GEOLOGICA CARPATHICA, APRIL 2005, 56, 2, 103 – 112

Geophysical and structural characteristics of the pre-Tertiary basement of the Mura Depression (SW Pannonian Basin, NE Slovenia)

ANDREJ GOSAR

Environmental Agency of the Republic of Slovenia, Dunajska 47, SI-1000 Ljubljana, Slovenia; andrej.gosar@gov.si
University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva 12, SI-1000 Ljubljana, Slovenia

(Manuscript received January 7, 2004; accepted in revised form June 16, 2004)

Abstract: The Mura Depression is located at the SW border of the Pannonian Basin in the transition zone to the Eastern Alps. The Periadriatic Lineament, Labot, Ljutomer and Raba faults govern its structural characteristics. Ridges trending in the NEE–SWW direction divide the depression into three sub-basins. Therefore, the thickness of Miocene to Quaternary sediments varies considerably. The greatest depth to the Paleozoic metamorphic rocks is over 5500 m in the Ptuj-Ljutomer synform. The structure of the pre-Tertiary basement is well resolved by seismic reflection, gravity and magnetic investigations, as well as by drilling for hydrocarbons and thermal water exploration. The main tectonic units of the Mura Depression were correlated by using geophysical data to the structures outcropping at its western and southern rims. A compiled structural map of the pre-Tertiary basement is presented and geophysical and structural characteristics of main geotectonic units discussed. Beside minor production of oil and gas, the Mura Depression is an important geothermal area. Some locations were also explored as promising for the construction of an underground gas storage facility in aquifers.

Key words: Pannonian Basin, Mura Depression, seismic reflection, gravity, magnetic, geothermal.

Introduction

The Mura Depression is one of the deep depressions of the Pannonian Basin system, and is situated at its SW rim. The largest part of the Mura Depression is located in NE Slovenia (Fig. 1), but it also extends into Austria, Hungary and Croatia. The Mura Depression is not a uniform sedimentary basin, but is divided into at least three sub-basins, by ridges trending in the NEE–SWW direction (Voncina 1965; Kisovar 1977). In Slovenia, the following tectonic units are distinguished (Fig. 2), listed from NW to SE: — Rdeci breg, — Radgona depression, — Murska Sobota massif, — Ptuj-Ljutomer synform, — Ormoz-Selnica antiform.

South-east from the Ormoz-Selnica antiform, the Cakovec depression is located within the Croatian territory (Mioc & Markovic 1998). The greatest depth to the pre-Tertiary metamorphic basement is over 5500 m, located west of Lendava in the Ptuj-Ljutomer synform (Plenicar 1970). The Mura Depression is an important geothermal area (Kralj & Kralj 2000), while the current production of oil and gas is rather low (Mioc & Znidarcic 1996). Some localities in the Mura Depression have potential for the development of an underground storage facility of natural gas in aquifers. Geophysical investigations related to this project are described in separate article in Gosar (2005).

In this article, an overview of geophysical data available for the Mura Depression, including gravity, magnetic, geothermal and seismic reflection data, is given. On the basis of these data sets and using borehole information, a structural map of the pre-Tertiary basement is presented. Geophysical and structural characteristics of the main geotectonic units are described and their correlation to the structures outcropping west and south of the Mura Depression is discussed. The interpretation of two seismic reflection profiles together with gravity and magnetic profiles from the NW part of the Mura Depression are presented, to put in a regional context a detailed seismic reflection investigation performed for underground storage of gas in aquifers of the Pecarovci and Dankovci structures located on the Murska Sobota massif.

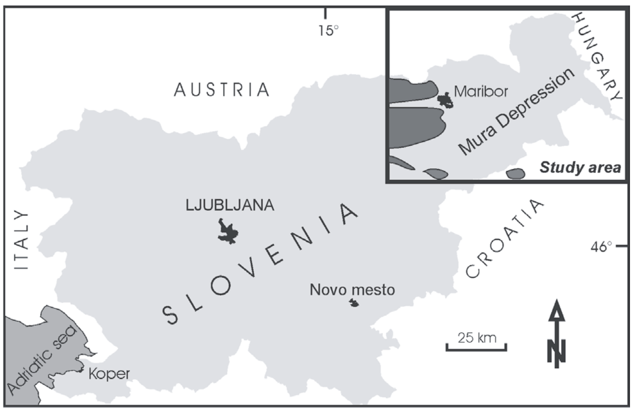

Fig. 1. Location map of the Mura Depression. Dark areas — outcrops of the pre-Tertiary basement.

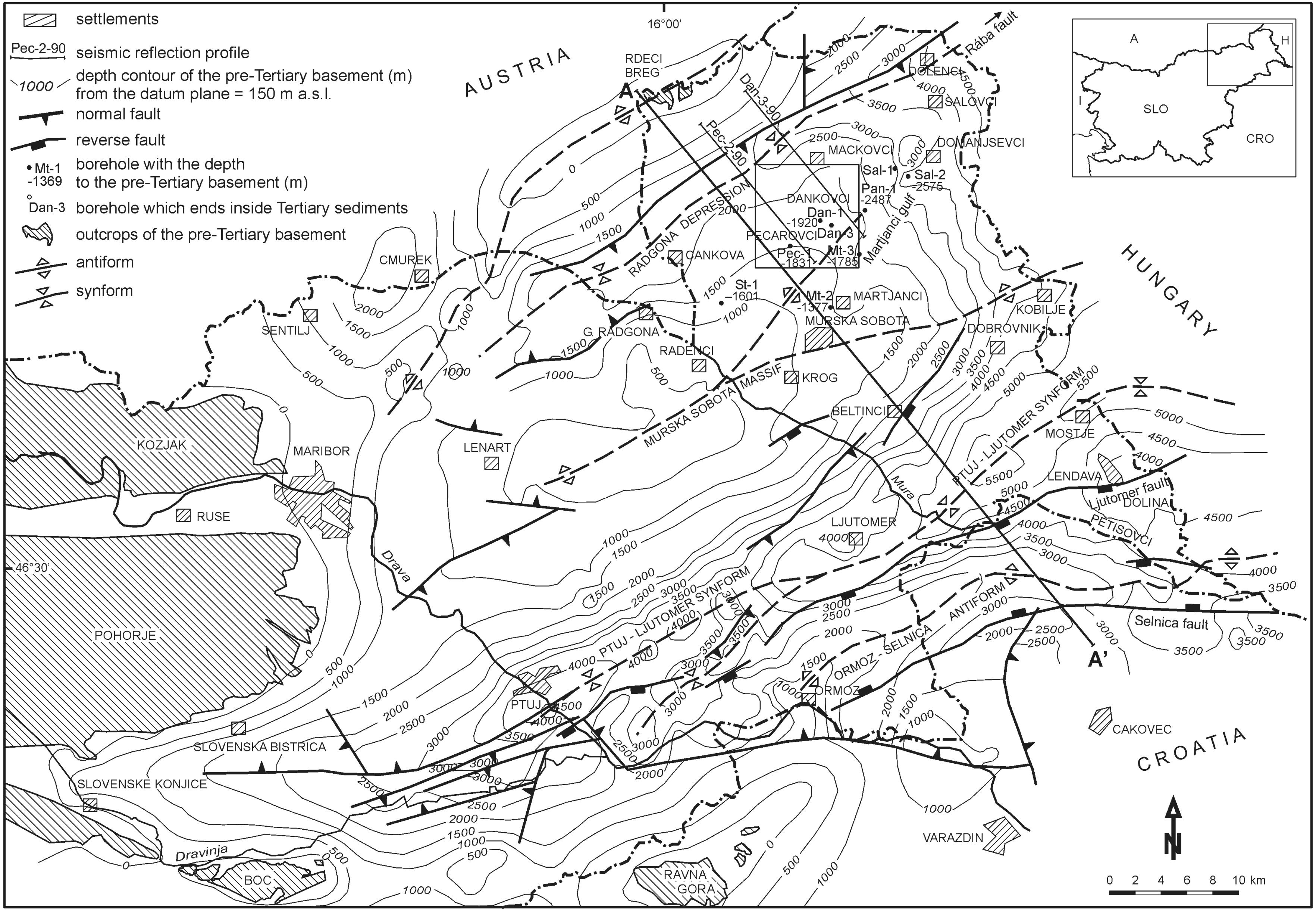

Fig. 2. Structural map of the pre-Tertiary basement in the Mura Depression. Cross-section A–A' shown in Fig. 6 and two seismic reflection profiles shown in Fig. 7 are indicated. The square area indicates detailed reflection profiling for underground gas storage in aquifers.

Geological setting

The Mura Depression is situated in the transition zone between the Alps, the Dinarides and the Pannonian Basin. This results in its quite complex structural pattern (Haas et al. 2000). To the west, the Mura Depression is confined by the Boc, Pohorje and Kozjak Mountains (Fig. 2) and to the south by the Donacka gora, Ravna gora, Ivanscica and Kalnik Mountains in Croatia. To the north and north-east, the border is represented by outcrops of Paleozoic rocks at Gleichenberg in Austria and at Közag in Hungary. From the Steiermark depression, towards the NW, it is separated by the structural height of Burgenland (Kroell et al. 1988) and from the Drava depression towards the SE, it is separated by the Inka massif. Separation from the Zala depression in the NE is not so clearly evident. Therefore, some authors (e.g. Márton et al. 2002) consider both depressions collectively as the Mura-Zala Basin. The total area of the Mura Depression is 3300 km^2, from which 2460 km^2 belongs to Slovenia.

The Mura Depression was formed due to a ENE–WSW trending crustal extension in the late Early Miocene (Márton et al. 2002). Firstly, marine sedimentation took place. Later, during thermal subsidence, deltaic and fluvial sediments were deposited. The main deformation took place in the latest Miocene–Pliocene as a result of NNW–SSE compression, which caused folds, reverse and strike-slip faults (Márton et al. 2002). The tectonic background is controlled by major faults, such as the Periadriatic Lineament, Rába, Labot and Donat faults (Fodor et al. 2002). The eastern continuation of the Periadriatic Lineament is most probably related to the Ljutomer fault and the mid-Hungarian line. These tectonic lines separate areas with different Paleogene and Early Miocene sedimentation (Sachsenhofer et al. 2001). The Ljutomer fault was formed in late Early Miocene as a normal fault and was reactivated in post-Miocene times as a reverse fault. It separates the Ptuj-Ljutomer synform filled with more than 5000 m thick Neogene sediments from the Ormoz-Selnica antiform (Fig. 2). Basin inversion, younger than the steep dipping Late Miocene sediments (Sachsenhofer et al. 2001), and the formation of anticlines is caused by rotation of blocks north of the Ljutomer fault and by dextral movements along the Labot fault (Fodor et al. 1998) situated at the SW rim of the Pohorje Mountain.

Lithostratigraphy

Pre-Tertiary basement. In the deep boreholes drilled within the Mura Depression, mainly Paleozoic metamorphic rocks were found beneath the Tertiary sediments. They outcrop in the western and southern border of the depression and in Rdeci breg. They are composed of quartz-sericite schists, phyllite and phyllite schists, amphibolites, pyroxenite and gneiss. In some places, on the top of the metamorphic rocks, Mesozoic rocks (limestone, dolomite and, also locally, lime marl and breccia) were found. In some places, their thickness is only tens of meters, but in others up to several hundred meters. During Tertiary and Quaternary, the basement was faulted and thrusted, leaving fractures that were widened in some places by dissolution (Rajver et al. 2002).

Neogene sediments. In the Mura Depression Miocene clays, sands, marls, sandstones and conglomerates as well as Pliocene clayey sediments prevail. Correlation of lithostratigraphic and chronostratigraphic units in the Mura Depression was presented by Znidarcic & Mioc (1989) and for the whole Pannonian Basin by Horváth & Pogácsas (1988). The Neogene sediments are divided into the Murska Sobota, Lendava and Mura Formations. The Murska Sobota Formation is up to 2000 m thick and comprises Lower and Middle Miocene units, including Eggenburgian (M_1, average thickness is 400 m), Ottnangian (M_2, 300 m), Karpatian (M_3, 300 m), Badenian (M_4, 350 m) and Sarmatian (M_5, 300 m) stages according to Central Paratethys divisions (Steininger et al. 1988). The Lendava Formation is up to 1500 m thick and consists of Upper Miocene and possibly Lower Pliocene rocks, including the Pannonian (M_6, 300 m) and Pontian (M_7 or Pl_1, 650 m) stages. The youngest Mura Formation is up to 1500 m thick and corresponds in its entirety to Pliocene rocks of the Dacian (Pl_1 and Pl_2) to Romanian (Pl_3) stages (Turk 1993). Upper Pliocene volcaniclastic sediments and alkali basalts related to basaltic volcanism in the neighbouring Styrian Basin are found in the central part of the Radgona depression (Kralj 2000).

Quaternary sediments. Quaternary sediments cover the whole Mura Basin, the Drava-Ptuj Lowland and large areas in Goricko, Slovenske gorice and Haloze. The Pleistocene cover is composed of sandy clay with lenses of gravel and sandy gravel in fluvial terraces. These sediments are up to 35 m thick. The Holocene layers are composed mainly of marsh sediments, deluvium, proluvium and alluvium deposits up to 15 m thick.

Geophysical data

Gravity, magnetic, geothermal and seismic reflection data acquired in the Mura Depression during more than 50 years were compiled from different published and unpublished sources. Potential filed data were mainly acquired in the 1950's and 1960's and are preserved in the archives of Geoinzeniring and Geological Survey of Slovenia in Ljubljana.

The Bouguer anomaly gravity map of the Mura Depression shown in Fig. 3 was constructed from 3700 points measured with an average density of 1.5 points/km^2 using Worden gravity meter (Urh 1956; Plenicar 1970). Bouguer anomalies were calculated using reference density values between 1.9 and 2.2 g/cm^3 derived from several profiles using the Nettleton method. Data were reduced to the datum plane of 150 m a.s.l. which is very close to the lowest elevation of the surface in the area. Terrain corrections were computed in a radius of 10 km using segmentation by concentric circles and radial division lines.

A magnetic map of the Mura Depression (Fig. 4) was extracted from the regional map of the vertical component of the magnetic field in Slovenia (Ravnik et al. 1995a). This is based on the surface magnetic measurements with an average density of 2 points/km^2 using balance magnetometer Ruska and torsion magnetometer Askania (Novak 1959; Miklic 1969). Therefore, the vertical component of the magnetic field is pre-

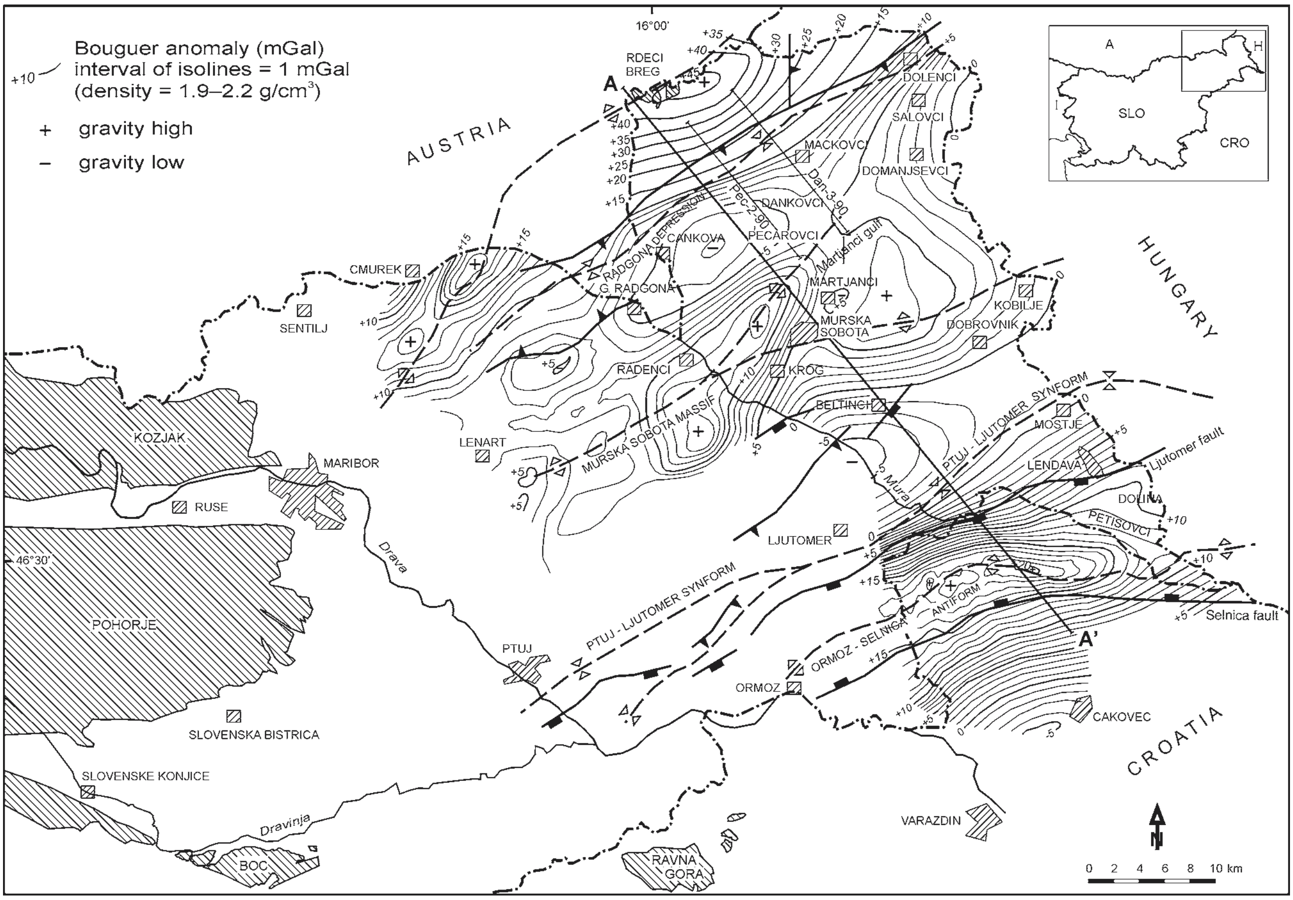

Fig. 3. Bouguer anomaly map of the Mura Depression (after Urh 1956). A–A' indicates cross-section shown in Fig. 6.

sented in the Fig. 4. Normal geomagnetic field was removed according to Bock (1959) with coefficients extrapolated for the epoch 1969. Smaller parts of the Mura Depression were later surveyed for the project of underground gas storage also with proton precession magnetometer. There was no aeromagnetic survey performed in this region yet.

The Mura Depression is an important geothermal area characterized by increased heat flow density in comparison to the other parts of Slovenia. Heat flow density is in the range of 80 to 120 mW/m^2 (Fig. 5). The highest values were detected between Lenart, G. Radgona and Murska Sobota within the Murska Sobota massif and on the SE flank of the Radgona depression (Ravnik et al. 1995b). The most important geothermal aquifers are Pliocene and/or Upper Miocene sands within the Mura Formation. They have an effective maximum thickness of 60 m, dipping from the surface down to the depths of 1500 m (Kralj & Kralj 2000). The thermal waters have temperatures of up to 80 °C. Mineralization (1–7 g/l) is mainly dependent on CO_2 content. Fig. 5 shows the temperature distribution in the Mura Depression at the depth of 1000 m (Rajver et al. 2002). Temperature gradually increases from the south-west part of the Mura Depression towards the Murska Sobota massif.

Altogether, more than 2000 km of reflection seismic profiles (Djurasek 1988; Gosar 1995) have been acquired to date within the Mura Depression, mainly due to hydrocarbon prospecting. The density of seismic profiles varies considerably. The densest coverage is close to the Lendava in the SE Mura Depression, where the oil and gas fields of Petisovci and Dolina are still producing, and near Dobrovnik, where the Filovci field has already been closed. Most of the profiles were recorded by Geofizika Zagreb using line explosive sources (Geoflex and Primacord). The distance between geophone groups was 30–40 m and CMP (common-midpoint) coverage 24 or 30 fold. Some newer profiles were recorded using the Vibroseis source. Data processing, using standard processing flow was performed mainly by INA-Naftaplin in Zagreb (Djurasek 1988).

Structure of the pre-Tertiary basement

The structural map of the pre-Tertiary basement was constructed using the interpretation of seismic reflection profiles and the data from about 40 exploration boreholes that reached the basement. In the area NE of the Mura river it is based on the map drawn by Djurasek (1989), which does not cover other parts of the depression. This part of the map was also modified according to newly acquired data and using improved seismic velocity information from reflection profiling and measurements in boreholes, which allowed more accurate time to depth conversion (Gosar 2005). The main tectonic

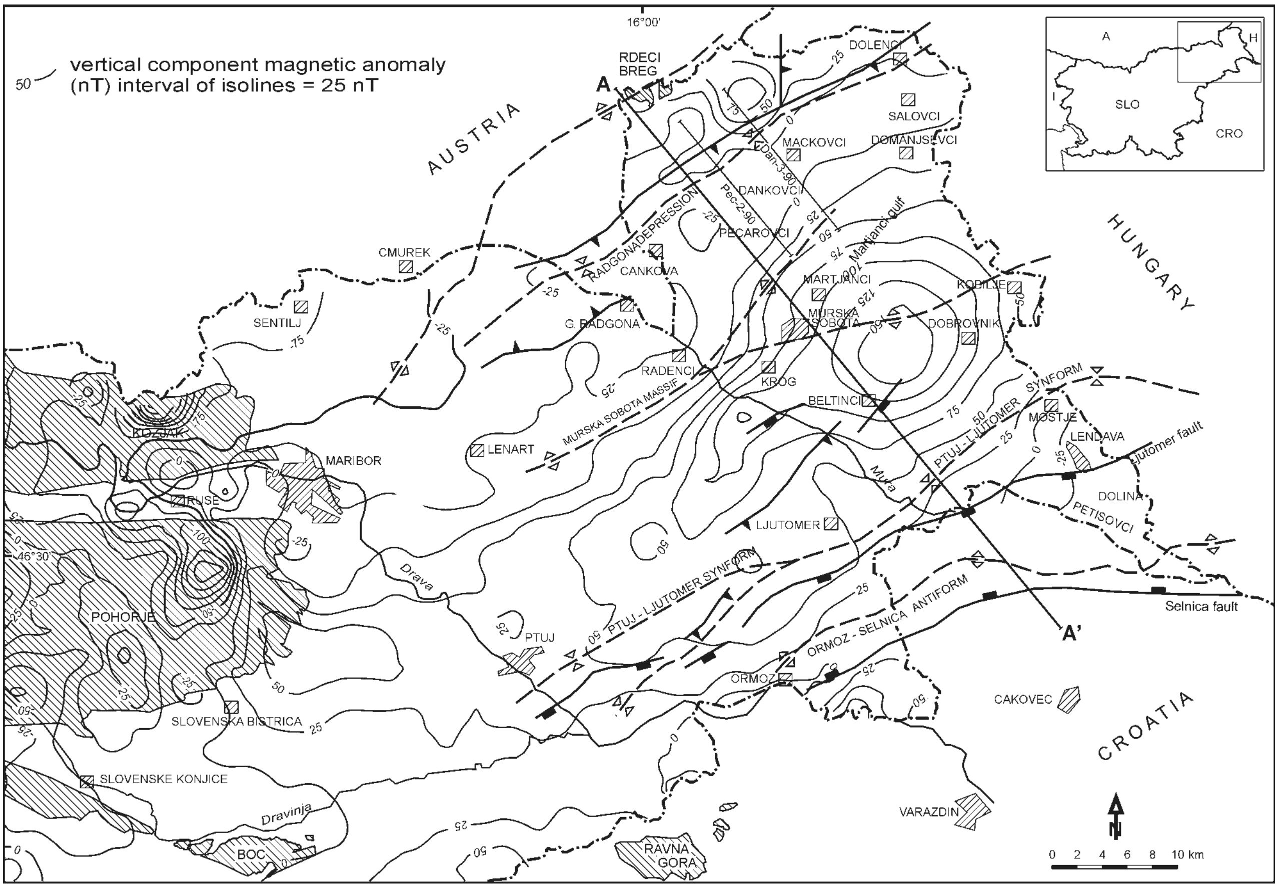

Fig. 4. Map of the vertical component of the magnetic field in the Mura Depression (after Miklic 1969 and Ravnik et al. 1995a). A–A' indicates the cross-section shown in Fig. 6.

units of the Mura Depression are shown in the structural map of the pre-Tertiary basement (Fig. 2), in gravity (Fig. 3), magnetic (Fig. 4) and temperature/heat flow density (Fig. 5) maps, and in a regional cross-section Rdeci breg-Cakovec (Fig. 6).

The topography of the pre-Tertiary basement is well reflected in the map of Bouguer anomalies (Figs. 3 and 6) which shows the main structures stretching in a SW–NE direction. Axes of antiform structures correspond fairly well with the gravity maximums, while there is a discrepancy between the axes of synform structures (Radgona depression, Ptuj-Ljutomer synform) and gravity minimums. The observed shifts are discussed later. The main tectonic units are not so well reflected in a magnetic map (Fig. 4) as in gravity data, especially in the SE part of the Mura Depression. It seems that lateral variations in susceptibility or deeper structures have greater influence on the magnetic anomalies than the topography of the metamorphic rocks. Since the metamorphic basement was drilled only in a few boreholes, the boundaries between different lithological units are only roughly known. Moreover, metamorphic rocks are covered with Mesozoic carbonates and clastic sediments in the Radgona depression, the SE part of the Ptuj-Ljutomer synform and the Ormoz-Selnica antiform.

Rdeci breg. Outcrops of quartz-sericite schists and phyllite at the border between Slovenia and Austria are the only outcrops of the metamorphic rocks inside the Mura Depression. They are expressed as prominent positive magnetic (+150 nT) and gravity (+46 mGal) anomalies. The latter continues to the SW into the Cmurek anticline (+18 mGal). Both are the eastward continuation of the Kozjak Metamorphic Complex. There is a strong fault separating Rdeci breg from the Radgona depression (Poljak 1984). It can be correlated with the Kungota fault to the SW (Znidarcic & Mioc 1989) and to the Rába fault, or a fault parallel to it, to the NE, in Hungary.

Radgona depression. The Radgona depression is located south of the structural height of Burgenland, which separates the Mura Depression from the Steiermark depression. It is a continuation of the Ribnica-Selnica tectonic graben located between the Kozjak and Pohorje Mountains (Znidarcic & Mioc 1989). The pre-Tertiary bedrock dips in a NE direction from the depth of 1700 m at Cankova to 4500 m at Dolenci. The NW slope of the depression towards the Rdeci breg is quite steep, producing a lateral gravity gradient of 5–7 mGal/km. Radgona depression has two closed minimum areas: +5 mGal between Lenart and G. Radgona and –5 mGal at Cankova, pointing to two smaller sub-basins. The third minimum to the NE has at Salovci a value of 0 mGal, but continues further into Hungary. The axis of gravity minimums is shifted to the SE with respect to the axis of the basement topography in the depression as is derived from seismic reflection data. Since only a few boreholes were drilled in the area through the Mesozoic carbonates and clastic sediments to the metamorphic rocks, there is not yet enough data about the lateral extent

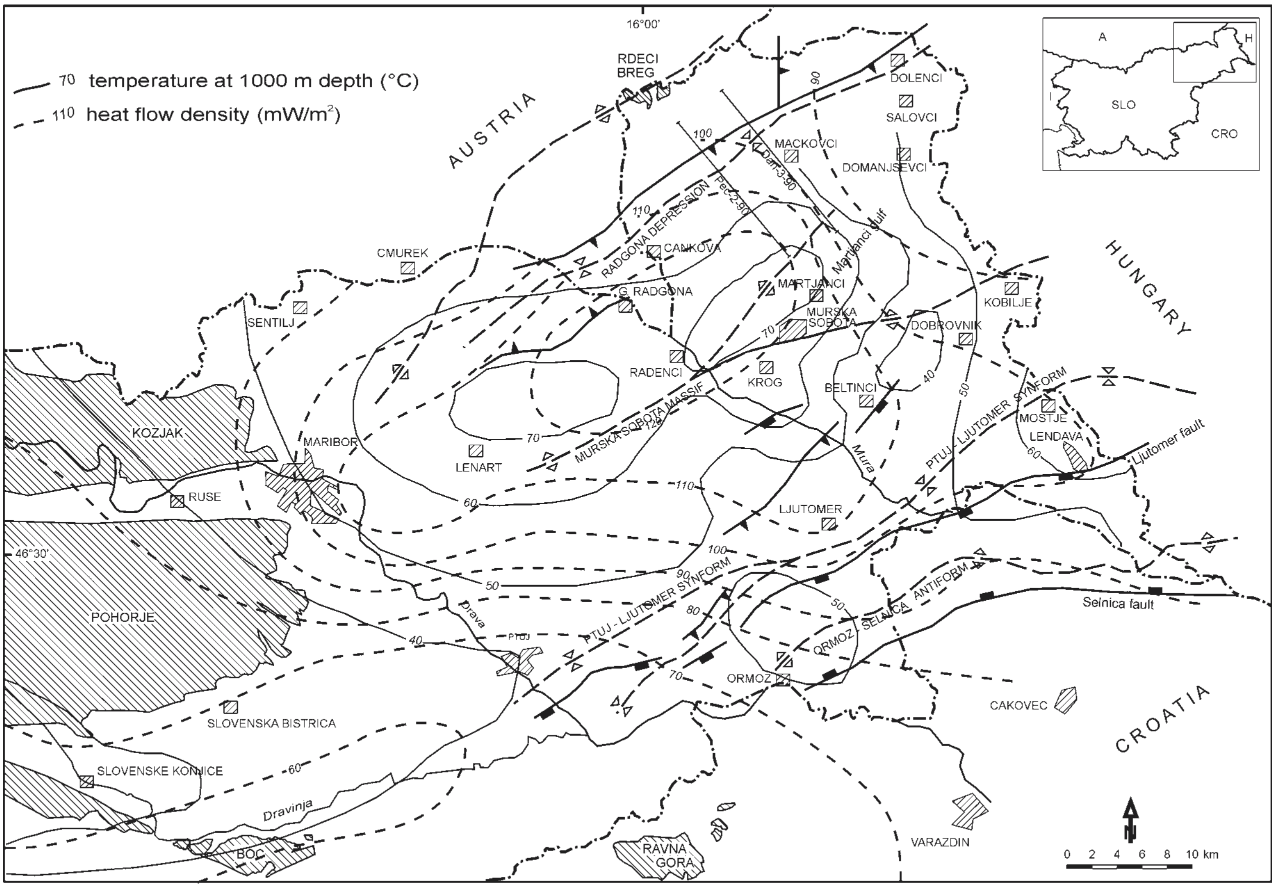

Fig. 5. Geothermal map of the Mura Depression. Temperatures (°C) at 1000 m depth (after Rajver et al. 2002) and heat flow density (mW/m^2) (after Ravnik et al. 1995b).

of individual lithological units and their densities to give an explanation for this observation. In the magnetic data the Radgona depression is expressed in its SW part as elongated negative anomaly (–25 nT). The small circular positive anomaly (+75 nT) NW of Mackovci is related to the Upper Pliocene basalts and basaltic tuffs.

Murska Sobota massif. This structure represents a direct continuation of the Pohorje Metamorphic Complex below the Neogene sediments of the Pannonian Basin. It is very clearly reflected in gravity and magnetic data. At Krog, it is split into two ridges: the northern one is the Murska Sobota ridge and the southern the Martjanci ridge. In-between is the Martjanci "gulf". In the SW part of the massif, the depth to the basement is between 400 and 500 m, while at the Murska Sobota it is in the range of 1100–1200 m. The Murska Sobota massif is cut by several minor faults with maximum displacements of several tens of meters. In the gravity map the Murska Sobota massif is expressed as a clear elongated positive anomaly with two maximums (+13 and +12 mGal). East of the Murska Sobota there is a wide plateau (+6 mGal) related to the Martjanci gulf. On the other hand, in the magnetic map there is a prominent positive anomaly (+150 nT), which is clearly shifted towards the SE with respect to the structural height of the Murska Sobota massif. Since in the NE part of the Murska Sobota massif all the boreholes were stopped in the Mesozoic carbonates and clastic sediments overlying the metamorphic rocks, it is not possible to make any estimation on lateral lithological variations in the metamorphic rocks to cause this discrepancy. The measured susceptibility of the amphibolites, pyroxenite and gneiss prevailing in the area also cannot explain the relatively high amplitude of this anomaly. Therefore, it is most probably that it is caused by a deeper unknown structure comprised of metamorphic rocks with higher susceptibility. Within the Murska Sobota massif the highest values (70 °C) of temperature at 1000 m depth in the whole Mura Depression were measured near Murska Sobota and between Lenart and Radenci. At the same time this is the area of highest heat flow density (120 mW/m^2). Within the Murska Sobota massif, two structures (Pecarovci and Dankovci) having potential for underground storage of gas in aquifers were also explored (Gosar 2005).

Ptuj-Ljutomer synform. This is the deepest sub-basin of the Mura Depression, which continues into the Zala depression in Hungary. It is separated from the Ormoz-Selnica antiform by the prominent Ljutomer fault. Gravity measurements covered only the NE part of the Ptuj-Ljutomer synform, but there is a clear shift of the gravity minimum observed between Ljutomer and Beltinci (–5 mGal) towards the NW with respect to the deepest part of this synform (5500 m) located between Ljutomer and Mostje. In the area between Ljutomer, Mostje and Lendava the metamorphic rocks are covered with Mesozoic carbonates and clastic rocks. On the other hand, between Bel-

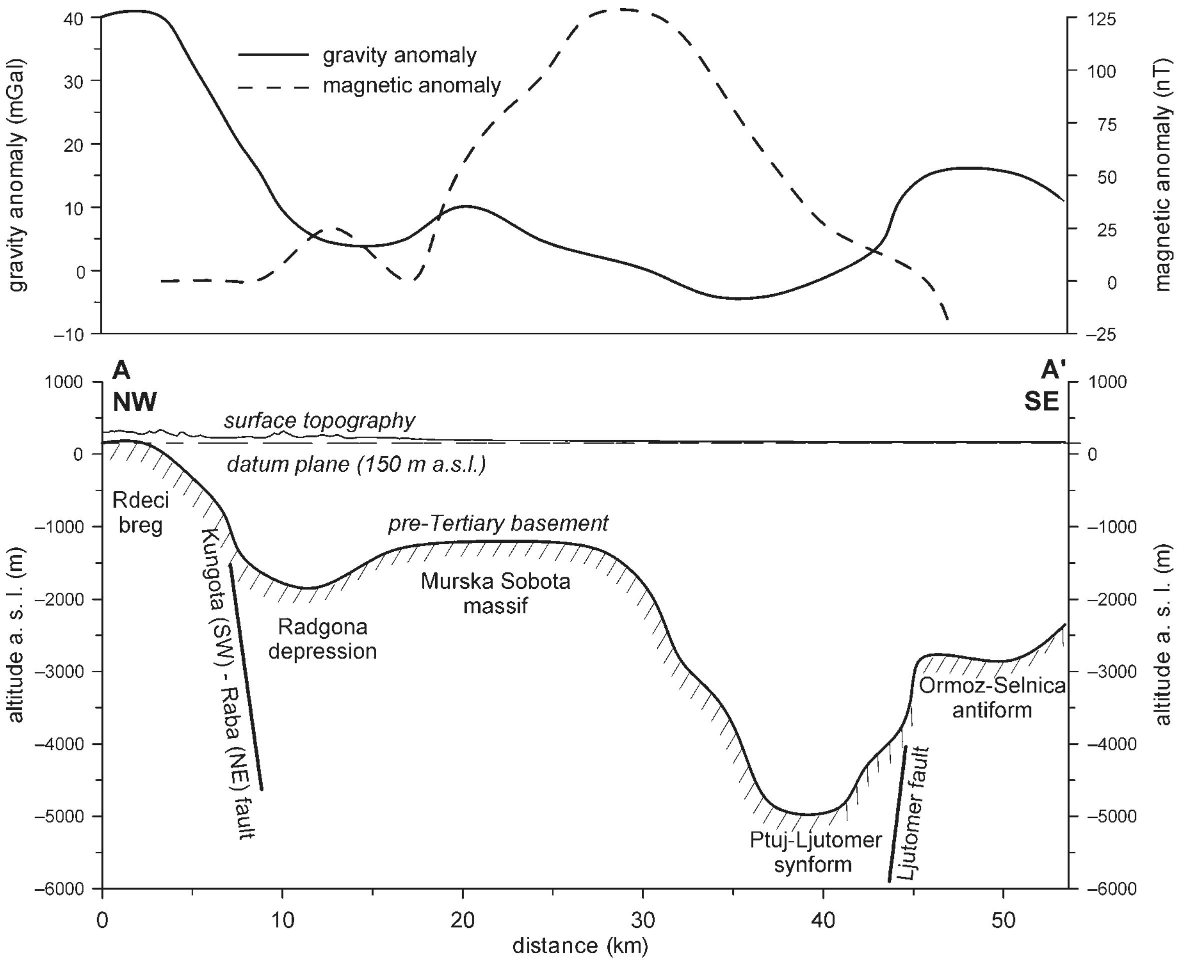

Fig. 6. Regional cross-section across the Mura Depression showing the topography of the pre-Tertiary basement, gravity and magnetic profiles.

tinci, Dobrovnik and Domanjsevci there are amphibolites and pyroxenites laying directly under the Neogene sediments. The variation of lithology and density of the pre-Tertiary basement is therefore not sufficiently known to explain the observed shift of the gravity minimum, which can be caused also by deeper structures. In spite of the fact that the strong positive magnetic anomaly (+150 nT) is also shifted from the Murska Sobota massif towards the Ptuj-Ljutomer synform, there is a clear minimum in the magnetic anomaly (–25 nT) related to the deepest part of the Ptuj-Ljutomer synform. Quite low temperatures (40 °C) were encountered in the transition zone between the Murska Sobota massif and the Ptuj-Ljutomer synform near Beltinci and Dobrovnik.

Ormoz-Selnica antiform. This structure is strongly deformed in longitudinal and transversal directions and confined by the Ljutomer and Selnica faults. In the gravity data, the Ormoz-Selnica antiform is expressed as a strong positive anomaly (+20 mGal) which diminishes towards the NE. This is in agreement with the dipping of the bedrock from 2500 m in the central part of the antiform to the depth of 4000 m on the border with Hungary. Gravity data show that the northern limb of the structure towards the Ptuj-Ljutomer synform is steeper than the southern limb dipping towards the Cakovec depression. Only the small part of the Ormoz-Selnica antiform which belongs to Slovenia is covered by the magnetic data. The maximum value of the magnetic anomaly is +75 nT. In the NE part of this unit, there are oil and gas fields at Petisovci and Dolina. These are the single hydrocarbon accumulations in the Mura Depression, which are still in production.

Interpretation of two regional seismic reflection profiles

In the next section, the interpretation of two regional seismic reflection profiles recorded in the NW part of the Mura Depression is presented, together with gravity and magnetic profiles, and correlated with the profile recorded approximately 20 km to the NE, within the Zala Basin situated in Hungary.

The seismic reflection profiles, Dan-3-90 and Pec-2-90 (Fig. 7), are located in a NW–SE direction 4 km apart, across three tectonic units which spread in a SW–NE direction: Rdeci breg, the Radgona depression and the Murska Sobota massif (Fig. 2). The profiles are 15 and 14 km long respectively. The basic structural characteristics of both profiles are similar. In the NW, the pre-Tertiary metamorphic bedrock is approaching

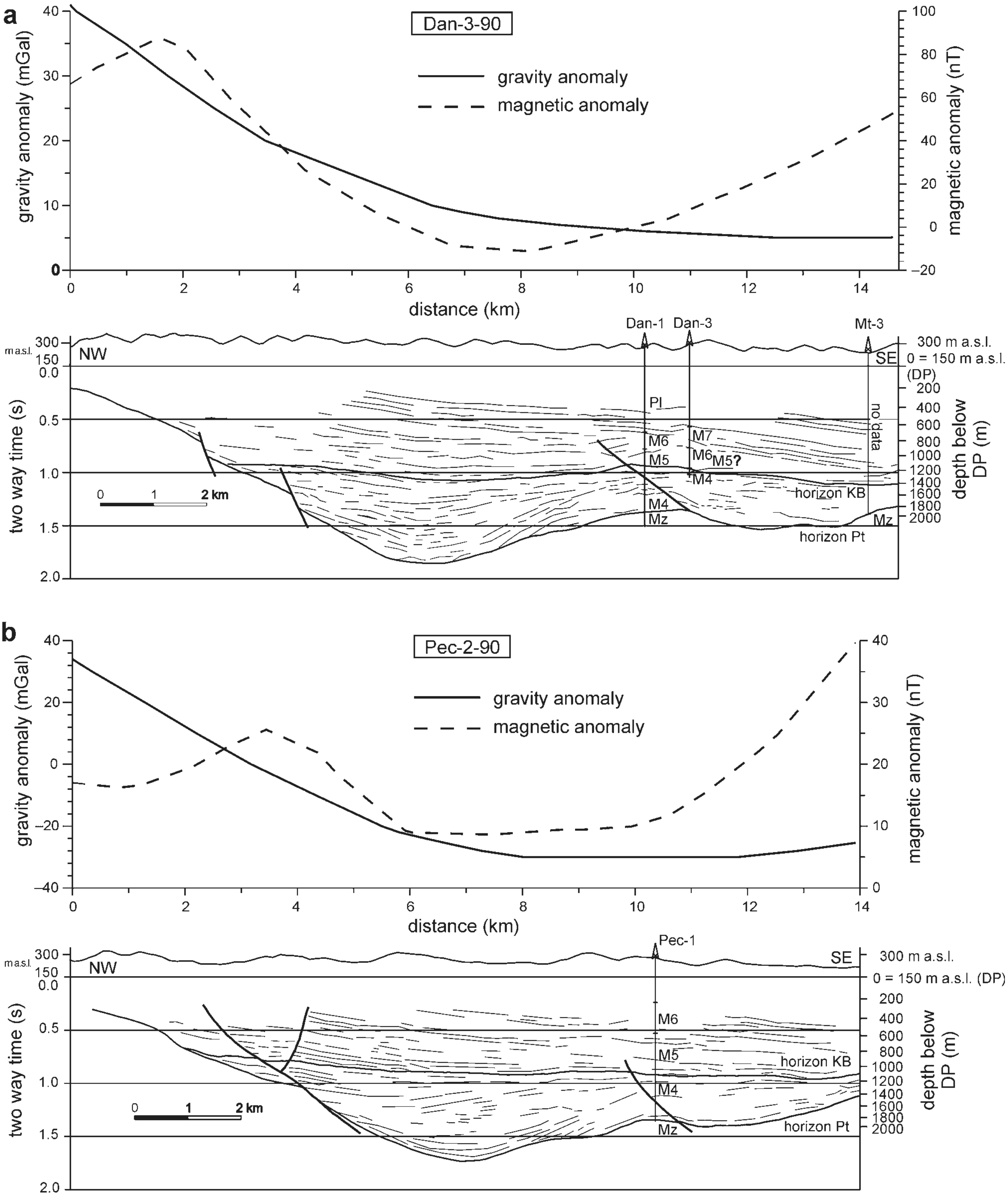

Fig. 7. The line drawing interpretation of two regional seismic profiles, Dan-3-90 **(a)** and Pec-2-90 **(b)**, with gravity and magnetic profiles. The KB horizon corresponds to the boundary between the Badenian and Sarmatian sediments and the Pt horizon to the pre-Tertiary bedrock. **Mz** — Mesozoic, **M4** — Badenian, **M5** — Sarmatian, **M6** — Pannonian, **M7** — Pontian, **Pl** — Pliocene.

the surface, as it is outcropping in the continuation of the Pec-2-90 profile within the Rdeci breg. In the transition zone between the Rdeci breg and the Radgona depression, there is a stronger unnamed fault, which can be correlated to the Kungota fault to the SW and to the Rába fault, or a fault parallel to it, to the NE, in Hungary. It should be stressed however, that the appearance of this fault is different in both profiles considered. In the Dan-3-90 profile, there are two parallel normal faults clearly displacing the pre-Tertiary basement (Pt horizon), but without visible displacement of Neogene sediments. In the Pec-2-90 profile, a single listric normal fault is interpreted in the basement, which also cuts the KB horizon (discordant top boundary of Badenian layers) and Middle Miocene strata. It is accompanied by a clear antithetic fault. In the maps presented by Djurasek (1989) and Poljak (2000), this fault is shown as a normal fault. Rumpler & Horváth (1988) have interpreted more faults related to the regional Rába fault in the profile Zi-108 from the Zala Basin. According to their interpretation, this fault expresses oblique displacement but it has a much greater strike slip component than a dip-slip component. On the other hand, Znidarcic & Mioc (1989) suppose for the Kungota fault (SW continuation of this fault system in the Slovenske gorice) a reverse character. Despite incomplete information about the lithology on both sides of the fault in the Mura Depression, a strike-slip fault with an important dip-slip component seems to be more realistic.

The maximum depth to the pre-Tertiary basement within the Radgona depression is on the Dan-3-90 profile around 2800 m and on the Pec-2-90 profile around 2500 m. From the deepest point, towards the SE, the basement gradually rises towards the Murska Sobota ridge, which is the northern branch of the Murska Sobota massif. In this area, two structures (Pecarovci and Dankovci) were investigated for possible underground storage of gas in aquifers. Two boreholes, Pec-1 and Dan-1, were drilled in this area down to the pre-Tertiary basement and one, Dan-3, down to the KB horizon. The metamorphic rocks are here overlaid by layer of Mesozoic carbonates up to 100 m a thick. On the SE side of both structures, a normal fault with a minor dip-slip was interpreted in both seismic profiles. A more detailed image of the faults in this area was obtained by extensive reflection profiling carried out for the project related to underground gas storage (Gosar 2005). A smaller sub-basin is located in the SE part of the Dan-3-90 profile. The depth to the pre-Tertiary basement at its SE termination is calibrated by the Mt-3 borehole. The topography of the pre-Tertiary basement is also well reflected in the gravity anomalies (Fig. 7), while magnetic profiles seem to be more sensitive to lateral variations in the magnetic susceptibilities of metamorphic rocks, but a clear correlation with the basement topography is also evident.

Tectonic and kinematic characteristics of the Mura Depression

The structural characteristics of the Mura Depression derived from geophysical data and presented in this paper can be related to the results of structural-geological investigations in the border areas and to the larger structural context of the SW part of the Pannonian Basin (Royden et al. 1983; Horváth 1993). According to these studies the Mura Depression was formed due to the ENE–WSW trending crustal extension in the late Early Miocene. The main deformation took place in the latest Miocene–Pliocene as a result of NNW–SSE compression, which formed folds, reverse and strike-slip faults (Márton et al. 2002). The formation of anticlines separating the Mura Depression into more sub-basins is caused by the rotation of blocks north of the Ljutomer fault and by dextral movements along the Labot fault situated SW of the Pohorje Mountain (Fodor et al. 1998).

Rumpler & Horváth (1988) have provided analysis of a regional stress field based on the structural interpretation of selected reflection seismic profiles from the Pannonian Basin. According to their analysis, the tectonic activity culminated in the Middle Miocene, but locally minor activities have continued until recent times. For the most of the transition zone between the Alps, the Dinarides and the Pannonian Basin, two sets of conjugate strike-slip faults are characteristic: NE–SW strike faults are left-lateral and NW–SE strike faults are right-lateral. Areas of extension and normal faulting are associated with discontinuous or divergent strike-slip faults and with fragmentation in zones bounded by two major strike-slip faults. Locally thrust faults and folds are also present. In the Mura Depression, a similar tectonic style is observed, governed by the main regional faults which are: Periadriatic Lineament, Rába, Labot and Donat faults. The development of compressional and extensional structures occurred at about the same time. Rumpler & Horváth (1988) think that separate periods characterized by contrasting styles of deformation cannot be distinguished in the Pannonian Basin for the period between the Miocene and Quaternary. In spite of the fact that some temporal variations in the stress field may have occurred, the spatial variation seems to have been more important. Analysis of geophysical data and the structural characteristics of the Mura Depression has shown that this is also valid for this depression located at the junction between the Eastern Alps and the Pannonian Basin.

Conclusions

The structure of the Mura Depression was analysed on the basis of the compilation of older gravity and magnetic data and newer seismic reflection, borehole and geothermal data. The presented structural map of the pre-Tertiary basement is constructed from the interpretation of seismic reflection profiles using new seismic velocity information and data from boreholes. In the major part of the depression the correlation of this map with potential filed data is rather good, but in some parts there are important discrepancies between the topography of the basement and gravity or magnetic anomalies. Since in the areas under discussion only a few boreholes have reached the metamorphic basement, covered mainly by Mesozoic carbonates and clastic sediments, in general it was not possible to explain the source of observed shifts. The strongest positive magnetic anomaly (+150 nT) in the depression, observed between Beltinci, Murska Sobota and Dobrovnik, which is shifted with respect to the structural height of the Murska Sobota massif, is most probably caused by a deeper structure. Gravity and magnetic modelling can give some additional insight into these questions, but in-situ data on the density and magnetic susceptibility of the metamorphic rocks from the basement is too sparse for reliable conclusions. Nevertheless, it was possible to correlate the established structures with the outcrops of the metamorphic complexes to the west of the Mura Depression.

The interpretation of two regional seismic reflection profiles measured from the Rdeci breg, across the Radgona Depression to the Murska Sobota massif has shown that also the interpretation of major faults in the Mura Depression cannot always be unique. Two alternative interpretations of the strong fault in the transition zone between Rdeci breg and the Radgona depression, which can be related to the Rába fault towards the NE and to the Kungota fault towards the SW, are therefore given.

The presented structural characteristics based on the geophysical data are in agreement with the results of structural-geologic investigations in the border areas and with the structural context of the SW part of the Pannonian Basin. A more detailed seismic reflection investigation performed for underground storage of gas in aquifers of the Pecarovci and Dankovci structures located on the Murska Sobota massif is presented in a separate article in Gosar (2005).

Acknowledgments: The author is grateful to M. Bielik, P. Krzywiec and J. Mrlina for thorough and constructive reviews of the article. Geoinzeniring and the Geological Survey of Slovenia are acknowledged for the provision of geophysical data from their archives.

References

Bock R. 1959: A European field of the normal geomagnetic vertical intensity and its secular variation. *Geophys. Prospect.* 7, 4, 389–413.

Djurasek S. 1988: Results of geophysical investigations in Slovenia in years 1985–87. *Nafta* 39, 6, 311–326 (in Croatian).

Djurasek S. 1989: Overview map of the pre-Tertiary basement in the Mura depression, 1 sheet, Nafta Lendava, Lendava (internal report, in Slovenian).

Fodor L., Jelen B., Márton E., Skaberne D., Car J. & Vrabec M. 1998: Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic line and surrounding area — implication for Alpine-Carpathian extrusion models. *Tectonics* 17, 690–709.

Fodor L., Jelen B., Márton E., Rifelj H., Kraljic M., Kevric R., Márton P., Koroknai B. & Báldi-Béke M. 2002: Miocene to Quaternary deformation, stratigraphy and paleogeography in NE Slovenia and SW Hungary. *Geologija* 45, 1, 103–114.

Gosar A. 1995: Modelling of seismic reflection data for underground gas storage in the Pecarovci and Dankovci structures — Mura depression. *Geologija* 37–38, 483–549, (in Slovenian).

Gosar A. 2005: Seismic reflection investigations for gas storage in acquifers (the Mura depression, NE Slovenia). *Geol. Carpathica* in print.

Haas J., Mioc P., Pamic J., Tomljenovic B., Árkai P., Berczi-Makk A., Koroknai B., Kovacs S. & Felgenhauer E.R. 2000: Complex structural pattern of the Alpine-Dinaridic-Pannonian triple junction. *Int. J. Earth Sci.* 89, 377–389.

Horváth F. & Pogácsas G. 1988: Contribution of seismic reflection data to chrono-stratigraphy of the Pannonian basin. In: Royden L.H. & Horváth F. (Eds.): The Pannonian basin: A study in basin evolution. *AAPG Memoir* 45, 97–105.

Horváth F. 1993: Towards a kinematic model for the formation of the Pannonian basin. *Tectonophysics* 226, 333–357.

Kisovar M. 1977: Contribution to the structural relations in the Mura depression. *Znanstveni savjet za naftu, JAZU, Zbornik radova I* 311–322 (in Croatian).

Kralj P. 2000: Upper Pliocene alkali basalt at Grad, NE Slovenia. *Geologija* 43, 2, 213–218.

Kralj Pe. & Kralj Po. 2000: Thermal and mineral waters in north-eastern Slovenia. *Environmental Geol.* 39, 5, 488–500.

Kroell A., Fluegel W. & Weber F. 1988: Steiresches Becken-Suedburgenlandische Schwelle, Reliefkarte des preterciaren Untergrundes, 1:200,000. *Geol. Bundesanstalt,* Wien.

Márton E., Fodor L., Jelen B., Márton P., Rifelj H. & Kevric R. 2002: Miocene to Quaternary deformation in NE Slovenia: complex paleomagnetic and structural study. *J. Geodynamics* 34, 627–651.

Miklic F. 1969: Magnetic map of Slovenia. *Geol. Surv. Slovenia,* 1–84 (internal report, in Slovenian).

Mioc P. & Znidarcic M. 1996: Geological characteristics of the oil fields in the Slovenian part of the Pannonian basin. *Geol. Croatica* 49, 2, 271–275.

Mioc P. & Markovic S. 1998: Basic geological map 1:100,000, Sheet Cakovec with explanatory text. *IGGG,* 1–84 (in Slovenian).

Novak J. 1959: Report on geophysical investigations in NE Slovenia in years 1956–1958. *Geoinzeniring* 1–17 (internal report, in Slovenian).

Plenicar M. 1970: Basic geological map SFRJ 1:100,000, Sheet Goricko with explanatory text. *Zvezni geoloski zavod,* 1–39 (in Slovenian).

Poljak M. 1984: Neotectonic evolution in the Pannonian basin based on satellite images. *Advances in Space Research* 11, 139–146.

Poljak M. 2000: Structural-tectonic map of Slovenia, 1 sheet. *Geol. Surv. Slovenia,* Ljubljana.

Ravnik D., Stopar R., Car M., Zivanovic M., Gosar A., Rajver D. & Andjelov M. 1995a: Applied geophysical investigations in Slovenia. *History of Slovenian geodesy and geophysics. Book of contributions*, SZGG, 49–67 (in Slovenian).

Ravnik D., Rajver D., Poljak M. & Zivcic M. 1995b: Overview of the geothermal field of Slovenia in the area between the Alps, the Dinarides and the Pannonian basin. *Tectonophysics* 250, 135–149.

Rajver D., Ravnik D., Premru U., Mioc P. & Kralj P. 2002: Slovenia. In: Hurter S. & Haenel R. (Eds.): Atlas of geothermal resources in Europe. *Official Publications of the European Communities,* Brussels, 54–56.

Royden L.H., Horváth F. & Rumpler J. 1983: Evolution of the Pannonian basin System. 1. Tectonics. *Tectonics* 2, 1, 63–90.

Rumpler J. & Horváth F. 1988: Some representative seismic reflection lines from the Pannonian basin and their structural interpretation. In: Royden L.H. & Horváth F. (Eds.): The Pannonian basin: A study in basin evolution. *AAPG Memoir* 45, 153–169.

Sachsenhofer R.F., Jelen B., Hasenhuettl C., Dunkl I. & Rainer T. 2001: Thermal history of Tertiary basins in Slovenia (Alpine-Dinaride-Pannonian junction). *Tectonophysics* 223, 77–99.

Steininger F.F., Mueler C. & Rögl F. 1988: Correlation of Central Paratethys, Eastern Paratethys and Mediterranean Neogene stages. In: Royden L.H. & Horváth F. (Eds.): The Pannonian basin: A study in basin evolution. *AAPG Memoir* 45, 79–87.

Turk V. 1993: Reinterpretation of chronostratigraphic in lithostratigraphic relationships in Mura depression. *Rud.-Metalur. Zbor.* 40, 1–2, 145–148 (in Slovenian).

Urh I. 1956: Gravity measurements in Pomurje. *Geol. Surv. Slovenia,* 1–70 (internal report, in Slovenian).

Voncina Z. 1965: Geotectonic division of the Mura-river depression. *Nafta* 1, 1–3 (in Croatian).

Znidarcic M. & Mioc P. 1989: Basic geological map SFRJ 1:100,000, Sheets Maribor and Leibnitz with explanatory text. *Zvezni geoloski zavod*, 1–60 (in Slovenian).