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Structural maps of seismic horizons in the Krško basin

Strukturne karte seizmičnih horizontov v Krški kotlini

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Abstract: Structural maps of the pre-Tertiary basin and of five horizons inside the sequence of Neogene sediments were prepared based on the interpretation of seismic reflection profiles recorded in three surveys performed in the Krško basin so far. Interpolation of the Mesozoic basement between seismic profiles was supported by gravity data. The structural maps clearly shows rather regular synclinal shape of the Krško basin which is composed of two depressions. The larger Globoko depression in the eastern part is 2050 m deep and the smaller Raka depression in the western part is 1600 m deep. The thicknesses of some Neogene sequences in-between seismic horizons varies considerably. Most prominent is thickening of the Ottnangian and Lower Badenian layers between horizons C and B from 300 m in the Globoko depression to up to 1000 m in the Raka depression. On the other hand the thickness of the Upper Pontian sand, gravel and clay increases from 100 m in the western part to up to 500 m in the Globoko depression. There are several indications of synsedimentary folding of the area but also some indications of postsedimentary activity. The structural models of seismic horizons allow additional geophysical and structural-geological interpretations of the area. Together with seismic velocity models they served also as input data for the construction of two-dimensional cross-sections in arbitrary directions for numerical modelling of seismic ground motion in the frame of seismic hazard assessment

Izvleček: Na podlagi interpretacije refleksijskih seizmičnih profilov izmerjenih v okviru treh raziskav opravljenih do sedaj v Krški kotlini so bile izdelane strukturne karte predterciarne podlage in petih horizontov znotraj neogenskih sedimentov. Interpolacija mezozojske podlage je bila podprta z gravimetričnimi podatki. Strukturne karte jasno kažejo dokaj pravilno sinklinalno obliko Krške kotline, ki jo sestavljata dve depresiji. Večja je Globoška depresija v vzhodnem delu kotline, ki je globoka 2050 m, manjša pa Raška depresija v zahodnem delu, ki je globoka 1600 m. Debelina nekaterih neogenskih sekvenc med seizmičnimi horizonti se znatno spreminja. Najbolj izrazita je odebelitev ottnangijskih in spodnjebadenijskih plasti med horizontoma C in B od 300 m v Globoški depresiji do skoraj 1000 m v Raški depresiji. Po drugi strani pa se debelina zgornjepontijskih peskov, prodov in gline poveča iz 100 m v zahodnem delu na do 500 m v Globoški depresiji. Podatkih kažejo precej indikacij na sinsedimentarno gubanje območja, pa tudi nekatere indikacije za postsedimentarno aktivnost. Strukturni modeli omogočajo dodatne geofizikalne in strukturnogeološke analize raziskanega območja. Skupaj s seizmičnimi hitrostnimi modeli so služili tudi za izdelavo dvodimenzionalnih prerezov v poljubnih smereh za numerično modeliranje potresnega nihanja tal v okviru ocenjevanja potresne nevarnosti.

Key words: seismic reflection, seismic horizon, gravity data, structural map, Krško basin, pre-Tertiary basement

Ključne besede: seizmična refleksija, seizmični horizont, gravimetrični podatki, stukturna karta, Krška kotlina, predtercirana podlaga

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Scientific paper

Introduction

Several geological and geophysical investigations have been performed in the Krško basin starting about fifty years ago for a wide range of objectives: for oil and gas prospecting, for exploitation of geothermal energy, for underground gas storage in aquifers and for assessment of earthquake hazard at the location of the Krško nuclear power plant (NPP). Although the goals of these investigations were different, it was realised that a thorough understanding of the regional structural-tectonic setting of the basin is essential for most of these objectives. According to the prevailing hypothesis the Krško basin was considered as a tectonic graben structure (Pleničar & Premru, 1977; Šikić et al., 1979; Poljak & Živčić, 1995), although that no proofs were available for supposed normal border faults at the northern and southern margin of the basin. Since most of geophysical investigations were limited to the flat central part of the basin, it was not possible to confirm this hypothesis, before multi-fold seismic reflection profiling was completed (Gosar, 1998; Persoglia et al., 2000). Based on these data the Krško basin is considered now as a folded syncline with no border faults at least in the eastern part of the basin (Gosar, 1998; Verbič et al., 2000; Poljak & Gosar, 2001).

Three seismic reflection surveys were performed in the Krško basin so far. From two to six seismic horizons were interpreted on these profiles depending on the quality of the seismic data recorded in time span from 1959 to 2000. The deepest horizon correspond to pre-Tertiary bedrock composed of Mesozoic carbonates. Another one to five horizons were interpreted inside the sequence of Neogene sediments. The aim of this paper is to present structural geological maps of all six seismic horizons for the Krško basin which is composed of two depressions. The western Raka depression is up to 1600 m deep and the eastern Globoko depression is up to 2050 m deep. The structural model of the Krško basin will allow additional geophysical and geological interpretations of the area based on the variation of unit thicknesses. It served also as input data for the construction of two-dimensional cross-sections in arbitrary directions for numerical modelling of seismic ground motion in seismic hazard assessment.

Seismic reflection investigations

Single-fold analogue reflection profiling in 1959

The first seismic reflection investigations were performed in 1959 by *Geofizika* Zagreb for oil and gas prospecting. Four profiles with analogue recording and single fold coverage were measured in length totalling 36.5 km (Figure 1), three in transverse (P-83/59, P-84/59 and P-85/59) and one in longitudinal direction (P-86/59) with respect to the axis of the syncline. 24-channel seismograph with 3 geophones per point and 20 m group spacing were used and explosive as a source. The original report of these measurements and their interpretation is not preserved.

The analogue seismic data were later digitized and reprocessed (Kaloper, 1984). In comparison with modern digital profiles the quality of these sections is rather poor. In general deeper part of the basin is better imaged, whereas the noise is dominating in

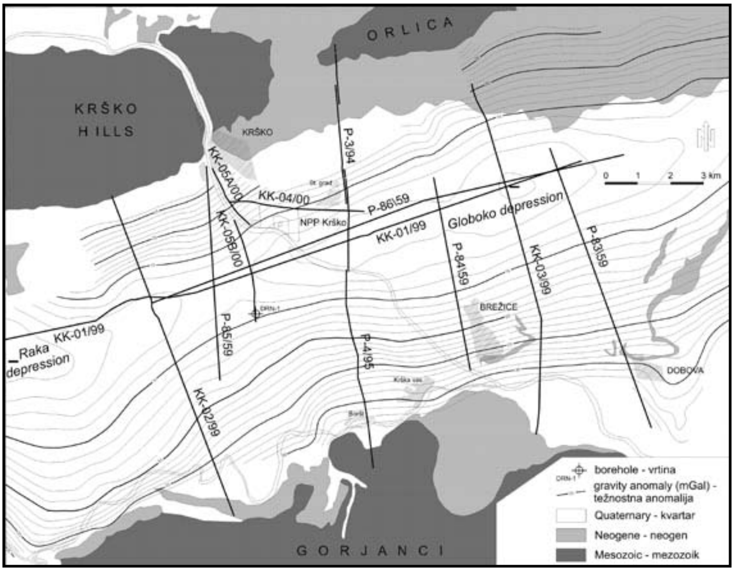


Figure 1. Simplified geological map of the Krško basin (after Pleničar & Premru 1977; Šikić et al., 1979) with Bouguer anomaly map (after Urh, 1955) and location of seismic reflection profiles

Slika 1. Poenostavljena geološka karta Krške kotline (po Pleničarju & Premruju 1977; Šikiću et al., 1979) s karto Bouguerjevih anomalij (po Urhu, 1955) in položajem refleksijskih seizmičnih profilov

the shallow part. The profiles were reinterpreted using new structural and velocity data obtained from the multi-fold data recorded in 1994/95. In general it was possible to interpret two horizons (Table 1), the top of Badenian limestone (horizon B) and the pre-Tertiary basement (horizon C) (Gosar, 1996). These seismic lines do allow interpretation of the main Krško syncline axis. The southern limb of the syncline is also secondarly folded in segments as is seen in the P-85/59 profile. Among faults, visible on these profiles is the most important south verging steep reverse Artiče fault (P-84/59) that crosscut the whole Tertiary sedimentary sequence.

Multi-fold reflection profiling in 1994/95

To improve the structural model, high-resolution seismic reflection methods were used in the first phase of the re-evaluation study of the Krško NPP site. Profiling in two depth ranges was performed in the frame of national research project entitled *Neotectonic investigations in the vicinity of the Krško NPP* (Poljak et al., 1996). The goal of the near-regional profile of intermediate depth penetration was to collect structural data down to the pre-Tertiary basement (Gosar, 1996; 1998). A 13-km-long profile (P-3 and P-4/95) was recorded 2 km east of NPP (Figure 1) by using 15 m group spacing, arrays of 12 geophones and 12-fold coverage. Acquisition parameters and processing parameters were optimised to improve the resolution.

The most prominent reflections were obtained from the top of the Badenian limestone (horizon B), whereas the Mesozoic (horizon C) basement was less pronounced (Table 1). In the upper section, a clear image of the boundary between Pontian sandy marl and Pannonian marl (horizon A) was obtained. A folded structure is clearly visible from the profile. The maximum depth to the Badenian limestone is 1200 m, whereas the depth to the pre-Tertiary basement reaches 1500 m. The northern limb of the syncline is steeper than the southern one, where more steps are visible in the basement.

The reflections in the northern part of the syncline, down to the horizon B, are predominantly parallel and could be an indication of postdepositional folding, although this observation is made over a limited distance of 1 km. On the other hand, surface geological observations indicate a condensed thinned Neogene section near the north margin of the basin that is an argument in favour of synsedimentary folding (GOSAR, 1998).

Reflection profiling in the frame of the EC-PHARE project

Reflection seismic profiling continued with an international project entitled *Geophysical Research in the Surroundings of the Krško NPP* financed by the European Commission - program PHARE. This was so far the largest geophysical project in the Krško area (PERSOGLIA ET AL., 2000). The main project goals were: obtaining good subsurface information about geological and tectonic features, locating possible faults cutting through the bedrock and sediments, and defining the position of faults at or near the surface as accurately as possible.

The geophysical program (Figure 1) was composed of:

1) three near-regional reflection lines totalling 42 km length,
2) three near-regional lines totalling 9.5 km recorded close to NPP and
3) four high-resolution profiles in length totalling 4 km to resolve the shallow features at selected locations.

Regional profiles were measured with explosive source fired in 5-10 m deep boreholes. By placing the source below the water table, the signal strength was significantly improved and the level of source generated coherent noise reduced. For data acquisition 120 active channels were used with arrays of 12 geophones. The group spacing was 15 m, the shot interval 15 m and the nominal coverage 18-fold (ACCAINO ET AL., 2003).

Good penetration of the seismic signals was obtained for the near-regional profiles (KK-01/99, KK-02/99, KK-03/99), within the basin down to the Mesozoic rocks (horizon C) at depths greater than 2 km. The explosive charge placed beneath the weathered zone, produced seismic signals having a wide frequency band, well suited for the required resolution and characterization of the different geological layers and for revealing the structural elements. In the shallow section, frequencies were around 80 to 90 Hz; at the base of the basin the signal frequencies were still between 40 and 60 Hz, giving a resolution of around 5 m in the shallower parts and 25 m near the base of the basin.

Further extension of the program was proposed to close the loop of seismic lines around the NPP location. The extended program (lines KK-04/00, KK-05A/00 and KK-05B/00) was completed using a mobile accelerated weight drop (Hydrapulse) source. This choice was required by the proximity of houses, factories and other constructions. The acquired data offer good images of the terminations of the Tertiary and Quaternary sedimentary units at the northern flank of the basin (the anticline of the Libna). The line KK-05B/00 permits a tie of seismic data with the Drn-1/89 well and the stratigraphic correlation of seismic horizons with the markers encountered by the well.

In next paragraphs main three near-regional seismic lines are presented. All depths are referred to the elevation of the datum plane at 150 m above sea level.

KK-01/99 profile follows the longitudinal axis of the Krško syncline close to its deepest part. Two large sub-basins as also identified by the Bouguer anomalies (Figure 1) are clearly visible in this profile. The depth to the pre-Tertiary basement reaches more than 2000 m in the eastern sub-basin (Globoko depression) and about 1600 m in the western one (Raka depression), rising to around 1100 m depth at the saddle, interpreted as the top of Dinaric thrust. They are differentiated by the thick Lower and Middle Miocene sequences in the western part and by thicker Pliocene and Quaternary deposits in the eastern one.

KK-02/99 profile (Figure 2) crosses the basin in NNW-SSE direction between Krško hills and Gorjanci in a transition zone between structural height and the Raka depression. Some thrusts moving the Mesozoic bedrock were observed in this profile and the folding of the whole Neogene sequence. The fault system in the northern part of the profile possibly corresponds to Orlica fault.

KK-03/99 profile (Figure 3) crosses the basin in N-S direction between Orlica and Čatež. It clearly represents the almost symmetric cross-shape of the syncline in the deepest part of the Globoko depression. The Artiče fault is an important tectonic feature confirmed in the northern limb of the depression with this profile (Accaino et al., 2003). It displaces the Mesozoic bedrock as well as most of the Neogene horizons. Towards the surface the throw between different units becomes smaller. The fault can be traced to very shallow depth, but no indications of deformation were found in recent sediments.

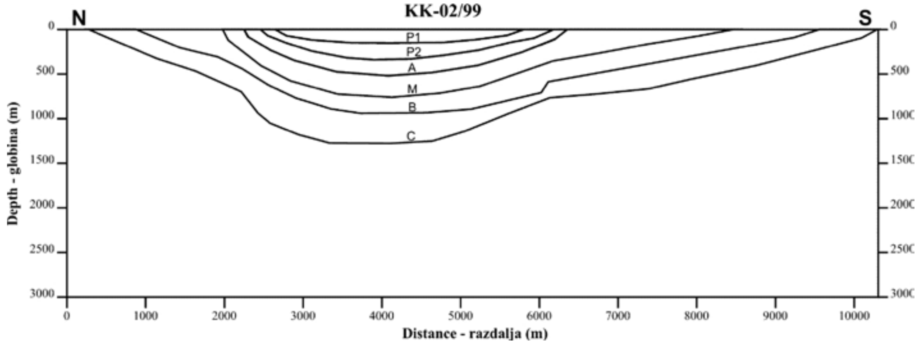


Figure 2. Interpretation of seismic reflection profile KK-02/99. Marked seismic horizons are described in Table 1.

Slika 2. Interpretacija refleksijskega seizmičnega profila KK-02/99. Označeni seizmični horizonti so opisani v tabeli 1.

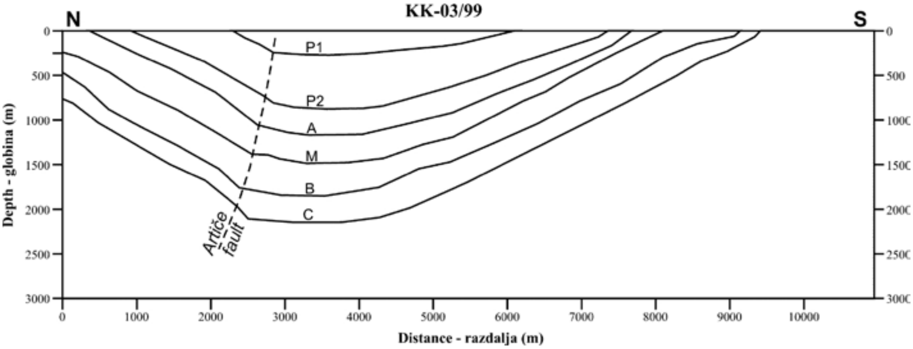


Figure 3. Interpretation of seismic reflection profile KK-03/99. Marked seismic horizons are described in Table 1

Slika 3. Interpretacija refleksijskega seizmičnega profila KK-03/99. Označeni seizmični horizonti so opisani v tabeli 1

Gravity data

The Krško basin area was investigated so far with gravity method in two detailed surveys, first for hydrocarbons exploration (URH, 1955) and the second one for underground gas storage in aquifers (STARČEVIĆ ET AL., 1989). Both maps showed good correspondence. Since the first survey comprises larger area, we used this map for contouring the maps of seismic horizons.

The gravity study performed in 1955 (URH, 1955) enclosed an area of 258 km^2 (Figure 1). Altogether 751 points were measured giving an average density of 3 points/km^2. Bouguer anomalies were computed using a density of 2.0 g/cm^3, derived from laboratory measurements and with Nettleton method. In the Bouguer anomaly map (Figure 1) the shape of the syncline is clearly reflected. Its axis is in WSW-ENE direction. At Drnovo there is a saddle which separates Raka and Globoko depressions. Bouguer anomalies range between +11 and +32 mGal. The minimum values in both depressions are +11 mGal.

Two-dimensional gravity modelling was performed along six transversal seismic reflection profiles (GOSAR, 2001) acquired in various projects across the Krško basin (Figure 1) including profiles KK-02/99 (Figure 2) and KK-03/99 (Figure 3). Modelled gravity anomalies were compared with observed anomaly profiles extracted from detailed gravity survey (URH, 1955; STARČEVIĆ ET AL., 1989) available in this area. The modelling was proved useful for the interpolation of the shape of the pre-Tertiary bedrock of the basin between seismic profiles. However the possibility to extrapolate the structures interpreted on seismic data to the area outside the grid of reflection seismic profiles is restricted due to the limited extent of the area covered by gravity surveys.

Contouring the maps of seismic horizons

In reflection profiles recorded in the frame of PHARE project six horizons were identified (Table 1). They include the Mesozoic basement (horizon C) of the Krško basin and five horizons within the Neogene sequence

Table 1. Seismic horizons interpreted on profiles recorded in the Krško basin with generalized unit thicknesses (Poljak et al., 1996) and horizon depths drilled in Drn-1/89 borehole (Kranjc et al., 1990; Gosar, 1998)
Tabela 1. Seizmični horizonti interpretirani na profilih posnetih v Krški kotlini z generaliziranimi debelinami posameznih enot (Poljak et al., 1996) in globinami horizontov navrtanimi v vrtini Drn-1/89 (Kranjc et al., 1990; Gosar, 1998)

Horizon horizont	Stage stopnja		Thickness debelina (m)	Depth in Drn-1 globina v Drn-1 (m)	Lithology litologija
P1	Pontian pontij	Pl_1^2, Q	200		sand, gravel, clay pesek, prod, glina
P2		Pl_1^1	600-700	48	sandy marl peščen lapor
A	Pannonian panonij	M_3^2	150-300		marl lapor
M	Sarmatian sarmatij	M_3^1	100		sandy marl, marly limestone peščen lapor, laporni apnenec
B	Badenian badenij	M_2^2	350	647	limestone, sandy marl apnenec, peščen lapor
	Ottnangian ottnangij	M_2^1	300		sand, gravel, conglomerate pesek, prod, konglomerat
C		$K_{1,2}$ or T_3		969	marly limestone or dolomite laporni apnenec ali dolomit

to capture its internal structure. The most prominent reflection was obtained from near the top of Badenian limestone (horizon B).

For contouring the structural maps of seismic horizons we did some trials with computer contouring algorithms (Hamilton & Jones, 1992). These gave quite satisfactory results in case of pre-Tertiary basement (horizon C) (Gosar et al., 2005) which was imaged in all considered profiles, but not so good results in all other horizons inside Neogene sequence (Božiček, 2006). By using computer methods it was also not possible to support interpolation by the use of gravity data. Therefore we decided for manual contouring of maps (Tearpock & Bischke, 2003). We didn't consider the faults in contouring, because the vertical displacements of individual horizons are mostly very small.

Time to depth conversion of seismic reflection profiles was based on velocity analyses data. The seismic velocities range from very low values in some parts of the near surface deposits to more than 2500 m/s for the Neogene sequences and 3000 m/s or larger for the Mesozoic. Lateral variations inside individual units are in general small and smooth (Božiček, 2006). For time to depth conversion of old single-fold profiles we used therefore an average velocity function derived from multi-fold reflection profiles. The depth control was available in five boreholes that reached the pre-Tertiary basement (Gosar et al., 2005). The most important is Drn-1 borehole (Kranjc et al., 1990) located near Drnovo in the central part of the basin close to the saddle which separates Raka and Globoko depression.

The depths in all structural maps are shown from the elevation 0 m a.s.l., but in the text the depths are considered from the average elevation of the surface which is in the Krško basin 150 m a.s.l..

Seismic horizons

The lithostratigraphic description of interpreted seismic horizons (Table 1) is summarized after PERSOGLIA ET AL. (2000), POLJAK ET AL. (2002), GOSAR ET AL. (2005) AND POLJAK (2006, personal communication).

The deepest horizon mapped was the top of Cretaceous flysch or of Triassic dolomite (horizon C). The lowermost Neogene sequence between horizon C and B represents the Ottnangian sediments transgressively deposited over the Mesozoic basement. These have relatively weak and diffuse seismic signals which is probably caused by their heterogeneous lithological content that consists of gravel, sand, sandy clay and conglomerate. They show several distinct angular discordances with visible onlaping structures that suggests a synsedimentary activity of the depression.

In Badenian *Lithothamnion* limestone (horizon B) was transgressively deposited over Ottnangian sequence. Upwards it transits into sandy and marly limestone, and sandy marl of Badenian to Sarmatian age. They could be distinguished as a separate unit between horizons B and M. This sequence has relative uniform thickness of 200 m, except in the eastern part of the Krško basin (Globoko depression), where it shows a slight increase. This thickness increase is well expressed by overlapping of seismic horizon that corresponds to sandy marl.

The next sequence is the Pannonian marl that corresponds to the unit between horizons M and A. Its almost uniform thickness (about 100 m) is slightly increased only in the Glo-

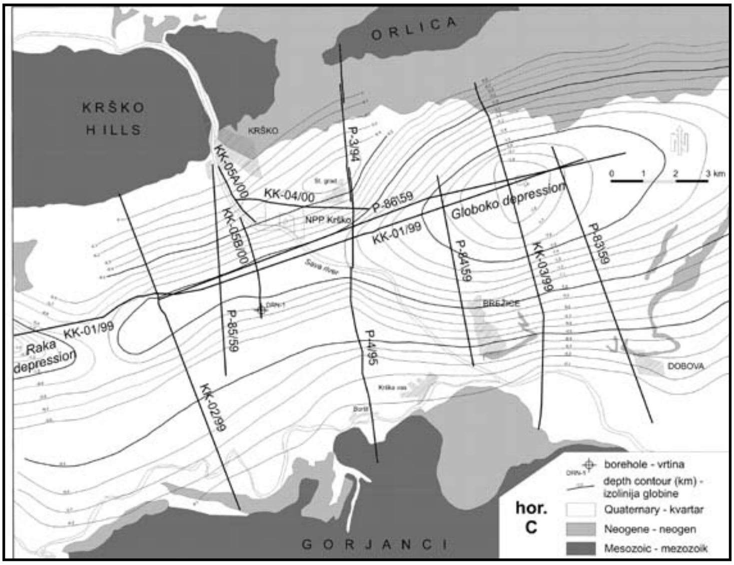


Figure 4. Structural map of seismic horizon C (pre-Tertiary basement)
Slika 4. Strukturna karta seizmičnega horizonta C (predterciarna podlaga)

boko depression. Upwards, this marl transits into sandy marl of Lower Pontian age, which could be distinguished as a separate sequence between horizons A and P2.

The Upper Pontian is represented by sand with rare lenses of gravel, except in the Globoko area, where a lateral equivalent consisting of gravel, sand and clay with coal is developed. The beginning of this sequence is recognized as the P2 seismic horizon. The main characteristics of this unit is variable thickness, from 100 m in the western part to up to 500 m in the Globoko depression in the east. The uppermost horizon P1 is related to no clear lithological change within Upper Pontian.

Seismic horizon C (pre-Tertiary basement) (Figure 4)
The structural map of the pre-Tertiary basement clearly shows the shape of the basin which is elongated in WSW-ENE direction. In the cross direction is the syncline rather symmetric. The average dip of the basement towards the central part is 20^0. This dip is similar to the average dip of Neogene sediments (Poljak et al., 1996) what is an indication of postsedimentary folding. The eastern Globoko depression has very regular elongated shape and reaches the maximum depth of 2050 m (from the surface) close to the intersection of KK-01/99 and KK-03/99 profiles south of Globoko. The western Raka depression is only partly seen in this map, which is limited to the extent of gravity data. This depression is smaller than the Globoko depression and reaches the maximum depth of 1600 m. Both depressions are separated by a wide saddle at a depth of 1150 m.

Seismic horizon B (Badenian-Sarmatian boundary) (Figure 5)
This prominent seismic horizon related to *Lithothamnion* limestone of Badenian age clearly shows a closed syncline in the

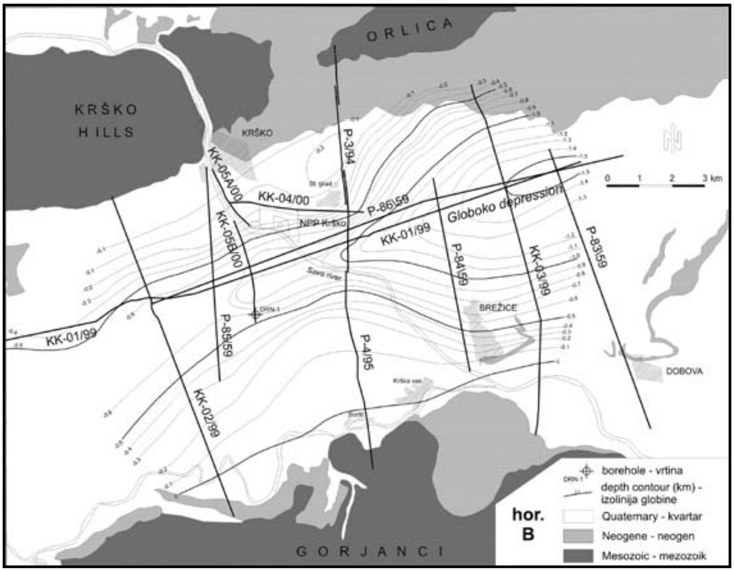


Figure 5. Structural map of seismic horizon B (inside Badenian)
Slika 5. Strukturna karta seizmičnega horizonta B (znotraj badenija)

Globoko depression where it reaches the depth of 1650 m. On the other hand in the Raka depression there is no syncline visible at this horizon and the maximum depth is only 650 m. The average thickness of Ottnangian and Lower Badenian sediments (between horizons C and B) varies therefore considerably in the Krško basin. In the Globoko depression it is about 300 m, but in the western Raka depression these sediments reach thickness of up to 1000 m. Such a great thickness is anomalous even for the entire Sava folds (Placer, 1998). Thus, the presence of older Tertiary units should not be excluded. Onlaping structures visible in seismic profiles suggests a synsedimentary activity of the depression.

Seismic horizon M (Sarmatian-Pannonian boundary) (Figure 6)
The seismic horizon M has very similar shape as horizon B. The sequence of sediments in-between has therefore relative uniform thickness of 200 m, except in the Globoko depression, where it shows a slight increase. This thickness increase is well expressed by overlapping of seismic horizon that corresponds to sandy marl that lies over the *Lithothamnion* limestone.

Seismic horizon A (Pannonian-Pontian boundary) (Figure 7)
The prominent seismic horizon related to the boundary between Upper Miocene and Lower Pliocene shows again a closed syncline in the Globoko depression with the maximum depth of 950 m. At the saddle between both depressions is its minimum depth 450 m. The thickness of the Pannonian marls is from 200 m in the shallow western part to 400 m in the Globoko depression.

Seismic horizon P2 (Lower Pontian-Upper Pontian) (Figure 8)
The depth of the P2 horizon which separates Lower Pontian sandy marl from Upper Pon-

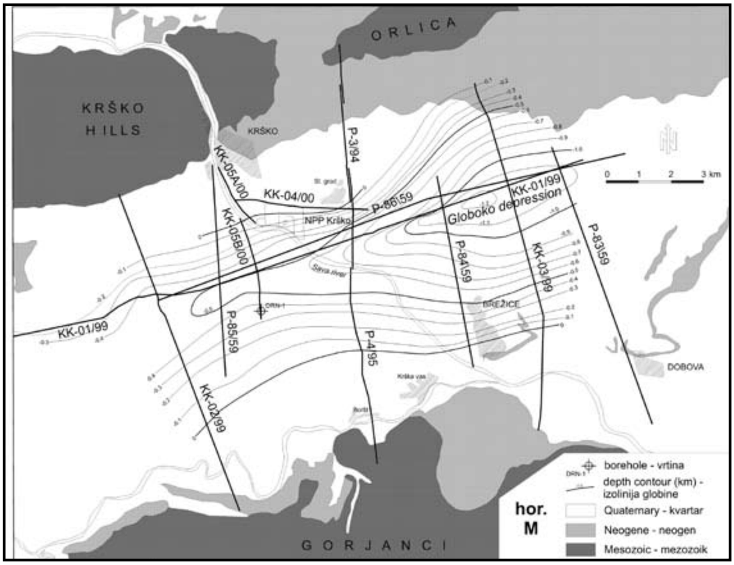


Figure 6. Structural map of seismic horizon M (Sarmatian-Pannonian boundary)
Slika 6. Strukturna karta seizmičnega horizonta M (meja sarmatij-panonij)

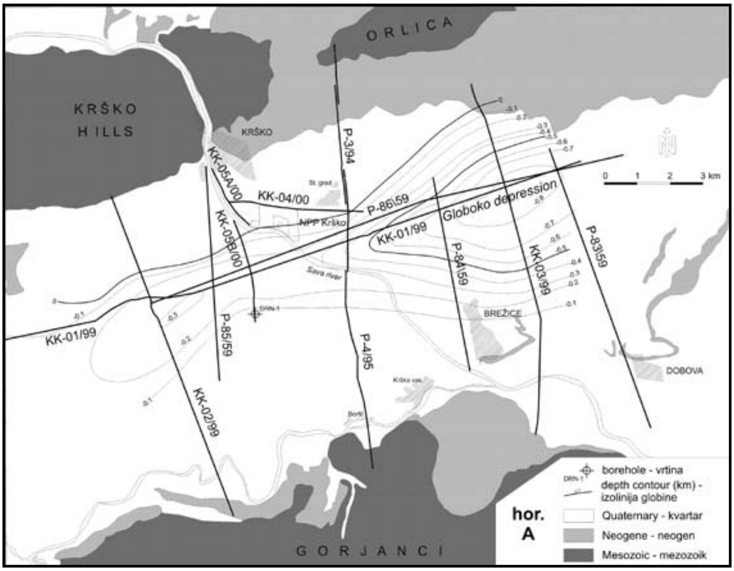


Figure 7. Structural map of seismic horizon A (Pannonian-Pontian boundary)
Slika 7. Strukturna karta seizmičnega horizonta A (meja panonij-pontij)

tian sand, gravel and clay varies considerably from 250 m in the western part to 650 m in the Globoko depression. The thickness of the Lower Pontian sandy marl is from 200 m in the west to 300 m in Globoko depression.

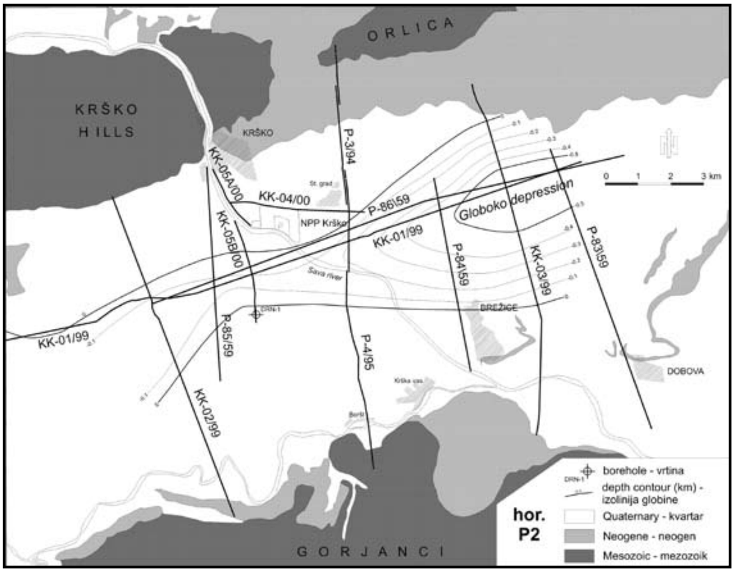
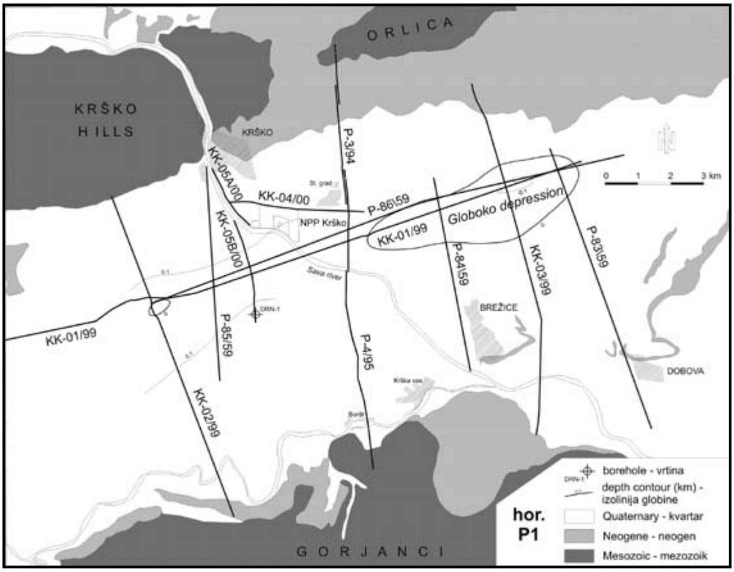


Figure 8. Structural map of seismic horizon P2 (Lower Pontian-Upper Pontian boundary)
Slika 8. Strukturna karta seizmičnega horizonta P2 (meja spodnji pontij-zgornji pontij)

Figure 9. Structural map of seismic horizon P1 (inside Upper Pontian)
Slika 9. Strukturna karta seizmičnega horizonta P1 (znotraj zgornjega pontija)



Seismic horizon P1 (inside Upper Pontian) (Figure 9)

The uppermost horizon P1 was imaged only along the axis of the syncline at shallow depths from 150 m at the crossing of KK-01/99 and KK-02/99 profiles to 250 m in the Globoko depression. The thickness of the Upper Pontian sand, gravel and clay between horizons P2 and P1 is highly variable, from 100 m in the western part to up to 500 m in the Globoko depression.

CONCLUSIONS

Structural maps of the pre-Tertiary basin and of five horizons inside the sequence of Neogene sediments were prepared based on the interpretation of eleven seismic reflection profiles recorded in three surveys performed in the Krško basin so far. Interpolation of Mesozoic basement between seismic profiles was supported by gravity data. The maps clearly shows rather regular synclinal shape of the Krško basin which is composed of two depressions. The larger Globoko depression in the eastern part is up to 2050 m deep and the smaller Raka depression in the western part is up to 1600 m deep (Figure 4). The thicknesses of some Neogene sequences in-between seismic horizons varies considerably. Most prominent is thickening of the Ottnangian and Lower Badenian sequence between horizons C and B from 300 m in the Globoko depression to up to 1000 m in the Raka depression. On the other hand the thickness of the Upper Pontian sand, gravel and clay increases from 100 m in the western part to up to 500 m in the Globoko depression. There are several indications of synsedimentary folding of the basin, but also some indications of postsedimentary activity.

The structural models of seismic horizons will allow additional geophysical and structural-geological interpretations of the area. Together with seismic velocity models they served also as input data for the construction of two-dimensional cross-sections in arbitrary directions for numerical modelling of seismic ground motion in seismic hazard assessment for the location of Krško NPP (Čarman, 2006).

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