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Lithologic Composition and Stratigraphy of Quaternary Sediments in the Area of the "Jakuševec" Waste Depository (Zagreb, Northern Croatia)

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Key words: Pleistocene, Holocene, Freshwater sediments, Erosional unconformity, Palaeoclimate, "Jakuševec" waste depository, Zagreb, Croatia.

Ključne riječi: pleistocen, holocen, slatkovodne taložine, erozijska diskordancija, klima tijekom kvartara, smetlište "Jakuševec", Zagreb, Hrvatska.

Abstract

In the area covered by the "Jakuševec" waste depository, to a depth of 101 m, six lithological units were determined based on fieldwork and laboratory geologic-geophysical investigations. It was discovered that the silty-clayey units (units 1, 3 and 5) are covered by sandy-gravely (units 2 and 4) and gravely ones (unit 6), respectively. These units constitute the sediments of the Middle and Upper Pleistocene and Holocene and are separated by erosional unconformities. The Pleistocene gravels are predominantly of quartz-quartzite composition, while the Holocene ones are composed of carbonate cobbles and pebbles. In contrast, the sands exhibit a fairly uniform mineral composition throughout the column. The Pleistocene silt and clay are mostly composed of muscovite-illite and quartz with lesser amounts of chlorite, kaolinite and smectite. There is a difference in composition of this fraction in unit 6, where the quartz, calcite and dolomite particles prevail and smectite and illite/smectite are absent. Unit 3 is characterised by the goethite content. The Pleistocene layers were formed in a lacustrine-marshy environment while the Holocene sediments are fluviatile. This sedimentary sequence is interrupted by occasional terrestrial phases, or drying-up periods, dependent on the palaeoclimate conditions, particularly the interchange of cold and dry glacials with the warmer and more humid interglacial stages.

Sažetak

U području smetlišta "Jakuševec" do dubine od 101 metra na osnovi terenskih i laboratorijskih geološko-geofizičkih istraživanja razlučeno je šest litoloških jedinica, pri čemu se izmjenjuju prašinasto-glinovite (1., 3. i 5. jedinica) s pjeskovito-šljunkovitima (2. i 4. jedinica), odnosno šljunkovitima (6. jedinica). One izgrađuju naslage srednjega i gornjega pleistocena te holocena, a odvojene su površinama erozijskih diskordancija. Pleistocenski šljunci pretežno su kvarc-kvarcitnog, a holocenski vapnenačkog sastava, dok je mineralni sastav pijesaka kroz cijeli stup dosta ujednačen. Pleistocenski prah i glina u glavnini sadrže muskovit-ilit i kvarc uz stanovite količine klorita, kaolinita i smektita. Za razliku od toga, u šestoj jedinici prevladavaju kvarc, kalcit i dolomit, a smektita i ilit/smektita uopće nema. Znakovita je prisutnost getita u trećoj jedinici. Pleistocenske taložine nastale su u jezersko-močvarnom, a holocenske u riječnom okolišu, s povremenim kopnenim fazama ili isušivanjima ovisno o paleoklimatskim okolnostima, tj. izmjeni hladnih i suhih glacijala s toplijim i vlažnim interglacijalima.

1. INTRODUCTION

In the scope of the groundwater quality monitoring programme near the remedied part of the "Jakuševec" waste depository (Fig. 1), the three deeper structural-piezometric wells were drilled, all of the similar depth, between 100.20 and 101 m. The wells were cored all the way, which means that a total of 301.70 m of core was available for field determination, whereby 92 samples were taken for various laboratory investigations. Upon the correlation of the core determination with the well-logs, 82 samples were chosen in such a manner that all the stratigraphic and lithological units are covered by an equal density of samples and most were adequately represented (Fig. 2).

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Synthesis of all the data obtained from geologic-geophysical exploration resulted in certain ideas regarding the subsurface-geological relations of the "Jakuševec" waste depository area being formed. A detailed lithological determination was performed which helped to delimit the three chronostratigraphic units in the rank of series together with some smaller units.

The large waste depository "Jakuševec" contains a mixture of communal and technological waste, and is presently partly arranged and organised. It is situated at Prudinec locality between the villages of Jakuševec and Mičevec in the south-eastern outskirts of Zagreb (Fig. 1). The waste depository lies parallel to the Sava river on its southern bank, it is 1,500 m long and 400 m wide, covering an area of 600,000 m^2. This position is totally unfavourable in many ways. Apart from being located in the vicinity of the town, some 6.5 km from the centre, the waste-depository also lies in the groundwater

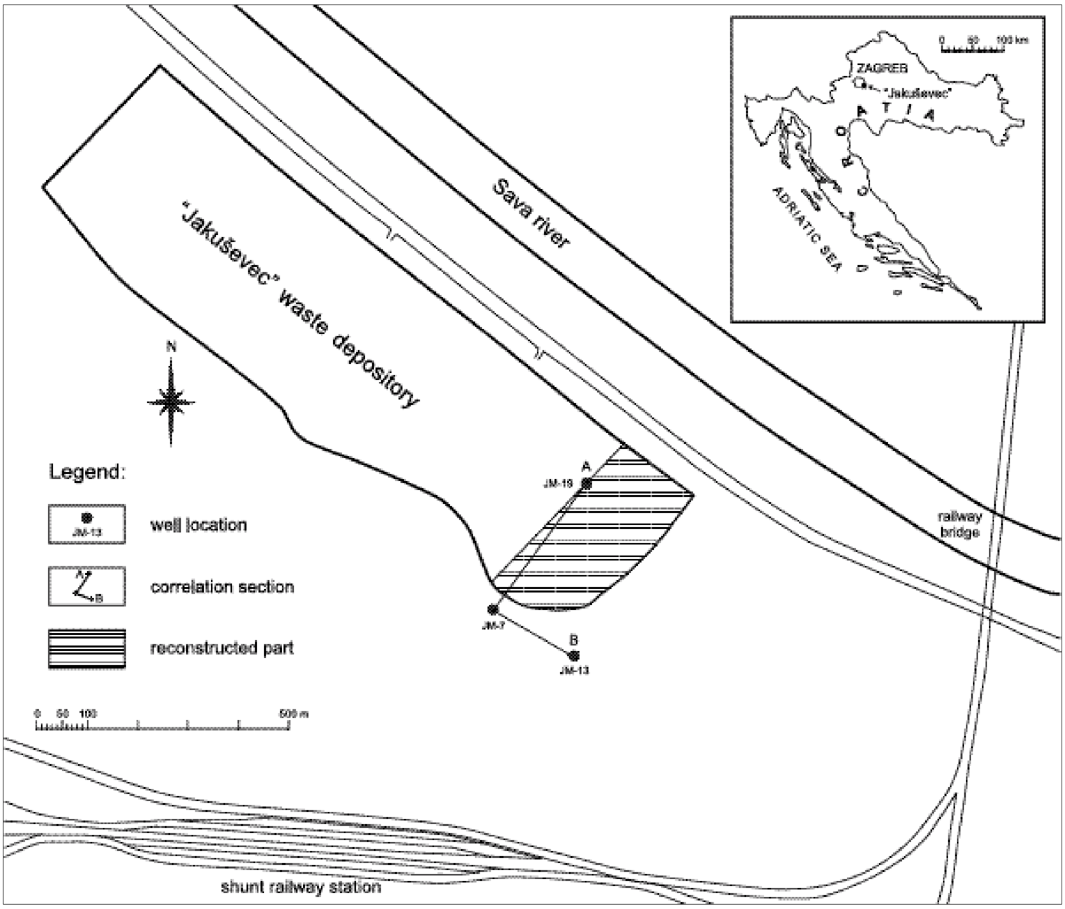

Fig. 1 Location map.

protection zone of both the existing and planned-to-be-built well fields (MAYER & MARKOVAC, 1992). Therefore, remediation of the waste-depository site was highlighted as the best solution in order to prevent its negative influence on environment, especially on groundwater quality.

The Quaternary sediments surrounding Zagreb were firstly described in the beginning of the century (GORJANOVIĆ-KRAMBERGER, 1908). More recent papers can be grouped into hydrogeological ones (MILETIĆ & BORČIĆ, 1967; NOVINSKA et al., 1967; BORČIĆ et al., 1968; ČAKARUN et al., 1987; MAYER & MARKOVAC, 1992) and a geological group (CRNKOVIĆ & BUŠIĆ, 1970; ŠIMUNIĆ & BASCH, 1975; HERNITZ et al., 1981; ŠIMUNIĆ et al., 1988). Since 1991, there has been a partial modification in approach to these kind of studies. Based on the synthesis of all the available geologic-geophysical data and application of subsurface-geological methods, a successful reconstruction of the composition and structure of Pleistocene and Holocene sediments was completed to a depth of approximately 100 m. Adequate chronostratigraphic subdivision was obtained with an improved understanding of the influence of drastic climate changes and Quaternary palaeotectonism. The process started with exploration near Samobor in the west (VELIĆ & SAFTIĆ, 1991) and gradually encompassed the Zagreb area (VELIĆ & DURN, 1993; VELIĆ et al., 1995). The most recently explored area is a section of the south-eastern outskirts of Zagreb (VELIĆ & SAFTIĆ, 1996).

2. LITHOLOGICAL COMPOSITION OF THE SEDIMENTS

Detailed lithological description, performed simultaneously with core determination undertaken in phases parallel to the advance of drilling, was later substantiated with granulometric measurements. Apart from the sedimentary composition, the colour, mottling, macrofossil content, and presence of concretions and rhizocretions were noted. Such complete analyses facilitated comparisons between the JM-7, JM-13 and JM-19 wells and correlation with previously explored localities (VELIĆ & SAFTIĆ, 1991; VELIĆ & DURN, 1993; VELIĆ et al., 1995; VELIĆ & SAFTIĆ, 1996).

Down to the depth of 100 m the sediments are composed of loose or weakly cemented clastics - gravels, sands, silts and clays in variable proportions. The shallowest part (upper 50 m) is dominated by gravels. They are underlain by a thin layer of silty clay overlying the following drilled sequence: gravels and sands; thin silty-clayey sediments; then more sand and finally silts and clays forming the lowermost 10 metres. Obviously,

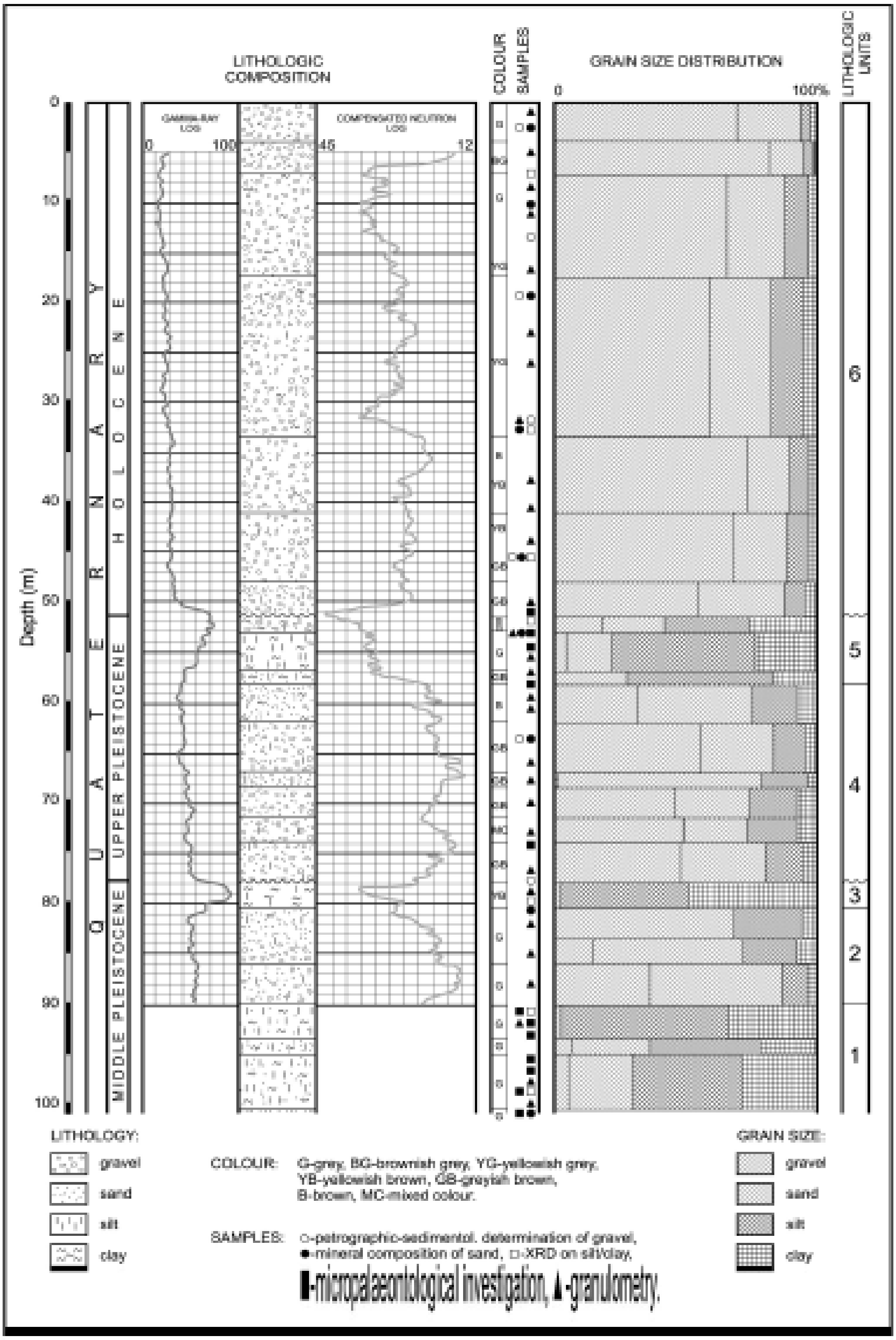

Fig. 2 Lithologic column of JM-13 well.

the 6 lithologic levels can be defined. Based on field determinations and results of various laboratory investigations, each of these units is described in detail below.

2.1. LITHOLOGIC UNIT 1

The oldest lithohorizon lies deeper than 90 m (JM-13 well, Fig. 2). In JM-19 well it was entered at a depth of 92.90 m, and in JM-7 well at 93.50 m (both in Fig. 7). Due to the fact that all three wells were stopped before encountering the basal margin of this unit, its thickness can only be estimated, but it is surely more than 10 metres. Granulometric measurements confirmed that this is the silty-clayey sediment that contains a certain amount of sand. The generalised composition is: 40-60 % silt, <20 % of clay with occasionally 20-30 % of sand. The colour varies from shades of grey and dark-grey, to bluish-grey and greenish-grey. A

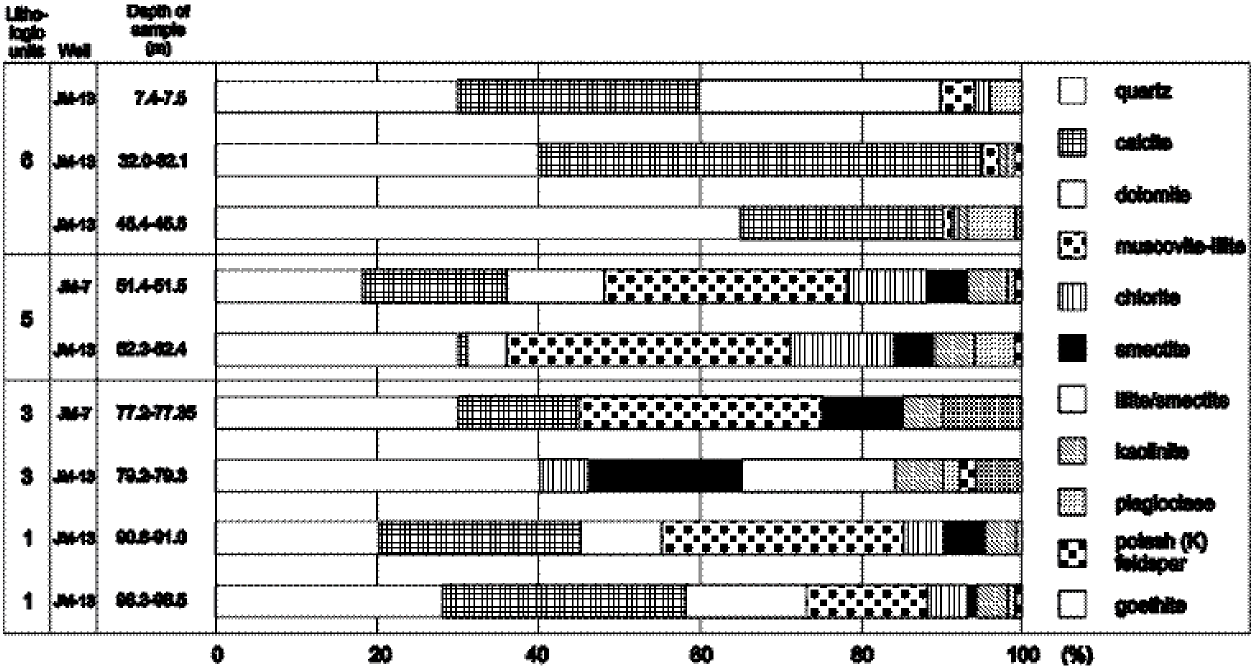

Fig. 3 Mineral composition histogram of core samples from wells JM-7 and JM-13 determined by X-ray powder diffraction.

dark-grey coloration predominates, for instance, the complete interval of this unit in the JM-13 well is solely grey (Fig. 2).

The x-ray diffraction analyses (Fig. 3) gave the following composition of silts and clays. The most abundant are particles of muscovite-illite and calcite as well as quartz, all in the range of 28 - 30 %. Dolomite comprises a significant 10 - 15 % while other minerals contribute 4 - 5 % - chlorite, kaolinite and smectite. The light mineral fraction of sand is composed of 65 % of quartz, 20 % of rock fragments, 12 % of feldspar and 3 % of muscovite. The heavy mineral fraction (Figs. 4 and 5) is dominated by transparent minerals (64 % in total) and is composed of garnets (41 %), epidote-zoisite (21 %), amphibole and tourmaline (12 % each), together with disthene, staurolite and apatite (each approximately 3 %).

These fine-grained deposits contain weathered white concretions, sporadic pebbles of lithothamnium limestone and flint, weathered and crumbly mollusc shells, gastropod operculums and carbonised plant remnants. An ostracod fauna was also determined, characterised by a uniform composition and quite a large number of specimens, indicating a lacustrine depositional environment and Middle Pleistocene age. The topmost 5 m of this unit is laminated. Lamina-sets consist of a sequence of silty clays, clayey silt and fine-grained sand (< 1 mm thick laminae) thus making an alternation of dark-grey and light-grey laminae. Each pair of lamina can be interpreted as a varve, whereby laminae of fine-grained sand were deposited in warmer periods, and silty-clayey ones in colder periods. These laminae depict lacustrine sedimentation, in other words, the transport of fine-grained material by watercourses flowing on the surrounding flood-plain. Once brought into the lake, the fine-grained material spread in suspension and was deposited very slowly.

2.2. LITHOLOGIC UNIT 2

The previously described silty-clayey unit is covered by another lithohorizon with a relatively abrupt contact between the two units. In the aforementioned three wells, this unit appears at different depth intervals: in JM-7 well it lies between 78.90 and 93.50 m (Fig. 7), in JM-13 it is between 80.40 and 90 m (Figs. 2 and 7) and in JM-19 in 80.30 - 92.90 m interval (Fig. 7). In this way, the sandy unit 2 has a drilled thickness in the range of 9.60 - 14.60 metres, with a maximum in the JM-7 well and minimal thickness in JM-13.

With a ratio of 30 - 90 %, sand is the dominant granulometric fraction of this sediment. The maximal amount of sand was drilled in the JM-7 well, in the deepest 2.5 m of this unit. The most common sand ratios are in the range of 50 - 60 %. Other grain-sizes are also present. Gravels occur in the range of 15 - 58 %, but mostly under 20 %. There is an increased amount of gravel in the 82.40 - 88.10 m interval of the JM-7 well. The maximal portion of silt is 25 % and clay was determined in the 5 - 10 % range.

Unit 2 was described in the field as a mostly grey or ash-grey uncemented sediment. It was also noted that sand contains sporadic pebbles and fragments, 3 - 4 mm in diameter, of both grey and white quartz, black quartzite, dark-red sandstones, green diabase and orange slate. Occasionally, these pebbles are covered by a limonite coating having the colour of rust. In the JM-13 and JM-19 wells, the deepest 3 - 4 m are composed of fine-grained gravel and coarse sand. This interval is

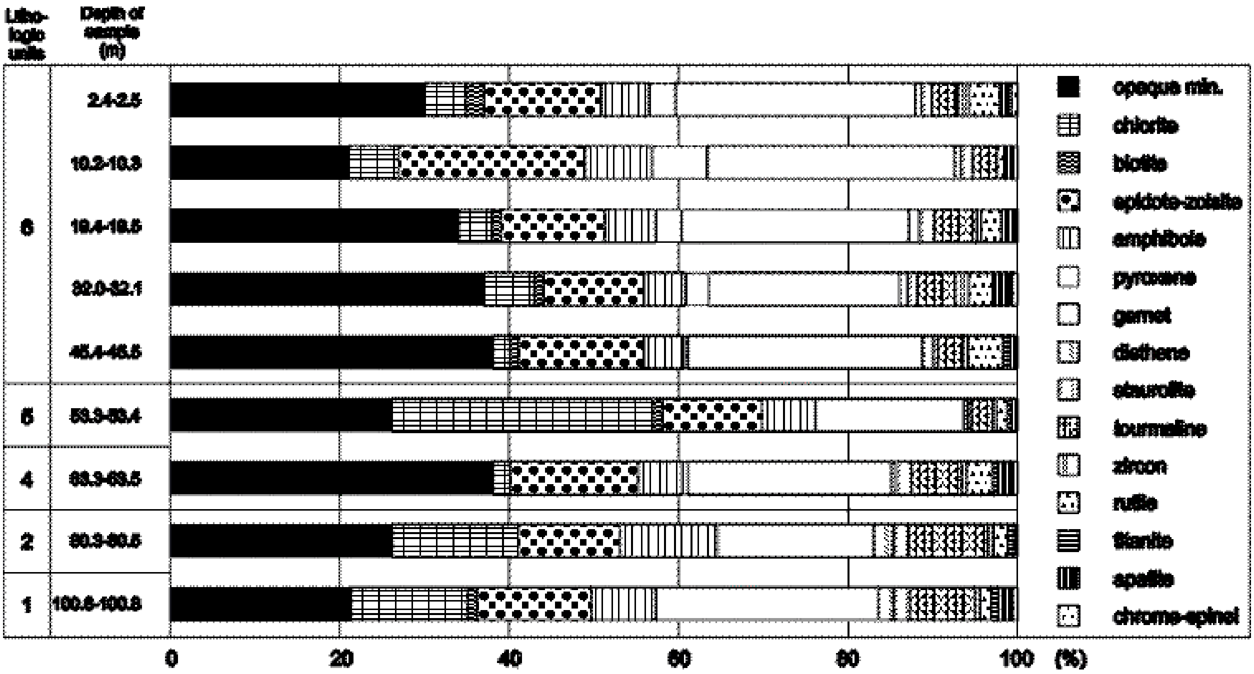

Fig. 4 Heavy fraction mineral composition of sand samples from well JM-13.

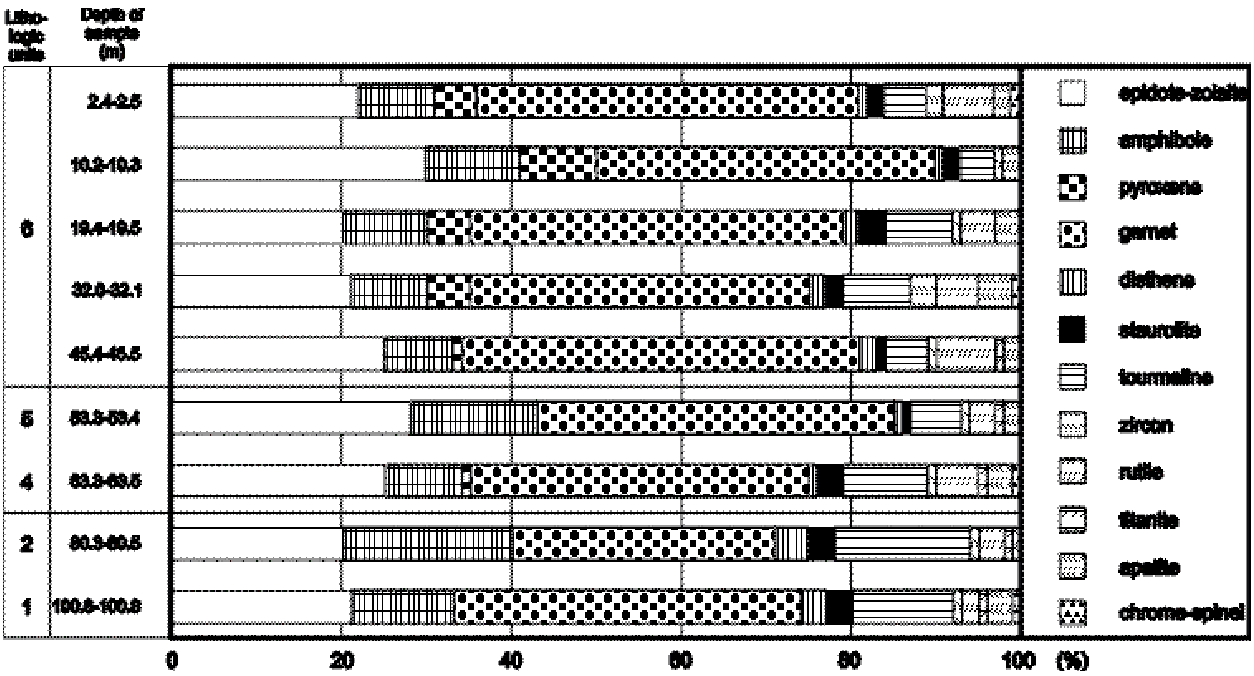

Fig. 5 Transparent heavy minerals composition of sand samples from well JM-13.

covered by medium-grained sand, while the top of the unit is made of fine-grained sand with small amounts of silt and clay. Such a clastic sequence, described on the basis of the field grain-size estimations, is substantiated by laboratory measurements and in part depicts the normally graded bed.

In comparison to the older unit 1, sands of this unit contain a 10% higher ratio of quartz (70-75 %), significantly more muscovite (up to 9 %), somewhat smaller amount of feldspar (9-11 %), while the presence of rock fragments varies (14-21 %). The mineral composition of the transparent heavy mineral fraction remained the same - prevailing garnets followed by epidote-zoisite, amphibole and tourmaline (Figs. 4 and 5).

The cobbles, pebbles and fragments of the gravel fraction are mostly composed of quartz and quartzite (56.8-63.3 %), then of dark-grey and black sandstones and siltites - probably of Palaeozoic age, and of dark-red Triassic and/or Cretaceous sandstones and siltites (22.6-23.1 %). Other rock fragments are the crystalline schists (0.9 - 8.5 %), extrusives (1.4 - 6.3 %), limestones (2.7 - 5.4 %), chert (0.7 - 3.6 %) and the dolomite (under 3.5 %).

In the JM-7 well, the clastic fraction with diameters larger than 4 mm is poorly sorted. It contains a quantity of well-rounded to subrounded and abraded grains measuring between 4 - 10 mm, with solitary cobbles and angular fragments that reach up to 20 mm in diameter. The chert, extrusives and quartz/quartzite particles are well rounded and abraded. Contrary to the situation in JM-17, in the JM-19 well the fraction above 4 mm is well sorted.

Due to the high level of roundness and comparatively small dimensions, most of the siliciclastic particles are interpreted to have gone through a number of cycles of reworking and redeposition. These grains must have originated from older clastic sediments, probably from the Palaeozoic, Triassic and Cretaceous sandstones and siltites.

2.3. LITHOLOGIC UNIT 3

The third unit is a bed of clayey silt and/or silty clay. In the JM-17 well it was drilled in the 77.10 - 78.90 m interval, so it is only 1.80 m thick (Fig. 7). In the JM-13 well this unit is 2 metres thick and comprises the 78.40 - 80.40 m interval (Figs. 2 and 7), while in the JM-19 it has a thickness of only 0.9 m and lies between 79.40 and 80.30 m (Fig. 7). These clays and silt contain sporadic granules and small fragments (measuring a few millimetres) of quartz and quartzite. The unit is characterised by a mottled rusty-brown to brownish-orange and gray coloration. Apart from the irregular coloration, coloured lamina-sets were observed with characteristic change of the same range of tones. Based on the granulometric analyses of cores taken from the JM-7 and JM-13 wells, the grain-size distribution of this sediment is such that clay particles prevail (48 - 50 %) but with an almost equal amount of silt (44 - 48 %). Remaning particles have a size of fine-grained sand (Fig. 2). There is a slight difference in composition of sediment drilled in the JM-19 well, where unit 3 is found to be composed of 22 % clay and 32 % silt with predominant sand (43 %) and some gravel (3 %).

Based on the cores taken from the JM-7 and JM-13 wells, the mineral composition of the silts was analysed (Fig. 3). The dominant mineral constituents are muscovite-illite and quartz (30 - 40 %). The sample taken from the 77.20 - 77.35 m interval of the JM-7 well gave 15 % of calcite, while in the same unit, this mineral has not been determined in well JM-13. An additional common characteristic of the unit 3 mineral composition is a significant amount of smectite and illite-smectite (10 - 19 %). Due to the adsorbing capabilities of smectite, even smaller proportions in the underlying rocks are of importance for the remediation process of the "Jakuševec" waste depository, because of the implications for the preservation of the groundwater quality. There is another important fact that has to be pointed out, too. This is the presence of goethite (up to 10 % in JM-7, and 6 % in JM-13). The dolomite has not been identified, not even in very small quantities.

The presence of goethite in the unit 3 is in concordance with the characteristic brown colour of this sediment. It is interpreted as being formed after the lake/marsh infilling, when a certain break in aquatic sedimentation occurred and a short-lasting terrestrial phase commenced with characteristic oxidation processes.

2.4. LITHOLOGIC UNIT 4

In comparison to the previously described units, this one has the greatest thickness. In the JM-7 well it was drilled in the 52.70 - 77.10 m interval (Fig. 7), in JM-13 between the 56.80 and 78.40 m (Figs. 2 and 7) and in JM-19 in the depth interval 51.70 - 79.40 m (Fig. 7), so the drilled thickness of this unit in the three wells thus is 24.40, 21.60 and 27.70 m. Based on the granulometric composition, unit 4 is composed of several layers - apart from the prevailing sands, there are sandstones, gravels and conglomerates. There are also a variety of colours - grey, yellowish-grey, greyish-brown, brownish-grey and rusty-brown sediments were found. The sands and fine-grained gravels sporadically contain quartz and quartzite pebbles larger than 1 cm. The weakly cemented sandy conglomerate layers are 20 - 100 cm thick and are marked with the mottled cement - grey, violet and rusty-brown. They contain a large portion of silty-clayey matrix.

Comparison of the granulometric composition did not result in the reliable correlation of this unit in all three wells, because the ratios of some fractions significantly vary with depth. The JM-7 well has the following column - domination of sand (58 %) in the lowest 3.5 m, covered by 11 m of mostly sand and gravel (28 - 40 % each) with the addition of silt and clay-size particles (less than 30 % together), and with the upper 9 metres of a prevailing sandy fraction (54 - 68 %) and addition of 20 % of silt.

The composition of unit 4 in JM-13 well is dominated by gravels which contribute around 50 % or more in most of this unit's interval. There are only two smaller intervals that are the exception - 67.00 - 68.50 m mostly of sand (77 %) with remains of gravel and silt, and 59.40 - 61.90 m with nearly half sand (48 %) and rest of silt (Fig. 2).

It is only in the JM-19 well that unit 4 shows a certain degree of granulometric regularity. Namely, there is an upwards-fining sequence with a gradual increase in the sand and silt content and a parallel reduction of gravel-size grains. The lower 9.5 m is dominated by 62 - 72 % of gravel, while the upper 16 m (or less) are characterised by a reduction in the gravel content from 18 % to 9 % followed by the increase in sand ratio from 20 % to 57 - 65 % and silt ratio from 9 % over 18 % to 28 %. There is a potential for interpretation of this data in terms of depositional environment, especially of dynamic sand influx from a number of transport direc-

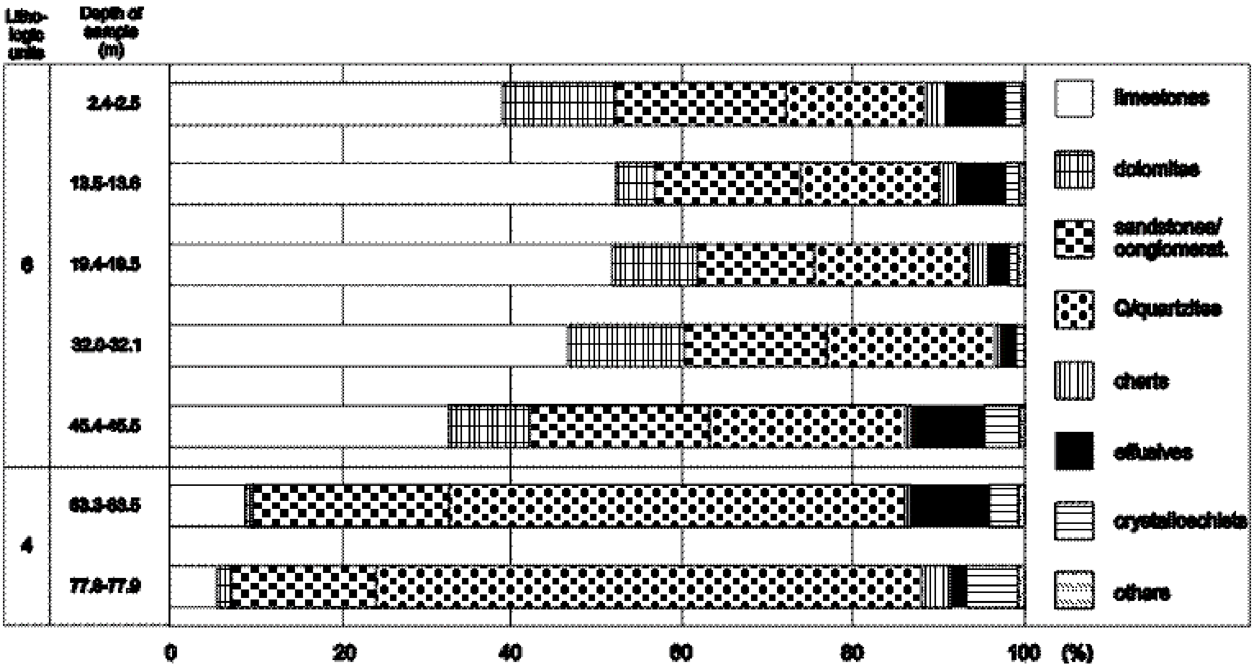

Fig. 6 Mineral-petrographic composition of gravel fraction from well JM-13.

tions. However, in order to reach a more decisive and more substantiated conclusion, a larger number of analyses are needed from several wells. The quality of the analyses is also critical - they have to be performed very carefully, taking measures to prevent the finer fractions from being washed out from the core.

The laboratory analyses of 7 gravel samples showed the pebble-size contents in the 15.6-41.3 % range with 58.7-84.4 wt. % of clayey-silty sand sediment. Almost all the fractions above 4 mm are well sorted. Their composition is markedly dominated by sub-rounded pebbles and fragments of quartz/quartzite measuring between 4-8 mm. There is also a comparatively high content of dark-grey and dark-red sandstones, probably of Palaeozoic, Triassic and/or Cretaceous age, with some fragments of siltites and pelites. Each of these rock components contributes within a characteristic range - quartz and/or quartzites 53.4-68.5 %, sandstones and conglomerates 12.2-29.1 %, limestones 3.2-13.4 %, extrusive rocks 1.2-9.3 %, crystalline schists 1.8-6.2 %, dolomite 0.8-5.6 % and chert 0.8-3.6 % (Fig. 6).

The sand mineral composition is generally comparable with that determined in the older units. Light mineral fraction is composed mostly of quartz (58-75 %), rock fragments (17-30 %), feldspars (4-13 %) and muscovite (1-8 %). Garnet remained dominant in the transparent heavy mineral fraction, followed by epidote-zoisite and tourmaline. Pyroxene and rutile were for the first time determined as the fourth most frequent minerals.

2.5. LITHOLOGIC UNIT 5

The previously described sandy-gravely unit is covered by clays and silts of unit 5. The pronounced lateral change of thickness is the marked characteristic of this layer. In the JM-7 well unit 5 lies in the 51.00-52.70 m interval and is 1.7 m thick (Fig. 7). In the JM-13 well it is between the 51.40 and 56.80 m (5.4 m thick, Figs. 2 and 7). In the JM-19 well, the depth-interval of unit 5 is 48.00-51.70 m, where it is of medium thickness - 3.70 m (Fig. 7). These fine-grained clastics are, also like the older ones, coloured in shades of gray, bluish-grey, brown and rusty-brown, with an occasional mottled appearance. Especially important is the topmost 20 cm of this unit in the JM-13 well, which has a very distinctive brown colour, resulting from palaeogeographic location and being due to soil forming processes during phases of subaerial exposure (VELIĆ & DURN, 1993). The clays of unit 5 contain thin, <20 cm thick layers of fine-grained sands with some gravels. These layers are in brown tones and contain fossil mollusc shells, which are crumbly and impossible to separate from the sediment, so they could not be determined. In the JM-7 well, this was noted in the 51.50-52.30 m interval that contains 58 % of sand. In the JM-19 well, such a layer lies between 49.20 and 49.60 m having 20 % of sand and 57 % of gravel. Apart from the aforementioned, the granulometric composition of this unit is 54-67 % of silt and 23-42 % of clay. In addition to the fossil fauna, the clays contain carbonised plant remnants and angular quartz and quartzite fragments up to 5 mm in diameter.

The mineral composition of silts and clays in unit 5 is dominated by muscovite-illite (30-35 %) and quartz (18-30 %). There is again a difference in the calcite contents - in the JM-7 well it was found to be around 18 %, and in JM-13 only 1 %. The same spatial relation was observed in the unit 1. In both of these two wells, unit 5 contains a significant amount of chlorite (10-13 %) which makes a marked difference from all the previously described units and from the overlying unit 6. Also, the second appearance of 5-12% of dolomite is stressed because it is totally absent in the unit 3 (Fig. 3).

In the thin layer of fine-grained gravel, the fraction above 4 mm is dominated by well-rounded platy and ellipsoid carbonate pebbles (49.3%) and fragments measuring between 6 and 30 mm. A secondary component includes subangular to subrounded, occasionally rounded pebbles and fragments of quartz/quartzite (27.4%). Well rounded, mostly platy pebbles and fragments of sandstones and sandy conglomerates compose 10.5%, and angular to subangular grains of chert and extrusives form 4.2%, the same proportion as the crystalline schists.

From each of the three wells, one specimen of sand was taken from the unit 5. Based on the mineral composition analyses, there are no significant differences from the composition of older lithohorizons. In the transparent heavy mineral fraction, together with garnet and epidote-zoisite as the prevailing components, the topmost part of the unit contains equal proportions of amphiboles, tourmaline and rutile - 6%.

2.6. LITHOLOGIC UNIT 6

The youngest and shallowest unit is mainly composed of gravels and sands mixed in different proportions. The following intervals were determined: in the JM-7 well from the surface down to the depth of 51.00 m (Fig. 7), in JM-13 to the depth of 51.40 m (Figs. 2 and 7) and in the JM-19 to the 48.00 m (Fig. 7). These sediments are characteristic for the domination of well-rounded limestone and dolomite pebbles and cobbles, as well as for their colour. Contrary to the older deposits, these sediments are markedly light-coloured - light-grey, occasionally pale-yellowish. The two general conclusions can be drawn based on the granulometric results - (1) the gravel fraction is markedly dominant (55-80%) and (2) the granulometric composition is more-less uniform throughout the interval, meaning that gravel dominates the whole unit. Sand forms the secondary component (18-25%) and the remainder is silt and clay. The average clay content is only 1-3%. Neither the field core determination, nor the laboratory analyses, enabled identification of any phenomena that would facilitate further, more detailed correlation within this unit.

The gravels of this topmost unit were represented by eleven samples. They contained 41.8-85.4% of fraction above 4 mm, with a weight percentage of muddy sand sediment in the 14.6-58.2% range. The fraction larger than 4 mm was found to contain both well-sorted and poorly sorted pebbles and cobbles with a diameter range up to 70 mm. The contribution of different petrographic types is - limestones 32.5-57.7%, quartz-quartzites 6.8-27.3%, dolomites 3.4-23.3%, sandstones and/or conglomerates 8.7-21%, extrusives 1.7-8.7%, cherts 0.7-6.8% and crystalline schists 0.6-6.3% (Fig. 6). It is notable that the well rounded, platy to ellipsoidal carbonate pebbles and cobbles are the primary component of unit 6. There are also significant contributions of the well rounded, mostly platy, pebbles and cobbles of sandstones and conglomerates (under 21%), and of the sub-angular to sub-rounded, seldom rounded quartz and quartzite grains (less than 27.3%) that as a rule make the finest part of the gravel fraction.

The light mineral fraction of sand is composed of up to 70% quartz with lithoclasts (16-26%), feldspars (7-14%) and muscovite (1-5%). The transparent heavy mineral fraction in this unit remained dominated by garnet in a somewhat smaller percentage (47%) and by epidote-zoisite (under 34%). It is interesting that a number of minerals comprise the fourth place - amphibole, pyroxene, tourmaline and rutile. The presence of pyroxene is significant in light of the results of RAFFAELLI & MUTIĆ (1982), who found this mineral to be characteristic for the Holocene sediments of the Zagreb area.

In relation to the older units, the difference in composition of clays and silts of the unit 6 was expected. The most frequent mineral components are quartz (30-65%) and calcite (25-55%), with an addition of dolomite (30%) in the shallowest sample from the JM-13 well (7.4-7.5 m sample in Fig. 3). The rest of the minerals were present in small proportions (1% to exceptionally 6%). The absence of larger quantities of chlorite is significant (<2%), while smectite and illite-smectite are totally absent (Fig. 3).

2.7. COMPARISON OF THE RESULTS OF QUANTITATIVE DETERMINATION OF MINERALOGICAL-PETROGRAPHIC COMPOSITION

Based on the results of quantitative determination of the mineralogical-petrographic composition of the gravel fraction, down to the depth of 92.8 m, two mineralogical-petrographic assemblages can be discerned. Due to their petrographic-sedimentary characteristics, they are interpreted as being formed by depositional cycles with the same or similar source areas.

The predominantly carbonate assemblage is described by the samples taken shallower than 32.20 m in JM-7 well, 45.5 m in JM-13 well and 46.9 m in JM-19 well. These are the Holocene sediments and the Sava river deposits. All of the other gravel samples are from the older, predominantly siliciclastic (quartz-quartzite) assemblage. According to its petrographic-sedimentary characteristics, these sediments are made of detritus that resulted from erosion of the Mesozoic and Palaeozoic rocks where by grain dimensions, roundness of the quartz/quartzite clasts and the high content of the most resistant clasts, it was found that the grains have undergone multiple cycles of weathering (erosion), transport and deposition. This makes it likely that the detritus of this assemblage, although it is from primary crystalline rock, in the Holocene sediments mostly originates from the erosion and redeposition of the Mesozoic and Palaeozoic conglomerates and sandstones. With respect to the 6 determined units, this means that the units 2 and 4 (and most probably one gravely-sandy layer of the unit 5), pertain to the older siliciclastic assemblage, while the unit 6 has a composition of the younger, carbonate mineral assemblage. These facts are very important for stratigraphic analysis.

Analysis for characteristic transparent heavy mineral compositions in the chronostratigraphic units was only partly successful. Garnet is the most abundant mineral in all of the samples, occurring in the 30-60% range regardless of sample location. Epidote and zoisite are next with ranges from 9-34%, and similar proportions were determined throughout the whole studied sedimentary sequence. It is only on the basis of the quantities of amphibole, tourmaline and rutile that certain changes are observed. In more detail, the older, Pleistocene sediments often have tourmaline as the third major mineral component (6-16%) and sometimes rutile, also. This is especially true for units 1, 2 and 4. In the units 5 and 6 the third mineral component is amphibole (8-11%) and the pyroxene is determined in just a few percent, enough to characterise the Holocene sediments. Based on the mineral composition and morphologic characteristics of particles, it is concluded that the detritus originates mostly from the metamorphic and older sedimentary rocks, very rarely from the acidic igneous rocks. This finding is in concordance with the petrologic-sedimentary characteristics of gravels.

By comparison of all the values of XRD analysis of silts and clays, the following factors are found to be potentially important for discrimination between units 1-6:

- unit 1 is dominated by muscovite-illite, quartz and calcite with a smaller amount of dolomite and some chlorite and kaolinite;
- unit 3 is characterised by the absence of dolomite and a lot of goethite - the highest content within the studied sediments;
- units 3 and 5 have a predominance of the muscovite-illite and quartz with a significant quantity of smectite and kaolinite;
- unit 6 is mainly composed of quartz, calcite and dolomite, while the smectite and illite/smectite are totally absent.

3. STRATIGRAPHIC RELATIONSHIPS

It is possible to define the stratigraphic relationships in the "Jakuševec" waste-depository area to the depth of 100 m, namely for the sedimentary sequence that was explored in detail by the three wells - JM-7, JM-13 and JM-19. It is regrettable that JM-19 was not drilled to the depth of 120-150 m as suggested, because the basement of the Middle Pleistocene sediments could have been reached, and this stratigraphic surface roughly corresponds to the regional well-log marker Q'. Having taken the results of the previous exploration of Quaternary sediments in the lowlands of the Zagreb area (around Samobor and Podsused, VELIĆ & SAFTIĆ, 1991), in the area of Prečko (VELIĆ & DURN, 1993) as well as in the area of the Zagreb centre (VELIĆ et al., 1995), and comparing them with the findings from "Jakuševec", the sediments are interpreted to belong to the Quaternary system, and the Pleistocene and Holocene series within. The Pleistocene sediments are further divided into the Middle and Upper Pleistocene.

This subdivision is partly confirmed by the results of the palaeontological investigations on 30 samples that were all macerated. The common characteristic of these samples was that they were not fossiliferous - only 1 of 9 samples taken from the JM-7 well had a microfauna content, 4 out of 12 from the JM-13 and 3 out of 9 from the JM-19 well contained fossils. The most frequently encountered microfossils were ostracods, remains of gastropod operculums and partly destroyed micromolluscs. Among the ostracods, two species were determined - *Scottia gagicae* SOKAČ and *Cytherissa lacustris* (G.O.SARS) together with the larval forms of the *Candona* genus. The majority of samples contained only a small number of fossil specimens. The opposite was the case for unit 1 - clayey silts and silty clays where an exceptionally rich and well preserved fauna of ostracods was found. Although located at different depth intervals (93.80-94 m in JM-7, 92-92.2 m and 93.4-93.5 m in JM-13 and 93.8-93.95 m in JM-19), all of the samples pertain to the same layer. The determined ostracod fauna of uniform composition allows a Middle Pleistocene age to be assigned to these sediments (SOKAČ, 1978).

While drilling, the Middle Pleistocene sediments were encountered at different depths in the three wells (in JM-7 at 77.1 m, in JM-13 at 78.4 m and in JM-19 at 79.4 m). The quoted depths are given according to the core determination in the field. The well-logs shown in Figs. 2 and 7 show slightly different depths and there is a small discrepancy between the well-log curve and lithological intervals drawn after the core determination.

The Middle Pleistocene sediments encompass units 1, 2 and 3, two of which have the clayey-silty lithologic composition and one of sand. Unit 3 is significant, because it marks the final phase of lacustrine-marshy sedimentation in the Middle Pleistocene and was for a certain period of time exposed on the surface, which resulted in its brownish and rusty colour. Due to the fact that the basement of this chronostratigraphic unit was not reached by any of the three wells, the total thickness is difficult to estimate, but it is surely more than 23 m.

Between the Middle and Upper Pleistocene sediments there is an erosional unconformity. The Upper Pleistocene sediments encompass the lithological units 4 and 5. They were both deposited in the newly-formed sub-aqueous environment and contain roughly equal proportions of gravels and sands. There is also a marked difference in thickness (the biggest in JM-19 well is

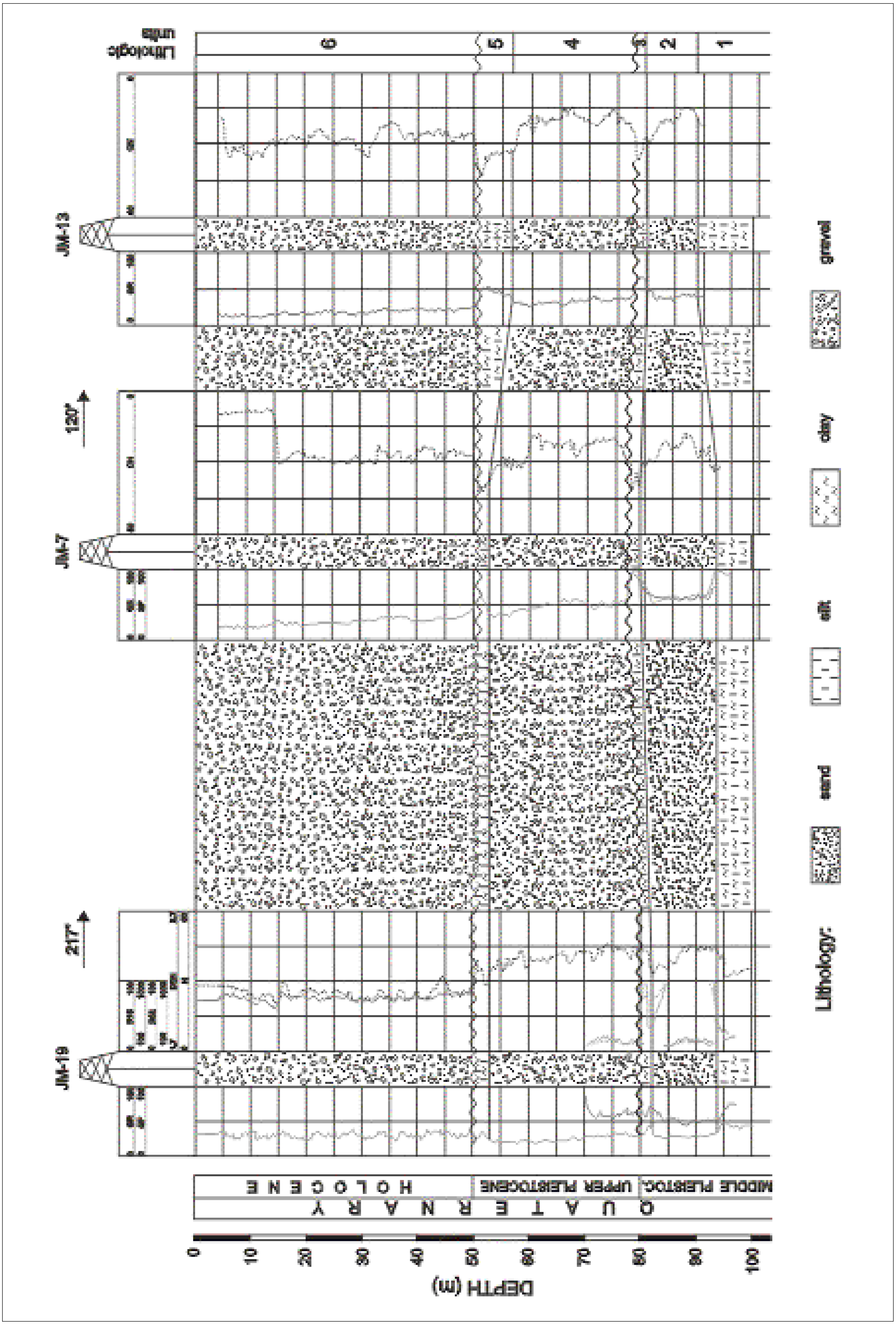

Fig. 7 Correlation cross-section.

31.4 m, over 27 m in JM-13, to the smallest value of 26.1 m in JM-7). The apical part of this chronostratigraphic unit is also composed of fine-grained clastics that were altered under atmospheric influence. The presence of goethite is significant in this sense, because this is the mineral that forms from iron minerals in the oxidation zone of the weathering crust. This is a clear evidence of a second terrestrial phase.

Subsequent to the climatic changes and tectonic processes that enabled the Sava to start flowing in its present river bed, the youngest chronostratigraphic unit was deposited. These are the Holocene carbonate gravels (lithological unit 6) that were transported by the river and its neighbouring smaller tributaries and then deposited when the water flow lost the necessary energy, thus forming the Sava alluvium. These gravels have a thickness in the range of 48 m (in JM-19 well) to the 51.4 m (in JM-13). In the JM-7 well, the 51 m was drilled. This thickness is several times greater than the thickness of the Sava carbonate deposits that was determined in the Prečko area (VELIĆ & DURN, 1993) which depicts local changes of depositional environment most probably due to the tectonic movements. The exact explanation would become possible only after the additional study of both the "Jakuševec" locality and its broader surroundings.

The relationship between the delimited chronostratigraphic units is illustrated by the schematic correlation cross-section (Fig. 7). The most important features are deviations of the gamma-ray log (natural gamma radiation) in the intervals of erosional unconformities. This is because of the increased radioactivity of clays and silts in the topmost parts of the Middle Pleistocene and Upper Pleistocene sediments.

4. RESULTS AND CONCLUSION

Based on the synthesis of the fieldwork and laboratory results, the subsurface geological relationships under the reconstructed part of the "Jakuševec" waste depository are defined. The following findings are the most important.

1) The shallowest 100 m of sediments is composed of loose or poorly cemented gravels, sands, silts and clays mixed in variable proportions.
2) The six lithologic units are defined, depicting the changeable sequence of coarse- and fine-grained clastics. The oldest, unit 1 is mainly composed of clayey silt and has a thickness of more than 10 m. Unit 2 is 9.6-14.6 m thick and has a sandy-gravely composition. The third unit is again composed of clayey silt and is only 0.9 to 1.8 m thick. The overlying unit 4 is sandy-gravel and has a thickness in the 21.6-27.7 m range. Unit 5 is clayey-silt and 1.7-5.4 m thick, while the topmost, youngest gravely-sand unit has a thickness of 48-51.4 m.
3) The gravels of units 2, 4 and 5 are clearly differing from the ones in unit 6. The first gravels belong to the siliciclastic (quartz-quartzite) assemblage that was formed from detritus originating from the erosion of the Palaeozoic and Mesozoic rocks and has undergone multiple cycles of weathering, transport and deposition. The gravels of unit 6 are composed of carbonate (limestone) comprising the Sava alluvium of Holocene age.
4) The sand mineral composition is quite uniform. In all of the samples of the transparent heavy mineral fraction the most frequent minerals are the garnets, epidote and zoisite. In the older, Pleistocene sediments (units 1, 2 and 4) tourmaline appears as the third most frequent mineral, while in the units 5 and 6 this place is taken by amphibole. This might represent one of the additional criteria for subdivision of Quaternary sediments in the studied area. According to the described mineral composition and the morphologic characteristics of grains, the sand mostly originates from the metamorphic and older (Palaeozoic - Mesozoic) sedimentary rocks.
5) The mineral composition of silts and clays is also comparatively uniform. There is a general predominance of muscovite/illite, quartz and calcite. Certain differences were also observed that enable identification of the lithologic units. Unit 1 is characterised by the regular presence of small amounts of chlorite and kaolinite. Unit 3 has a significant proportion of goethite, smectite and kaolinite, and the last two minerals are also significantly present in unit 5, but without goethite. Unit 6 is totally without smectite and illite/smectite. Due to the adsorbing capabilities of smectite, even small proportions can be of importance for groundwater protection. That is why the hydrogeological significance of unit 3 is stressed, because it contains almost 20 % of smectite.
6) The studied sediments have a low fossil content. It is only in the samples taken from the 92-94 m interval that the uniform fauna of ostracods typical for the Middle Pleistocene was determined.
7) The sediments of units 1, 2 and 3 are of Middle Pleistocene age. Above the erosional unconformity covering the unit 3, lie the Upper Pleistocene sediments of the units 4 and 5. There is another unconformity on the top of the Pleistocene sediments which are overlain by unit 6 of Holocene age. The sedimentary sequence is interpreted in terms of interchangeable deposition in the aquatic (lacustrine-marshy) and in alluvial environment with occasional emersion phases or dry-up periods which resulted from the climatic changes as described by VELIĆ & DURN (1993).
8) The achieved results indicate that only comprehensive and systematic geological investigation can yield the reconstruction of the subsurface relations

and enable reliable correlation to be made. This correlation is most important from the hydrogeological point of view, especially in the groundwater protection aspect that was and still remains the aim of the "Jakuševec" waste depository remediation project.

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