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GEOLOGY OF THE ZAGREB AQUIFER SYSTEM

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ABSTRACT

The aquifer of Holocene age that is currently supplying the City of Zagreb with potable water is exposed to contamination and to the verge of being overpumping. Thus, investigations on deeper deposits have been undertaken. Interpretation of geological structure and lithologic composition of the deposits has revealed deeper water bearing layers of Pleistocene and Upper Pliocene age which might play an important role in the future water supply of the city.

KEY WORDS: stratigraphy, tectonics, Quaternary, aquifer system, permeable layer, Zagreb, Croatia

1. INTRODUCTION

Water supply of the City of Zagreb, the Croatian capital (Fig. 1), is based on exploitation of groundwater from the aquifer of Holocene age. The results of the groundwater table measurements indicate continuous trend of decrease in groundwater level. This fact points to overpumping of the aquifer. Further, the poorly permeable overburden is either not encountered or has thickness of a couple of meters. Groundwater chemical analyses have shown that the most of the aquifer system surface is polluted to a certain degree. So far, fifteen Zagreb well fields within the narrower city territory have been closed down because of contamination. Overpumping and contamination indicate that the municipal water supply is seriously threatened. These are the reasons for which investigation of deeper deposits was undertaken. As a first stage, the interpretation of geological structure and lithologic composition on the base of existing data has been made, as elaborated below.

Fig.1. Location map

Investigated area encompases greater Zagreb (Fig.1). Regarding orography, three areas are distinguished: northern, belonging to the northern foothill zone of Mt. Medvednica to altitude of 340 m; central, belonging to the Sava River lowlands (about 100-120 m a.s.l.); and southern, belonging to the NE part of the hilly zone of the

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Vukomeričke Gorice hills.

For the preparation of the geological map in Fig. 2 were used the data from geological maps in scale 1:100,000, sheets: Zagreb, ŠIKIÆ et al. (1978); Sisak, PIKIJA (1987); Ivaniæ Grad, BASCH (1981).

2. STRATIGRAPHY

The geological characteristics of this area conditionally shows two highly diverse and hydrogeologically clearly individualized complexes: (a) geological units underlying the aquifer system and (b) rocks constituting the Zagreb aquifer system.

(a) Geological units underlying the aquifer system

The Paleozoic is represented by metamorphic rocks forming, on the surface, the central part of the Mt. Medvednica (to the north of the research site) and consisting of parametamorphic and orthometamorphic rocks. In the underground, oil boreholes were drilled on different depths in these rocks (Fig. 3), and the rocks are made of chlorite schist, argillite, and low metamorphic subgraywacke (PAND•IÆ, 1986).

The configuration of the area of neogene sedimentation, had been initiated earlier or predetermined by the paleorelief forms (KRANJEC et al., 1978). The differential movement of individual blocks during Neogene caused frequent oscillations in coastal lines and interruptions in sedimentation, particularly on the basin boundaries. The sedimentation had been continuous only in the deepest parts of the sedimentation area. The researched area is built of the Middle Miocene and Pliocene sediments.

The oldest Neogene sediments fall into Helvetian but they are not encountered on the surface of the analyzed area. These are fresh water sediments of molasse type in erosion discordant relation with the Paleozoic metamorphites. They consist of conglomerate in base, and marl and sandstone.

Intensive tectonic activity in the wider region during Helvetian caused further progressive subsidence of individual areas and marine transgression in the Upper Helvetian. Transgressive sediments of Badenian (Fig.2, M_2^2) consist, in their basal part, of breccia and conglomerate, to be followed by alternating marl, sandy marl, sandstone and limestone. In some deep boreholes (PAND•IÆ, 1986), these sediments form direct overburden of the Paleozoic metamorphic rocks.

Regional geotectonic events during the period of transition from Badenian into Sarmatian in the Paratethys area, which affected this territory as well, caused marine conditions for sedimentation to cease and sedimentation area to disintegrate into separate basins and their salinity to decrease. Sedimentation of Sarmatian deposits (Fig. 2, M_3^1) occurred under the brackish conditions. They consist of marl, limestone and sandstone. During the Pannonian (Fig.2, M_3^2), salinaty decreasing of the sedimentation area continued and the sedimentary environment of Caspian brackish type was formed. The tectonic movements in the Upper Pannonian caused intensive sinking of this area and intensified accumulation of sediments and thickening of sedimented deposits. The lower portion is predominated by marly limestones, and the upper with marl and rarely sandstone. However, the boundary parts of the sedimentation area (including the SW part of Mt. Medvednica, Fig. 2), have partly been in regressive phase.

During the Lower Pliocene, tectonic activity of lower intensity continued, and its result is reduction and further salinity decreasing of the sedimentary environment with frequent occurrence of ingressive leaning of Pontian deposits against older sediments. Continuous sedimentation is happening of marly deposits in Lower Pontian (Fig.2, Pl_1^1) and of sandy deposits in Upper Pontian (Fig.2, Pl_1^2).

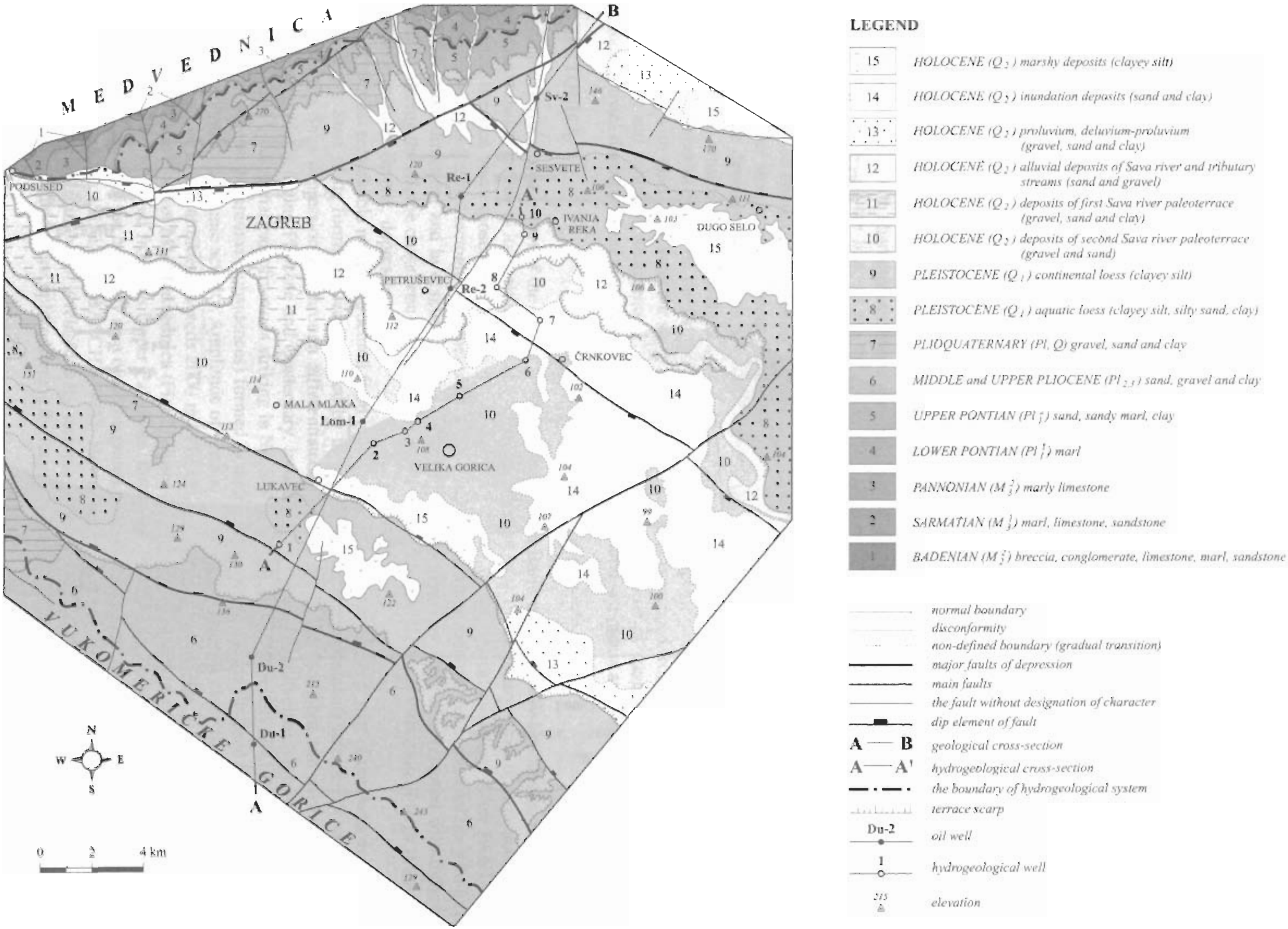
(b) Rocks constituting the Zagreb aquifer system

These include the Middle and Upper Pliocene (Fig.2, $Pl_{2,3}$) and Quaternary deposits which have direct importance for the hydrogeological analyses.

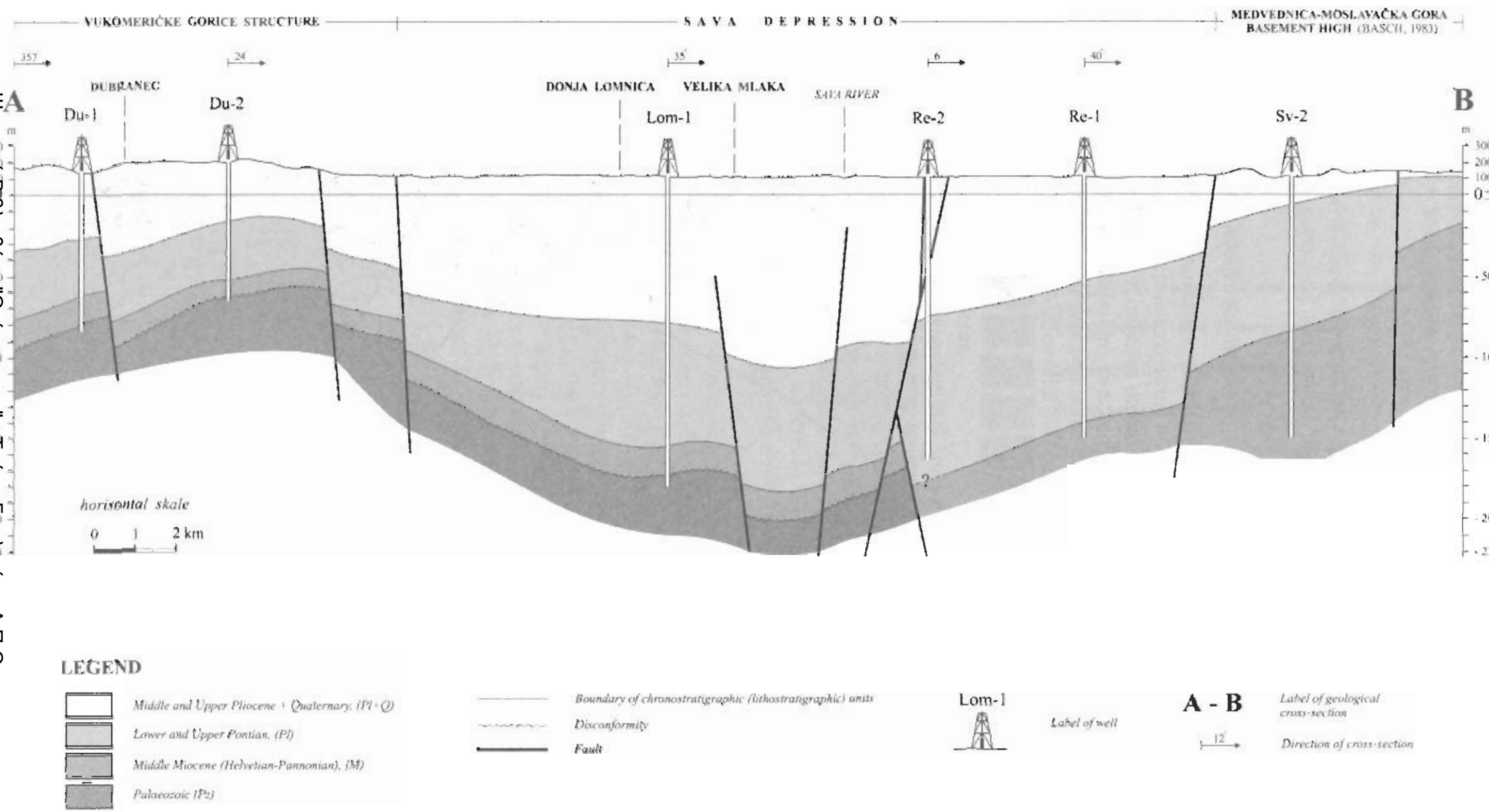
During the Middle Pliocene tectonic movements form a relief with pronounced altitude differences and reduction in sedimentation area. The fresh water deposits are sedimented: sand, gravel, clay with coal intercalations and conglomerate.

During the Upper Pliocene, the final stage in formation of the tectonic framework and relief of this greater Pannonian region stared. In this way, the uplifted massif of Mt. Medvednica and neighboring mountains became the source region of clastic material for sedimentation of the fluvial-lacustine and proluvial sediments of the molasse-foreland type of Pliocene-Quaternary age (Fig.2, Pl,Q). The deposits have sedimented in the boundary areas of the existing lakes, while the coarse clastic materials (various gravels) were deposited along the banks, maybe even on the land as a proluvial drift cones. Fine-grained sediments (sand, clay) deposited in still lacustine environments.

Sediments of Quaternary age cover most of the surface in the analyzed space. The sediments are divided into



MEDVEDNICA
VUKOMERIČKE GORICE
ZAGREB
PODSUSED
SESVETE
IVANIA REKA
DUGO SELO
PETRUŠEVEC
ČRNKOVEC
MALA MLAKA
VELIKA GORICA
LUKAVEC
Sv-2
Re-1
Re-2
Lom-1
Du-2
Du-1
A
A'
B
N
S
E
W
0
2
4 km
LEGEND
15 HOLOCENE (Q_2) marshy deposits (clayey silt)
14 HOLOCENE (Q_2) inundation deposits (sand and clay)
13 HOLOCENE (Q_2) proluvium, deluvium-proluvium (gravel, sand and clay)
12 HOLOCENE (Q_2) alluvial deposits of Sava river and tributary streams (sand and gravel)
11 HOLOCENE (Q_2) deposits of first Sava river paleoterrace (gravel, sand and clay)
10 HOLOCENE (Q_2) deposits of second Sava river paleoterrace (gravel and sand)
9 PLEISTOCENE (Q_1) continental loess (clayey silt)
8 PLEISTOCENE (Q_1) aquatic loess (clayey silt, silty sand, clay)
7 PLIOQUATERNARY (Pl, Q) gravel, sand and clay
6 MIDDLE and UPPER PLIOCENE ($Pl_{2,3}$) sand, gravel and clay
5 UPPER PONTIAN (Pl_1^2) sand, sandy marl, clay
4 LOWER PONTIAN (Pl_1^1) marl
3 PANNONIAN (M) marly limestone
2 SARMATIAN (M) marl, limestone, sandstone
1 BADENIAN (M) breccia, conglomerate, limestone, marl, sandstone
normal boundary
disconformity
non-defined boundary (gradual transition)
major faults of depression
main faults
the fault without designation of character
dip element of fault
A — B geological cross-section
A — A' hydrogeological cross-section
the boundary of hydrogeological system
terrace scarp
Du-2 oil well
1 hydrogeological well
215 elevation


VUKOMERIČKE GORICE STRUCTURE
SAVA DEPRESSION
MEDVEDNICA-MOSLAVAČKA GORA BASEMENT HIGH (BASCH, 1983)
357
24
35
6
40
DUBRANEC
DONJA LOMNICA
VELIKA MLAKA
SAVA RIVER
A
B
Du-1
Du-2
Lom-1
Re-2
Re-1
Sv-2
m
300
200
100
0
500
1000
1500
2000
2300
?
horisontal skale
0 1 2 km
LEGEND
Middle and Upper Pliocene + Quaternary, (Pl+Q)
Lower and Upper Pontian, (Pl)
Middle Miocene (Helvetian-Pannonian), (M)
Palaeozoic (Pz)
Boundary of chronostratigraphic (lithostratigraphic) units
Disconformity
Fault
Lom-1
Label of well
A - B
Label of geological cross-section
12
Direction of cross-section

Pleistocene and Holocene, and further subdivision respects the genetic types.

The deposits from the Lower Pleistocene have not been discovered on the surface. The boreholes revealed the sediments from the Lower Pleistocene of highly variable lithologic contents. Somewhere, they consist of sand mixed with clay containing carbonized plant remains (HERNITZ et al., 1981), while in other areas alternating clay and gravel have been encountered. The Middle Pleistocene deposits are characterized by significant permeability because of large content of sandy and gravel material. In the top parts of these deposits, same as in the deposits of the Lower Pleistocene, paleosol characteristics have been noted (VELIÆ & DURN, 1993). The sediments of Upper Pleistocene are predominantly of eolian origin. Depending on an environment which received eolian material, the aquatic loess and terrestrial loess were singled out. They alternate both vertically and laterally. They are discordantly sedimented on the bedrock and follow the structures formed in Upper Neogene. Their generation is connected with the colder periods in Pleistocene (glacial and stadials). In interstadials or interglacials, the fluvial sediments, fen clay and peat were deposited.

Late in Pleistocene, revival of the tectonic activity in paleofaults running in NW-SE direction and forming of new faults of the same orientation caused subsiding along the boundaries of Mt. Medvednica and Vukomerièke Gorice hills and formation of the Sava depression in a narrow sense. This tectonics enabled disintegration of the barrier and inflow of water from NW into the Zagreb depression (ŠIKIÆ & BASCH, 1975). The depression formed in this way was filled with river sediments in which courses of the Sava River and its tributaries gradually formed concurrently with characteristic forms of fluvial erosion and accumulation: river terraces, meanders, dead waters, sand-shelfs and the like. At the same time, the surrounding hilly zones were exposed to erosion and denudation, which formed a relief much similar to the present one.

On the surface, Holocene deposits are divided into a number of genetic types (Fig. 2). The sediments of the second Sava terrace consist of alternating coarse-grained gravel and sand. Among sedimentary structures, those important for river streams are frequent (imbrication, graded bedding and cross-bedding). The sediments of the first Sava terrace developed along the Sava River course (Fig. 2). Forming of the second terrace sediment was followed by the erosion and denudation phases, so that the Sava cut into its own sediments. Old riverbeds are visible in a number of places on the first terrace. The lithologic composition is predominated by coarse-grained gravel mixed with sand. The water for supply of the City of Zagreb is pumped from the first and second terraces.

Recent and subrecent sediments are of small thicknesses and some of them cover large surfaces. These include alluvial deposits of the Sava River, proluvial sediments, flood sediments and bog sediments (Fig. 2).

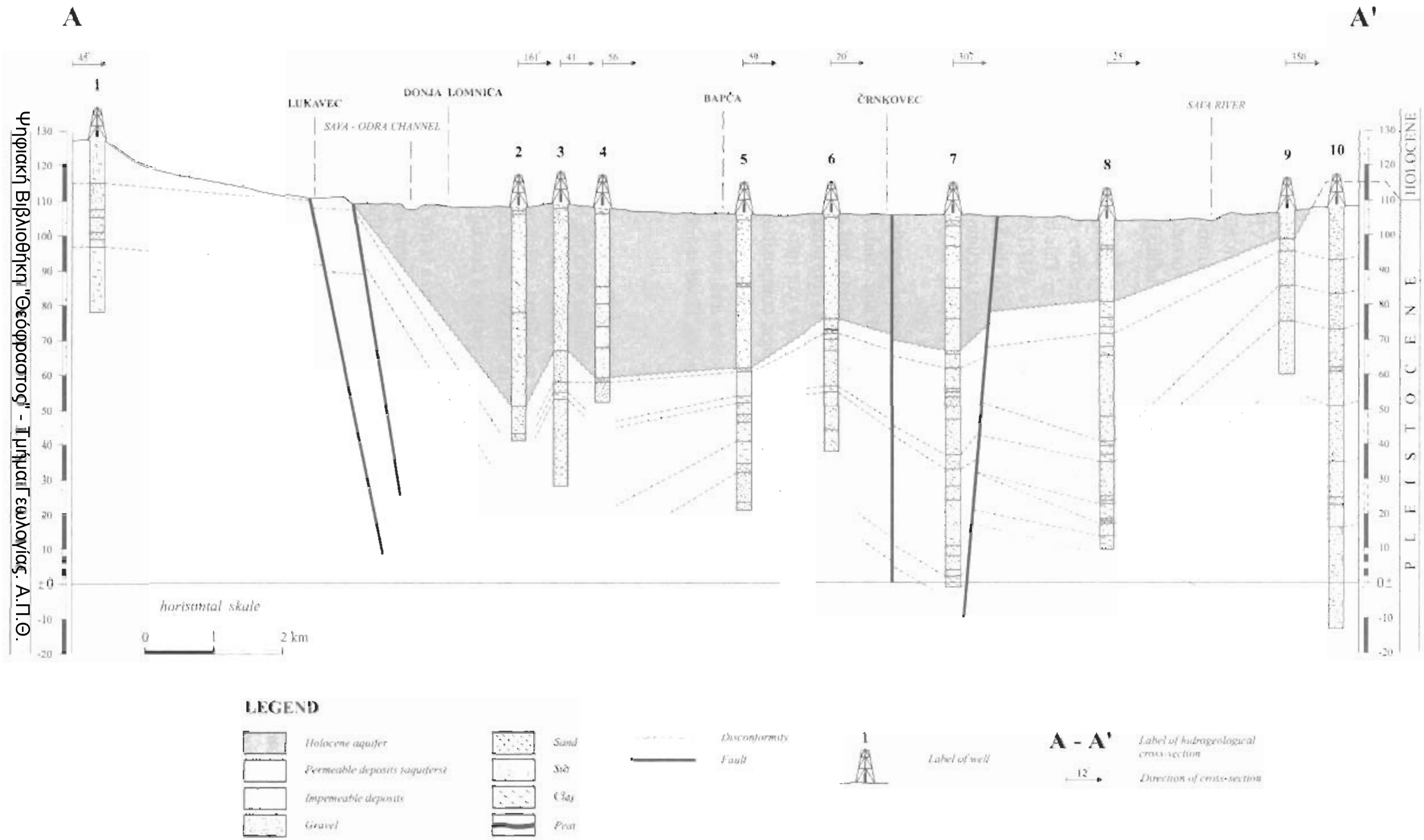
3. TECTONICS

The described area is part of the Dinaric Alps and Pannonian Basin on its far NW boundaries, and the Sava depression inside it. Due to its position and very complex relations with the boundary zones of Alps and Outside Dinarics, the area was exposed to intensive tectonic activity during the geological evolution. After PAND•IÆ, (1986), already the oldest tectonic movements (Paleozoic and older), which resulted in longitudinal deep faults of NW-SE strike direction, and in diagonal faults running in NE-SW direction, have also recurred with different intensity during the Alpine orogenetic cycle. These fractures played a crucial role in formation of large (regional) morphostructures (horsts, depressions).

The most remarkable morphostructural form in the analyzed area is the far NW part of the **Sava depression** (Figs. 2, 3). Start of its formation was initiated by the Pyrenean tectonic movements late in Eocene. Its basic contours the Sava depression got through differentiated subsiding along the "southern and northern boundary faults", particularly during Pliocene and Quaternary. In addition to the said longitudinal fractures, a significant role was plaid by diagonal paleofractures striking in NE-SW direction and in its vicinity (PAMIÆ, 1975; ŠIKIÆ, 1978). The greatest minimums (subsidences) formed in their intersections with longitudinal faults. These are the points of pronounced seismic activity. Amplitude of vertical subsiding movements along the boundary depression faults, also active in recent times, exceeds 2000 m (VELIÆ, 1980).

The tectonic block of **Mt. Medvednica** (Fig. 2) closes the Sava depression on the north-west. Its geotectonic evolution may be followed from the Upper Paleozoic, through Mesozoic and Tertiary when, as an independent tectonic unit or a part of the boundary area of disintegrated Pannonian mass, it considerably affected evolution of the neighboring areas (ŠIKIÆ & BASCH, 1975). However, the main phase in formation of the recent Mt. Medvednica structural framework is related to the tectonic movements in the Middle Miocene and Pliocene, when the complex Mt. Medvednica horst uplifted among the longitudinal faults of the SW-NE strike direction (PAND•IÆ, 1986).

The structure of **Vukomerièke Gorice** hills (Figs. 2, 3) is a positive form of the Dinaric direction which separated the Karlovac zone from the main Sava depression zone. The analyzed area encompasses NE parts of



A
A'
LUKAVEC
SAVA - ODRA CHANNEL
DONJA LOMNICA
BAPČA
ČRNKOVEC
SAVA RIVER
HOLOCENE
PLEISTOCENE
horisontal skale
0
1
2 km
LEGEND
Holocene aquifer
Permeable deposits (aquifers)
Impermeable deposits
Gravel
Sand
Silt
Clay
Peat
Disconformity
Fault
Label of well
A - A'
Label of hidrogeological cross-section
Direction of cross-section

this structure. ŠIKIÆ, & BASCH (1975) related its formation to the tectonic activity during Quaternary.

4. HYDROGEOLOGY

Presently, the water supply of the City of Zagreb is based on exploitation of the groundwater from the Holocene gravel-sand aquifer that has been relatively well researched. However, this layer is underlaid by two to three gravel-sand intervals (Fig. 4) separated from the Holocene aquifer and from one another with poorly permeable clayey silt (loess). This is the material washed down during the Middle and Upper Pleistocene interglacials and interstadials by the streams from the neighboring mountains and deposited in the lakes and marshes. Due to such conditions of depositing high material heterogenity encountered, both vertically and laterally. In adition to detected Upper and Middle Pleistocene aquifers, there are indications of permeable layers inside Lower Pleistocene and Upper Pliocene deposits. The northern boundary of this aquifer system is an impermeable boundary interfacing with the Lower Pontian marl, and the southern boundary is a morphological divide running along the Vukomerièke Gorice ridge. The Zagreb aquifer system is a part of the Sava River catchment, so its western boundary could be defined as an inflow, and the eastern as the outflow boundary.

5. CONCLUSION

The Holocene aquifer supplying today the City of Zagreb with potable water is exposed to contamination and on the verge of being overpumping. Thus, investigations have been undertaken in deeper deposits. The conducted investigations have determined that the Holocene layer is underlaid with several permeable intervals of Middle and Upper Pleistocene age which might play an important role in the future water supply of the city. They are separated from the Holocene aquifer with clayey silt, and consist of alternating permeable gravel and sand. Their thickness is considerable. Their replenishment under natural conditions is the result of infiltration of precipitations in the Vukomerièke Gorice area. In adition to detected Upper and Middle Pleistocene aquifers, there are indications of permeable layers inside Lower Pleistocene and Upper Pliocene deposits. It is imperative that the additional geological and hydrogeological investigations be conducted for exact spatial position and exploitation reserves of these deposits to be determined.

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