followed on profiles GP-1 and GP-2, but its depth decreases and fully disappears on profile GP-3 and cannot be seen on profiles GP-5 and GP-6, as well. The effect of the Adriatic units (Adria derived thrust sheets in the Fig. 2), consisting of continental crustal rocks that were exposed to the processes of metamorphosis, cannot be in any way seen on profile GP-6, which, according to the tectonic map, covers a large area in the central part of the profile. It can also be stated that the gravity models of profiles GP-5 and GP-6 are very similar.

8. Discussion on calibrated densities

In the initial gravity modelling a constant density of 3.2 g cm^{-3} was assumed for the upper mantle. However, extremely low densities (2.47 g cm^{-3}) were obtained in the Pannonian crust and also very low densities in the Transition zone (2.56–2.64 g cm^{-3}), and this model was not further considered. Using constant mantle density of 3.30 g cm^{-3} resulted in maximum differences of 35 mGal between calculated and observed gravity values (Fig. 4, blue line). When this uniform density was assumed, a fit to the observed gravity values could only be obtained by employing a very low density in the Pannonian crust (2.59 g cm^{-3}), as well.

The variations of velocities in the upper mantle are clearly seen on the seismic model, with the highest velocities below the Dinarides and the lowest below the Pannonian crust (Fig. 4). Therefore, in the second step a lateral change in densities in the upper mantle was assumed. Three blocks of different densities were assumed: the block of highest density below the Dinarides, the block of intermediate density below the Transition zone and the block of lowest density below the Pannonian crust, with densities of 3.3, 3.21 and 3.18 g cm^{-3}, respectively. In this model, relatively low densities were obtained for the

Pannonian crust (2.59 g cm^{-3}). Therefore, the densities lower than 2.69 g cm^{-3} for the crust were not considered, which are generally logical, and consequentially, in the final model lateral density variations were reduced to only two values in the upper mantle, 3.3 g cm^{-3} below the Dinarides and 3.25 g cm^{-3} below the Pannonian crust and the major part of the Transition zone (Figs. 4 and 6). The impact of this variable density for the upper mantle can be clearly seen on the presented curves in the Fig. 4.

The discussed density values are illustrated by the selected characteristic example of profile GP-3 (Fig. 6). The figure shows two discussed density models, the models with two and three blocks in the upper mantle. It should be emphasized that the analysis clearly points out that both calibrated density models result in very similar structural relations. All structural units (Dinaridic crust, Pannonian crust and Transition zone) can be easily followed in both density models. The interface depths, particularly of the Mohorovičić discontinuity, also do not significantly change regardless of the applied density model. However, the density model with two blocks in the upper mantle is more acceptable as it gives more reasonable densities in the crustal part. But the asymmetrical flanks for the deepest Moho below the Dinarides are clearly documented (Fig. 6). In the case of symmetrical flanks at the Moho, a mass deficiency on the northern flank causes significant discrepancy of measured and modelled data (blue curve in the Fig. 6). This situation can be also followed on all other gravity profiles (Fig. 5).

9. Tectonic interpretation

In order to define more clearly the surface of the Mohorovičić discontinuity, its values were interpolated between the density models of the profiles and a structural map was constructed. Due to the marked 2-D shape of the structures, it can be considered that the interfaces on the profiles were relatively accurately determined, thus the map would also define well depth relations across the entire study area (Fig. 7).

The map indicates a constant width of the Dinarides root, with changes only of the Moho depth. In the area of the Alp07 profile, the maximum depth of the Mohorovičić discontinuity equals approximately 40 km, while in the SE area, on the GP-5 and GP-6 profiles, it is about 46 km. The shallowest Mohorovičić discontinuity is located in the Pannonian basin, in the NE of the study area, where the depths are less than 20 km. But, it should be noted a thicker crust would be obtained in the Pannonian basin, meaning at the ends of the profiles GP-3, GP-5 and GP-6, if crustal densities would be greater (Fig. 5a and b). Lateral changes of densities can be hardly discovered on the basis of gravity data, therefore constant lateral properties were supposed. The maximum is also located in the southernmost part of the South Adriatic, SE of Dubrovnik, with depths equalling approximately 26 km.

All main structural elements can be already recognized on the gravity map, although some important differences can be seen as well, i.e. some elements cannot be recognized. Thus the gravity minimum widens and deepens from the NW towards the SE, whereas the minimum on the structural map is generally of constant width. The gravity maximum in the South Adriatic is higher than the maximum in the Pannonian basin. But the situation is the opposite on the structural map, the maximum is significantly higher and more marked in the Pannonian basin than the one in the Adriatic (Figs. 3 and 7). The structural map shows very steep dips in the Mohorovičić discontinuity and a sudden increase in depth on the south and north side of the

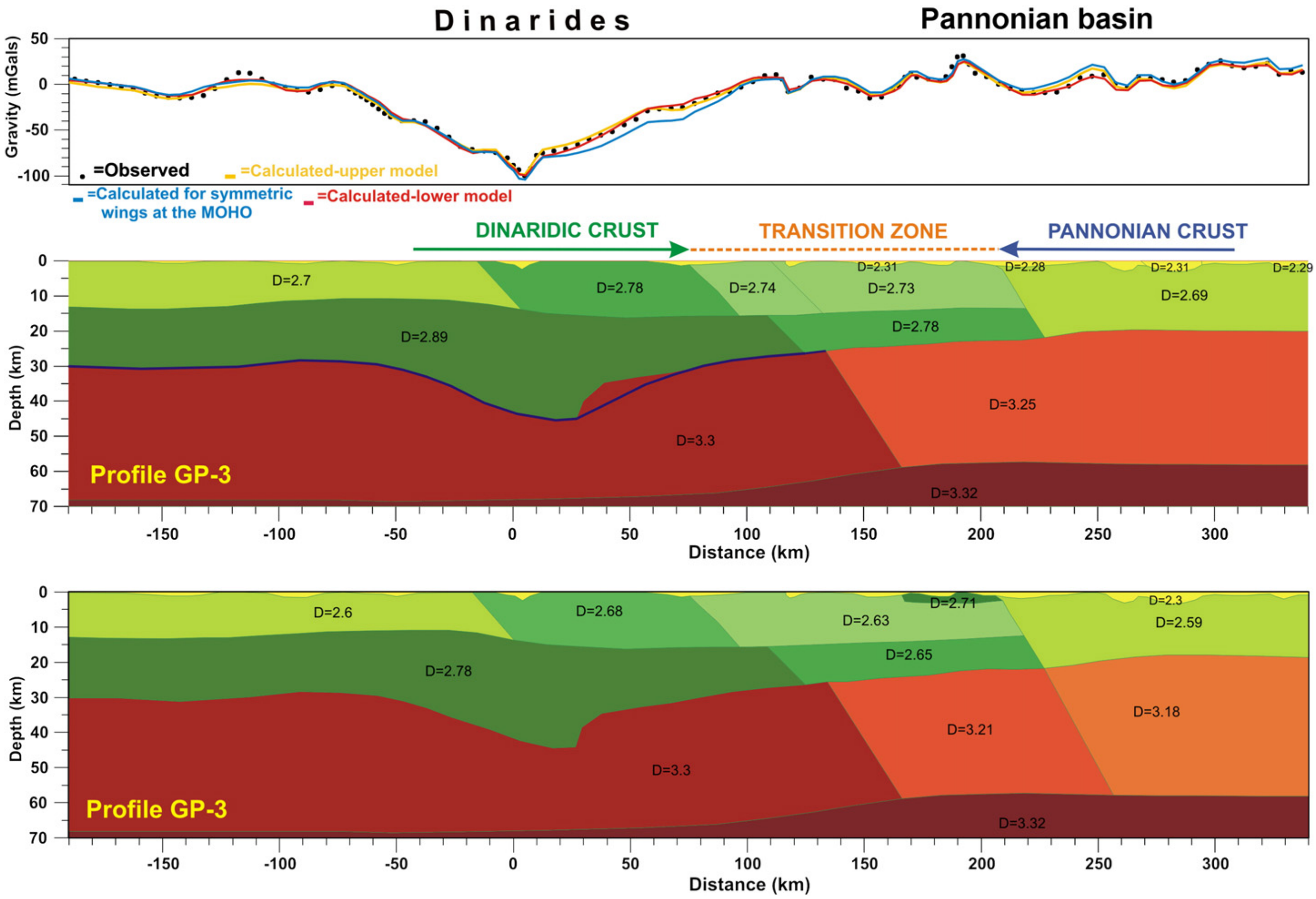

Fig. 6. Density analysis on the GP-3 profile. Gravity models are obtained by the use of two different sets of calibrated densities. The final calibrated densities are shown in the upper part, while the lower part shows higher lateral variation of the upper mantle densities causing very low crustal densities.

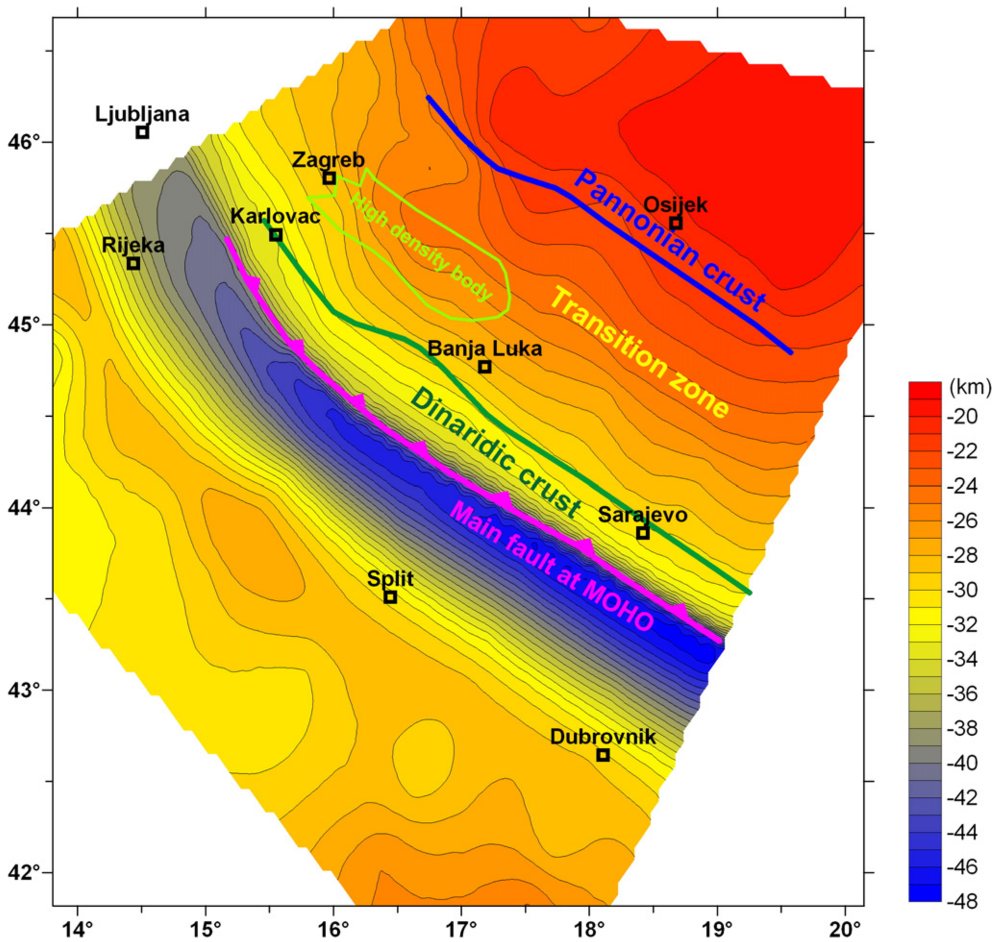

Fig. 7. Structure map of the Mohorovičić discontinuity, which is designated by using two-dimensional gravity models of the profiles, with main tectonic features.

Dinarides. This subsidence of the Moho is particularly marked on the north side of the Dinarides, at the contact with the Pannonian basin, where, based only on structure geometry, subduction can be assumed and main fault on the Moho is designed.

For the purpose of easier geological interpretation, the main structural elements are presented on the Moho map of the study area (Fig. 7). The map shows the boundaries between the Pannonian crust, Transition zone and Dinaridic crust in the surface part. All boundaries are evidently parallel and strike in the general Dinaridic NW–SE direction. The map shows clearly a relatively wide contact zone, i.e. Transition zone. A High Density Body (HDB), interpreted as a block of oceanic-crust rocks, stretches in the same direction, but only in the NW area of the Transition zone, mainly beneath the Sava depression.

When comparing the position of the Transition zone with the tectonic map by Schmid et al. (2008, Fig. 2), it can be concluded that it corresponds with the Sava and the Dinaridic ophiolite zones. However, the Transition zone is significantly wider than the ophiolite zones. The NE boundary of the Transition zone generally corresponds with the Drava fault (Fig. 2), whereas the Tisia block stretches relatively deep below the Drava fault. It could be said that, based on both data sets the seismic and the gravity modellings, the Tisia block is actually the Pannonian crust while the Dinaridic crust would be related to the structural units of the Adriatic. The SE boundary of the Transition zone generally corresponds with the contact of the ophiolite zones and the Dinarides on the tectonic map, which is in general the south marginal fault (SMF) of the Pannonian Basin.

Very clear difference in geophysical properties, densities and seismic velocities, of the Dinaridic and Pannonian crusts approves their different geneses. SMF is mainly thought as a contact of the Pannonian and the Adriatic, but wide Transition zone could be considered as a wide suture zone between them. According to both geophysical models, this zone consists of elements of both, the Pannonian and the Adriatic. The zone can be also considered as a mix of oceanic-crust and continental-crust rocks. HDB in the gravity model indicates directly the presence of the oceanic-crust rocks. This body stretches in a great block in the NW part of the Transition zone (Fig. 7), on the profiles Alp07, GP-1 and GP-2 (Figs. 4 and 5a), but it doesn't mean there is no oceanic-crust rocks in the SE part of the Transition zone, on the profiles GP-3, GP-5 and GP-6 (Fig. 5a and b). The rocks could occur in smaller blocks that couldn't be seen as separate blocks due to resolution of the applied methods. Different upper mantle densities in the gravity model also point to the contact of the plates below the Transition zone, but to the different origins of the Pannonian and the Adriatic, as well (Figs. 4 and 5).

The boundaries of individual crustal parts correlate well with the seismicity of the study area shown through positions of earthquake epicentres (Herak et al., 1996, updated in 2006, Fig. 8). All foci are located within the crust, mostly to a depth of about 20 km, but in some areas under the Dinarides a depth of 34 km has been obtained (Kuk et al., 2000). At the level of the Moho no events have been observed. Accordingly, these data also indicate different crustal properties. The highest earthquake density is observed in the area of the Dinaridic crust, appearing in two separate areas, which points to a very intensive movements. The first area stretches over a wide area from Split to Dubrovnik, and continues further in SE direction. The second area is located in a relatively narrow zone around Rijeka. Both areas stretch in the Dinaridic direction (Fig. 8). Very rare earthquakes, mostly of low intensity, are located in the area of the Pannonian crust (the area of the Tisia block) indicating a stable plate. In the Transition zone, an intermediate earthquake density is observed, but with spot concentrations

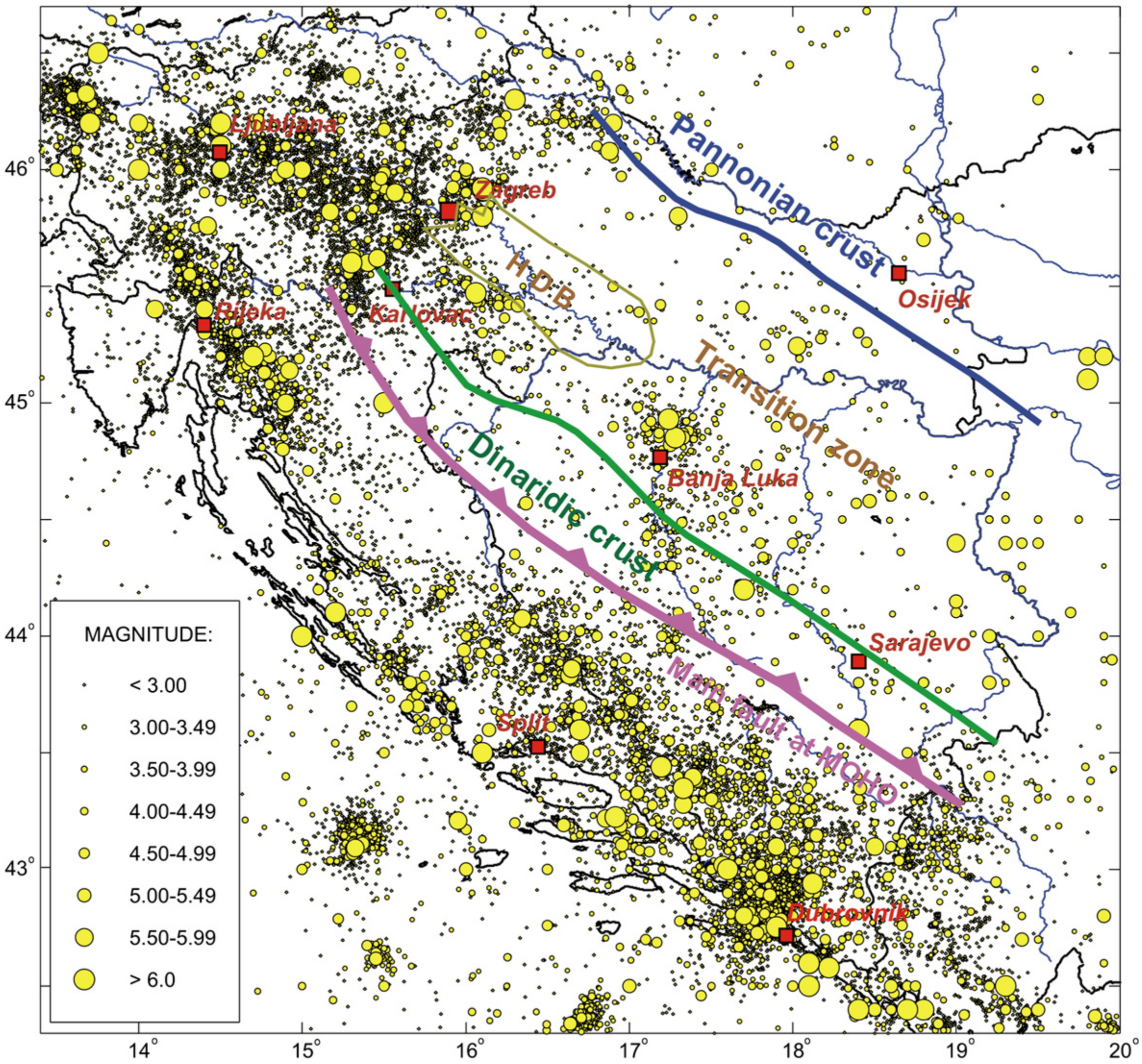

Fig. 8. Correlation of the main interpreted tectonic features with the seismicity of the area, shown through positions of the epicentres (HDB — High Density Body).

of earthquakes in locations around Banja Luka and in the area of Pokuplje at the boundary of the HDB zone. These earthquakes point to intensive movements inside the crust in the transition from Pannonian to Dinaridic parts. It should be of interest to note that it was precisely an earthquake in Pokuplje, in the vicinity of Zagreb, that prompted Mohorovičić (1910) to discover the main discontinuity in the lithosphere, which was later named after him. The main fault in the upper mantle is located exactly on the NE boundary of the area with the highest earthquake density.

10. Conclusions

Good quality seismic data and gravity modelling along the Alp07 profile offered information on the crustal structure and densities of the lithosphere in the transition area between the Dinarides to the Pannonian basin. The basic structural units were defined as well as the depths of the interfaces, particularly of the Mohorovičić discontinuity. Seismic data, which enable the achievement of significantly higher resolution in comparison to gravity data, were used for density calibration. The interpretation procedure consisted of three main steps. In the first step, seismic modelling was applied on the Alp07 profile in order to determine the structure of the crust and the upper mantle. In the second step, gravity modelling was applied in order to reduce the ambiguity of the interpretation. By the use of interfaces from the seismic model that remained fixed, calibrated densities were obtained, which were used in the third step in the wider study area for determination of the structural relations. This procedure significantly improved the resolution of the gravity modelling.

The units defined on the Alp07 profile (Pannonian crust, Dinaridic crust and Transition zone) can be very easily followed on all other profiles from GP-1 to GP-6. The shallowest Mohorovičić discontinuity is located in the Pannonian basin and the deepest in the Dinarides. The Mohorovičić discontinuity in the Dinarides root is shallowest on the Alp07 profile with the smoothest flank slope, while the depths strongly increase on the GP-1 and GP-2 profiles and the borders become very steep, furthermore on the other profiles the depths and the flank slopes remain similar.

The High Density Body (HDB), which is defined on the Alp07 profile and interpreted as a block of oceanic-crust rocks, is located only on the GP-1 and GP-2 profiles and belongs to the NW area of the Transition zone. The boundaries of the Transition zone defined on the profiles and presented on the Moho map show its great width and spreading since it covers the majority of the Pannonian basin in Croatia and Bosnia–Herzegovina. It corresponds with the Sava and Dinaridic ophiolite zones on the tectonic map, which was published by Schmid et al. (2008), but it is wider than the ophiolite zones. Based on geophysical data, the Tisia block corresponds with the Pannonian crust, while the Dinaridic crust would be related to the structural units of the Adriatic. However, the NE boundary of the Transition zone is located much further north than the boundary of the Tisia block and the ophiolite zones on the tectonic map.

Based on geometric relations that are particularly evident on the structural map of the surface of the Mohorovičić discontinuity, a conclusion can be drawn about the subduction of the Adriatic microplate. The subduction area, namely the contact of the microplates at the level of the upper mantle, is located on the NE flank of the Dinarides and is defined as the main fault. The boundaries of the individual crustal blocks correlate well with the seismicity of the study area (Herak et al., 1996, updated in 2006), where all foci are located within the crust, generally to the depths of about 35 km. The highest earthquake density is observed in the area of the Dinaridic crust. Very rare earthquakes, mostly of low intensity, are located in the area of the Pannonian crust, and the medium earthquake density is observed in the Transition zone.

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