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Identification of Karstification Depth in South-Western Bosnia Using the Tracer Method

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Key words: Karst hydrogeology, Karstification depth, Underground barrier, Groundwater watershed, Karst spring, Underground retention, Tracing, Bosnia and Herzegovina.

Abstract

The Glamočko Polje is the surface and underground watershed between the river basins of the Black Sea and the Adriatic Sea. The recharge areas of groundwater, flow towards the Bistrica, Žabljak, and Duman springs (in the Livanjsko Polje and River Cetina basins) towards the south; to the Ribnik and Sana river springs towards the north, and to the Pliva and Janja river springs. Complicated thrust tectonics, hanging and deep-lying hydrogeological barriers give rise to complicated hydrogeological relations. Groundwater tracing helped to determine the position of watersheds and depths to groundwater in this part of the Dinaridic karst. Water discharge at the named springs is controlled (besides the temporary flooding of the poljes), by groundwater karst conduits from the swallow holes to the springs.

1. INTRODUCTION

The study area in south-western Bosnia forms part of the External Dinarides. In the central part of the area, the Glamočko Polje is bounded by the mountains Vitorog and Slovinj, in the south, and the Cincar, Šator and Staretina mountains, to the south-west and north-west. Waters from the springs of the Sana and Pliva rivers and those from the north-eastern margin of the Livanjsko Polje come from the Glamočko Polje. The discharge rate of the springs is from 1 to 4 m^3/s (minimum) to over 80 m^3/s (maximum) averaging 5-15 m^3/s. In the marginal parts of the Glamočko Polje, geological and hydrogeological exploration, including the tracing, has quite positively identified the underground linear and zoned watersheds over the Glamočko Polje and the Mounts Vijenac, Šator and Staretina. The south-eastern watershed from Skucani Ponor to Mt. Slovin has not been determined, and the watershed between the springs of the Sana and Pliva rivers is zoned as indicated by tracing of the Čardak Livade swallow hole. During high water periods, when the Glamočko Polje is partly flooded, the watershed between the Black Sea and Adriatic Sea basins is determined on the surface, as part of the flooded waters overflows towards the sinkholes which drain in the Pliva river basin and partly in the Livanjsko Polje basin. Features including medium-deep open joints and other karst forms were determined using the tracer method. Based on the recession directions, the deep flows were estimated during the dry periods of the year. From the use of fictional velocities and the known great differences in altitude between the sinkholes and springs, it was found that the underground karst forms are large and that they reach depths up to 200-400 m.

2. GEOLOGY

In the broader area of the Glamočko Polje, Permo-Triassic, Mesozoic, Tertiary, and Quaternary rocks are exposed. Most of the terrain is composed of Triassic, Jurassic and Cretaceous limestones and dolomites. Clastic rocks are present in some parts of the Mesozoic, Palaeogene and Neogene. The Quaternary is represented by clay, sand, fluvio-glacial, and limno-glacial deposits (PAPEŠ, 1985). Pyroclastic rocks are interlayered with the Ladinian and Miocene sedimentary rocks. Only two volcanic bodies crop out in the Podgorje area and in the upper courses of the Šujica River.

Tectonically, the area is characterised by thrust structures, reverse faults and very prominent transverse faults. Five tectonic units can be distinguished (Fig. 1): the Dinara unit (1), the Šator unit (2), the Staretina unit (3), the Glamoč unit (4) and the Vitorog unit (5). The tectonic units are thrust over each other from the north-east with south-western vergence. The lowermost is the Dinara unit which is thrust by the Šator unit and this is covered by the Staretina thrust etc. Accordingly, this area is characterised by the overlapping of complete tectonic units, brought about by significant horizontal movements (PAPEŠ, 1985).

The Dinara tectonic (thrust) unit has a comparatively small surface area around Šator and Tušnica Mountains. At Mt. Šator, the Dinara tectonic unit crops out as a large tectonic window beneath the Šator formation. In fact, Triassic dolomites of Mt. Šator are thrust over Cretaceous and Jurassic limestones of the Mt. Dinara unit.

The Šator unit crops out only at Mt. Šator, and in other parts of the terrain it is hidden by the Staretina and Glamoč thrust units.

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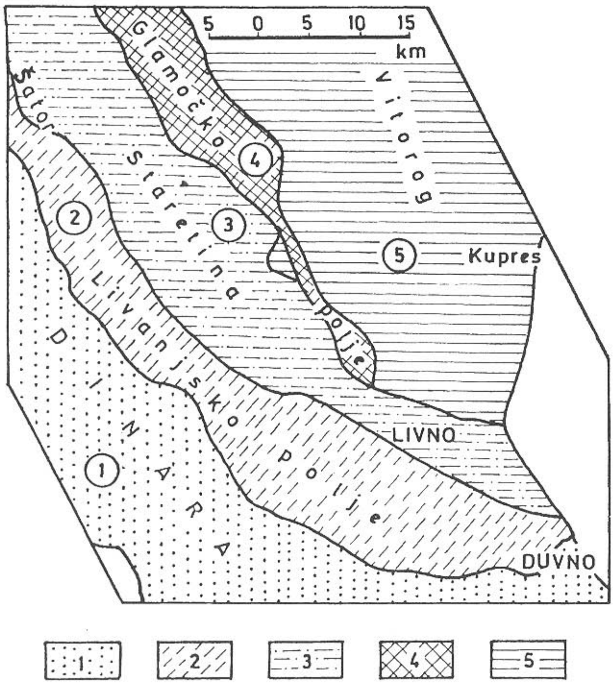


Fig. 1 The main tectonic units in southwestern Bosnia (after PAPEŠ, 1985). Legend: 1) Tectonic unit of Dinara; 2) Tectonic unit of Livno; 3) Tectonic unit of Staretina; 4) Tectonic unit of Glamoč; 5) Tectonic unit of Vitorog.

The Staretina unit crops out over a large surface area from Rore, in the north-west to Livno, in the south-east. This unit is overthrust by the Glamoč unit which in turn is thrust by the Vitorog unit, which stretches along the central parts of the study area, from Vrbljani, in the north-west to Šujica, in the south-east. The Vitorog unit consists of a very large and strongly faulted anticline (the Mts. Cincar, Slovinj and Hrbljina) and the Čardak Livada syncline. It is significant to note that at Glamoč this thrust is underlain by thick series of gypsum-anhydrite and the Werfenian beds. Such a relationship is the basic factor which controls the recent hydrogeological relations of this area.

3. HYDROGEOLOGICAL FEATURES

3.1. KARSTIFICATION DEPTH

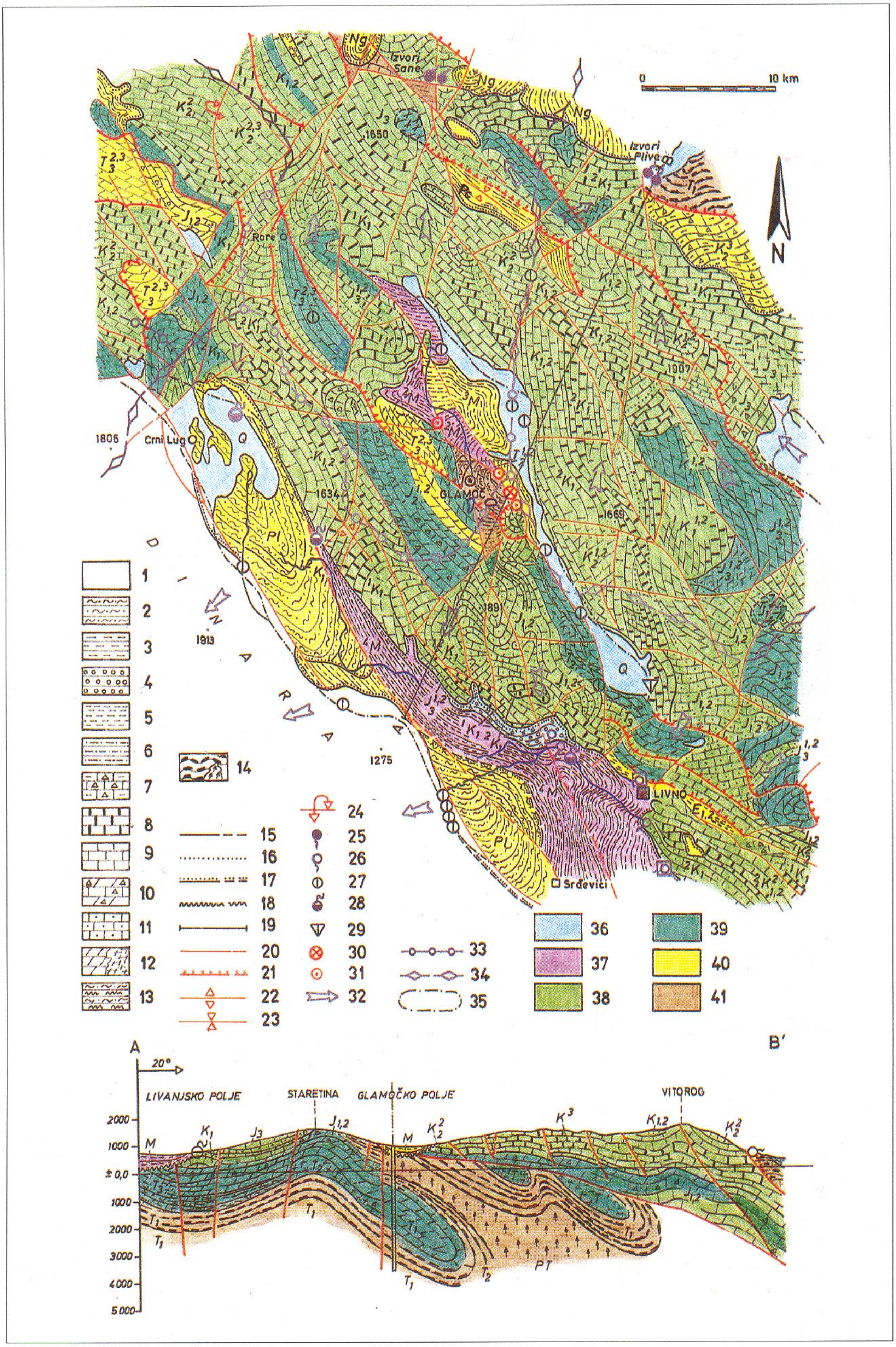
The karst area of south-western Bosnia represents a region characterised by all the high karst phenomena. All authors recounting the hydrogeology of Bosnia and Herzegovina emphasise the main features of this area as shown by deep and intensive karstification of the carbonate formations (in some places up to 1000 m deep).

POLJAK (1958) is of the opinion that karstification depends mostly on the intensity of tectonic movements reaching to great depths and to a lesser extent on the nature of the carbonate formations themselves. According to ROGLIĆ (1961), the karstification depth reaches the bottom of the limestone mass. MILANOVIĆ (1965) mentions that some oil wells drilled in the karst areas (Ulcinj, Vis, Nikšić, Glamoč) have registered cavernous limestones at depths some 2000 m below sea level.

Karst water circulates underground along main drainage systems, including horizontal and vertical channels and joints which, together with the main drainage channel, compries the drainage system. These drainage flows are mainly active, particularly if they are connected to permanent surface flows. It can be concluded that most of the karst water flows out through large conduits which reflect the number and higher discharge rates of the karst springs. The tracings (after MAGDALENIĆ, 1979; SLIŠKOVIĆ, 1991), performed in the study area, showed that the karst area of southern Bosnia discharges through eight large karst springs.

The hydraulics of the aquifer are complicated and calculations are based on certain hypotheses. It is a well known fact that the water flow in karst media takes place through the conduit systems which could be approximated to a series of connected reservoirs of different size, shape and capacity. The water circulation in the karst underground, depending on the degree of tectonic rupture and karstification of rocks, can be considered in two ways:

Fig. 2 Hydrogeological map of southwest Bosnia. Legend: 1) Q, Alluvial deposits - clays, sands, gravel, limnoglacial and fluvial deposits; 2) Ng, 1-4 M, Pl - Marls, marly limestones, clays, conglomerates, sandstones; 3) E_3, Ol_2, Ol - Conglomerates, breccias, sandstones - Promina beds; 4) $E_{1,2}$ - Flysch I - marly shales and calcarenites; 5) Pc - Flysch II - conglomerates,breccias, calcarenites; 6) K_2^3, $K_2^{1,2}$, K_2^2 - Flysch III - breccias, marls, calcarenites; 7) K_1^2, $K_{1,2}$, K_2^1, K_2^2, $K_2^{1,2}$, J_3 - Limestones, brecciated limestones with interlayered dolomites; 8) $^1K_1$, $^2K_1$ - Bedded limestones; 9) $J_1^{1,2}$ - Dolomites and limestones with interlayered breccia; 10) J_1, $J_{1,2}$, $J_2^{1,2}$, $J_3^{1,2}$ - Limestones and dolomites; 11) J_1, $J_{1,2}$, $T_3^{1,2}$, $T_3^{2,3}$ - Dolomites; 12) $T_3^{2,3}$, $T_{2,3}$ - Dolomites interlayered with chert; 13) T_1^2, T_2^1, T_2^2 - Platy limestones, dolomites, sandstones, cherts, breccias; 14) T_1, PT - Shales, sandstones, marly limestones and gypsum; 15) Geologic boundary - normal and inferred; 16) Gradual transition; 17) Transgressive geologic boundary on map; 18) Transgressive geologic boundary on cross-section; 19) Lines of cross-section; 20) Fault - normal and inferred; 21) Nappe - reverse fault - observed and inferred or covered; 22) Anticline; 23) Syncline; 24) Axis of inclined anticline; 25) Karst spring; 26) Periodical spring; 27) Swallow hole; 28) Estavelle; 29) Pit with water; 30) Deep drilled well; 31) Drilled well; 32) General direction of underground watercourse; 33) Surface and groundwater divide proved; 34) Water divide zone; 35) Boundary of karst polje; 36) Quaternary sediments - aquifers of different, mainly low yield; 37) Tertiary sediments - Discontinuous, mainly low yielding aquifers; 38) Limestones mainly - Intensively karstified, highly transmissive terrains; 39) Dolomites, mainly low permeability; 40) Dolomites and flysch - Very low yielding terrains; 41) Sandstones schists, gypsum - practically impermeable terrains.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- The specific type of a discontinuous environment in which the dynamics and accumulation of groundwater is analogous to the water movement in open channels and tubes either beneath a water table or under pressure. In this case, the mathematical solution for the groundwater dynamics is based on the theories of Darcy, Weisbach and Chezy (after CASTANY, 1968).

- The specific type of environments with two-fold porosity in which the karst channels represent the main water transport paths and the rocks between them represent "blocks" of lower porosity.

The classification of rock masses, which makes possible a mathematical description of these phenomena, significantly deviates in numerous cases from real environments and processes of the movement of groundwater in them. In the real environments (depending on observation), the environment can be continuous or discontinuous in terms of porosity. Over shorter distances, the flow regime can pass from laminar to turbulent. At the junction of different flow systems, the different flow regimes can be mixed.

3.2. HYDROGEOLOGICAL FUNCTION OF ROCKS AND TERRAINS

In the area surrounding Glamoč limestones and dolomites are the most common rocks in which the joints and pores, originated by postsedimentary tectonic processes, are very unevenly distributed. Palaeogene and Neogene sedimentary rocks function as hanging barriers, which controlled the direction of karst evolution from the Palaeogene to the Recent.

The Upper Permian and Lower Triassic (mostly micaceous sandstones) are impermeable and function as the stratigraphically lowest "confining" formation to karst aquifers. They are the "(hydrogeological) basis of the Dinaric karst" - as ŠARIN (1983) called these deposits. In the Miocene sediments, marly limestones are a lateral barrier for waters in the area of Jurassic and Cretaceous carbonates in parts of the terrain where they were displaced at the same altitude (Fig. 2).

The aquifers are the rocks with the karst-jointing porosity and are characterised by high filtration features and great apparent circulation of groundwater velocities. The foot-barrier to groundwater are deeply lying Werfenian clastic rocks which are mainly located on the boundary with the Mid-Bosnian hydrogeological terrain (PAPEŠ, 1985; SLIŠKOVIĆ, 1991). The Werfenian beds represent thus the foot and lateral barriers for the springs of the Sana, Ribnik and Pliva rivers (Fig. 2).

Anisian (T_2^1) limestones are characterised by well defined karstification as recognised in the oil well GLA-1. The karstification of the Anisian limestones took place repeatedly so that the present karstification processes are continuous over the palaeokarst. Lower and Upper Ladinian (${}_1T_2^2$ and ${}_2T_2^2$) rocks (platy limestone, calcite shale, sandstone, tuff, and chert) are mostly impermeable and thus distinguished as a group of impermeable or low-permeability formations. The Carnian (T_3^1) formations are of low permeability whereas Upper Triassic (T_3^{2+3}) dolomites are in some places cavernous; their thickness is about 1000 m and they belong to the group of rocks with weak fissure porosity.

Jurassic rocks are variable in porosity. Lower Jurassic dolomites (J_1) are of low permeability, whereas Middle and Upper Jurassic limestones ($J_{2,3}$) are very permeable. Cretaceous limestones ($K_{1,2}$) are very karstified, and thus belong to the group of highly permeable formations.

Palaeogene formations (Pc) are located in the troughs of the Čardak Livada syncline and in the area east of Livno. In the Čardak Livada area, conglomerates, breccias and calcarenites also represent the hanging incomplete barrier for the underground conduits from the north-east towards the Duman, Žabljak and Sturba springs.

Based on their hydrogeological and lithological features, the Miocene (M) rocks, can be divided into four groups. The lowermost packet (^{1}M) is impermeable and overlain by marls and sandstones. The next packet (^{2}M) consists of limestones characterised by secondary porosity which gives rise to the selected directions of groundwater flow, and is included into the group of very permeable formations. The middle Miocene group (^{3}M), represented mostly by marly clayish limestones, belongs to the group of low-permeability formations. The youngest group (^{4}M) consists of marly limestones characterised by primary and secondary porosity. This is the most permeable Miocene member. Pliocene and flysch-like sediments are impermeable.

In the area of the oil well GLA-1, Miocene and Pliocene sedimentary rocks are underlain by Permo-Triassic clastic sediments and, thus, represent a complete barrier to groundwater flow. In other parts of the Glamoč area, the Neogene formations, which overlie Mesozoic carbonate rocks, represent the hanging barrier (Fig. 2).

3.3. UNDERGROUND CONNECTIONS, WATERSHEDS AND SPRINGS

The aquifers of the Glamočko Polje area and the Šator, Vitorog, Staretina, Golija and Slovinj Mauntains drain into the Cetina, Una, Sana and Vrbas river basins. The fast groundwater flow and steep recession curves reflect low aquifer retention capacities. This is manifested in the great fluctuations of the discharge rates of permanent and intermittent karst springs. The degree of karstification of the holokarst terrains is best demonstrated by the tracing results from which the apparent velocities were calculated.

On the basis of ten groundwater tracings, the position of groundwater watersheds has been determined and thus defined the pertinence of the separate parts of the river network of the Black Sea (Sana and Una Rivers) and the Adriatic Sea (the Cetina River). The water divide between the Black Sea and the Adriatic

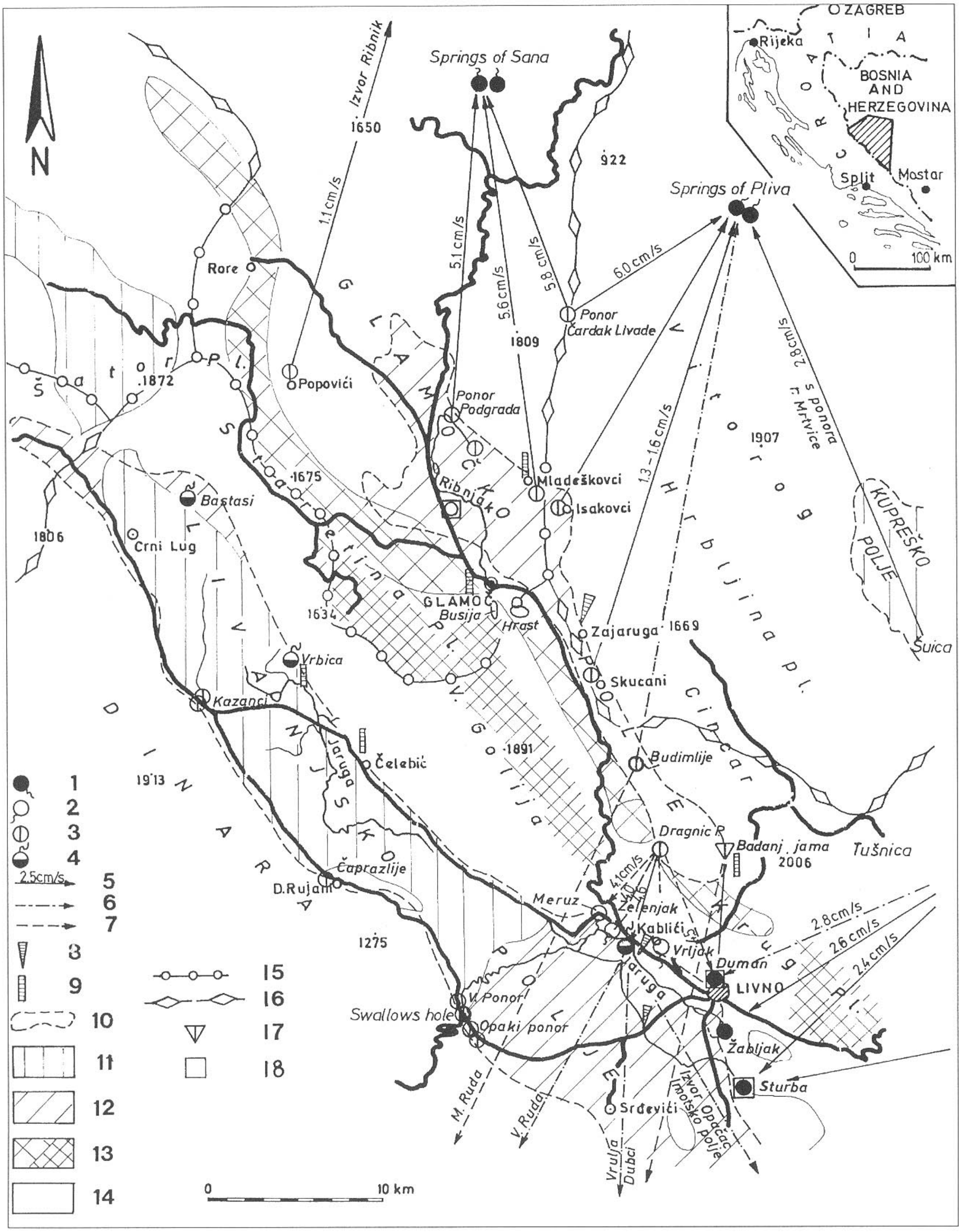

Fig. 3 Underground water pathways and barriers. Legend: 1) Permanent spring; 2) Intermittent spring; 3) Swallow hole; 4) Estavele; 5) Strong underground water pathway; 6) Proved underground water; 7) Problematic water; 8) Water gauging station; 9) Rain gauging station; 10) Karst polje; 11) True barriers; 12) Relative barriers; 13) Depth barriers; 14) Aquifers; 15) Surface water divide; 16) Zonal groundwater divide; 17) Karst shaft with water.

sea basins represents a wide "zonal" watershed due to the fact that some of the water during the strong pluvial periods overflows from the Sana and Pliva basins into the Cetina basin and vice versa (Fig. 3).

In the south-western parts of the Glamočko Polje, Triassic dolomites of the Šator and Staretina Mountains built up a raised anticline which represents a reliable barrier to groundwater which would otherwise flow out from the Popovići area towards the south. Figures 2 and 3 demonstrate that, besides the drainage of surface water into the River Sana basin, groundwater flows from the north-eastern and north-western parts of the Glamočko Polje and the Rore, Mladeškovci and Čardak Livade karst depressions.

The best aquifers are Cretaceous limestones which make up the northern, eastern and southern marginal parts of the Neogene Glamoč Basin. Groundwater of the northern part of this carbonate complex discharges through the Ribnik and Sana springs, with the eastern and north-eastern parts discharge into the River Pliva basin.

The most significant regional tracing under increased pluvial conditions was carried out in the northern, eastern and southern margins of the Glamočko Polje. The swallow hole at Popovići village was traced in January 1973, with 72 kg of dye, which after 28 days appeared at the Ribnik spring. A total of 82.5% of the dye flowed out indicating that the Popovići and Rore area can be included in the River Ribnik basin.

The tracing from the Podgreda and Mladeškovci swallow holes evidenced the connection with three Sana river springs. The apparent tracer velocity of 5.1 cm/s indicates that the tracing water was transported by underground conduits. The Mladeškovci swallow hole was traced during the flood period and the traced water occurred after 10 days in high concentrations at the Sana river springs. The apparent velocity of the tracer was 5-6 cm/s which indicates a direct underground connection.

The Čardak livade swallow hole was traced with 90 kg of dye under high-flood water conditions and the traced water occurred at the west Pliva river spring in high concentrations (45%), with the apparent velocity of 6 cm/s. Also at the Sana river spring 33% of the coloured water flowed out with the apparent velocity of 5.5 cm/s. These data indicate that must be a zonal underground watershed there.

The Isakovci swallow hole was traced in December 1970 with 100 kg of dye and the coloured water occurred in high concentration 13 days later at the Pliva river spring. 75% of the tracer flowed out with an apparent velocity of 1.6 cm/s. As the southeastern or right Pliva river spring 5.5% of the tracer flowed out 17 days later and the apparent velocity was 1.3 cm/s.

The Skucani swallow hole in the Glamočko Polje was traced with 50 kg of a tracer and the tracer appeared only on the Pliva river spring in high concentration (75%) with an apparent velocity of 3.2 cm/s. The Budimlje swallow hole indicated an uncertain connection with the Pliva river spring; also the Kablić estavelle with the Black Sea Basin, and the submarine spring Dubci with the Adriatic Sea basin.

The Dragnić swallow hole was traced under high-water conditions on November, 21st and 22nd, 1960 with 150 kg of dye. The traced water appeared in the springs occurring along the north-eastern margin of the Livanjsko Polje: in the Meruz spring on November 23rd 10.0 kg of dye appeared indicating a strong hydraulic connection and apparent velocity of 4.1 cm/s; a strong connection was also indicated in the Zelenjak spring on November, 23rd when 2.3 kg of dye appeared with the apparent groundwater flow velocity of 4.0 cm/s; in the Mali Kablić estavelle on November 23rd indicated a weak connection with the apparent velocity of 4.6 cm/s; in the Vrljak spring on November 23rd where 0.1 kg of dye flowed out and a questionable connection was realised, and in the Bistrica (Duman) spring 27.4 kg of colour flowed out and the strongest groundwater connection was realised. It remains open the question of the left tracer because the outflow below the Neogene Livno basin directly into the River Cetina basin and the Dubci submarine spring and the Adriatic Sea can be presumed.

On the basis of these tracings, zonal and (in some places only) also linear watersheds can be established (Figs. 2 and 3). The run-off of the south-eastern part of the Glamoč Polje belongs to the River Cetina catchment area, the north-western and northern parts of the Glamoč Polje to the Sana and Ribnik river catchment areas whereas the eastern part of the Glamoč Polje is common with the catchment areas of the rivers Pliva, Cetina and Sana.

The liner watershed, both underground and superficial, can be traced from the Glamoč Polje to Mt. Staretina and further to Mt. Šatora and it bends at Tičevo towards the south on the watershed between the rivers Cetina and Krka. In the area east of Budimlje, the watershed is zonal between the Pliva river and Livanjsko Polje (the Cetina river) catchment areas.

The Sana drainage begins with its underground flow at Podgreda and Mladeškovac on the Glamoč Polje. However, the Čardak Livade swallow hole indicates the connection with the springs of the Sana and Pliva rivers so that along the complete watershed only an underground zoned watershed can be drawn. The area of Rore and Popovići belongs to the drainage of the Ribnik spring, the first west tributary of the river Sana.

Groundwater from the middle parts of the eastern margin of the Glamočko Polje flow out through the Isakovci and Skucani swallow holes into the Pliva river spring. It can be thus concluded that about one third of the orographic surface of the Glamočko Polje and its complete north-eastern margin belong to the river Pliva catchment area.

4. IDENTIFICATION OF KARST UNDERGROUND FORMS

On the basis of the tracing of underground karst waters, data obtained from one deep well, geophysical prospecting, geological mapping and hydrogeological exploration allow the determination of karstification depth and the approximate sizes of underground karst forms of this part of the Dinarides.

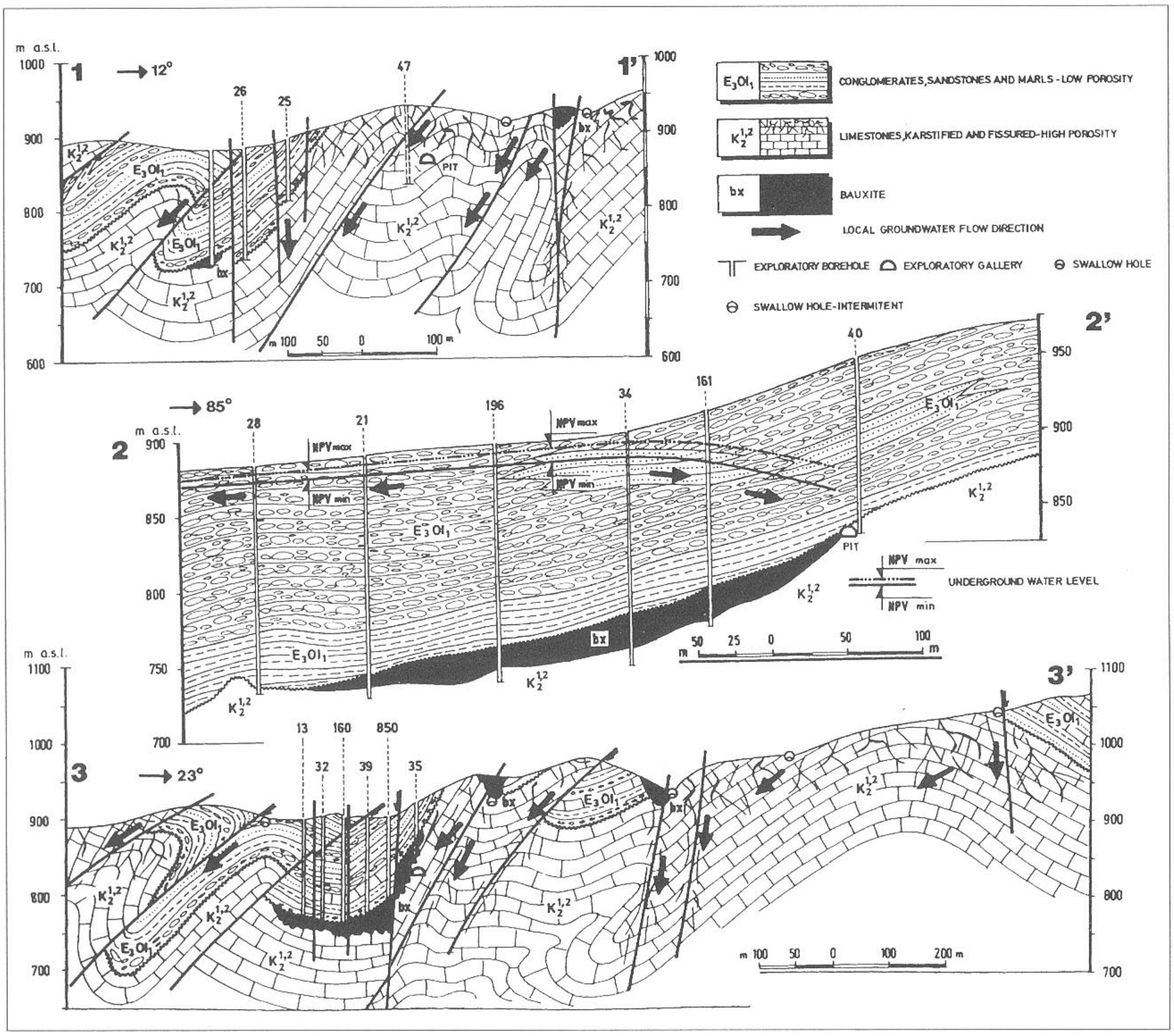

Fig. 4 Hydrogeological cross-sections at Studena Vrila locality.

In the framework of regional and detailed geological and hydrogeological explorations, ten tracings were carried out mostly in the area of Glamočko Polje. From the data obtained, the apparent flow velocities through karst joints, caverns, and open and closed "channels" (with numerous widenings) were determined. It was found that "high" groundwater circulates near the surface at depths of approximately 100-200 m (depending on the relief), whereas the "low" water is located mainly under the depth of approximately 200 m. Groundwater retention is five times longer in dry periods of the year indicating that the karst terrains at greater depths have smaller pores and open joints. There are such examples in the adjacent terranes in the area of Studena Vrila, south-east of the Duvanjsko Polje where very intense karstification with conjugated joint systems is located at depths of 100-300 m; the open joints are very rare in deeper parts (Fig. 4). The monitoring supports the idea of the existence of united (connected) groundwater in the aeration zone of groundwater. The piezometric surfaces are deeper (50-150 m) during the low-water periods and the generation of privileged groundwater flow directions occur along rare joints in the deeper parts of the karst (Fig. 4). In the near-surface zone at depths of 100-200 m, it was found that the jointing coefficient $K_i > 10$ and that the groundwater flow is very fast. This is also reflected in the total dissolved solids content in groundwater which is 180 mg/l during the high-water period and 250-300 mg/l during the low-water period.

Generally, geophysical prospecting (resistivity sounding and seismics) indicates that high-karstified and tectonically disturbed zones reduce with depth. The total volume of joints relative to the volume of rock masses as a whole is greatly decreased by the karstification depth. The complex exploration of the Dinaridic karst includes geological, geomorphological, hydrogeological, geophysical and hydraulic methodologies but also, above all, the tracing as one of the oldest methods. From data obtained in this study, the best parameters needed for the identification of karst terrains and water use potential included in these terrains were obtained. Accordingly, the geology, morphometry, geophysics, surveying and tracing, indicate that the karst phenomena in the investigated area are most intensively developed down to 200-300 m depth and that they greatly decrease in number downwards. In most of the terrain, swallow karst aquifers are commonly connected and thus make a unique complex aquifer. At depth, they grade into syphonic and separate aquifers with different water tables.

5. CONCLUSION

From the regional geological point of view, the area of the Glamočko Polje and the surrounding mountains is included in the Dinaridic karst, which is mainly represented by deep karst covered by the Neogene freshwater basin. This terrain consists of Triassic dolomites and dolomitic limestones, Jurassic and Cretaceous limestones, Upper Cretaceous flysch sediments, Palaeocene clastic sediments, Eocene flysch sediments and Neogene deposits.

The karstification of carbonate rocks is controlled by strong tectonic deformation, particularly by the Alpine faulting. The Upper Triassic dolomites have very important hydrogeological role, as complete barriers, as do the Jurassic and Cretaceous dolomites to a lesser extent, whereas the Palaeogene and Neogene deposits form incomplete barriers.

The surface water, which sinks in the Glamoč Polje area flows out in the Sana river catchment area in the north, in the Pliva (Vrbas) river catchment area towards the east-northeast, and in that of the Cetina river (Livanjsko Polje) towards the south. All the springs and surface streams, which originate on the slopes of Mt. Staretina, flow out towards the north, south and east of the Glamočko Polje. That water sinks and again appears in the springs of the Sana and Pliva rivers and in the springs found along the north-eastern margin of the Livanjsko Polje.

During the 1920's, different tracers such as uranine, radasine, halite and others were used for the first time and gave good results. Thus by this method the watersheds have been successfully determined in most of the karst area.

The karstification depth can be best identified by using this method combined with geophysical and geomorphological analysis. These data can also be used in order to determine the directions and depths of groundwater flow, including their approximate dimensions.

Almost all the mentioned major swallow holes have strong underground connections with karst springs pointing out the existence of large-scale underground conduits. Circulating waters widen the channels and produce larger and smaller widened rooms, cavities, irregular gut-like and cavernous forms and connections. These forms are controlled by tectonic breaks and larger joints on the intersections of which are generated the larger underground caverns.

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