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PREFACE

Quite a lot is currently spoken and written about the karst. Constructive and thorough discussions on karst are carried out in the broadest circles of interested scientists and researchers. This was also facilitated by various regional symposia and colloquies organized over the past 15–20 years worldwide by IAH, IAHS, FAO and UNESCO within the International Hydrologic Decade (HID) and International Hydrologic Programme (IHP). It should also be noted that IHD included a Commission for the study of carbonate rocks in Mediterranean countries, and that since 1970 a permanent Commission for karst hydrogeology exists within IAH.

It seems that the reasons for such an increasing interest in karst lies in the rapid technologic development of our civilization, which highly actualized, at this moment, the problems of water resources, their systematic study, rational utilization and protection, and in relation with this, management of hydrological and hydrogeological systems. Karst is also considered from this aspect as it occurs in many parts of the globe (frequently covering a substantial part of the national territory of individual countries), whose water potentials usually represent the sole or most important natural resource which directly affects their social and economic development. Under such conditions, the problems of study, utilization and protection of water resources, or using contemporary terminology, management and control of water resource systems obtain an exceptional importance, and this has an increasing effect on the orientation of research.

Hence, the original concept of study of karst, as an exceptional natural phenomenon, is currently supplemented more and more by new approaches oriented towards more rational and more complete utilization of water resources, paying due consideration to technical, economic and social aspects. This concept became fully apparent in solving numerous water economy problems in Dinaric Karst.

However, one should always bear in mind that the »key« for the successful solution of the problems lies in the geology, i.e. hydrogeology of the Karst. Therefore, the complexity of karst phenomenon also requires the involvement of other scientific disciplines, so Karst is currently becoming an important factor of interdisciplinary closeness of world's science, this certainly being the best guarantee for the successful solution of complex water economy problems.

From May 15 to 28, 1983 the Field Trip to the Dinaric Karst will be held in Yugoslavia, organized, under the initiative of the Executive Committee of IAH, by the Yugoslav National Committee of IAH, i.e. Union of Mining, Geologic and Metallurgic Engineers and Technicians of Yugoslavia.

This monograph is prepared for this occasion under the general title »Hydrogeology of Dinaric Karst«. The volume includes 13 papers prepared by Yugoslav authors dealing with karst hydrology and methods of investigation. A review of the papers makes it apparent that the volume is not a guide through the areas to be visited by the professional Field Trip, but it will provide, we believe, a broader insight into hydrogeologic problems of Dinaric Karst, thus contributing to wider and more comprehensive exchange of information and opinions on all actual problems of hydrogeologic systems in karst areas worldwide.

Belgrade, May 1983

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GEOLOGY OF KARST TERRAINS AND THEORY IN THE WORKS OF JOVAN CVIJIC

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Of the scientific works of Jovan Cvijić, the works on geology, hydrography and geomorphology are classified as the master works of world literature, of the early twentieth century. Because of broader significance of such works, even today, we shall present here the most important results of Cvijić's researches in the field of karst phenomena.

GEOLOGY OF KARST TERRAINS

Being very interested and engaged in his work, the great man of Yugoslav science, Jovan Cvijić, made many trips through numerous karst terrains in Yugoslavia and throughout the world. Already during his studies in Vienna, usually during vacations, he undertook scientific excursions visiting Istria, Slovenian Littoral, Montenegro, Dalmatia and a part of Macedonia. This helped him to collect many valuable data and to use them for preparation of his doctor's thesis "Das Karstphänomen" in the second half of 1882. Later on, he devoted a number of his works to the geology and morphology of karst terrains, based on deep comprehension and understanding of geologic composition and tectonic structure of such terrains, which were accepted with appreciation all around the world.

Having in view such extensive works on karst geology and geomorphology, apart from many other different geological problems and geographic studies, we can only admire the inexhaustible energy and abilities of this author. Our admiration for his work is even greater if we have in mind that in his time the geologic understanding of terrains was much poorer in general, and that conditions for work in rough karst regions were difficult. Armed with knowledge, with high ability for complex and immediate observations, Cvijić collected a great number of data which enabled him to present easily and convincingly the facts about geologic specific qualities and features of many terrains of such particularly complex environment as karst could be.

This productive scientist had published his observations on geologic, geomorphololologic and hydrographic conditions of individual karst terrains and karst in general, in a number of books. To mention, first of all, his book "Karst, Poljes of Western Bosnia and Herzogovina" (1900) and "Geomorphology, Vol. II" (1926), as well as his work in the region of Kučaj in the Eastern Serbia, Morava River region and in other areas.

Before Cvijić's works appeared, the knowledge about karst phenomena, and particularly about karst poljes, were rather shallow. Being aware of that, Cvijić had oriented himself to this subject from his youth, undertaking the following trips to the Dinaric karst regions:

1892: to the Gatačko polje

1897: to the Gatačko polje, Dabarsko, Fatničko, Stoličko, Crničko and Plansko poljes

1898: to the Kupreško polje, Glamočko, Ravno, Vukovsko, Livanjsko, Duvanjsko, Posušje, Kočerničko, Mostarsko Blato and Mostarsko poljes.

Fortunately such bright brain appeared to present karst phenomena to the world, i.e. such an interesting geological product which is more developed in Yugoslavia than anywhere else. In his work "Karst Poljes of Western Bosnia and Herzegovina" (2) early in this century, Cvijić discovers one of the most remarkable karst holes in the world scale, the territory which is more than rich with heterogenous karst phenomena and with very complex conditions of ground waters circulation. Description of individual karst poljes, including accompanying forms and hydrographic network, fill us with wonder how his conclusions are clear, detailed and logical. Many of his suppositions were proved by the investigations of his followers, for instance, the one on existing connections between some ponors and springs, or the one on tectonic predisposition of certain poljes. It is quite understandable however, that there are opposite cases as well; there is a disproportion between the data that were available to Cvijić in relation to the present situation. Among other things, we have now detailed geologic maps with many structural details. It is not strange to conclude, therefore, that the following Cvijić's observation about the Ravanjsko polje was wrong, for instance: "Contrary to the adjacent poljes, depression of this one is not on the fault, neither it is tectonically predisposed at all. It is an example of true erosion polje which originated from a single karst uvala."

Cvijić's contribution to the understanding of the central Dinaric karst, and particularly its main phenomena - the karst poljes, is in his interpretation of poljes origination, their evolution and hydrographic features. Through his study of morphology, lithologic and structural relations, the positions of abrasive planes, terraces and coastal lines and dried courses on their surfaces through which the Neogene and Diluvial lakes discharged, Cvijić refutes with arguments earlier views on the genesis of the poljes, presenting his own interpretation which by its major part is even today accepted and confirmed. According to Cvijić, the poljes are erosion forms but their tectonic predisposition is often highly expressed. Namely, the target points of the erosion process are often connected to marginal and other faults. The effects of other factors are also evident, such as epirogenic movements and climate conditions from the Neogene and Pleistocene. The process of poljes destruction, expressed through disappearance of hydrologic network, and gradual narrowing of poljes were also the subject of a particular Cvivić's interest.

Geology of karst, in karst hydrography, is the subject of the major part of his work "Geomorphology, Vol. II" (4). "None of the rocks, except limestone, has such specific forms conditioned by chemical composition" writes Cvijić and continues with the picturesque and gradual discovery of the secrets of such environment, its inner and outer forms, water tables (karst springs, seepages and estavellas), underground bifurcations of karst surface, etc.

Separating three morphologic types of limestone terrains in general - holokarst, merokarst and transition karst Cvijić presents broader or narrower descriptions of a great number of the Yugoslav karst regions and of other countries throughout the world which he also had visited. Chalk of the Cretacious in England, Moravian karst, Franconian Jura, Belgian karst, the central massif in France, Alpine karst, karst areas of far Jamaica, Java, Australia, and other terrains were the subject of Cvijić's studies. Reading the descriptions of these karst areas we discover their geologic and hydrologic pecularities. This rich material was of good use to Cvijić's followers, in the first place to the numerous explorers of the present time, as the signposts towards further geologic explorations aimed at realization of various practical tasks. Results achieved in the post-war period in the Dinaric karst region in building surface water storage reservoirs and utilization of underground water sources for human needs, and drainage of karst fields, are really significant. In all these efforts the contribution of Jovan Cvijić was present.

SYNTHETIC THEORY OF KARST

For us, it is important now to see, to what extent Cvijić had influenced scientific thought development in setting the general concepts on karst evolution and to what extent he had influenced the work of his contemporaries and subsequent generations of explorers.

Being an efficient explorer with the exceptional talent for observation and intuition, Cvijić knew well that the problems of karst ground water distribution and circulation were the key issues, without understanding of which, the most important karst phenomena could not be explained at all.

Ground water distribution and circulation problem was the topic one at the turn of the 19th century, initiated particularly by the hypothesis of A. Grund and A. Penck, on water tables existence in karst. Katzer opposed sharply this hypothesis and also E.A. Martel, who had their own views on the isolated subsurface flows and etage draining systems.

The problem of morphologic or erosion cycle in karst was closely connected to the underground circulation and particular attention was paid to such problem by Penck, Richter, Sawicki, Daneš, Grund and de Marton. To all of them the starting point was erosion cycle which was determined in impervious terrains by W.M. Davis.

In his work "The Underground Hydrography and Morphologic Evolution of Karst" (3), published in Grenoble in 1918, in French language, Cvijić presented in whole his theory on karst terrains evolution. In the introductory part of this important study, Cvijić says that he had tried "using all available data which were published and also his own investigations" to define morphologic classification, terminology and methods of karst relief origination. His study was supplemented with additional explorations on origination and hydrography of karst poljes and glacial relief.

Complexity of relations in the Dinaric karst terrains and intention to apply the cyclic theory to karst, forced A. Grund (1903,1904, 1914) to try to discover karst hydrography patterns. He established his well known theory on "double layers" water bearing media, according to which the lower layer is "stagnant" without move (except in some rare cases below the sea level), while the upper layer is completely movable.

The first notable opposition to Grund's theory comes from F. Katzer in 1909 and 1921. He makes differences between the shallow and deep karst. According to him, shallow karst rocks are karstified up to negligible depth; in deep karst, however, karstification penetrates very deep, since impervious base lies at uncertain depths. Katzer explains the peculiarity of karst underground circulation asserting that waters are stored and move in fissure systems (Karstgerinne) which spread all over the karst terrain, i.e. in different ways at different depths. Because of that the continual water tables with uniform inclination do not exist in deep karst, and therefore all deductions based on this one, may only result in wrong conclusions.

It is interesting, however, that both authors cite Cvijić's observations on this matter.

There are many examples, even instructive ones, which confirm both theories, but opposite proofs can also be cited. Uselessness of arguing about the rightness of one or another theory Cvijić had immediately noted and did not want to stand in support of either, and many other scientists - karstologists reacted in the similar way.

Criticizing Grund's views on "water head or water tables distributed through fissures", Cvijić underlines that "there are hydrographic phenomena which could prove that ascending and descendig of karst water bodies really occur".
"Particularly ascending are flows which enable appearance of springs at the bottom of karst poljes during rainy periods in the Dinaric karst area, even in uvalas and dolines where they had never been noticed before". On the other hand, says Cvijić, "existence of underground channels (Karstgerinne) and true and simple underground flow hydrography can not explain by itself the above mentioned and other phenomena" (he refers here to Katzer's theory).

Nobody before Cvijić had presented a view on coexistence of these two opposite hydrodynamic concepts about karst. At that time, it was difficult, perhaps, if we have in mind big qualitative differences between Grund's and Katzer's theories. Nowadays, after so many explorations of karst terrains, some of which were really extensive, and with so many new information collected, it is clear that Cvijić's study about "three hydrographic zones in karst" was the first coherent synthesis on the evolution of karst relief (inner and outer) under the influence of hydrologic and climate factors. All other authors writing about the same problem after Cvijić (Rižikov, Sokolov, Gèze) do not essentially change his postulations anyhow.

At the beginning Cvijć points out occurence of pre-karst valleys which were formed prior to karst process development. At that time, primary fissures were neither widened nor transformed into caves. Waters of the river, which were developing on the surface were sinking sporadically through fissures owing to, which waters could cut deeper their beds, effecting thus normal formation of valleys. But fissures widened by time, even the deeper ones; caves appeared and a part of the surface became dry; valley was disorganized by the appearance of karst forms at its bottom, and became shortened between the mouth and the spring due to the occurence of ponors. There were certain cases, however, that desorganization firstly occured in the upper part of the valley. Paralell with one water course another appeared as the consequence of denudation of karst surface. This process may be deep due to supererosion of a larger number of underground channels. In this connection Cvijić explains succession of time and space in three hydrographic zones formation and their continous moving to the depth. He explains this phenomena as follows "To mention, first of all, the main difference that exists between water flows movement in impervious terrains and the hydrography of karst terrains. While waterflows in impervious terrains are oriented towards the sea level, the karst water move, more or less vertically, through fissures and caves, following the gravitation principle without regard to the sea level. If a water table lies on an impervious bed, below the sea level, karst water sinking will be stopped on that bed. In this way the hydrographic zones develop and move between the karst surface and the impervious bed".

Briefly, Cvijić's postulations concern three hydrographic zones in karst (Fig. 1.1 and 1.2).

1. Dry zone. The surface is characterized by complete dryness; caves and widened fissures of the zone conceal the flows only during the rainy periods. Appearance of ascending waters is rather absent here.
2. Transition zone, as Cvijić points out, "shows two phenomena, one of permanent another of periodic nature. In its fissures and caves the permanent water flow is noted, even the underground courses here and there. At the points where this zone comes in contact with relief surface, these ground waters appear as springs whose yield varies considerably during the year". Here Cvijić allows occurence of ascending water courses, linking them with various karst depressions in which springs "work", only during floods.
3. The zone with permanent water flows is, in fact, a water saturated area in karst, and according to Cvijić's definition it is linked with Grund's "Grundwasser". Cvijić says that "water of this zone does not appear on the surface in the same proportion as water of higher zones. The major part drains towards the water body on the impervious bed". Ascending flows appearing in this zone at the bottom of the highest poljes, even in the deeper uvalas, are a normal phenomenon.

Cvijić's observations of this zone are also interesting, since this zone is important for understanding of hydrogeologic relations in karst area. To this zone is given a very important role in coastal karst areas by Cvijić, where its water appears at the sea level and below it: "If we connect submarine springs on a map then we, shall get a line of hydrostatic balance, i. e. this will be the line on which equalization of sea water pressure and hydrostatic pressure of karst waters coming from different elevations occurs." Correctness of this observation was proved, particularly in the post-war period of explorations of coastal and submarine springs in the Adriatic coastal area for water supply requirement.

All three hydrographic zones remained unchanged. Their evolution, according to Cvijić, continues from one to another zone owing to which, due to the permanent move of the zones downward, the karst surface lowers by denudation. By common action of these processes, the limestone masses will be finally deduced to limestone rags "which rise slightly above water body lying on the impervious bed". During the last phase of the development only the dry zone will remain in the lowered karst which is marked with residues of limestone with waterless caves, concealed by separate hillocks.

Such was the general course of karst terrain evolution under the influence of hydrologic and climate factors. But it is wrong to think, warns Cvijić, that the above three zones "are distinctively separated between themselves". "One zone always transforms into another, unnoticed. The boundary between zones lowers here and there then rises forming a zig-zag line, most often of wavelike shape". This line, according to Cvijić, results from unequal distribution and intensity of fissures and from lithographic homogeneity of limestones.

Cvijić puts also the stress on the geologic structure, underlying that "superposition of zones is highly conditioned by the geologic structure of any karst area". He says, therefore, that three hydrographic zones are less expressed in the shallow karst in general. Even in the deep karst, as that of the Adriatic coastal area, "distribution of zones will be sporadically interrupted by the appearance of more or less impervious layers". On such layers, says Cvijić, "local or even regional water bodies can be formed. Such are, for instance, water tables in the Dinaridic karst which are connected with Vengenian sandstone and melophyre bedded and intruded into the Triassic limestone layers". Cvijić cites such cases in the surroundings of the Kupreško polje.

With a number of examples Cvijić illustrates his concepts and concludes that "from all specific cases and many others it comes out that certain local phenomena of karst hydrography, which often are very complex ones, cannot be solved without deeper comprehension of the geologic structure which may change the general hydrographic principles established in this paper".

To this nothing has to be added. As the explorer of karst Cvijić primarily was the geologist and this is the main reason of his successful involvement in the karst problem. Nowadays, when not only regional, but also detailed hydrogeologic explorations of karst terrains have become the first task all over the world, Cvijić's warnings about the dependence of of karst phenomena on the geologic history of a terrain are even more significant. Those involved in the explorations of karst area aware of the fact that without proper understanding of field geology it is impossible to detect and capture waters of karst aquifers with a real sucess.

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FIGURES

1.1. Evolution of water circulation and development of karst relief after Cvijić (1918). I, II, III and IV are phases of karst development. A - Calcareous cover, B - impervious base, a-b - lower limit of the first "hydrographic zone", v - allogene river; 1 - dry zone, 2 - periodically innundated zone, 3 - permanently innundated zone.

1.2. Hydrographic zones in karst after Cvijić (1918).

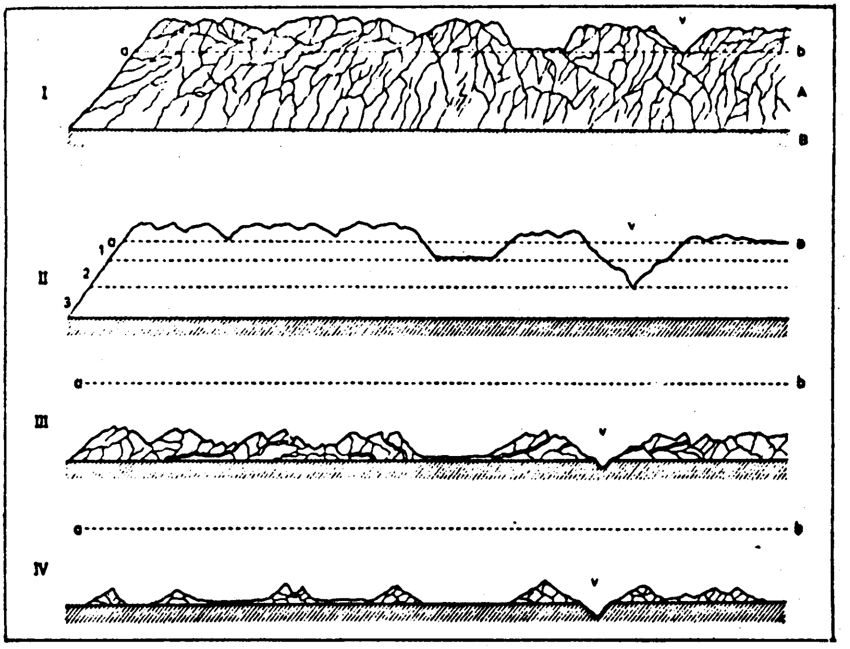

Figure 1.1

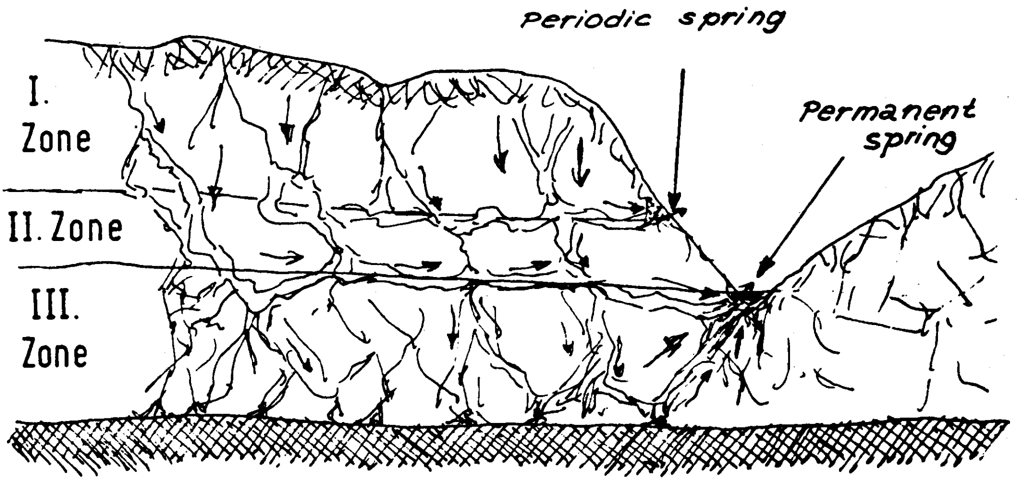

Figure 1.2

2

E A R T H   C R U S T   I N   Y U G O S L A V I A

ASPECTS OF CRUSTAL STRUCTURE, ITS RELATIONSHIP TO THE DEEP STRUCTURES AND ITS DEVELOPMENT*)

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1. INTRODUCTION

In Yugoslavia the Alpine and Dinaric belts are in contact either directly, or through the so-called Median (Intermediate) zone. 1) In the first case as in the northern part of the country, the boundary between the two belts consists of the Drave-Gail suture, which is characterized by en-echelon faults and Mesozoic to Tertiary magmatic rocks. The formations display a fan structure, being nearly vertical in the middle part with opposing vergences and a gradually more horizontal dip in the lateral parts. 2) The second case occurs in the eastern and southern parts of the country, where the Serbian Median zone separates the Carpathian-Balkan arc from the Dinaric belt. The limits between the median zone and the two orogenic belts consists of deep-seated faults associated with magmatic bodies. During the Alpine orogenesis the formations making up the median zone have been submitted to the same tectogenetic processes as the geosynclines, so that the setting at the margins is also fan-like as in the neighbouring belts. The opposite dip in the belts has already been noted at the boundaries between the belts and the Median zone.

The transition between the northern and the southern - eastern parts of the orogenic belts is concealed by the superimposed molassic depression of the Pannonian basin. The molassic complex, Neogene in age and sometimes up to 5 km thick, covers the tectonized Alpides in the North, and also the Dinaric belt, Median Unit and Carpathian-Balkan Arc in the South.

The distributions of the orogenic belts in Yugoslav territory (Fig. 2.1.) has been considered by Leopold Kober (1952, p. 4), who states: "Das alpine Orogen zeigt in Jugoslawien, im Profile von der Donau des Eisernen Tores bis an die Adria den klassischen Bauplan des Aufbaues: Die Zweiseitigkeit

*) First published in Zeitschrift dt. geol. Ges. 131, pp. 949-961, Hannover 1980, under the title: "Das zweiseitige Orogen in Jugoslawien".

der Bewegung. Kein anderes Land in Europa hat diese klare Zweiseitigkeit der Stämme."

One notes that across the same profil Kober assigned the Median Unit to the Carpathian-Balkan Arc, whereas he sonsidered the ophiolitic complex of the inner Dinarides as forming the suture zone between both belts. The intramountainous massif would be, according to this author, in the Pannonian basin, and the autochthonous foreland of the Dinarides would consist the region of Adriatic Sea, etc. This subject will be discussed later on.

J. Aubouin (1959) demonstrated that the orogenic belts of Southern Europe form a much more complicated system, i.e. a bicouple consisting of a centripetal couple and a centrifugal one (that is a bilateral orogen). In this system the centripetal couple is composed of the Italides and Dinarides, while the Dinarides-Alpides and Carpatho-Balkanides form the centrifugal couple. Here the representation of a simple symmetry is already perturbed, and the autochthonous Adriatic foreland acquires a new meaning: the Dinarides do not terminate at the Adriatic margin, but, according to Auboin's and also to my personal observations, the external Dinaric zones develop a centripetal couple together with the Italides. Instead of a crystalline massif constituting the autochthonous foreland, a median, young molassic depression is developed.

I have been interested also in the geotectonic development of Yugoslavia as well as of the neighbouring regions and I have already presented my opinions acquired through the study (analysis) of the formations and the structures, and their bearing on the paleogeographic and geo-historic interrelationships of the Dinarides, Hellenides and Italides, on the relative succession of both tectonic and magmatic events, and on related problems. In earlier papers (1960-1963) I gave evidence that in the orogenic belts tectogenesis, orogenesis, and magmatic activity do not migrate in one direction, along the cross-section (Cvijić 1924; Aubouin 1959), but in both directions along the cross-sections and also longitudinally. This point will be discussed in more details later.

Intensive geophysical studies during the last decade (gravimetry, magnetometry, deep seismicity) and interpretation of data obtained (Cirić 1972, 1974 and others) resulted in a three-dimensional appraisal of the Alpine-Dinaric system in this part of Europe, as well as of its current relationship with the upper mantle. This new spatio-temporal dimension, in my opinion, has to be taken into account when interpreting the tectogenesis and its origin.

Kober's model on bilateral orogen (actuallay derived from E. Suess) is now modified in many aspects, but his assumption that the Alpine orogen in Yugoslavia clearly represents a bilateral structure, remains in certain respects unchanged. The structural organization in the shallow part of the crust would be that of divergent bilateral symmetry. The divergent bilateral structure emphasized by Kober, existing at all levels from the "Magmazone" (i.e. upper mantle) up to the surface with internides, centralides, and externides, and in particular the symmetrical bilateral movements during the orogeny, do not appear in Yugoslavia, and probably do not in any other place either.

The main point in Kober's model (as well as those of other contractionists) concerning the formations mechanism of bilateral orogenic belts lies in the symmetrical opposition of two rigid bodies, which younger belts are vergent to. This reminds one of plate tectonics theory: without motion, obduction and subduction of stable plates, there is no tectogenesis. The significance of rigid bodies exerting an active part has penetrated deeply into the minds of tectonicians, so that new theories are only mutations of old ones.

2. NEAR-SURFACE ASPECTS OF THE BILATERAL OROGEN IN YUGOSLAVIA

If the Pannonian basin is accepted as a superimposed molassic depression onto the tectonized belts constituted by the Alpides, Dinarides and parts of the Serbian Median Zone, a divergent symmetry is actually observed in the Yugoslavian belts, as I have already stated: apart from some exceptional cases, the vergence in the shallower parts of the Alpides and the Carpathian-Balkan Arc is towards the north and east; in the Dinarides, structures are directed toward the south and west.

Even the boundary between the median unit and the Carpathian-Balkan Arc occurs as fault recumbent toward the east along its entire length. The eastern vergence is still more pronounced in the Paleozoic schists nappe (Morava nappe). The next nappe, consisting of Permian Red Sandstones, is in many aspects, and in particular its vergence, the most remarkable structural unit of the Carpatho-Balkanides in Serbia: the amplitude of its thrusting onto Tertiary formations reaches approximately 10 kilometers. More to the west, the structures are less clear because Neogenic faults considerably concealed the initial Alpine structural architecture. However, in Romania the nappes' amplitude increases toward the east (which is not the case in Bulgaria, where the structure is also controlled by the Rhodope crystalline massif)

West of the Median Zone similar structures do appear. In the direction of the Dinarides the boundary zone consists of a recumbent fault along which crystalline and Paleozoic - Mesozoic geosynclinal formations, including the first ophiolitic zone, are in contact. In the Dinarides the large magmatic massifs and the old Paleozoic cores do not show any trace of considerable horizontal displacement; the other geosynclinal formations are folded and occur in the nappes and slices system which moved toward the southwest.

In the external Dinarides, including all Adriatic islands, however, the southwest vergence is obvious in thrusts of considerable amplitude, with only the exception of minor folded structures. Apart from the Durmitor nappe, which is gravitate in origin, the Kuči nappe with its accompanying minor nappes is the most important nappe; next in importance are the Grahovo nappe, the Stara Crna Gora nappe, the Budva nappe and other nappes which replace one another (like coulisses) along the Dinarides. The interesting point is that in the Italides, on the western Adriatic coast, the structures show an opposite vergence, towards east and northeast, centripetal with regard to the Dinaric structures. The "Adriatic Foreland", the "Adriatic Crystalline Basement" do not appear in this region.

In addition to compressional structures, folds and nappes, numerous faults of various direction, age and size, can be observed at a near-surface level of the Yugoslav belts. These faults give to some areas a parqueted structure. Such structures are best noticed on satellite pictures, and some of them even have been detected in this way.

However, the bilateral orogen and its symmetrical structure actually comes to an end with the above-described vergence of the shallow structures. Their geo-historical development, magmatism and tectogenesis, as well as the deep structures, are throughly different and asymmetric.

3. GEOLOGICAL DEVELOPMENT

The geologic formations which are part of the shallow structures, above all those of the Alpine cycle, generally are not isotopic, and if there are such isotopic formations, they are not symmetrically disposed. In the following I shall put the stress on the main differences.

In the Carpathian-Balkan Arc, the Upper Permian and Lower Trias consist of red sandstones commonly deposited in a continental environment (marshy, lacustrian, shallow sea-type and alluvial, according to Maslarević 1961) in part in a hot and desert environment; the material has not been transported over long distances, and near the Median Zone the beds contain clastics derived from crystalline and other rocks of this zone. In the Dinarides the same period is represented by shallow-water, but typically marine, sediments: "rauhwackes", dolomites and Werfenian sandstones. The Anisian flysh and the Ladinian porphyritic-chert formation of the Dinarides are unknown in the Carpatho-Balkanides of Eastern Serbia. Almost the entire Jurassic system is differently represented on the western and eastern sides of the Median Zone, but the most striking feature is the absence of the jurassic ophiolitic complex on the eastern side. The magmatic rocks and the Cenomanian-Senonian volcano-sedimentary formation developed in Eastern Serbia do not exist in the Dinarides.

Differences in structural substages, or tectonic phases, are also striking. If the same cross-section as that presented by Kober is considered, the following Alpine structural substages are distinguished in the Dinarides and in the Carpathian-Balkan Arc.

3.1. In Eastern Serbia

3.1.1. Above the red sandstones sedimentation continued with marine Triassic sediments (mostly limestones; the oldest beds contain Ceratites trinodosus of the Muschelkalk, Nesič 1953); sedimentation locally continued during upper Trias and Liassic times, but in most zones these periods are missing the stratigraphic column. Middle Jurassic is generally transgressive on the older formations, beginning with clastic, coarse-grained sediments. The interval from Permian to Liassic can be considered as the first structural substage, ending with the Paleokimmerian phase.

3.1.2. The second sedimenation period, which is represented by clastic material and the different limestones, extends over the time interval from Middle Jurassic to the end of Lower Cretaceous (including Aptian). Some stratigraphical gaps indicated by "hardgrounds" do not impede conformity between the layers which they separate. The Austrian phase interrupts this continuity.

3.1.3. In the extensional period that followed the Austrian folding phase, Upper Cretaceous formations were deposited (volcano-sedimentary complex with pyroclastites and andesitic flows, carbonates and flysh-type series). Upper Cretaceous thus constitutes a separate substage, the upper boundary of which is marked by a considerable unconformity between the Upper Cretaceous formations and the younger layers originating in the Laramian or Pyrenean phase. The most important structures of Eastern serbia all formed during this time span, concealing the earlier deformations.

3.1.4. The Lower Molassic substage encompassed Oligocene and Lower Miocene. In the inner zone the large nappe of Permian sandstones extended over the sediments of this period, and this led some authors to consider the Savic phase as the main folding phase in whole Yugoslay territory. At any rate, the Miocene sediments are more tectonized than the younger ones, so that they form a separate structural substage.

3.1.5. The upper Molassic substage, devoid of any trace of folding began during Upper Miocene. It overlies all tectonized units present in the depression where is formed, from the Median zone to the more external zones.

3.2. Dinarides

3.2.1. The first Alpine substage in the herited basins of the internal Dinarides consists of formations representing the interval between Upper Devonian and Middle Jurassic (Jadar, Polimlje, et al.). In the area which was land during upper Paleozoic time, marine sedimentation started in Upper Permian and lasted until the end of Lower Jurassic. Here, too, the Paleokimmerian phase interrupts the sedimentation.
In the external Dinarides this first substage lasts until Upper Cretaceous. As a matter of fact, flysh formations (Anisian, Tithono-Valanginian) indicate some movements, but no unconformity can be observed.

3.2.2. In the internal Dinarides the second substage began in the Middle Jurassic and lasted until Uppermost Jurassic. The Middle Jurassic is represented by the lower part of the diabase chert-bearing formation which, as can be observed on good exposures (Krš pod Gradcem, Ovčar-Kablar Defile) lies uncoformably on older formations.

From a geotectonic point of view, this is the main substage, because at that time oceanization developed to a maximum in the geosynclinal troughs, resulting in the formation of the ophiolitic complex. The inversion of the geosynclinal troughs at the end of Upper Jurassic left considerable gaps, which increase in length of time from the internal zones outwards. They extend from Tithonian-Valanginian to Albian-Cenomanian and even Senonian times. This period is marked by mechanical and chemical alteration of the ophiolitic complex.

By the end of this period, some anticlinal domes formed, giving way to décollement and gravitative nappes. The best example is that of the Paleozoic dome of Lim, which generated the Pešter nappe. The folding which preceeded this gravitative décollement of Triassic cover could correspond to Stille's Austrian phase.

3.2.3. The third structural substage in the inner Dinarides corresponds to the second one of the external Dinarides. It extends in time from the Albian to the end of Cretaceous. The beginning of the transgression was not synchronous in all areas, but an angular unconformity and basal clastic coarse-grained sediments representing the beginning of this substage are present everywhere. During this period a flysh-type sedimentation developed in many regions, locally even at different times (internal zones and Kopaonik). Its largest extension occured by the end of Upper Cretaceous. Rocks of this substage have been tectonized in the time span between Danian and Upper Eocene, most probably during the Laramian phase. Some gravitative nappes are related to this folding and uplift, in particular the Durmitor nappe, which is the largest nappe in the external Dinarides.

In the external zones of the external Dinarides, a third substage is specifically developed in Paleocene and Eocene times. It also ends with flysh-type sediments which were tectonized during the Helvetian phase, between Eocene and Oligocene. All main nappes of the sea coast can be related to the movements.

3.2.4. In the internal Dinarides the Lower Mollasic substage begins in Upper Eocene. The Priabonian beds lie on the Alpine tectonized structures at many places (Vardar Zone, Drim Zone, Majevica).

In the external Dinarides it is later than Upper Eocene, and is represented by the famous Promina-beds, which are comprising of conglomerates representing a true polygenic "Nagelfluh".

3.2.5. The Uppper Molassic substage corresponds in time to Mio-Pliocene in the whole Dinaric area, and is represented almost everywhere by terigenous lacustrian deposits. An exception is represented by the depression in the outer parts of the outer Dinarides, where this substage happened in a marine environment (Scutari depression, bottom of the Adriatic Sea). As a consequence of a western migration, this substage continued until the present (present Adriatic Sea).

4. MIGRATIONS OF MOVEMENTS

Tectonic, orogenic and magmatic migration is not regular and symmetrical with respect to the axes of the bilateral orogen. On the other side of the Adriatic sea, in the Italides, the tectogenesis and magmatism were still happening while there was no longer any trace of them in the Dinarides. The movements are gradually younger inwards, in the direction of the Italic eugeosynclinal units and toward the Mediterranean Sea (evidence of which lies in flysh sediments, folding, overthrusting and volcanism). On the other hand, the corresponding zones of the Dinarides have been the first to be tectonized.

In each zone the migration of the movements also occurs in a longitudinal direction, as it has been mentioned many times since 1963 (B. Ćirić) under the name longitudinal migration. Migration is most obviously expressed by the neotectonic stage, and by the recent magmatic and tectonic phenomena. The migration process has a general distribution. For instance, to the south of the Dinarides and in the Hellenides the first molassic deposits are already upper Eocene in age (see above), and they lie over the tectonized contacts between the crystalline basement and the neighbouring divergent belts. The same occurs with the andesitic volcanism. Further to the north the molassic deposits become gradually younger, but the subsidence also shows an undulatory migration (in Bosnia, Upper Eocene again consists of molassic deposits). The undulatory longitudinal migration reversed itself, so that the youngest movements and the youngest volcanism occured in Macedonia (basaltic flows near Mlado Nagoricane, solfatare of Koselj, etc.). Further south, in the Egeidic domain, a change in the structural character of the earth's crust can be recognized: the old crystalline median body has deeply subsided, and young, shallow depressions have formed over the elevated upper mantle. The crust thus is greatly reduced in thickness. The coeval movements and volcanism are happening before our eyes.

The longitudinal variations are also characteristic of the northern branch of the orogen, in the Alps, Carpathian-Balkan Arc, Caucasus, etc. With regard to the Caucasus, in addition to volcanism and to variation in the characteristics of the earth's crust in the depressions of the Black Sea and Caspian Sea, recent Quaternary folding is known. This folding is spatially limited, but very clearly developed (folding of the doleritic flows located near Chalka, in the headwaters of the Hraml River).

The movements which produced the epidermic tectonization of the Carpatho-Blakanides, the Dinarided and the Italides, have not been synchronous and symmetrical, but were wholly independent. The role played by the Median zone components during those movements has been entirely passive. They are themselves tectonized, at different times in different parts, and their structures dip in different directions. The asynchronous tectonization in one and the same orogenic zone is difficult to relate to movements of the ancient platforms and rigid blocks. The strike-slip faults along lineaments commonly run parallel to the margins of the platforms and Median Zone, whereas judging by the movements of these bodies, the fault should be perpendicular to their margins. These examples show that the lineaments at the boundary between the Median zone and the Vardar Zone are sutures between the Alps and the Dinarides, etc.

The origin of all the above-mentioned variations in the crustal structure and the regional to local tectonization must be sought in my opinion, in the activity of the upper mantle.

5. RELATIONS IN DEPTH

The present tectonic constitution of the crust under Yugoslay territory is, on the whole well known. The tectonic features are recognized and studied from numerous direct observations, as well as on aerial and satellite photographs. Their surficial position and their shape and extension have been less commonly studied, the depth structures and relations are studied only sporadically, customarily in the course of geodetic mapping of present-day movements in the earth's crust, or of neotectonic and geophysical mapping (principally for magnetic, then gravimetric, seismic and seismologic maps). Thus one has become aware of many active and destructive deep-seated dislocations, and their location and extension at depth have been approximately determined.

Here I want to emphasize that, in my opinion, in Yugoslav territory there is no sufficient evidence of deep faults extending through the whole crust down to the upper mantle. The deep faults indicated in the cross-sections of deep seismicity (Dragašević & Andrić 1973-1974) are entirely hypothetical and cannot be related to the great shallow lineaments. This statement on the absence of faults extending down the mantle is best supported by seismic data concerning the depth of hypocenters.

The neotectonic map of Yugoslavia (1 : 1, 500.000) shows faults with their activity period, location of hypocentres of earthquakes greater than 6 in magnitude, and calculated depth of hypocenters, according to data available at the time (Ćirić 1967). The probable depth of the faults related to these earthquakes has been deduced from these data. The deepest hypocenters in Yugoslavia do not exceed 26 km (Drave suture), that is they do not reach the so-called Conrad discontinuity. It is very likely that the above-mentioned dextral strike-slip movements occur along those planes.

The presence of the Conrad discontinuity under Yugoslavia has been suggested by R.F. Mende (1972) on the basis of gravimetric measurements in Montenegro. He found that the boundary between the granitic and basaltic layers lies at a depth between 17 and 29 km, and it is bulging upward, in contrast to the Moho discontinuity (this thus implies a thickening of the basaltic layer). Other data on this discontinuity are not existent.

Most earthquakes in Yugoslavia have hypocenters at a depth of 10-15 km, i.e. in the zone between sediments and crystalline basement. At this depth a discontinuity has been recognized through various geophysical measurements in the external Dinarides; this discontinuity is assumed to represent the gliding surface of great nappes. Most earthquakes have their hypocenters at a depth of 3 to 5 km, at the base of the Tertiary; these earthquakes are the most frequent and the largest ones. Such a depth also corresponds to gliding surfaces of some nappes in the Dinarides (ancient Montenegro nappe, Budva nappe, etc.).

The Mohorovičić (or M) discontinuity itself, i.e. the boundary between lower crust and upper mantle, lies at a depth of 22-55 km.It is, on the whole, slightly undulatory and forms two bulges and one hollow. One of the elevations, the Adriatic bulge, extends along the Adriatic Sea and the western part of the external Dinarides from Istria to Boka Kotorska. It is about 300 km long and 150 km wide. The upper surface of this bulge lies at a depth of 28-35 km, as indicated by gravimetric observations (Roksandić 1966), magnetometric measurements (Stojković and al. 1976), and seismic studies (Dragašević 1973-1974). This doming is considered to be an asthenolith of the upper mantle (Damnjanović, Turajlić and Ćirić 1972). For the greater part, the hollow extends below the external Dinarides; its base is at a depth greater than 55 km (Dragasevic 1973-1974), thus forming the root of the Dinaric orogenic belt. The Moho discontinuity rises under the internal Dinarides, where it reaches about 30 km under the ophiolitic zones, and 22-24 km in the Pannonian Basin (Mitukh & Pozgay 1967). A surprising fact is that in sections across the Median Zone and the Carpathian-Balkan Arc, no root of the orogenic belt is to be seen, and neither are deep-seated faults between the Median Zone and the recent orogenic structures. On the contrary, the upper mantle has been domed in the same manner as under the recent molassic depressions, and this, in my opinion, represents another great astenolith.

In the boundary between Dinarides and Alpides, indicated at shallow levels, by the famous Drave-Gail suture which is accompanied by Tertiary eruptive bodies and tonalitic intrusions and which recent en-échelon dextral strike-slip faults, the magnetic and gravimetric fields are the same as in the neighbouring Dinaric and Alpine terrains, and without any variation. Some deep structures which extend east of Pohorje, indicated by anomalous zone, lie in diagonal and perpendicular positions with respect to the lineaments separating Alps from Dinarides. These structures also are obvious in the gravimetric and geomagnetic maps of Austria and Hungaria.

6. STRUCTURE OF THE CRUST

From the data presented above, it can be concluded that the present deep structures do not correspond to the shallow components and to the surface structures. Deep and shallow structures have formed at different times and under different conditions. Planes along which a tectonic activity developed, and still is developing, undoubtedly exist at levels deeper than those surfaces that are within reach of direct obeservation. Three of these surfaces can be regognized on the cross-section presented by Dragašević. On the whole, the following fundamental surfaces or discontinuities can be accepted as being in the known domain:

- base of Tertiary (5 km deep),
- base of Mesozoic (8-12 km),
- upper boundary of the crystalline basement (at different depth for the different areas; approximately 15 km),
- Conrad discontinuity (at different depth also)
- Mohorovičić discontinuity (22-55 km).

From the fact that the surface structures and the topography of the underlying upper mantle (as well as the other discontinuities) do not agree, it can be concluded that the morphology of the upper mantle surface is a recent feature and that it results only from the present-day relationships between earth's crust and upper mantle.

At the surface, present day tectogenetic processes appear as vertical movements which show different directions and velocities in various areas (based upon data from repeated survay of high accuracy), as well as horizontal movements of some blocks along great faults and on some discontinuities.

The shallow development thus has been differentiated both spatially and in time, especially in what concerns tectogenesis and magmatism. However, this does not exclude the fact that some phenomena had a regional, even global character; nevertheless, even in such phenomena local differences can always be observed. Again it must be emphasized that the general features in the formation of the orogen (great transgressions, magmatism, tectonic phases) are not symmetrical in relation to the Median Zone, and are not even synchronous everywhere in the same zone (see above).

7. ALPINE DEVELOPMENT OF THE CRUST IN THE DINARIDES *)

Much has been written recently about the origin of the Alpine Tethys **). At the 26th International Geological Congress this problem was specially dealt with by Colloquium C5 (Geology of the Alpine chains born of Tethys), and in the scope of this colloquium the theme N° 4 has been dedicated directly to the bearing of the Alpine Tethys. All papers published in that Colloquium, as well as many others of that time, reflect the conception of the very widespread theory of the plate tectonics. The model is very attractive and simple: the Tethys has been, according to them, created by moving apart from the continental plates, these of Euro-Asia in the north and of Africa in the south, from Triassic to the end of Early Cretaceous; then "collision", "closing" had originated and the Alpine chains had been created.

Some moments have been shown contradictorily.

On the whole, there is no subduction. The greatest oceanization of the Tethys had been in the course of the Jurassic. But there ought to have then been general obduction of the oceanic crust upon the continental one, denoted by disposition of ultrabasic massives. All the elements which do not fit by time and space into movement of the fundamental plates, as the bending of the chains, volcanism of various time and tectonization have found the explanation in moving of micro-oceanic and micro-continental plates, in numerous "openings" and "closings" of the oceans, ephemeral by duration, and by area resembling pools; merely in the terrain of Yugoslavia, for instance, about ten continents and oceans could be created from such models!

I have stared this review, initially domestic, from the geotectonic development of the Mediterranean terrains, basing my considerations on the data obtained by simple geological methods: maping and by analysis of formations.

The Tethys was not first created in the course of Alpine cycle. It is a primeval element of the Earth's crust, which, in the course of time, was changing its character in various of its parts, from a vast system of sea basins of various depths, to a ocean with deep trenches, but also to the

*) This paragraph is taken from my paper "The Mediterranean Tethys in Alpine Time - Evidence for Earth Expansion". - Bulletin Geol. Survey, A. LX. 1982 Beograd, and Expanding Earth Symposium, Sydney 1981, Ed. Carey S.W. University of Tasmania, 1983

**) Like the majority of authors, especially European, I use the adjective "Alpine" mostly for time; the Alpine cycle comprises a period approximately from Late Permian to Tertiary.

status of epiplatform. The sea sediments of all periods beginning from Cambrian are found in terrains of the present Alpine chains, and in different parts even submarine ophiolites of various times and magmatic products in general; all these formations in different areas were subjected to a varied degree of metamorphism. The composition of these formations and textural characteristics of their members reveal to daylight the conditions of their creation, particularly the depth of the sea of that time. We also know that under the proved Cambrian, there are also thick Precambrian formations of geosynclinal origin, also with green metamorphic rocks - at the proper time, ophiolites of oceanic bottom.

We must, therefore, reminded of Stille's statement (1958) that the Tethys had existed as an enormous orthogeosyncline since the earliest stages of the Algonkian. Shtreis (1964) also wrote that in the northern continents at the Tethys zone "the Paleozoic, Mesozoic and Cenozoic geosynclinal systems, which have been inherited from the Riphean (1500 to 600 Ma), were transformed into the Caledonian, Hercynian, Mesozoic and Alpine folded structures " which do not exist on the continents of Gondwanaland class because the development of "the northern and southern line of continents was passing periodically bipolarly". For Termier and Termier (1978) the Tethys had been in the course of Earth's history "a vast group of lineaments and broken zones, an oceanic totality, an essential paleographical, paleobiological and paleoclimatological element" and "its descendents had sunk into new structures".

The last pre-Alpine formations in the Tethys space are marine Devonian and Carboniferous, very widespread, often with terrigenous sediments and coal. Between Late Carboniferous and Late Permian the greater part of the Tethys bottom rose like an epiplatform, with small and narrow sea basins and low archipelagos and isthmuses. Some of these isthmuses had connected even Africa and middle Asia, that is Siberia (Angaraland), to which the identical fauna and flora of those regions bear witness (Shwedov 1964; Lutkevich 1964).

The Alpine cycle of the Tethys begins, on the whole*, in Late Permian. The epiplatform began sinking again, and the shallow sea, full of archipelagos and lagoons, comprised the vast spaces between Africa and Euro-Asia; they were deposited the shallow water sediments (evaporites and others) mostly concordantly over the older formations (in the Dinarides, for instance there is no discordance between the pre-Alpine and Alpine formations). The Early Triassic inherited the same development, but there

*) Emersion in some regions had lasted longer, and so the Alpine cycle in them began later, but these are sporadic phenomena. Emersions of some regions in the Tethys appear from time to time in the course of the whole Alpine cycle.

was also some deepening of the bottom (sandstones and violet argillites).

In the Middle Triassic the spectacular differentiation of the bottom appeared: throughout the Mediterranean Tethys (Alps, Apennines, Dinarides, Hellenides, Carpathians, etc.) countless little trenches where the bottom was more or less depressed along faults, submarine volcanism of intermediate character and a specific porphyrite-chert formation was created (Ćirić 1954). The marginal faults of these trenches are here and there still preserved and visible.

The first period of spreading of the Alpine Tethys, therefore, had not originated from some median ridge with a rifting zone and bilateral symmetric "opening" with rythmical long-term extrusion of basalts. It had been also provoked by differential movement of blocks along a system of faults, with prevalent sinking of the terrain between Afraica and Euro-Asia (with their possible and probable uplift). Such a development of the epidermal part of the crust in the area of the Tethys implies also corresponding processes in the upper mantle, which would be compared first of all, to my mind, with the processes which led to the creation of the Paratethys in the Tertiary (compare fig. 2.4. and 2.5.).

The epiplatform regime still reigned in the greater part of the Tethys in the course of Late Triassic and to the end of Early Liassic. During that time thick masses of the shallow-water carbonate sediments (limestones and dolomites) had been deposited. In some regions, however, deeper basins had also been created with poor sedimentation of pelagic carbonates and radiolarites (Cukali), or throughs with strong volcanism of intermediate and even of basic character (Caucasus: more throughs with valconogeno-sedimentary formations, andesite-dacite or diabase-gabbroic groups with argillites and other sediments). Although limited in area, these phenomena are of exceptional importance for creating a realistic picture of the Tethys as a community of paleogeographic regions with periodically independent particular phases of development; the Caucasus region is in that regard the most expressive, with its own exclusive develpoment from Late Jurassic uo to the present day.

The second event in the development of the Tethys which was of general importance and was taking place through great expanses throughout the Tethys, was the individualization of deep throughs with oceanic crust, in other words a trend to miogeosynclines and eugeosynclines. It had begun in the course of Middle Jurassic, after a short-term emergence of the bottom which most frequently was marked by unconformity on Liassic limestones and by gentle discordance toward the Triassic limestones. While in miogeosynclines thick strata of shallow-water limestones were being deposited, which bears witness to a steady sinking of the bottom, in eugeosnclines the thick volcanosedimentary Diabase-Chert formation was being created, with all magmatic and sedimentary members such as are being found today in the Mariana trench for instance. The deepening had been progressive followed by more and more intensive and more and more basic magmatism; here and there smaller ultrabasic bodies are also mixed with sediments (the Dinarides, Cyprus, the Taurides, the Apennines: Steinmann 1926; Rittmann 1963, and others). Culmination of events in eugeosynclines is represented by emplacement of large masses of ultrabasic rocks, which here and there cover a surface of even 1000 km^2 (the Dinarides), and reach a thickness of several kilometres. Because of them the followers of the platetectonics have introduced the idea of "obduction", assuming that these are the parts of oceanic bottom overthrust upon the the continental crust. The ultrabasic bodies, however, lie regularly over different members of the Diabase-Chert Formation, therefore over the Oceanic crust, and the base of ultrabasic bodies is made by metamorphic parts of Diabase-Chert Formation: amphibolites in centimetre alternations with marbles; gneisses with garnets; schists with chlorites; etc. The grade of metamorphism declines going from the peridotite bodies downward, with depth, and metamorphic rocks pass gradually into non-metamorphic members of the Diabase-Chert Formation. Because of that I have treated all peridotites (now mostly serpentinized) as magmatic products; all these formations I have assumed as a unique ophiolite complex, which with possible little variations (Caucasus) appears in all eugeosynclines of the Tethys, even far from its Mediterranean segment, in Cuba for instance.

I do not see the reason why the creation of eugeosynclinal throughs and the creation of the Jurassic magmatic formations of the Tethys could be in any other way than was the case with the trenches of the Tertiary Paratethys and of the Tethyan Middle Triassic; the essential difference is only in their depths. The upper mantle in the course of the Jurassic had been raised more and more, and by the end of Late Jurassic had reached the bottom of the throughs, weakened enough and with the crust thin enough that ultrabasic lava could erupt without contamination with acid components, which had accompanied magmatism in other epochs. (Similar ideas of permeability of the bottom in eugeosynclinal troughs and extrusion of ultrabasic magma have been presented by Shtreis 1951; Beloussov 1972, and others.)

I have classified the Tethys and its essential paleographical units to geosynclines having in mind first of all the fact that the Mesozoic formations, deposited at their base are 8-10 km thick, and in some regions even considerably thicker. Beside classical definitions of such units, I would with pleasure recall the recent statement of Moore (1970) in his presidental address to the Geological Society of America with the dogmatic sentence "The Earth's crust is stable" (thinking of horizontal movements). "The geosynclines are distinguished mainly of much-increased thickness of sedimentary formations, which predominantly are of shallow-water marine origin, but may include subaerial deposits in large quantity. Geologically younger geosynclines and arcuate belts of volcanic islands in the East Indies, West Indies and West Pacific define a so-called mobile belt of the Earth's crust that largely girdles the Pacific Ocean and follows the course of the Mediterranean sea called Tethys, extending eastwards from Gibraltar to Malaysia. It is marked by frequency of earthquakes, mostly shallow origin, but in some districts of intermediate depth, or deep focus type".

Tectonization of the Alpine Tethys and all the events which came after the inversion of geosyncline took place asynchronously and selectively: in different regions in different times and with different products; this especially refers to the eugeosynclines which were considerably more mobile than the miogeosynclines.

The Early Cretaceous, for instance, is characterized in miogeosynclines by inherited sedimentation of thick carbonate series. However, in eugeosynclines there are also basins with flysch sedimentation, here and there even from Late Jurassic. Eastward from the Serbian median zone, the neighbouring part of the Carpatho-Balkanian arc, there is a zone with the Late Jurassic flysch; westward of the median zone, however, the flysch is that of Early Cretaceous, and just on the transition of the inner and outer Dinarides there is again one district with Late Jurassic flysch, as well as in some regions of the Caucasus.

This differentation in eugeosynclines denotes also the beginning, more exactly, the first phase of the geosynclinal regime, and at the end of that period the first evident tectonization takes place: the raising of the mighty ridges and slipping gravitational nappes from them (i.e. the nappe of Pešter).

The process of differentation continued in Late Cretaceous. The sedimentation of carbonate series went on in the exterior parts of miogeosyncline, but also some troughs were formed in which terrigenous sediments were being deposited (oliostostrome, scaglia, flysch) here and there even with the phenomena of volcanism (outer Dinarides). Further eastwards, however, a new disjunctive tectonics is more and more expressed (Radoičić pointed it out many years ago); it is manifested in many parts of the eugeosnyline in the creation of ophiolite-mêlange, a special tectonic formation comprising blocks of all formations of the corresponding terrains of older than the Maestrichtian, the strata of which tranquilly covered the mêlange. In the Carpatho-Balkan arc, on the spot where East Serbia is now situated, a tectonic trough had been created, where, beside the sedimentation, in the course of the whole Late Cretaceous violent volcanic activity was present. A similar case is still known only in Caucasus, at a distance of about 2500 km, where volcanism had been more intensive and basic.

The whole Tethys was, therefore, divided into numerous regions with different physiography, such as trenches with unstable bottom, shallow-sea districts, and raised blocks. This division was very favourable for the definitive inversion of the geosyncline tectonization, and orogenesis. Thus different regions were tectonized at different times, from the end of Late Cretaceous (the inner Dinarides), to the Eocene-Oligocene boundary (outer Dinarides), and in some regions even in the Miocene (the Outer Alps, Apennines, the inner zone of Carpathians), and even in the Quartenary (small districts of Caucasus and southern Caspian).

8. CONCLUSIONS

The direct origins of the tectogenesis and the transmission mechanisms of the tectogenetic movements in the earth's crust remain uncertain, for the conditions prevailing and the modifications occuring in the deep levels of the earth are unknown and belong in the realm of hypothesis. Convection currents seem to be a plausible mechanism to explain such processes as the tectogenetic one; the existence of mantle plumes and hot spots is unquestionable in many areas and in various times, and their tectogenetic role is very likely. These processes, and many others, could be involved in the complicated geotectonic pattern of an expanding earth.

At any rate, the active part belongs to the interior part of the earth and not to the crust with ist plates and rigid bodies, which were and remain passive elements in global development.

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FIGURES

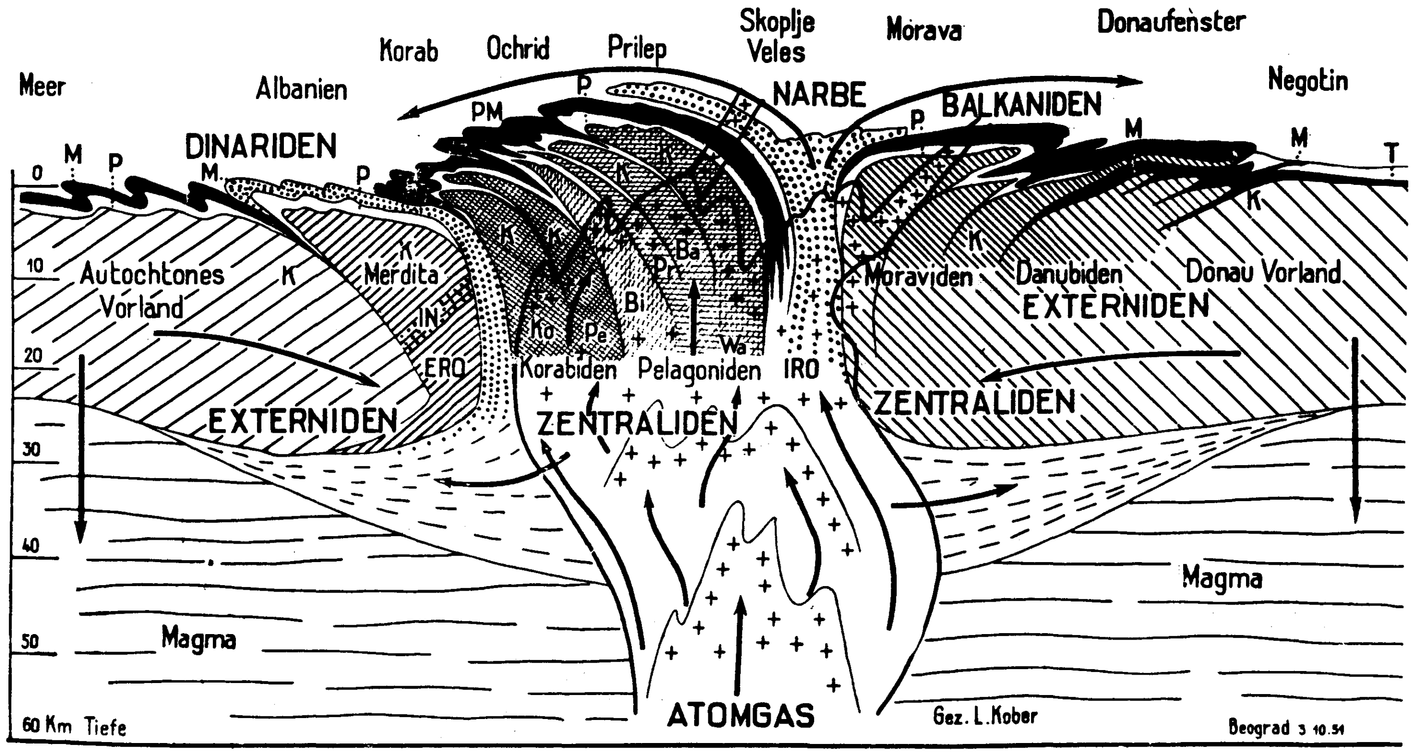
2.1. Generalized profile of the Alpine Orogen of Yugoslavia. After L. Kober (1952).
M - Mesozoic, P - Paleozoic, K - crystalline basement, IRO - Inner Ophiolitic Complex. Arrows indicating the sense of tectonical movement.

2.2. Main tectonic characteristics of the Dinarides and their serpentine massifs.
A - Alps, B - Pannonian basin with Neogene molasses, C - Carpatho-Balkan Arc, D - Serbo-Macedonian crystalline mass, E - old Dinaric cores, F - Inner Dinarides - eugeosyncline

2.3. Structure of the crust after Dragešević (1973-1974).

2.4. Probables relationship between the mantle and the crust in the Dinaric region during some periods of Alpine time. The position of the recent Adriatic is on the left, that of the pannonian basin on the right.
1 - Sedimentary layer, 2 - Granitic layer, 3 - Basaltic layer, 4 - Upper mantle, 5 - Igneous rocks: intermediates in Tr2 basic in the J2-3, ultarbasic in J3, and intermediate in M2, 6 - Deep faults. Tr2 - Middle Triassic, J2-3 - Middle and Late Jurassic, J3 - Late Jurassic, M2 - Middle Miocene, Q2 - Late Quaternary. Q2 is from the data of geophysical measurements; the other periods are by comparison between geological events of those periods and corresponding events and relationship in the Recent ocean's morphostructures.

2.5. Lithostratigraphic columns of Outer Dinarides (A) and Inner Dinarides (B), indicating the environmental changes during the Alpine time.
1 - crystalline schists, 2 - argillitoschists, phyllites, 3 - limestones, 4 - conglomerates, 5 - porous limestones (Zellenkalke), 6 - sandstones: varicoloured in Early Triassic, grenn in Albian of Inner Dinarides, molassic in Tertiary, 7 - dolomites, 8 - flysch, 9 - porphyrites, 10 - formation of porphyrites and cherts, 11 - limestones and cherts, 12 - reef limestones, 13 - limestones with intercalations of argillites, 14 - ammonitico rosso, 15 - ultrabasic rocks, 16 - formation of diabase and cherts (15 + 16 = ophiolitic complex), 17 - bauxites, coals, 18 - dacito-andesites and granodiorites, 19 - formation of andesites and cherts, 20 - mélange, 21 - andesites-basalts and basalts, 22 - unconformities, 23 - hiatus in sedimentation.
Pi - Precambrian and Early Paleozoic, Ps - Late Paleaeozoic, P2 - Late Permian, t1 - Early TRiassic, t2 - Middle Triassic, t3 - Late Triassic, j1 - Early Jurrasic, j2 - Middle Jurassic, j3 - Late Jurassic, cr1 - Early Cretaceous, cr2 - Late Cretaceous, e - Palaeocene and Eocene, o-m - Oligomiocene.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Ochrid
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Autochtones
Vorland
Merdita
Moraviden
Danubiden
Donau Vorland
EXTERNIDEN
Korabiden
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IRO
ERO
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Gez. L. Kober
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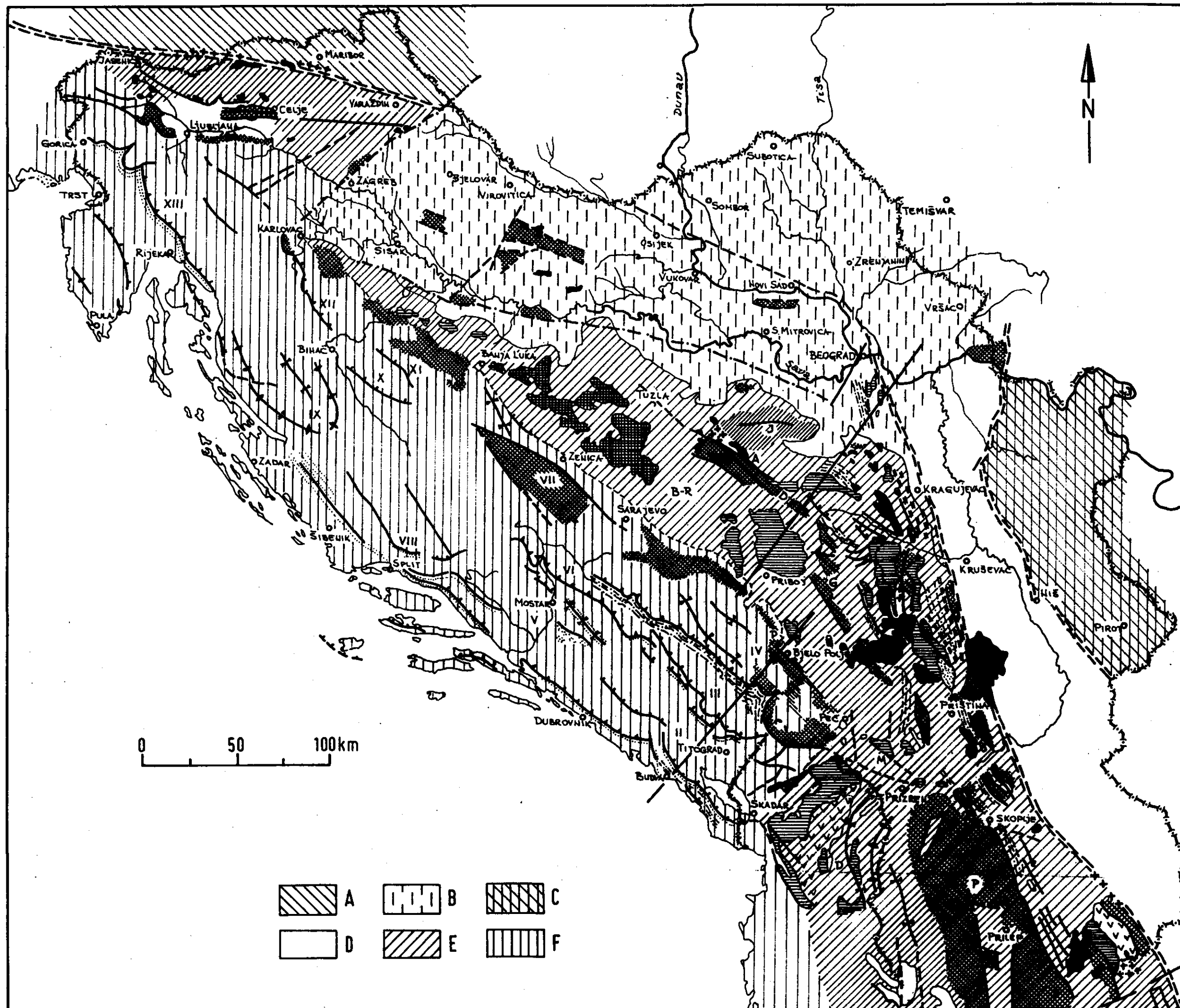
Figure 2.1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Bjelovar
Virovitica
Karlovac
Sisak
Osijek
Vukovar
Subotica
Sombor
Temišvar
Zrenjanin
Novi Sad
Vršac
S. Mitrovica
Beograd
Sava
Dunav
Tisa
Bihać
Banja Luka
Tuzla
Zenica
Sarajevo
Zadar
Šibenik
Split
Mostar
Dubrovnik
Titograd
Budva
Skadar
Priboj
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Priština
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Skopje
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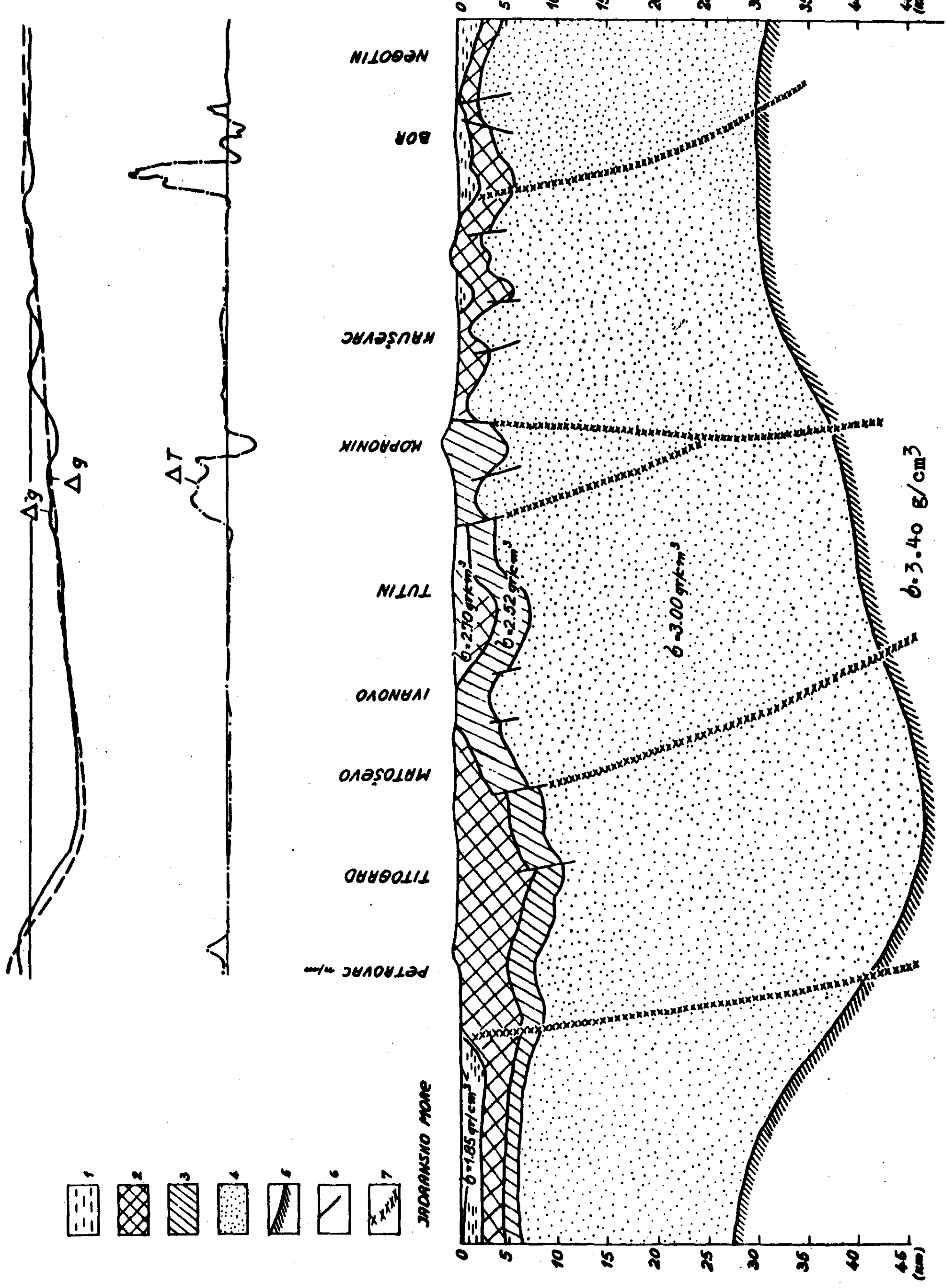
Figure 2.2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BOR
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Figure 2.3

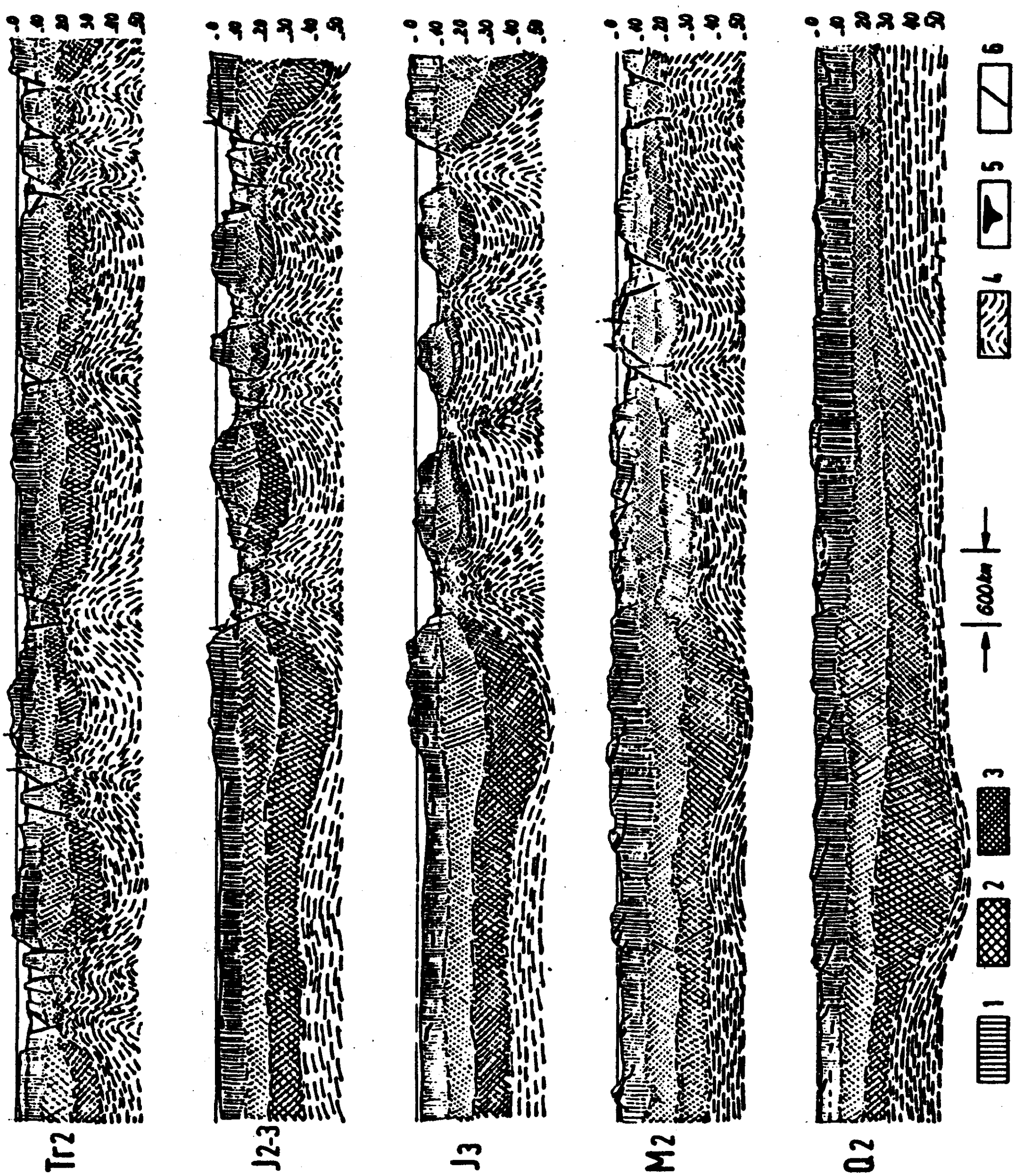

Figure 2.4

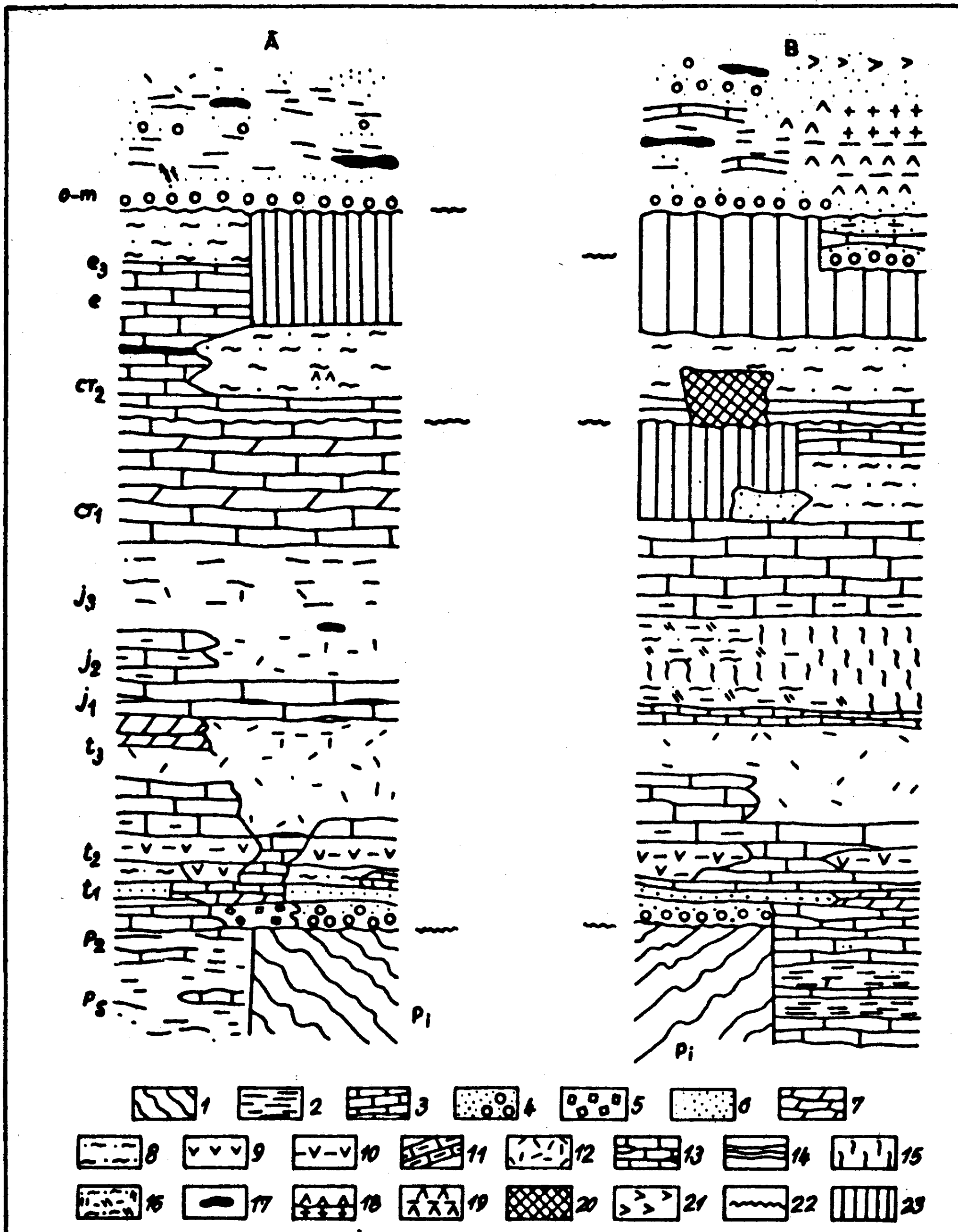
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Figure 2.5

3

HYDROGEOLOGIC REGIONAL CLASSIFICATION OF KARST IN YUGOSLAVIA

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REVIEW OF PREVIOUS CLASSIFICATIONS

This part of Europe was the cradle not only of the proper name "karst" (the German derivation of the local name of a district in Slovenia, "Kras"), but also of the first karstologists: J. Cvijić, A. Penck, A. Grund, and F. Katzer. After the first studies of this "locus typicus" of the karst, they soon started to classify and differentiate areas with similar karst features.

F. Katzer distinguished "deep" from "shallow" karst already in 1909. While erosion reached the impervious basis in the "deep" karst, it stopped within the carbonate rocks in the "shallow" karst.

A. Grund (1914) introduced the German term "Halbkarst", meaning "semikarst" or "partial" karst to describe the karst areas composed of dolomites where karst and fluvial erosion processes exist combined.

Yugoslav geographer J. Cvijić, who in 1893 described the karst morphology in his world-wide known monography "Das Karstphänomen" and introduced into international terminology local morphologic names (ponor, doline, uvala, polje), in 1924 accepted Grund's definition for "Halbkarst" but changed it into a Greek term "holokarst" in the meaning of "full" or "complete" karst, for the terrains where all the karst phenomena were developed. A very long and wide belt extending from Italy to Albania we may attribute to the "holokarst" with a transitional type of karst, at the northeastern border of this region, in the central parts of Yugoslavia.

40 years had passed until new classifications appeared. After the World War II, the study of karst morphologic and hydrogeologic phenomena explosively expanded, caused by countless explorations, many of them very comprehensive, related to vast water power and water-supply development as well as to more or less pure scientific work (studies and cartography) in the field of geology, morphology and hydrogeology. A series of authors

have been engaged in classifications of karst types and terrains in Yugoslavia.

From the postwar generation of authors who studied regional features of karst, M. Herak has been most effective. In 1957 he introduced an entire geologic approach to the solution of theoretical and practical karst hydrogeology, thus influencing his and other authors' classifications.

B. Stepanović (1957), in his Dr. Sc. thesis, classified the Yugoslav territory into eight hydrogeologic provinces with two of them pertaining to the karst terrains : the Adriatic hydrogeologic province and Dinaric holokarst hydrogeologic province. The Adriatic province was a very narrow strip not wider than 1 or 2 kilometers at the most along the Adriatic coast, where the sea water presumably mixed or influenced hydraulically the continental fresh water. That province includes also all of the islands.

J. Roglić (1960) introduced the term "fluviokarst" defining by it the karst process and fluvial erosion. It is a combination of water sinking and solution with wathering and wash-out. This type of karst relates to terrains built of pure dolomites, or of rocks in which limestone and dolomites alternate, or of marly limestones. The term "fluviokarst" is basically a substitute to the earlier introduced terms "Halbkarst" and "merokarst".

J. Roglić (1965) presented a map of Yugoslavia showing the distribution of karst. Two types of karst terrains are shown, "karst" and "fluviokarst". The "karst" has the meaning of "holokarst" (Cvijić 1924) and "fluviokarst" the same as in his earlier work (1960).

M. Komatina (1965) pointed out the role of geology and considered it the primordial factor in the development of hydrogeologic, hydrologic, and geomorphologic features of karst areas. He classified karst terrains of Yugoslavia in (1) the zone of Tectonic Contraction and (2) the zone of Earth Crust Expansion. The first zone comprises a wide littoral belt along the Adriatic coast, including the island, while the second zone extends over the continental hinterland, but both pertain to the previously defined "holokarst" area. The littoral belt is much wider than the Stepanović's Adriatic hydrogeologic province. Its border passes over the line Obrovac - Muć - Mostar - Kotor - Skadar that in some places reaches up to 50 kilometers inland.

Within a comprehensive interpretation of the karst hydrogeologic features in Croatia (Herak, Bahun & Magdalenić 1969) the karst of this part of Yugoslavia was divided into three zones: the Adriatic, Central and Inner zones. The Adriatic zone includes all the islands and seaward slopes of the mountains along the coast. The most specific hydrogeologic features are vruljas (submarine springs) caused by sinking of the sea bottom of the northern Adriatic Sea and rising of the sea level with results that karstified land came under the sea. The Central zone comprises all the highest peaks of the Dinaric Mountains. The zone is characterized by the presence of all the karst morphologic and hydrogeologic features, including poljes and estavelles, and by discordances between morphologic and hydrogeologic (i.e. surface and ground-water) divided. Anticlines with dolomites in their cores and clastic bedrock control directions of ground-water flow. The inner zone comprises areas where there are neither poljes, nor estavelles, nor large ponors, but ponikvas are frequent. Deep ground-water percolation exists only occasionally.

P. Habič (1969) classified the karst of Slovenia taking into account primarily runoff characteristics but, no doubt, geologic and morphologic features were considered about equally. Two runoff types were distinguished: simple (underground) and complex runoff (surface and underground combined). In that way, the Slovéne karst was classified into three main areas: Alpine Karst, Dinaric Karst and Isolated Karst. The Alpine Karst area includes the karst of the Julian Alps, Karawanken Mountains, and Kamnik Alps. The Dinaric Karst area contains three longitudinal belts: (1) Outer or Littoral Karst, (2) Central Dinaric belt consisting of the High Karst of Inner Carniola, and (3) Inner Dinaridic belt characterized by the low and shallow karst of Lower Carniola.

Within the monograph on the karst of the northern hemisphere, where he described in detail the karst features of Yugoslavia, M. Herak (1972) kept entirely the previous regional classification of the Croatian karst (Herak, Bahun & Magdalenić, 1969) only slightly renaming the zones. By the way, the territory of Croatia comprises 85% of the 2, 092 kilometers long continental coast of Yugoslavia, all her islands and includes all the karst types. The author divided the karst areas in Yugoslavia into three regions: (1) the Adriatic Insular and Coastal region, (2) High Karst region, and (3) Inner region. The morphologic and hydrogeologic features in each region remained the same as in Croatia, similarly considering all the karst terrains of the whole Yugoslav territory northeast of the High Karst region to pertain the Inner region.

Two hydrogeologists, B. Mijatović and F. Fritz, have for a long time dealt with various hydrogeologic explorations within the Adriatic coastal karst area. B. Mijatović (1972) explained the generalized geohydraulic conditions within (1) low and near the sea and (2) hilly and mountainous land. They are the smaller regional units into which M. Komatina (1965) subdivided his "tectonic contraction zone". F. Fritz (1979) disputed the validity of that and similar subdivisions within that zone (that comprises besides all the Adriatic islands also large continental parts of the North and South Croatian Littoral and of Herzegovina). This author based his opinion on new and comprehensive hydrogeologic research carried out in that zone.

J. Josipović (1974) classified hydrogeologically the karst terrains Bosnia and Herzegovina and put them into two karst regions: Herzegovina and Central Bosnian hydrogeologic regions. The Herzegovina region corresponds to the High Karst geotectonic unit and is limited to the High Karst belt while the Central Bosnian region to the "fluviokarst" or Inner belt, as previously defined by the other authors.

M. Komatina (1975) developed further his earlier regional classification of karst. He classified all the karst occurences into two main types: (1) the karst platforms and (2) the karst of geosynclines. According to the author, within the second type to which belongs also the Dinaric Mountains pertain, two territories might be distinguished: (1) the Karst territory, meaning to consist entirely of karst terrains, and (2) the territory with Isolated Karst terrains. The former corresponds to the "karst" and the latter to the "fluviokarst", as named by J. Roglić (1965). The Karst territory was separated into the Littoral Karst (i.e. Zone of the Earth crust contraction) and Inner Karst (Zone of the Earth crust expansion). The geographic position and boundary between these two zones are the same as in the previous work of this author (Komatina 1965). Both zones are situated within the Outer Dinarides geotectonical unit. The Inner Dinarides geotectonic unit was divided into two areas: (1) Area with Large Carbonate terrains and (2) Area with Isolated Carbonate masses.

In 1977, M. Herak returned again to the karst classification, only his approach was neither morphologic nor hydrogeologic but tecto-genetic, considering that such an access may better help in the interpretation of regional hydrogeology. Within a classification of tecto-genetic types of karst occurences in the world, dividing them into two main groups of types, the epi-orogenic and orogenic karst, the author classified the karst of Yugoslavia into three types: (1) folded orogenic karst, (2) accumulated orogenic karst, and (3) dissected orogenic karst. The first karst type characterizes the outer part of the miogeosyncline and transitional zone to the foreland. The folds dominate, with carbonate anticlines and clastic synclines. This definition refers to the area previously named as the zone of Earth crust contraction (Komatina 1965, 1975). The accumulated orogenic karst type is the "karst prototype at the locus typicus in the Dinarides", as pointed out by M. Herak, and "Not only a great primary thickness of rocks but also a secondary one (hence the accumulation of karst terrains) and karstification below the deepest valleys and below the sea level - at least in the coastal region, are specific features." All the karst morphologic forms are developed. This description relates to the area defined earlier fully or partially by the mentioned authors under the names "deep" karst,"holokarst", "karst" and zone of the Earth crust expansion. The third type, the dissected orogenic karst, relates to the areas basically named in the previous classifications as the "shallow" karst, "merokarst", "fluviokarst" or to the area comprised within the Central Bosnian hydrogeologic region

In that work, M. Herak shortened the name of the Adriatic Insular and Coastal belt into a simpler form, the Adriatic belt. The remaining two belts kept their previous names, the High Karst and the Inner belts.

THE MOST RECENT HYDROGEOLOGIC REGIONAL CLASSIFICATION OF THE KARST IN YUGOSLAVIA

The author of this chapter made a sort of synthesis of the earlier classifications, that are briefly reviewed within the first part of the chapter, and of a study of hydrogeologic conditions of the karst of Yugoslavia that resulted with a slightly new hydrogeologic regional classification of these areas. It has recently been presented within his description of the Karst hydrogeologic region (one of three hydrogeologic regions of Yugoslavia) within the comprehensive textual Explanation of the Hydrogeologic Map of SFR Yugoslavia, 1 : 500,000 (Šarin, in print).

Actual hydrogeologic conditions as well as their basic practical consequences, domination of most important hydrogeologic specific characteristics, and integrity in geographic distribution were the factors used in the shaping of this regional hydrogeologic classification. Naturally, the regions, of which either features or boundaries were previously defined and which match the mentioned prerequisites, were entirely accepted as well as most suitable names - that was an easy work due to a great number of previous names.

All the mentioned factors point out the following regional hydrogeologic classification of the karst in Yugoslavia:

- Adriatic Karst belt,
- High Karst belt,
- Fluviokarst belt,
- Isolated Karst.

The first three belts represent subregions of the Karst hydrogeologic region, while the Isolated Karst are isolated karst areas within two remaining hydrogeologic regions of Yugoslavia, the Inner region in central and eastern parts and the Pannonian region in the north-central and northeastern parts of the country.

The Karst hydrogeologic region comprises an integral, long and wide belt at the southwest part of Yugoslavia, extending from Italy and Austria in the northwest to Albania in the southeast. Its southwest border is the southwestern coastline of the extreme Adriatic islands and northeastern border is the boundary of the Inner hydrogeologic region. All the islands are included. This region is about 650 kilometers long and 60 to 150 kilometers wide in case that only the continental part is considered, but it widens to 159 to 200 kilometers when the islands are measured as well. The area amounts to approximately 69,650 km².

The Isolated Karst is widely dispersed all over the remaining two hydrogeologic regions, particularly within the Inner region. The total area of limestones, dolomites and marbles, of which this subregion is composed, measures on the land surface approximately 18,300 km².

Hence, all the four subregions give the total area of karst terrains near 88,000 km² - that is 34,4% of the Yugoslav territory.

ADRIATIC KARST BELT

The belt extends over the entire Slovenian, North and South Croatian, and Montenegrin Littorals including all the Adriatic islands and practically a continuous belt along the whole of Adriatic coast, interrupted only at some very short sections of the coast, as in the Bay of Bakar, near Novi Vinodolski, and near D. Brela. Its area amounts to about 9,900 km².

Its continental boundary, which is at the same time the border line with the High Karst belt, is not strictly defined. In principle, it is the edge of the area to where sea water hydraulically or hydrochemically affects fresh ground water, but it is also the northeastern boundary of a flysch belt stretching along large parts of the Slovenian and Croatian coastal areas and the northeastern edge of the Budva - Cukali geotectonic zone in Montenegrin Littoral. The name is accepted after M. Herak (1977).

M. Herak (1977) assigns this area to the folded orogenic karst type with the carbonate core of antiforms and clastic core of synclines. Imbricate structures are the essential characteristic as well as the occurence of large and deep impervious rocks (synclines of Pologene flysch and, if considered as the whole unit, impermeable clastic and volcanogenic rocks of the Budva - Cukali unit). These impervious rocks form full underground barriers to the ground-water percolation from the continental hinterland toward the Adriatic Sea along large sections of the continental coast. They also direct ground-water flow along the structures causing the appearance of highly-yielding springs in places where the barrier is interrupted or where continental fresh ground water may overflow due to a low height of the barrier top.

All the island springs and a great majority of those at the continental coast are brackish. There are many vruljas (submarine springs) and occasionally sea-estavelles. Sea water intrudes in some places up to several kilometers. All that is due to (1) a direct and very long contact of karstified carbonate rocks with the sea - a very indented coastline of the continental coast and islands combined is 6,116 kilometers long although the air distance from extreme points of the coast amounts to only 61o km; (2) the karstified sea bottom - the sea level has risen for about 1oo meters since last 25,000 years (after Segota 1968) resulting with submergence of a paleocoast, karstified during the the paleokarst processes, submerged under the sea level; and (3) a complex coastal karst geohydraulics.

HIGH KARST BELT

This hydrogeologic subregion extends parallel to the Adriatic Sea over a part of Slovenia, Croatia, Bosnia, Herzegovina and Montenegro. It is an uninterrupted belt, stretching from the Italian to Albanian frontier, about 30 to 110 kilometers wide. This area measures about 41,950 km^2. Its morphologic and hydrogeologic features were defined by many authors - F. Katzer (1909) as the "deep" karst, J. Cvijić (1924) as the "holokarst", J. Roglić (1965) as the "karst", and M. Herak et al. (1969) as the "Central Karst", and (Herak 1972) as "High Karst". The latter has been accepted as the name of this subregion. M. Herak (1977) classifies it as a typical accumulated orogene karst.

Since the base of this regional classification is not tecto-genetic but hydrogeologic (sea water influence limit or northeast border of flysch barriers) the High Karst belt in Dalmatian Zagora (Croatia) and Herzegovina includes also large sections of the folded orogenic karst type, thus, its boundary does not correspond to the boundary outlined by M. Herak (1977) but much more to his earlier solutions (Herak et. al. 1969; Herak 1972).

This belt is composed almost entirely of Mesozoic carbonate rocks. Jurassic and Cretaceous limestones prevail. The faulting is very significant, from normal to reverse faults, to large overthrusts.

Characteristically, all the surface and underground karst morphologic forms occur within this belt. It stands out above all by discordances between surface and ground-water divided, lost rivers, a great number of large karst poljes, estavelles, wide an fanlike bifurcations of "concentrated" ground-water flows, and by crossings of surface streams and ground-water flow directions.

A gradual rise of the Dinaric Mountains and the forming of karst poljes are very conspicious morphologic features of this belt. Those flat depressions situated on different altitudes combined with very permeable calcareous rocks and full or partial underground barriers consisting of dolomites and clastics produce a very peculiar hydrogeologic effect that we might call "hydrogeologic cascades" (Šarin, in print). The meteoric water that infiltrates into the underground emerges at one side of the polje, flows shortly over the surface, sinks at the other side of the polje, percolates subsurfacely toward the spring in a next, lower polje etc., until it reaches the Adriatic sea or a rare permanent river.

The flow pattern as described above occurs in a regional level between the karst hinterland in Bosnia and Herzegovina and the coast in the South Croatian Littoral.

FLUVIOKARST BELT

This belt occupies the whole, long northeastern side of the Karst region. In that way, this belt represents the marginal zone between the Karst and Inner hydrogeologic regions. It has the area of about 17,950 km².

Its characteristics were noticed already by F. Katzer (1909) and by J. Cvijić (1924) who called is "shallow" karst and "merokarst", respectively, but they assign to it even the areas separated here as the Isolated Karst. J. Roglić (1960, 1965) from whom the name of this belt has been accepted, considers the same. That name reflects best its basic feature - a karst belt with (permanent) surface streams.

Ground water, formed by the infiltration of meteoric precipitation through very permeable carbonate rocks, sinks vertically until it reaches deep aquifers hydraulically more or less connected among themselves and, within them, percolates under very gentle hydraulic gradients toward a relatively dense network of permanent surface streams that do not loose their water any more. If any portion of that river water disappears through permanent or intermittent ponors (swallow holes), it has merely a local significance since that very same water emerges from springs downstream, within the same river valley.

There are neither bifurcations nor crossings of ground-water flows as well as neither poljes nor estavelles. The ponikvas (dolines, sinkholes) are dominant morphologic features and they are very densely distributed in some areas. The caves and jamas (karst shafts) are rare; and if they occur, they are not very large. Within the Fluviokarst belt, the following hydrogeologic zones may be distinguished: (1) the Alpine Karst, (2) Croato-Slovene Low Karst, (3) Bosnian Shallow Karst, and (4) Montenegrin Highland Karst.

The Alpine Karst zone occupies the extreme northwestern part of the Fluviokarst belt and it is entirely in northwestern Slovenia. It is built almost exclusively of Middle and Upper Triassic limestones and dolomites. The trunk of the Triglav, the highest mountain in Yugoslavia, 2863 meters, is composed of more than 2000 meters thick pure Dachstein limestones (Gams 1965). The "highland" type of karst has been developed, characterized by very exposed peaks and plateaus with deeply eroded river valleys.

One morphologic feature is very specific for the Alpine Karst zone - the erosional kettle hole. Such a kettle hole in the Julian Alps has the size of 125 x 145 x 27 meters (Gams 1965). The "podi" or karst plateaus in many mountains are even more outstanding structural and erosional forms.

The Croato-Slovene Low Karst zone embraces a part of Gorski Kotar and the whole of Kordun, the districts in central Croatia, as well as a part of eastern Slovenia along the courses of the Kupa and lower Krka Rivers. The rivers and their tributaries cut their valleys in a mostly flat land with altitudes rarely higher than 400 meters. Triassic and Cretaceous limestones with dolomites dominate.

If the beds of upper river courses were more elevated, i.e. if the vertical distance between the upper courses and the regional erosion basis were greater, the rivers would become partially or fully lost and other High Karst features would presumably be modelled because in most parts of this zone the terrain is very permeable and the impermeable karst bedrock is very deep.

The Bosnian Shallow Karst zone is an area elongated northwest-southeast extending across the whole of Bosnia. The lithostratigraphy differs from the previous zone, Triassic carbonate and clastic rocks prevail here except in the area confined within the towns of Sanski Most, Banja Luka, Travnik, and Jajce, where they are substituted by Upper Jurassic and Lower Cretaceous limestones. "The Dinaric karst basis" - as the macroregional impermeable bedrock consisting of Lower Triassic clastics and directly beneath them Late Paleozoic clastics has been called (Šarin, in print) - is either at the ground surface or shallow below it.

This "shallow" karst, i.e. its shallow impermeable basis, enables the existence of a rather dense network of permanent surface streams that drain adjacent aquifers.

The Montenegrin Highland Karst zone includes northern Montenegro and a part of southeastern Bosnia. Within this zone, the high mountain massifs are situated: the Durmitor, Sinjajevina, Pivska Mt., Volujak, Maglić and others as well as large plateaus. The Drina, Tara, and Piva Rivers with their tributaries traverse this zone modelling in places up to 1000 meters deep canyons. Triassic and Upper Cretaceous clastics and Mesozois carbonate rocks are main lithostratigraphic units of this zone. For the largest part, this zone is, in fact, a huge overthrust - the Durmitor overthrust.

ISOLATED KARST

Within the remaining hydrogeologic regions of this country, the Inner and Pannonian regions, appear larger or smaller "islands" of karstified carbonate rocks surrounded by terrains having fissured or intergranular (porous) aquifers. P. Habič (1969) called such karst areas in Slovenia "the Isolated Karst", the name also used in this regional classification for the whole of the remaining Yugoslav territory. The earlier authors (Katzer 1909; Cvijić 1924; Roglić 1965; Herak et al. 1969; Herak 1972; Josipović 1974) considered these isolated karst areas to be the same karst type as the areas included in the discussed classification within the Fluviokarst belt.

There are many isolated karst areas and their total surface is particularly large in eastern Bosnia, southwestern and eastern Serbia, and southwestern and central Macedonia. Smaller karst areas occur in northeastern Slovenia, northwestern Croatia, and other parts of Yugoslavia. The total area of not covered carbonate rocks out of the Karst region amounts to about 18,300 km^2.

Two zones, where these karst areas are larger than elsewhere, are eastern Bosnian and southwestern Serbian zones. We could consider them as one regional unit if they were not interrupted by the large serpentine massif of Zlatibor Mountain. The geographic position, tectogenesis, lithostratigraphy, and general hydrogeologic conditions would support that opinion. They consist of Middle to Upper Triassic limestones, also of Jurassic limestones in southwestern Serbia. The limestones overlie Lower Triassic and Late Paleozoic clastics and are partially overlain by Jurassic volcanogenic and sedimentary rocks. If both the bare and covered areas were measured, these two zones might comprehend the total surface of about 10,000 km^2 and combined length of nearly 250 kilometers.

Another problem concerning these two zones is that the above mentioned authors have quite good reasons to include them into the main karst region, i.e. into the unit named the Fluviokarst belt in the discussed regional classification. The main reason why they are not included now is the lack of geographic integrity with the Fluviokarst belt. The zones are separated from the belt, along their full length, by a continous 10 to 30 km wide body of Late Paleozoic and Lower Triassic clastics - the so-called "Dinaric karst basis", having here not only the function of a regional impermeable bedrock but also of a regional full underground barrier.

The other bigger concentrations of Isolated Karst areas have a different lithostratigraphy. The large eastern Serbian zone is composed of Upper Jurassic and Lower Cretaceous limestones. Triassic and Upper Cretaceous limestones from the southwestern Macedonian zone, Paleozoic marbles are in the central Macedonian zone, and Triassic dolomites and Miocene limestones and calcareous sandstones form the zone in northeastern Slovenia and northwestern Croatia.

Within the Isolated Karst areas, there are a great number of ponikvas, ponors, jamas, caves and dry valleys. The encircling impermeable or semipermeable rocks force the karst ground water, derived from the infiltrated rainfall, to emerge where the top of the impermeable ring is low. If the drainage basin is larger, highly discharging karst springs appear. Minimal spring discharges of more than 1 m^3/s were recorded.

In northern Croatia and northeastern Slovenia, the isolated areas of carbonate rocks are frequently the outcrops of the thermal aquifers.

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FIGURES

3.1. Distribution of carbonate rocks and regional hydrogeologic classification of the karst of Yugoslavia. After Sarin (in print). A - land surface built of carbonate rocks, B - land surface built of noncarbonate rocks (they are underlain by carbonate rocks in almost all areas comprised within the Karst region), 1-3 - Karst region, 1 - Adriatic Karst belt, 2 - High Karst belt, 3 - Fluviokarst; 3.1. - Alpine Karst, 3.2. - Croato-Slovene Low Karst, 3.3. - Bosnian Shallow Karst, 3.4. - Montenegrin Highland Karst; 4 - Isolated Karst.

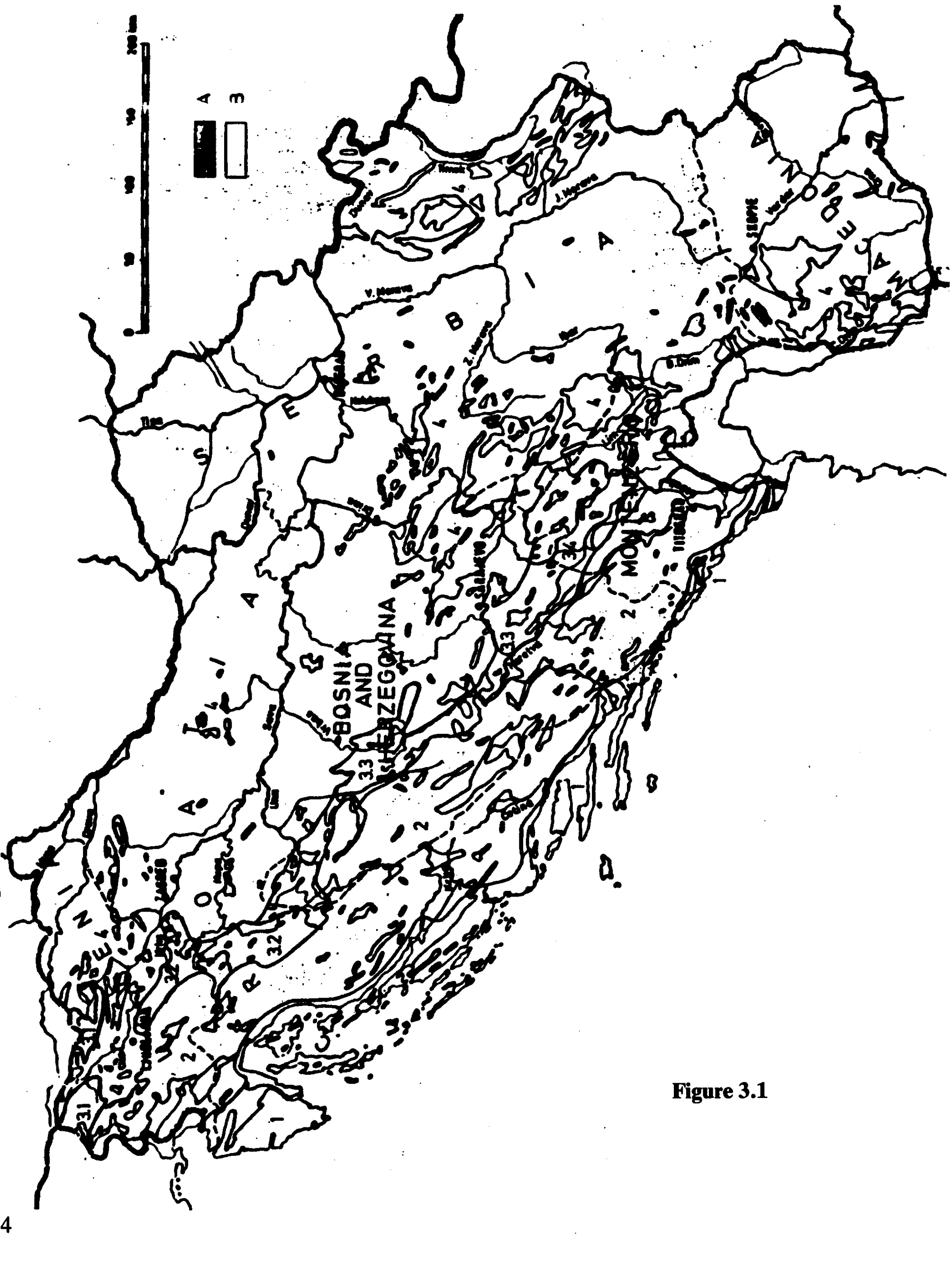

Figure 3.1

4

H Y D O G E O L O G I C   F E A T U R E S   O F   T H E D I N A R I C   K A R S T

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The Dinaric karst region ranges among the most remarkable karst wholes in world. Marked by a great number of heterogenous forms this region is well known in the world as typical locality of such kind of terrain (Fig. 4.1.). Karst developed to the maximum possible degree owing to very favourable geologic, morphologic and hydrometerologic conditions. Consideration of hydrogeologic relations, areal distribution, interconnection and ground waters circulation in such environment is more than difficult and tied with many suppositions, with more or less established facts. To mention, for instance, steplike position of drainage bases in the areas of large karst poljes of Western Bosnia and eastern Herzegovina, with extremely complex distribution of ground waters under conditions of highly developed holokarst areas. Nevertheless, results of intensive hydrogeologic studies, particularly those which were undertaken in the last 25 years for the requirements of water storage basins and other purposes, have lagerly contributed to better understanding of one of the complex natural formations i.e. one of discontinual and very complicated water bearing environment.

This region is basically composed of impervious rocks among which the most essential are tectonically damaged and by karstification process deformed limestones of the Mesozoic and Cainozoic age. Water impermeable formations are dispersed here and there in the lesser or bigger range. Impervious floor of the entire carbonate Mesozoic-Cainozoic complex, which is represented by clastic Werfenian and Permo-carboniferrous, is very deep in the major part of the territory.

Because of that, only smaller quantities of water move along those routes to which they are directed by the flóor insulator. The major part of water circulates through the limestones using paths of the smallest restistance - tectonically more broken karstified zones as the most suitable circulation medium, owing to which such zones represent main collectors in the karst.

Carbonate formations as the products of long lasting middle (passive) phase of the Alpine tectonic cycle, were exposed to the karst process several times. However, nowadays the forms of sub-recent and recent karst are of primary importance since through such forms recharge, moving and discharge of ground waters mainly occur. In this respect, of particular interest are karst forms which had appeared in the period of the Pleistocene glacial phases when fluctuation of the sea level was high. Only since Würm, according to Šegota (1963), the sea level have rised by nearly 100 m, which greatly characterizes hydrogeologic relations inside the karst environment.

HYDROGEOLOGIC PROPERTIES AND ROLE OF ROCKS

As it was mentioned, the Dinaric karst region is of the limestone structure mainly. After limestone mostly widespread are dolomites, the Eocene flysh, Werfenian clastite, schists, conglomerates and marles of the proline series, Neogene, igneous rocks and the Quarternary.

It is well known that limestones are more subdued to the karst process effects than other rocks. Depending on individual factors effects, for instance, chemical composition and tectonic damage of the rock mass, karstification is best expressed in light, chemically pure limestone, particularly characterized by richness of outer products of the process. As concerns tectonic damages, the diagonal faults of north-south trend are of primary importance from the hydrogeologic point of view, and they are well marked on surfaces by series of dolines (vrtača), uvalas and other karst forms (Fig. 4.2.). Along these karst forms numerous privileged drainage canals are developed (Drvar, Mlinište, Grab-Plat, Kotor faults etc.).

In limestone, a complex system of porosity is developed, but the fissure type of porosity, which is most expressed and most important for ground waters circulation, dominates. The limestone medium is by itself well permeable, by exception of marly plate-like limestones. At this moment, however, it is very difficult to discuss the quantitative norms of the porosity. Although the effective porosity of the limestone mass varies greatly from one to another place, the exploration works have shown that it mostly ranges within the limits of 0.5 to 1.5 %. To be able to evaluate water permeability of such medium we should mention here some characteristic indicators.

(1) at a number of localities some twenty faults were recorded per 1 sq.m. in the average length of 1 to 2 km (limestone block south of the Pliva river spring, the limestone block of the Rama river spring etc.);

(2) number of speleologic phenomena per 1 sq.m.: in southwest Slovenia 1.6; in the Popovo polje 7.4 and in the Nikšićko polje 14 (Šarin 1982).

(3) Fictive velocities of underground flows, determined at the large number of localities in the Dinaric karst, are classified in the category of very high velocities.

(4) high minimum and maximum yields of the springs and great variations in yield are reflecting high water conductivity of the aquifers.

In vertical cross section of the karst terrain, zone of more intensive karstification up to the maximum depth of 200 m is distinguished, and particularly its subsurface part of ten to 20 m thickness. In immediate subsurface zone of shallow karstification the inner karst forms of limited dimensions are extensively represented, and they are well interconnected making a thick network of collectors - ground water conductors. To the depth, karstification spreads along tectonically broken zones and faults. This deep karstification is manifested, more or less, by isolated larger karst cavities in otherwise compact rock masses (in the gallery at Postir, for instance, in a length of 470 m, six fault zones with collectors were discovered; in the Gorica-Plat intake tunnel, in the length of about 15 km, one fracture zone per 750 m of length was registered, in average).

Limestones are, first of all, collectors - conductors of ground waters. Systems of faults deformed by karstification represent suitable environment for free ground water flow towards erosion bases. Only smaller parts of porous limestone masses have the function of collectors-reservoirs, in immediate backgrounds of some karst springs. Hydrogeologic role of d o l o m i t e s is heterogenous and it depends on many factors (chemical composition, genetic type, inner position of fold structures, grade and style of tectonic damage, karstification and so on. Dolomites which have as rule the function of hydrogeologic barrier (the Upper Triassic limestone, Cenomanian-Turonian dolomite etc.). On the contrary, when they are in the wings of the fold structures or in sequence with limestones they may have the properties of highly permeable medium.

C l a s t i c m a t t e r s of Younger Paleozoic and the Lower Triassic are without exceptions true barriers. Younger matters, like the Palaeogene flysh and the Neogene lake formations appear in many regions as complete barriers for waters moving towards the lowest drainage basis - i.e. the sea. They have the role of drainage bases in which smaller or larger quantities of ground waters discharge, but in many cases such waters may flow under these barriers.

RECHARGE, MOVING AND DISCHARGE OF GROUND WATERS

Ground Waters Recharge

The Dinaric region is characterized by extremely high precipitations. At Crkvice near Boka Kotorska, for instance, the highest average rainfalls in Europe were recorded (5,317 mm/year) and precipitations of 2000 mm/year are typical for the major part of mountainous areas. The main part of precipitation infiltrates into highly karstified medium. Balances show that over 60% of precipitation is controlled at appropriate erosion bases. For the Cetina River catchment area, for instance, it was found by calculations that more than 80% of the precipitation appear at the terminal water gauge controlled profile, while in the Trebisnjica River catchment area this percentage is even higher (up to Arslanagića Most observation station) reaching even to 90%. However, in the total outflow the infiltration of precipitation i.e. the underground outflow is far more important component than the run off.

Distribution of precipitation during a hydrogeologic year is unfavourable. Precipitation occurs mainly during the colder half of the year. Because of that, recharge of ground waters is rather insufficient during summer period and the recession for the majority of underground water bodies is remarkable from June or July till October.

Distribution and Movement of Ground Waters

The problem of determining catchments areas in karst regions in general, and in the Dinaric karst in particular, is a primarily important one. Nevertheless, after extensive complex studies in can be said that ground waters distribution and movement in the Yugoslav karst regions are already rather known. Particularly helpful to this respect were the results obtained by tracing numerous under ground flows.

Position of the Adriatic-Black Sea Water Divide of Larger Catchment Areas

Watershed between the Adriatic and the Black Sea in the Dinaric karst is of the first range. Position of this water divide was the subject of studies on which many geologists, geomorphologists and hydrologists worked. These studies include different opinions, however, which only prove the complexity and difficulty of the problem.

According to geologic and hydrogeologic factors effecting direction of ground waters flow, the Adriatic-Black Sea watershed extends across Postojna, Velika Kapela massif, along the edge of the Krbavsko Polje, Staretina and Cincar Mountains towards Bitovnja, Lelija and Golija

Mountains in Montenegro. Waters from more than two thirds of the Dinaric karst territory are gravitating to the Adriatic Sea. The Sava River catchment area, i.e. the catchment area of the Black Sea, spreads mainly over the northwest half of the karst belt, including massifs of Grmeč and Plješevica and terrains between the Korana River and Ljubljansko Polje. At the farthermost southeastern part of the belt, wider karst areas of Durmitor and Sinjajevina Mountains also belong to this catchment area.

Forming of this watershed is mainly predisposed by the position of discovered and undiscovered impervious matters. From Lelija Mountain to the Kupreško Polje, for instance, it is typical surface watershed. In the central Dinaric karst, more precisely from Kupreško to Krbavsko Polje, dolomite has the main role as a typical barrier. Owing to its insulation properties, favourable position and depth, the main dolomite of Popović, Glamoč and Bosanski Petrovac influenced to a great extent the ground waters divison and their orientation towards southwest and northeast. Further westward, up to Postojna, in the carbonate terrain, the watershed is rather vague and it is discerned by means of directions established by underground flows tracing.

Ground waters of the Adriatic catchment area are drained, first of all, through the rivers Zeta, Neretva, Cetina, Krka, Zrmanja and Soča (Fig. 4.3.). Other parts of very extensive littoral terrain with islands represent the direct sea catchment area. The belt of the direct catchment area intrudes deeper inland in the background of Boka Kotorska, Trogir and Biograd and in wider rear area of Velebit massif and in the region of Istria.

Waters of karst terrains around the rivers Tara and Piva, Vrbas, Pliva, Sana, Una, the upper course of the Kupa River and Krka (in Slovenia) gravitate to The Black Sea catchment area.

Directions of Ground Waters Flow and the Results of Underground Flows Tracing

Concentration of ground water circulation directions towards a single or limited number of water bodies of such waters belonging to an area is a typical characteristic of the Dinaric karst. In the process of geomorphologic evolution of sub-recent and recent karst, the privileged collectors were developed more and more in the direction of hypsometric lower points of the close erosion basis, where main drains of the ground waters exist. In this way many catchment areas of karst springs were formed as hydrogeologic holes of a lower order.

In the central Dinaric karst, for instance, concentration of ground water circulation directions is reflected by the fact that only 55 stronger karst springs were registered in an area of nearly 19,000 sq.km. In other words, this means that each spring having the mean yield of 3 - 8 cu.m/s, the main part of ground waters of a karst area of 340 sq.km. is discharged (Komatina 1973).

Starting from the above fact, it is completely understandable that the situation with separate catchment areas and more important directions of ground waters flow is a very complex one. The catchment areas differ by shape and dimensions, hypsometric position and range. Each of them is of a specific geologic, geomorphologic and hydrologic structure, with its own "lows" of distribution and discharge of ground waters. This subject will be discussed under a separate headline.

Directions of flow were a separate subject of study within the explorations in the phase of regional hydrogeologic explorations for hydro-power generation project requirements in 1963-1975 period which included the entire Dinaric region. Owing to above mentioned hydrogeologic activities, in spite of the fact that extremely complex hydrogeologic relations of the major part of the terrain are in question, knowledge about the ground waters distribution is at an enviable level today.

By means of sodium fluoresceine and other traces, more than 650 interesting localities were investigated in the area of exploration. Only in eastern Herzegovina 281 localities were involved in tracer experiments, in the catchment area of the Cetina River 99 localities, in Skadarsko Jezero catchment area 77 localities etc.

Marking of ground water flows showed that localities with only one direction ponor-spring are sporadic. The following two situations with flow directions are predominant:

(1) concentration of flow directions from a series of ponors towards a single water body, and
(2) radial dispersion of a beam of directions from a single ponor towards a larger number of underground water bodies.

In some cases the determined directions of ground waters flow intersect.

Deceptive velocities of underground flows belong as by the rule to the category of very high velocities. In 380 cases, described by P. Milanović (1976) and A. Magdalenić (1971) the frequency of deceptive velocities is as folows: in 70% cases from 0 to 5 cm/s; in 20% cases 5 to 10 cm/s and in 10% cases more than 10 cm/s. In case of the entire Dinaric karst the average deceptive velocity of water flows reaches 3.6. cm/s. It should be mentioned, however, that the deceptive velocity of an subsurface flow may vary considerable, depending on the water level situation. For instance, between Čaprazlije ponor and Mali Rumin spring the deceptive velocity was as follows: in the dry period 5.1. cm/s; at high water levels 28.8 cm/s.

Ground Water Drainage and the Characteristics of Some More Important Water Outflows

We have already mentioned that hydrogeologic characteristic of the Dinaric karst terrain as concerns concentration of ground water circulation directions is a remarkable one, as well as their drainage at one or limited ground water outflows. If we take into account only stronger water discharge of over 0.5 cu.m./s yield, the number of drainage points will be about 105, 60% of which are waters of the Adriatic catchment area and the rest are springs from the Black Sea catchment area.

The main characteristic of the majority of underground waters outcrops is that they appear at the contacts of limestone and impervious medium, because of which J. Cvijić (1901) called them the c o n t a c t water outcrops. Another type of hydrogeologic phenomena are strong springs in the Tara River canyons and those in the canyons of the Piva and Komarnica, Neretva, Krka and other rivers. Within both groups the notable is the group of not so rare springs which were named by C. Cvijić (1926) the v r t a - č a s t i (appearing in dolines, which in the Yugoslav language are called vrtače). In such springs the terminal opening of the karst canal is bended upward in a form of a syphon getting the impression that water appears from a doline (vrtača), forming a lake of smaller diameter. Such are springs Raže Bug in the Kovačevo Polje, Opácac in the Imotsko Polje, springs of the Cetina River and others.

The underground water outflows are also characterized by big variations of yield during the period of one hydrologic year. It is very difficult to make a more precise categorization by average yield and evaluation of characteristic yields, since data on long term observations are not available. Nevertheless, more remarkable phenomena, according to measured and estimated mean yieldingness, may be divided into two groups. The first group: springs of mean yield over 10 cu.m./s like Velika Ruda in the Grab-Sinjsko Polje, Krupić and Bug in the Kovačevo Polje, the left spring of the Pliva River, Klokun in the Tihaljina River valley, spring of the Trebišnjica River at Bileća, Olebla near Dubrovnik, Glava Zete, Crno Vrelo in the Una River valley.

The second group: springs of mean yield of 5 to 10 cu.m./s: spring of the Riječina River near Rijeka, the main spring of the River Gacka, spring of the Zrmanja River, Veliki Praporac in the Neretva River Valley, Varvara in the Kovačevo Polje (Fig. 4.4.).

The most remarkable karst phenomenon is the spring of the Trebišnjica River with the mean yield of more than 40 cu.m./s; at the maximum water level its yield is over 200 cu.m/s. not far behind is the strongest coastal spring Ombla with the mean yield of about 40 cu.m./s and maximum flow of about 160 cu.m./s. It should be mentioned that the minimum capacity of this spring before the accumulation lake was 2,5 lower than today (Milanović 1980)

After A. Šarin (1982), variations in the yield, karstic springs expressed by Q max/ Q min ratio are bigger than 20 cu.m./s, and may reach even 100 and more than that: the spring of the Una River - 197; the Cetina River spring - 100 etc. Contrary to that, there are springs with relative more stabilized regime of issue: the Gacka River spring - 3.1; Varvara spring - 3.3; springs of the Pliva River - 4,4 etc. By the rule, the ratio of equality and yieldingness of springs during the hydrogeologic year is higher for contact springs as compared with other mostly gravitation outflows. Finally, to mention the special case of those springs which are water outflows of sinking rivers or which directly depend on floods in the fields. Such springs are particularly unstable and periodical, which is quite understandable, although they are often the contact phenomena (for instance, Rumin spring in the Cetina River valley which is directly connected to the Plovuća River in the Livanjsko Polje, Ričina on the horizon of Buško Blato - connected with the Šujica River in the Duvanjsko Polje, Baštica near Drvar - connected with waters of the Resanovačko Polje and others).

MORE REMARKABLE CHARACTERISTICS OF LARGER HYDROGEOLOGIC WHOLES

A review of more remarkable hydrogeologic wholes of the Adriatic and the Black Sea catchment areas and their characteristics will be presented according to A. Šarin (1982), M. Komatina (1975, 1981) and V. Raduvolić (1977), in general. Hydrogeologic specifities and more significant characteristics of given karst whole will be primarly underlined.

I. The Adriatic Catchment Area

Of hydrogeologic wholes from the Adriatic catchment area, we shall take the catchment areas of the rivers Soča, Zrmanja, Krka, Cetina and Neretva, then the wholes of Istria, the northern Croatian littoral, the direct catchment area of the sea in the Croatian coastal area, the catchment area of the Montenegrin littoral and the catchment area of Skadarsko Jezero (lake). In presentation of the mentioned holes we shall follow the sequence starting from the northwest and going towards the southeast.

The Soča River catchment area is composed of highly karstified limestone masses of Southern Alps, Trnovsksi Gozd, Huščica and Nanos. It has mostly properties of the Alpine fluvio-karst region. The main part of waters is discharged through the Vipava River spring whose minimum yield is about 1 cu.m./s.

Istrian catchment areas consist of three hydrogeologic units: (1) carbonate plateau, (2) central flysh zone, and (3) carbonate massifs Ćićarija and Učka. The karst plateau is located at the elevation of 150 to 300 m above sea level and it is composed of the Jurassic and Cretaceous limestone sequentially followed by dolomite. This unique aquifer is discharged through several fresh water and brackish springs. The most abundant is fresh water spring Gradole having the yield of more than 1 cu.m./s.

The catchment area of the Croatian littoral includes the catchment area of the Adriatic coast from Rijeka to nearly the mouth of the Zrmanja River. Ground water is accumulated in karst aquifers of Mala and Velika Kapela massifs, Senjsko Bilo and Velebit Mountains. In this terrain, the regional faults in big steps are often in the form of lines along which the watersheds extend, and the Lika fault represents even the underground barrier. Ground waters of Gorski Kotar, on their way towards the sea, reach a barrier represented by a longer zone of Palaogene flysh and discharge through a number of springs near Rijeka - Martinščica, periodic spring of the Riječina River of Q_{mean} = about 8 cu.m/s, Žrnovica at Novi Vindolosk.

The complex anticline of Velebit Mountain, with impervious Palaeozoic and Lower Triassic formations in the lake, represents a true barrier for ground waters from Lika flowing towards the sea, directing underground flows of the sinking rivers Lika and Gacka towards the coast section between Jurjevo and Jablanica, where at present only energetic surplus waters of the SENJ HE Plant are discharged.

The sinking rivers Ričica and Otuča have their underground connection in a brocken core of southern Velebit, with springs of the Krupa River, Orovača and Krnjeza. In addition to the above mentioned phenomena another spring is that of the Zrmanja River having Q_{mean} = 0.7 cu.m/s and the characteristic capacity of 185/8/1.

The catchment area of the Krka River can be divided in two units, two remarkable hydrogeologic horizons conditioned by the position of an impervious barrier, which extends along the Batušnica River valley and through the Kninsko, Kosovsko and Petrovo poljes.

In the eastern part of the terrain, the ground water circulation develops at hypsometrically higher levels, since the mentioned series of morphologic depression is at a rather high elevation above sea level. Of underground water bodies, particularly noted are the spring of the Krka River, and the periodic springs of the Čikola.

Numerous gravitation targets of the ground waters are at the levels lower than 90 m. Those are strong karst springs like those as the Miljacka spring, Roški Slap, Torak, Jaruga and Litnos barckish spring.

The Cetina River drains the extensive region well known west Bosnian poljes: Glamočko (southeastern part), Livanjsko, Kuprеško (southeastern part) and Duvanjsko, and Buško Blato in addition to its own direct catchment area. The catchment area itself is explicitly asymmetric, since the underground inflow from southwest towards the Cetina River is practically negligible. The discharge modul of the whole catchment area of 3765 sq.km. is 33.21 s/km². The annual discharge coefficient for Gardunska Mlinica profile ranges about 0.8 which proves very high percentage of infiltrated precipitate.

Very complex hydrogeologic relations within the territory of the Cetina River catchment area have contributed to ever increasing interest of the karstologists in this hole. The given relations result from the aereal position of limestone and impervious lake matters of Neogene Age.

In their flow towards the lowest erosion basis - the Cetina River valley and the Sinjsko Polje, a good part of waters reaches a barrier, comes to the surface and disappears again in its way towards the end target. The rest of waters find their way by passing barriers appearing directly at springs of the main horizon. There are five horizons - five stages at which ground waters flow out to the surface. Those are the Kuprеško Polje - level 1120; Šujičko Polje - about 915; Glamočko Polje and Duvanjsko Polje - 860 to 920; Livanjsko with Buško Blato - 700 to 710 and the Sinjsko Polje - 300 m above sea level.

This catchment area can be divided in three hydrogeologic parts. Those are: the western and eastern parts of the territory with their series of poljes, and the direct catchment area south of the Sinjsko Polje as the component of the littoral karst belt. Geomorphologic and hydrogeologic descriptions of the poljes are contained in Cvijić's work "Karstna polja zapadne Bosne i Hercegovine" (Karst Poljes of the Western Bosnia and Hercegovina) (1900) and the study "Hidogeoloske odlike centralo dinaridskog karsta" (Hydrogeologic Features of the Central Dinaridic Karst) (Komatina 1975). Because of the limited space here we shall mention only some more interesting moments.

The underground water connections of the catchment area are thick and complex. There are many crossings and branchings of these connections, particularly inside the Dinara massif. Capacities of the ponors are impressive (the Kovač ponor in the Duvanjsko Polje, for instance, with over 60 cu.m./s yield; the main flowthrough of the ponor in the Duvanjsko Polje amounts to 10 cu.m./s; Buško Blato 27 cu.m./s, and in the Livanjsko Polje 30 cu.m./s).

Permanent and big springs appear only on lower hydrogeologic stages, the Livanjsko and Sinjsko poljes. In the horizon of Livanjsko Polje the remarkable spring by its yield is the Sturba spring, having characteristic yields of 10/6/1. In the Cetina River valley, upstream from Sinj town, the attractive is the Cetina River source with characteristic yields of 100/18/1, then Veliki Rumin spring with expressive fluctuation in abundancy and water temperature, depending on floods duration in the Livanjsko Polje. Along the edge of the Sinjsko Polje, eastward from the town, along limestone and Neogene contact there are several stronger springs among which Rud and Grab are particularly noted. The mean yield of these springs is about 30 cu.m./s.

In the upper course of the Neretva River there are independent limestone aquifers in the massifs of Zelengora, Lelija, Treskavica, Visočica and Bjelašnica. Here a number of stronger springs appear.

The limestone tectonic block of Vran Mountain and surrounding terrain drains through the Rama River springs. The Neretva River catchment area particularly noted are privileged collectors the Ravno Polje - spring Varvara and Trebistovo-Orašačka uvala marked by dry valleys and ponors. The Neogene alone, of the Kovačevo Polje, served for modelling the hypsometric low erosion basis where about 30 cu.m./s of water is discharged (Fig. 4.5.) through Varvara, Krupić and Bug springs.

In the eastern half of the catchment area the series of hydrogeologic stages Gacko Polje - Popovo Polje - Ombla was the subject of extensive studies, the aim of which was utilization of water power for electric power generation purposes. In this geomorphologically and hydrogeologically interesting karst region, the catchment area of the largest European sinking river Trebišnjica and the Popovo Polje is most attractive as the central and largest form in the given catchment area.

The Trebisnjica River spring, as the most abundant spring in Yugoslavia, was discussed earlier. The main part of waters of this horizon disappears through a large number of ponors to appear again at the Ombla spring and in other water bodies of underground waters of the southern Croatian littoral. The rest of the Trebišnjica waters sink in the western part of the Popovo Polje and appear at springs along the Neretva River.

The Neretva River valley, southwest of Jablanica, is important drainage base for waters of adjacent karst massifs of Čvrsnica and Prenj and of other karst terrains. Here, there are several very abundant springs like Veliki and Mali Praporac, Peć-Mlini, Vrnoštica, the springs of the Studenčica and Prud rivers, all of them having a yield of over 1 cu.m./s during the period of minimum water levels. Springs of the Buna and Bunica rivers are also well known, both having the yield of over 5 cu.m./s.

The elongated mainland area of the direct catchment area of the Adriatic coast, between the Zrmanja River and Boka Kotorska, belongs to the maritime catchment area of the southern Croatian littoral. Two hydrogeologic holes we have here i.e. the northern Dalmatian and the central-south Dalmatian catchment areas. North Dalmatia represents the region of low surface forms and hills, and with a closer connection between collectors and diffusion discharge of ground waters, owing to which the connection with the sea is also very close. The second region belongs to the upland and mountainous terrains with concentrated subsurface flows which appear here more often and with ground water discharge through a limited number of more ambundant springs, having therefore weaker connection with the sea.

In Ravni Kotari the series of elongated folds is developed. Flysh synclines are by good part complete barriers, directing underground flows along the structures. There are several remarkable groups of coastal springs, mainly of lower abundancy.

In wider surrounding of Split the catchment areas of more abundant ground water springs are noted. First of all, here we have the hydrogeologic hole of Pantan, distinguished by large number of karst forms. The coastal spring Pantan, the Slanac spring and Arbanija and Slatina submarine springs of Kašteli are water bodies of a unique and very interesting hydrogeologic collector. More eastward, the springs of the Jadar and Žrnovnica rivers are of higher abundancy through which karst collectors of Mosor Mountain and adjacent terrains are drained, and here also the underground connection with the Cetina River exists.

The ground waters of the Biokovo massif and its background, moving towards the sea, come to a long flysh barrier and appear at such points where this barrier is completely eroded. In this way the biggest submarine spring at

D. Brela on the Adriatic coast was formed, then Drašnička submarine spring and the coastal spring Žrnovica near Gradac.

Between the Neretva River and Boka Kotorska the flysh barrier continues again, over which the Trebišnjica River waters overflow, mostly in the area of very strong Ombla spring.

The Montenegrin littoral extends from Herceg Novi to the Bojana River. This terrain is of very heterogenous and complex litho-stratigraphic composition and tectonic structure. Such geologic conditions contributed forming of specific geomorphologic features and complex hydrogeologic relations of the terrain itself. Here, there are several smaller hydrogeologic wholes, with exception of the whole consisting of wider karst background of Boka Kotorska.

In the territory of Boka Kotorska the biggest quantities of waters of the Montenegrin littoral are drained. Drainage from this morphologically remarkable terrain with high precipitate runs directly to the sea through a series of well known springs - Gurdić and Škurda, Ljuta, Sopat and Morinja. All hydrogeologic phenomena are characterized by high fluctuations of their yield.

Other karst water bearing wholes discharge through outflows of drinkable (simple) ground waters, such as Opačica, the Reževića Rijeka River, Kajnjak, Brca, Klezna and others of the minimum yield of 40 to 80 l/s.

The catchment area of Skadarsko Jezero (lake) is the largest hydrogeologic unit of the territory of Montenegro, with the total area of 4,460 sq.km. This terrain is mostly composed of highly karstified limestone of the Mesozoic Age. This is well known karst of old Montenegro.

Several hydrogeologic wholes of the lower order are noted here. To mention only the most important wholes:

1) The catchment area of Oboštičko Oko, Glava Zete and the Perućica River.

2) The catchment area of the Mareze River near Titograd.

3) The catchment area of the Morača River, upstream from the mouth of the Zeta River, discharges through the series of phenomena in the river canyon and the gorges of tributaries.

4) The whole of karst of Rumija Mountain with underground flow was evaluated to about 10 cu-m./s discharging to Skadarsko Jezero through a series of submarine springs.

5) Karst of Malo Blato background with dynamic reserves, measuring by height about 10 cu.m./s, discharging directly in the said lake.

II. The Black Sea (Savian) Catchment Area

In this case the subject of discussion are karst terrains of spring sections of the Sava River tributaries. These tributaries are the Ljubljanica, Kupa, Una, Sana, Vrbas, Bosna and Drina rivers.

The catchment area of the Ljubljanica River belongs to the high karst belt. It is characterized by the largest cave system in Yugoslavia to which the Postojinska Pećina cave belongs. Nine more abundant springs of the Ljubljanica and its tributaries have the characteristic total yields of 5/10/1.

In the Kupa River catchment area the anticline structures with dolomites in the lake, as complete barriers, hold back ground waters on their way towards the north owing to which there appear 12 permanent springs of the minimum yield about 1 cu.m./s. These springs form water courses which sink completely, immediately after dolomitic base. Water appears again at 12 points, in the lower hydrogeologic horizon, turning into permanent rivers the Kupa, Dobra, Mrežnica, Korana etc.

Along the Una River course the large karst accumulations discharge through several abundant springs: the spring of the Una River; the Krka River spring, Ostrovica. Klokot spring and so on. The yield ratio of the Una River spring is 114/6.4/1 and of the Krka River spring 40/9/1.

The Unac is very abundant tributary of the Una River. In its upper course, during the dry period, large quantities of water through numerous ponors are lost. The main spring is Crno Vrelo - over 4 cu.m./s, at which waters of the Unac River catchment area appear during low water level.

The limestone water bearing formations of Grmeč discharge through a series of big springs of the Dobra River (over 3 cu.m./s, Q max over 70 cu.m./s.) and of other smaller water courses.

Dyeing proved that one part of leading drains of the northwest end of the Glamočko Polje, the Odžak-Mlinište fault zone, discharges completely through the springs of the Sana River. To the catchment area of the Sana River spring, a relatively extensive limestone terrain belongs, southwest and south from the spring alone. The characteristic relations yields of this spring are 30/5/1.

The more extensive limestone terrains in the Vrbas River drain mainly through the left tributary, the Pliva River, with its tributary the Janj River. This is in fact a limestone tectonic block of 820 sq.km area. Within this medium, waters move northward through numerous shorter faults, to be directed northwestward by a clastite barrier of the Middle Triassic, i.e. towards the Pliva River springs. During 1954 the characteristic flowthroughs of the left and right springs of the Pliva River totalled 4.5/2.5/1.

Extremely thick limestone deposits are noted in the central parts of Bjelašnica and Igman massifs within which the unique karst aquifer originated. This aquifer drains by its major part at the Bosna River spring where the minimum issue amounts to 1 cu.m./s of water. The characteristic yields of this spring are 20/51/1.

The larger limestone masses in the Drina River catchment area are connected with the territory of northern Montenegro i.e. with the catchment areas of the Piva and Tara rivers.

The Piva River, with the Komarnica tributary, had cut through the limestone mass a deep canyon in which the Mratinje accumulation was formed. This accumulation covers the majority of well known karst springs such as Nozdrić, Kaludjerovo Vrelo, Pivsko Oko, Dubravska Vrela and others. Downstream the dam, is the Čokovo Vrelo spring.

The main part of ground waters of the Tara River catchment area discharges through a series of phenomena in the remarkable gorge over 80 km long. To mention some of these phenomena: the spring Poljska Bistrica, Ćorbudžak, Ljutica, Mušovi Bukovi, Bijele Vode, all of them having the minimum yield over 0.5 cu.m./s.

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FIGURES

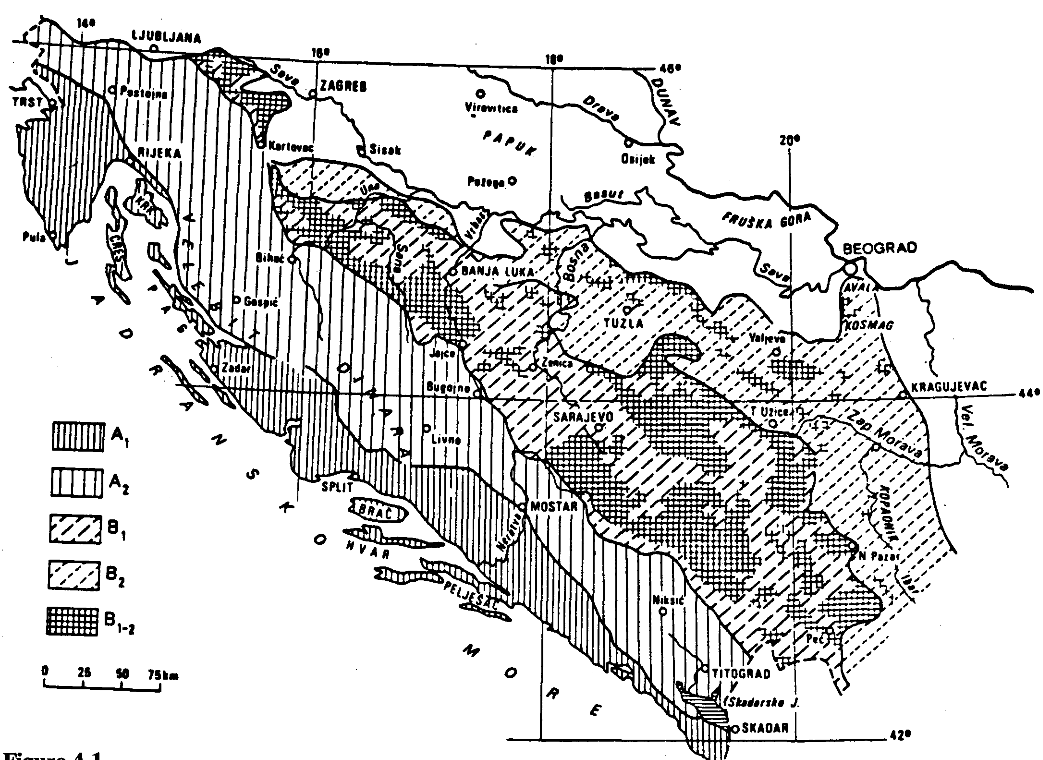
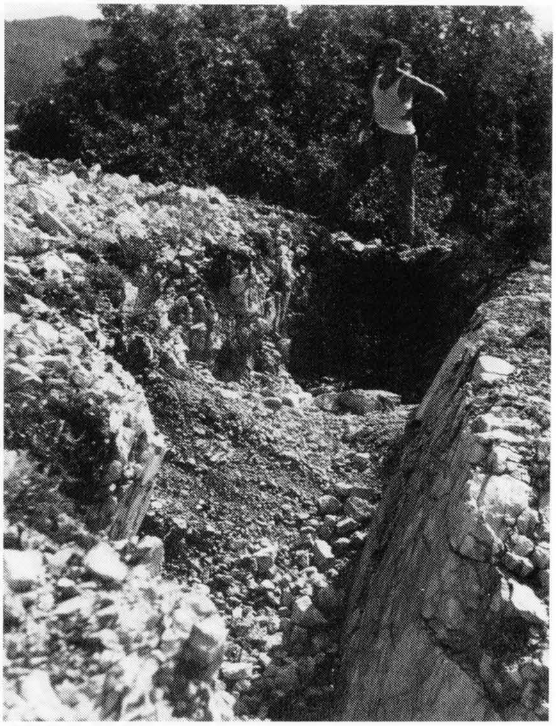
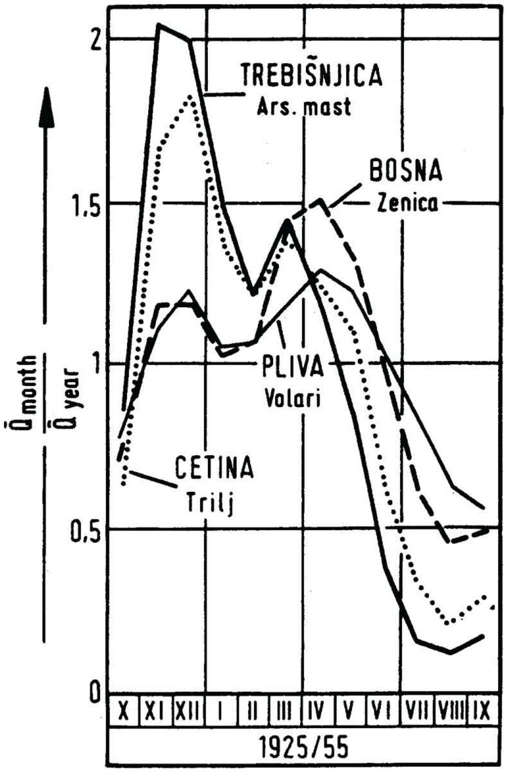


Figure 4.1

Figure 4.2





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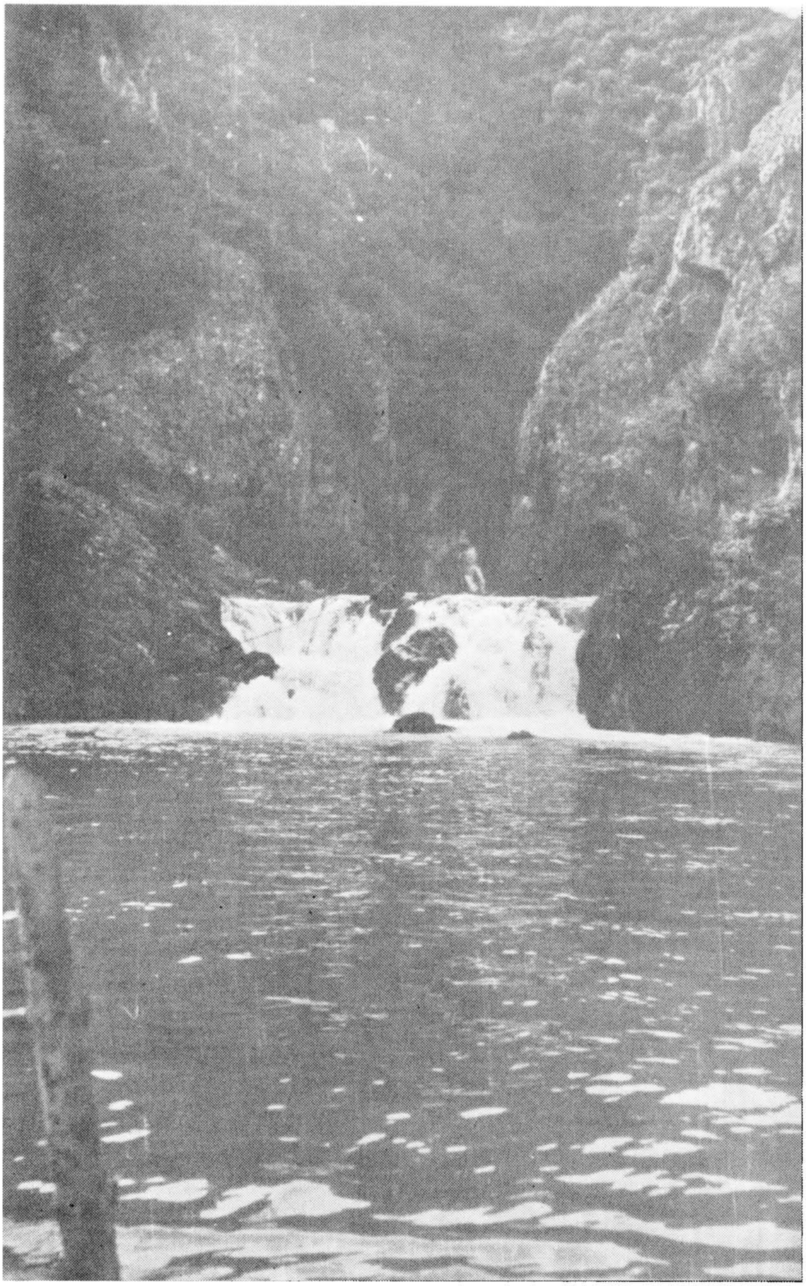

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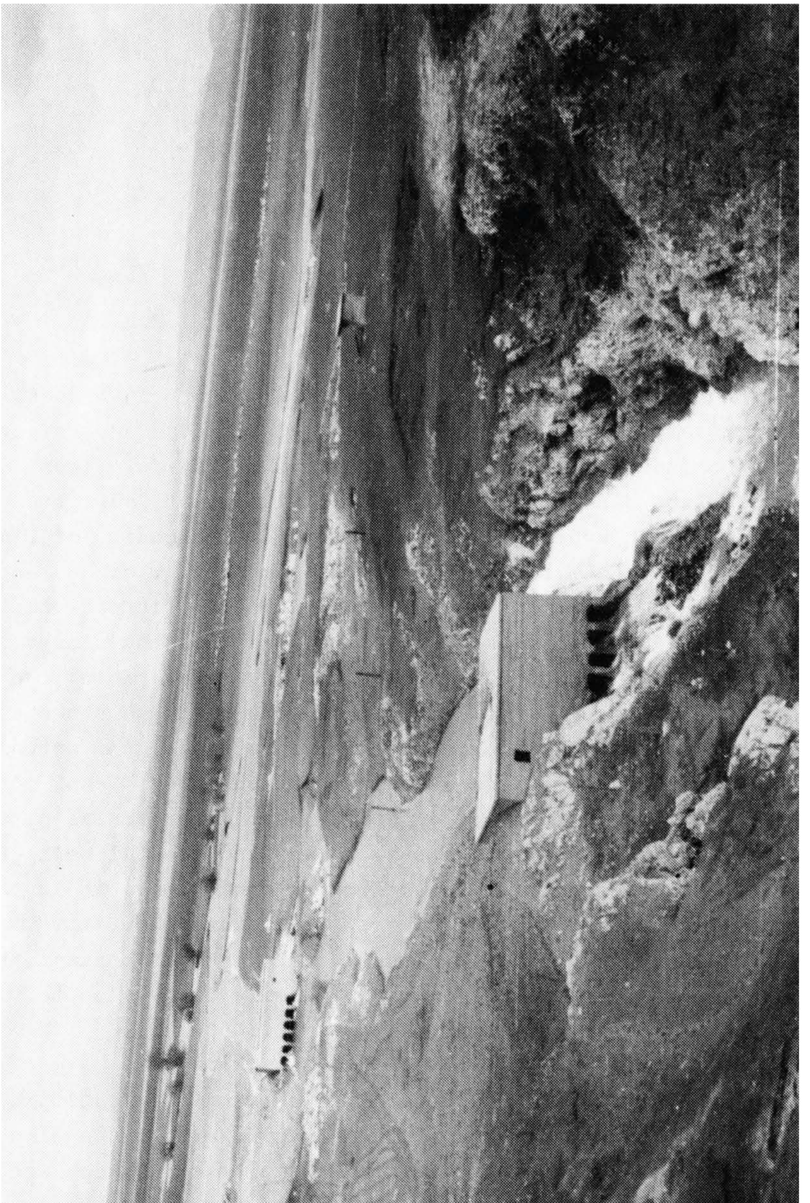

Figure 4.5

5

S P E L E O L O G I C A L   P H E N O M E N A   O F D I N A R I C   K A R S T

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INTRODUCTION

Dinaric karst is characterized by a thick sequence of carbonate rocks most of them relatively pure Triassic, Jurassic, Cretaceous and Paleozoic limestones and dolomites. Beside other impermeable rocks, dolomites, forming partial or complete barriers, directing the outflow of underground waters, have an important hydrogeological function. Cavernosity of Dinaric karst underground depends on tributaries from impermeable vicinity and specially on extreme precipitation quantity which on the littoral part of the central Dinaric ridge surpasses 3,000 mm per year; on the slopes of Orjen above Boka Kotorska even 5,000 mm. Beside annual quantities the day intensity is important, too, as there is not rare to have the showers with 300 mm, or even 500 mm of rain in one day. In average, the annual quantity for the whole Dinaric karst yields more than 1500 mm (Roglić 1976). Evidently, there are important differences among particular parts; we have to stress greater dryness in narrow island and coastal belt. For the development of karst caverns in such climatic conditions, it is extremely important from where, how, and where, the waters flow transforming the karst underground by corrosional and erosional means. Important are relative and absolute altitude differences, extending from 10 up to 2,000m and in strict sense of the Alps almost more than 2,5000m.

Naturally, time is always an important factor regarding the development of karst underground. In general shapes, the Dinaric karst is developed from the Pliocene onwards. Quaternary period, with its climatical and also tectonical properties left important traces in the underground. Complicated geologic setting, differentiated relief, high humidity and varied geologic history are thus the most important factors in which depend speleological properties of the Dinaric karst.

Karst underground is differently investigated in different regions, and thus we do not have the real idea about its entire cavernosity. All the recent speleological discoveries show that the character of the underground will be essentially completed. But even though we know that the available data are very incomplete we tried to classify the known caverns for their situation, dimensions, function, origin and development phases. Thus we got some general ideas of theoretical and practical value. This contribution is mostly based on the results of detailed speleological mapping of the Dinaric karst in Slovenia (NW Yugoslavia). The speleological properties in other republics are probably very similar in general, which we conclude on the basis of our observations and other published data.

HISTORICAL REVIEW OF SPELEOLOGICAL INVESTIGATIONS

The history of speleological investigations can be divided into two important periods. Older and longer period from the middle of the 16th century up to the 20th century can be characterized as a period of mostly individual speleological investigations, different in different parts of Dinaric karst. The most important share of the first period belongs, without doubt, to the classical karstic region betweeen Postojna and Trieste, from where all the oldest descriptions of karst underground originate (Habe, Kranjc 1981). In the second half of the 19th century important speleological discoveries followed in Croatia, Bosnia and Herzegovina and Montenegro.

Younger period of organized caving and systematical speleological investigations started at the end of the last century in Trieste, where in 1883 the first speleological society, within in the frame of Austro-Hungarian Empire, was founded, and in 1890 the first Slovenian caving society, called Antron, in Postojna started to work; in 1910 the Society of Cave Exploration in Ljubljana was founded. After the First World War, the speleological activity was received mostly in Slovenia and Serbia; the extreme NM part of Dinaric karst was ardently investigated by Italian cavers (land Venezia Giulia), and they published the book "Duemila Grotte and Cave cadastre". The real organized caving started with the foundation of speleological societies in Slovenia, Croatia, Montenegro, Bosnia and Herzegovina and by foundations of Speleological Association of Yugoslavia on the occasion of the First Yugoslav Speleological Congress held in Postojna in 1954. In the proceedings of the following speleological congresses in Split, 1958, in Sarajevo, 1961, in Ljubljana, together with International Congresss of Speleology, 1965, in Skopje, 1968, in Sežana, 1972, in Hercegovni, 1976, in Bor, 1981 the progress of speleological activity in the Dinaric karst and elsewhere in Yugoslavia is reflected. The congress publications cannot give us the entire review of this activity. It must be completed by other speleological publications, reviews and miscellany, as f.e. "Naše Jame", the review of Speleological Association of Slovenia, from 1959, 24 issues were published; "Speleolog", Zagreb, 27 issues;

"Naš krš", Sarajevo, 10 issues ; "Acta Carsologica", Postojna, 10 volumes; "Krš Jugoslavije", Zagreb, 10 volumes.

Several articles of speleological contents were published in professional publications of biological, geological, geographical, hydrotechnical and other professions. Among independent publications we have to mention I. Gams, Kras, 1974; M. Herak & V.T. Stringfield (Ed.), Karst. Important Regions of the Northern Hemisphere, 1972; Underground Water Tracing, 1976. From the short review of published works comprised in Karst bibliography (Herak, Magaš, Sarić & Habe 1976) the extreme prosperity of speleological and general karstological activity in the region of Dinaric karst is seen. Considerable progress was made in the sphere of the physical speleological discoveries, the number of surveyed caves quickly increases, there are more and more long and deep speleological objects known. The progress in speleological science is important too, in the knowledge of caves origin and development, on transformation processes, on cave sediments and their connection with morphological, climatical and tectonical occurences. There is a lot of knowledge on the radiometric age of particular speleological phenomena, and also on different function and value of karst underground in geological and historical past and in our actual life.

BASIC GEOSTRUCTURAL AND HYDROGEOLOGICAL DIVISION OF DINARIC KARST

Dinaric karst can be divided after general orographic morphological properties into three longitudinal zones. On Adriatic side along the coast Low Littoral Karst is situated; several Dalmatian islands and peninsula Istria belong to it. The second belt comprises the central reef of High Dinaric Karst, practically extending from Julian Alps to Prokletije and from the near sea at Velebit, Biokovo, Orjen and Lovcen differently deep into the interior. The central belt of High Dinaric Karst passes to interior more or less expressively in lower Innner Dinaric Karst where fluviokarst predominates because of bigger rate of dolomite and less pure limestones and because of other inliers of impermeable rocks (Herak 1965; Roglić 1965).

Morphostructural units of Dinaric karst correspond to geostructural; we must distinguish in littoral zone simple geologic setting, mostly gentle folded Cretaceous and Paleocene limestones and Eocene impermeable flysh. High karst is distinguished by overthrust structure where different blocks of Mezzozoic rocks are overthrusted on the others, where among the doubled or tripled sequences of permeable limestones there are inlied less or completely impermeable layers. The entire overthrust zone is intermingled by several longitudinal and cross-section faults, where particular blocks are additionally displaced, in submerged areas Neogene lacustrine sediments are deposited. In the inner Dinaric zone similar structure predominates, only the rate of less permeable and non-carbonate rocks is greater, tectonic setting is concordant to the border of Pannonian basin. Thus, from the central belt towards the Pannonian border, the thickness of Tertiary cover increases as well as its influence to karst formation.

In lithological point of view Dinaric karst developed mostly in pure, differently thick laid Paleocene, Cretaceous, Jurassic and Triassic limestones. There are less older carbonate rocks of Devon to Perm Age. Particular karst caverns developed in Pliocene and Quaternaey carbonate clastites, in fluvial conglomerates and in breakdown and slope breccias and travertines. Tectonically crushed material and lithological properties are the most important factors influencing the character and forms of karst underground cavernosity. The biggest, the deepest and the longest karst caverns developed in pure, thick laid limestones. Bigger caverns in dolomites are few, but there are important exceptions; in Upper Triassic dolomite, we know up to 1 km long and more than 200 m deep caves. In thin laid limestones and in limestones with non-carbonate inliers smaller caves developed attaining bigger dimensions only exceptionally. Some caves developed at the limestone contact with the impermeable base.

Speleological properties differentiate after particular hydrogeological units. The way and direction of underground runoff, depending on impermeable base or border are important. According to way of runoff direction karst can be divided in simple runoff units, from where the precipitations flow divergently to several directions, or, they are directed towards one spring. Second group is presented by through-flow karst units, where waters from neighbour karst and non-karst regions in the form of connected flow or ramified net of smaller canals join to the local precipitations in the underground. In speleological point of view the origin and quantity of water as well as its chemical and erosional power are very important. For the underground formation the water flow rate, quantity and mean of transport are very important. Karst underground is essentially differently formed in pure karst with dispersed flows and without transport, than in the regions with concentrated flows and big quantities of suspended load, and again differently in the regions with dispersed water veins in less pure carbonate rocks.

GENERAL SPELEOLOGICAL PROPERTIES OF DINARIC KARST

Karst caverns in pure limestone of deep karst can be distinguished by form and origin into two basic types, in mostly corrosional vertical potholes and erosional caves. By percolation of precipitations into karst underground, potholes develop, by uniting of percolating water into flows, more horizontal caves develop. In simple outflow karst there are more potholes, caves are more numerous at karst springs only. In through-flow karst the caves developed from ponor to spring karst, in intermediate part the potholes are numerous too. There are rather few examples when both types of caverns join, this is more occasional than legal, therefore only few potholes are connected with water caves.

Simple, deep potholes reach 200 to 300 m of depth. They are the most numerous in high karst where besides the convenient hydrogeological base, climatic conditions with lot of rain and snow are favourable. More than 100 m deep potholes are known in lower littoral karst and in the islands too, but they are rare and developed in extremely favourable conditions. A good half of 2700 simple potholes in Slovenia is deep from 10 to 100 m, their average depth is about 20 m. The majority of simple potholes closed high above the underground water level and very rare are the connections with bigger underground caverns. Several potholes are blocked in the bottom by breakdown rocks, only in few potholes the bottom is rocky.

Composed potholes are very characteristic, their singular vertical chimneys are connected by narrow galleries. A special type of composed karst caverns are systems of deep potholes, where vertical shafts pass to less steep water channels. Such systems developed where the water from limited impermeable surface drains into deep karst. In high Dinaric and in Alpine karst the abundant source of superficial waters are big snow-fields, in glacial Quaternary periods, a lot of water was given by glaciers and along their branches the deepest cave systems developed. Composed deep potholes are conditioned by characteristic distribution of percolating water, forming differently big and high chimneys in horizontal caves; on karst surface these forms are reflected in numerous dolines. Evidently there are more dolines than known potholes as the continuations to the depth are in general blocked. Seldom the dolines are directly continuing into the potholes. There are numerous openings to the potholes in the borders among dolines; in high karst they are deep from 100 to 300 m.

In high mountainous karst snow potholes and caves are quite frequent with permanent or temporary ice in them. Ice and snow-caves have usually very wide vault above the entrance, from where the snow falls down into the underground; the ice in the caves developed mostly by freezing of percolated rain- and snow-melting water. The highest lying snow cave is "Ivačičeva Jama" under Kredarica plateau at the altitude of 2450 m, but the snow caves are enough frequent even at the altitude between 700 and 800 m. In statical, pocket-shaped caves, ice and snow remain late in the summer even at the altitudes under 600 m. In the past, the cave ice was transported to littoral regions and was used for freezing food.

Till now in Slovenia there are 26 potholes deeper than 200 m investigated, in Croatia 22, in Montenegro 6, we do not have the data for Bosnia and Herzegovina. The deepest pothole in Yugoslavia is "Brezno pri Gamsovi Glavici" in Julian Alps, 776 m deep; deeper than 500 m are for the moment in Yugoslavia only 4 potholes, amomg them famous depression "Crveno Jezero" near Imotski, which is somewhere to the half flooded by water. There are 15 potholes and caves deep from 300 to 500 m.

Horizontal karst caverns and caves developed and are accessible mostly in through-flow karst. Relatively rare are the caves traversable from the ponor to the spring. More of them lie near the springs rather than near the ponors and there are less accessible water caves in intermediary parts of through-flow karst. On several places numerous unknown water channels are indicated by breathing holes, which are easy to be found in cold winter days, when, from karst floor the warm air is smoking like from chimnneys. In Slovenia, there are, among 5.000 surveyed caves, only about 9% of active water caves. Out of them, there are about 180 spring caves, 130 ponor caves and 110 caves with permanent or temporary flow. To this cave group belong all the longest caves, among them fiveteen are longer than 2 km. In Croatia till now only two are known, in Montenegro one and in Bosnia and Herzegovina one.

Beside active water caves, there is a lot of dry karst caverns, distributed differently deep under the surface. The longest are near actual sinking streams and underground flows. Some are still temporary flooded, others are completely out of hydrological function. Shorter sections of dry caves are known in higher and remote situations from actual flows. Even these caves are very different after the form and the content, they still show the former hydrographical function. From speleological point of view they are important because of rich traces or different morphogenetic activities in near and old past. Dry caves have different practical value, from simple refuge to important touristic objects.

Among special speleological phenomena we can range big collapsed dolines with precipied walls. They developed by the collapse of cave roof and show to bigger underground rooms even there, where they are not known. Collapse dolines are more frequent in through flow karst and after their distribution we can conclude the position of underground channels; but there are not yet known the methods rendering possible the detailed determination of hollow space near the collapse dolines. There are more collapse dolines on ponor than on spring side, f.e. near Imotsko, than in intermediate region f.e. on Notranjsko area. The deepest is, already mentioned collapse doline near Imotski, more than 500 m deep; the collapse dolines between

60 and 100 m predominate.

The former underground channels are proved by the remnants of roof in the shape of natural arches on the borders of contact fluviokarst, but also on ponor and spring sides of karst valleys, as f.e. in Rakov Škocjan near Postojna.

In relatively well investigated Dinaric karst of Slovenia there are from total 5,000, only about 30% of fossil caves. But all of them are shorter than 2 km. More than a half are small horizontal caves, two fifths are composed inclined caves with pits and levels. If these statistical data can be valuable for other republics too, then in general, on Dinaric karst short caves and not very deep potholes prevail. It corresponds to crushed rocks and great tectonic activity which unable, in spite of favourable hydrogeological conditions, the development and preservation of big connected cave systems, characteristic for tectonically calmer regions of Europe, Asia and America. The majority of underground water flows in through flow Dinaric karst is not accessible, we can follow them indirectly by different water tracing methods.

SPELEOLOGICAL PROPERTIES OF SOME PARTS OF DINARIC KARST

In Low Littoral and Coastal Dinaric Karst there are relatively rare, but important water caves as a source of drinking water (Božičević 1969). Dry, decorated caves are touristically interesting, as flowstone forms in littoral caves are extremely rich and colourful. Short cliff-foot caves and blocked caves are archaeologically and paleolithically interesting as Grapćeva Spilja on Islands Vis (Novak 1955) and Šandalja near Pula (Malez 1972). Even on Adriatic islands there are known remnants of former bigger caves, famous after nice decorations. At least we must mention touristically interesting but abandoned cave Vitezić near Rudine on island Krk. The speciality of coastal karst are blue holes, among which the best known is the one on Island Biševo; interesting blue caves are also on peninsula Ljuštica near Hercegnovi. Without doubt, there are along the Adriatic coast frequent flooded caves, similar to "Medvedja Jama" on Island Cres, where flooded concretions and cave bear bones were found (Malez, Božičević 1965). Submarine karst cavernosity is shown by submarine karst sources (vrulja) along the whole Adriatic coast. Deep under the sea the siphon channels of the spring caves reach and thus even their entrances are 20 to 30 m above the sea level, as f.e. Sopoti Bay in Risanski Bay of Boka Kotorska.

An interesting example of gradual karstification or perhaps tectonical distribution of active and dry channels is known from Montenegro karst (Radulović 1974). It seems that there the cave system is lowered in steps from Lovćen to the sea. At the altitude between 600 and 700 m is known the system of "Cetinjske Jame", followed by "Lipska Pećina" at the altitude between 500 and 700 m, still lower is lying "Zaćirska Pećina" in Petsko Brdo at the altitude between 250 and 300 m. Active spring water cave is "Obodska Pećina" ar the altitude of about 50 m, not far from the Lake of Skadar.

Middle karst plateaus have similar properties as Trieste karst and Notranjsko karst, meaning relatively big caverns accessible mostly through secundary entrances or potholes. The former water channels are much transformed by breakdowns and other weathering processes which had occured when the waters passed to lower levels. Old joint channels are dissected to shorter sections, intermediate parts are filled by sediments and breakdowns or concretioned. Even that through this karst considerable quantities of waters flow from flysh and other impermeable border, active water channels are known only in smaller extent near the ponors. Almost exceptional are active water caves in intermediate parts as f.e. 7 km long "Kačna Jama" near Divača, or about 4 km long "Dimnice" near Markovščina. At big karst springs there are deep siphon channels flooded and accessible only for expert divers as f.e. in "Divje Jezero" near Idrija (Krivic & Praportnik 1973)

On the border of flysh Pivka basin there are several smaller caverns, distributed at different altitudes in three to four levels. In any case, the biggest is about 15 km long "Postojna Cave System" in two levels. Important is also 6 km long cave system near Predjama, developed in three levels. Still more dissected is the underground world near Prestanek and Slavinje on the southern border of Pivka basin, while on Upper Pivka area shallow karst with temporary lakes and superficial runoff prevails; there are rare caves and estavellas. Specially interesting is more than 40 m deep estavella "Matijeva Jama" near the Lake of Palčje; in Košana valley the spring cave "Gabranca" has more than 100 m of water level oscillations.

For the through flow karst of Notranjsko relatively long water and dry caves are characteristic, as f.e. "Planinska Jama" (6 km), "Tkalca Jama" (3 km), "Zelške Jame" (3 km), "Karlovice" (7 km), "Križna Jama" (8 km), "Najdjena Jama" (4 km), "Mačkovica", "Logarček", "Gradišnica" and others in the region among Loško, Cerkniško, Planinsko, Postojnsko and Logaško Karst poljes and Ljubljana Moor. The total lenght of all these caves surpasses 50 km, amomg ponors and springs there is more than half of unknown underground. At the same time, this region is the best investigated region in Slovenia. In dry caves several sinter generation are known, traces of different quaternary sediments, erosional and accumulation phases which are the consequence of climatic and tectonic activities in Younger Quaternary (Gospodarič 1976). Similar speleological conditions can be expected along all Dinaric karst poljes.

In central reef of high karst scarce sections of older water caves are known as the secondary transformation of the entrances and of the whole underground essentially diminished the possibilities of access to these caves. The marginal karst regions with remnants of impermeable cover on karstified base as on Banjšice and Črni Vrh plateau have essentially different speleological character. In these regions several potholes developed in steps, deep more than 300 m, developed on the contact of limestones and dolomites, as f.e. "Jazben on Banjšice" (-334 m), "Habečkov Brezen" (-252 m) near Črni Vrh above Idrija. Similar origin has "Gotovž" near Klana (-320 m) and "Rašpor" in Istria (-365 m).

<u>Through flow karst in inner Dinaric zone</u> comprises different units. Superficial waters flow across or along the valleys. Water caves at sinking streams are difficult for access because of gradual settling of particular blocks on the border of Pannonian valley. More accessible are only underground channels near the sinking streams which are crossing uplifted units as near Velike Lašče and Rašica on Dolenjsko (Kranjc 1980), and between Grosuplje and Krka springs (Gospodarič 1973). Similar conditions can be seen further southeast in the region of Karlovac, near Ogulin, Bosanski Petrovac and elsewhere.

In this karst regions the actual water channels are rarely accessible, but the reasons for such conditions in low through flow karst of inner Dinaric zone are not yet enough explained. This karst was covered by thick layer of Pliocene chert sands and loams, and on the border it is still nowadays abundantly dammed by Neogene sediments. The higher western karst border with dispersed runoff influenced very little the development of connected underground channels. Negative influence had also the dolomitic neighbourhood which did not contribute neither quantitativeley abundant nor corrosionally aggressive waters. Among speleological objects in this low karst the most numerous are the water pits and a sort of karst windows where direct access to karst underground water from the surface is possible. The majority of karst waters flow superficially on characteristic narrow and meandrous canyon valleys; these are the only preserved parts of former extensive superficial water net. We can be sure about it especially in the region of Bela Krajina, and also along Dobra, Mrežnica, Korana and Una.

Speleogenetical properties of Alpine Karst are extremely numerous small potholes and kettles. These caverns are somewhere very dense. In the mountains above Bohinj area there are 78/km² of the surface (Kranjc et al. 1974) presenting the biggest cave density on Dinaric Karst. Several deeper potholes are known on inclined high mountainous karst pavements on Kanin Mountain (Kunaver 1973) and on Kamnik Alps.

By accumulation of snow and ice in the highest regions of the Alpine and Dinaric karst the outflow quantities augmented, as the ice reaches in the Würm culmination about 1,200 to 1,300 m of altitude, accelerating the formation of deep potholes and the net of outflow channels. Till now they are relatively well investigated in the longest and deepest caves of Kamnik and the Julian Alps as "Brezno pri Gamsovi Glavici" (l = 4,517 m, d = 776 m), "Pološka Jama" (l = 11,000 m, d = 707 m), "Brezno pri Leški Planini" (- 536 m), "Brezno presenečenj" (- 472 m), "Ljubljanska Jama" (- 310 m), "Triglavsko Brezno" (- 261 m), etc. Similar origin has "Duboki do" in Montenegro (- 350 m) and "Bunovac" on Velebit (- 445 m) and also "Velika Ledenica" in Trnovski Gozd (-385 m).

The third characteristic of high karst is connected to older phases of karstification when the high mountainous plateaus were relatively and absolutely lower and had different hydrographic conditions. The traces of older karst underground are such caves as "Potočka Zijalka" and "Mokriška Zijalka" (Brodar 1959) or "Kristalna Jama" and "Babja Jama" near Bled (Gams 1975).

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FIGURES

5.1. Distribution of various speleologic objects in Yugoslavia. After Malez and Božičević (1965).
A - Larger caves and caverns in general, B - caves with paleontologic palaeoanthropologic and archeologic remains, C - smaller speleologic objects and undefined karst features.

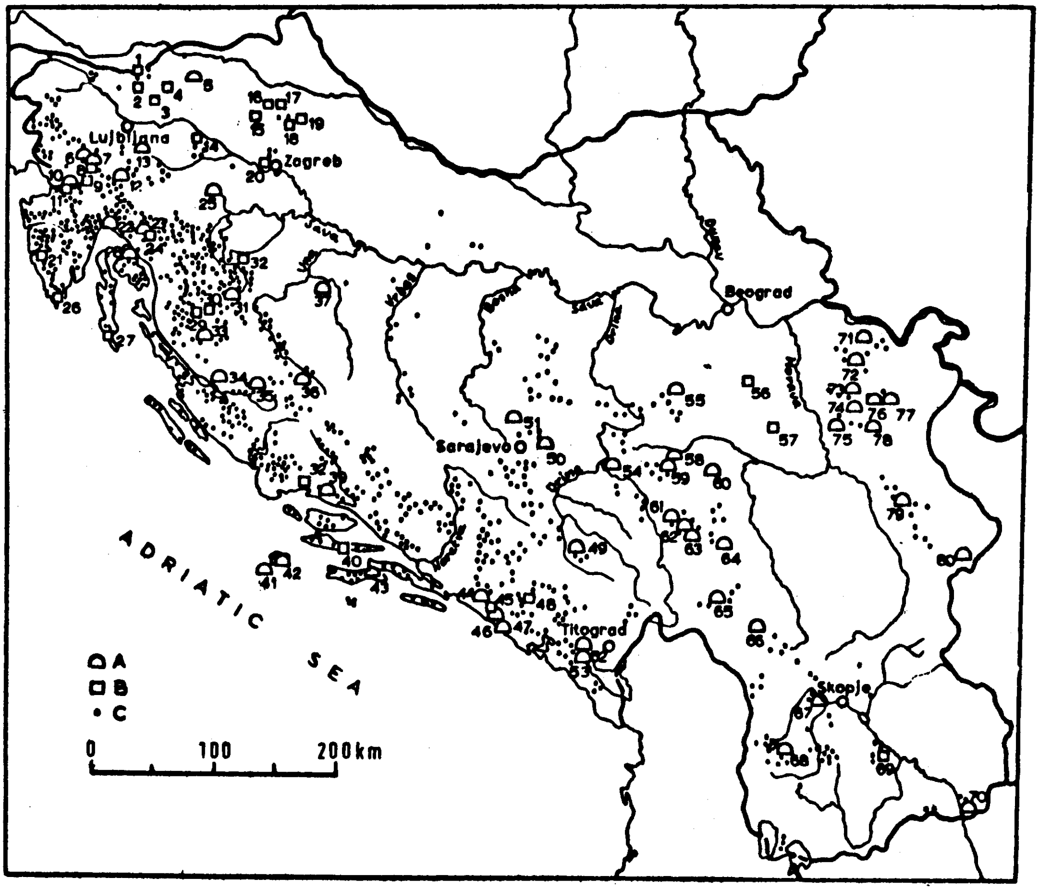
Zagreb
Beograd
Sarajevo
Titograd
Skopje
ADRIATIC SEA
A
B
C
0
100
200km

Figure 5.1

6

K A R S T   P O L J E S   I N   D I N A R I D E S

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1. INTRODUCTION

Karst poljes are the largest and markedly specific forms of carbonate rocks megarelief. They are known over the entire Alpine orogene range, from Pyrenees to Middle Asia, as well as on some larger Atlantic and Pazific islands (Jamaica, Cuba, Java, Borneo), but their most outstanding representatives occur in the Dinarides.

Formation of spacious depressions in Dinarides mountainous relief resulted as a consequence of successive and partially simultaneous action of a number of natural factors, of which two are of decisive importance:

1) Geological, which equally refer to all tarditectonic phases of formation of mountain range structures and intermountainous depressions and neotectonic movements that facilitated and accelerated hypsometric arrangement of poljes in several horizons, starting from the highest points in External Dinarides relief to Adriatic Sea level as the absolute erosion base of the whole Dinaride karst complex, and

2) Paleoclimatic, which refer to all climatic events in Oligomiocene. and particularly in Pliocene as well as in Older and Younger Quarternary; by powerful action on karst process with more intense chemical corrosion and mechanical erosion they accelerated karst poljes modeling into their present appearance.

Hydrogeologic watersheds of a majority of karst poljes are in the zone of high atmospheric precipitations, and due to this they have very suitable natural conditions for accumulation of large amounts of water. This fact, observed already at the end of last century, induced many experts to search for most suitable energetic and meliorative solutions in karst poljes.

Initial studies in karst poljes were mainly aimed at the defence of agriculturel land against floods; only postwar extensive and complex investigations indicated realistic possibilities of multipurpose and efficient utilization of waters. This was primarily achieved owing to highly detailed geophysical, hydrological and engineering-geological investigations in the areas of karst poljes of West Bosnia, Dalmatia and Herzegovina. The investigations afforded the possibility of reliable definition of some karst poljes features that essentially contribute to highlighting their genesis, evolution and functioning of hydrogeological system under paleoclimatic and contemporary natural conditions.

2. GEOMORPHOLOGIC GEOLOGIC-TECTONIC AND HYDROGEOLOGIC FEATURES OF KARST POLJES

Most of karst poljes in the Dinarides have a planar and elongated shape, basically ellipsoidal, with the longer axis parallel with the strike of mountain range, i.e. carbonate rocks beds. This is the so called Dinaric direction (direction NW-SE), although there are some exceptions, both in shape and general strike direction. Large poljes of Bosnia and Herzegovina, such as Glamočko, Duvanjsko, Livanjsko, Imotsko and Motarsko, together with some smaller ones, have the usual Dinaric direction of principal directries. High karst poljes, such as Kuprečko, Vukovsko and Ravno do not have the Dinaric strike direction, and a similar phenomenon was also observed in the positions of Nevesinjsko and Mokro Polje in eastern Herzegovina, and Nikšićko and Njeguško Polje in Montenegro.

The cause of varying derivation from the general Dinaric strike direction with cited karst poljes are undoubtedly related to the tectonic style of differential movement of individual rock blocks and structures within the geotectonic structure of Dinarides,

The karst poljes size is highly variable: there are some very small ones with a surface area ranging from 1 to 3 km³, while Livanjsko Polje, considered as the world largest karst polje, has a surface area of 380 km³, and together with Bučko Blato, which morphologically may be considered as an integral part of Livanjsko Polje, it totals 433 km³.

Table No 1 presents the characteristic physio-geographic features of some better known karst poljes in Central Dinarides.

Zonal arrangement of karst poljes is a characteristic occurence in the central and eastern parts of Dinarides. This is a consequence of spatial jaggedness and height division of mountain ranges, which constantly widen going southeastwards right down to Skader depression and Metohija Valley.

Hence, only a series of karst poljes is found on Lički plateau, Ličko and Gacko, also including Krbavsko and Gračačko. In Western Bosnia and Dalmatia, karst poljes are arranged in five series, and in Eastern Herzegovina and Montenegro, where the Dinarides have the greatest width, the karst poljes are arranged in four series (Fig. 6.1.).

In addition to the zonal arrangement of karst poljes, their step-like position is highly characteristic, not being a result of height division of Dinaride mountains. Therefore, all karst poljes have a step-like arrangement going from northwest to southeast, thus quite contrary to the height growth of Dinaric Mountain Ranges (Fig. 6.2. and 6.3.).

In Table 2, M. Komatina isolated five basic height horizons and two sub-levels of karst poljes in Central Dinaride karst.

As seen, height difference between individual horizons of karst poljes is variable, ranging from 96 to 241 m.

In Table 3, four height karst poljes horizons were separated in Eastern Herzegovina (Milanović 1973).

In this case, the differences between individual karst poljes horizons are higher, ranging from 134 to 330 m.

Most of karst poljes are tectonically predisposed, mainly by fault tectonics. Thus, peripheral faults are visible in Glamočko and Livanjsko Polje, discussed by J. Cvijić in his famous study "Karst poljes of Western Bosnia and Herzegovina" reported in 1900. Kosova, Petrovo and Sinjsko poljes are related to zones of diagonal faults, and Mućko, Aržano, Vinica and Rakitno poljes are predisposed by large reverse faults - block overthrust (imbricated structure). In Kuprežko Polje J. Cvijić found a fault along the northeastern edge, and in Duvanjsko Polje a reverse fault along the northeastern edge, where cretaceous limestones overlap neogene sediments, while the southwestern polje edge is predisposed by a longitudinal fault.

One of the common features of most karst poljes, particularly the large ones, is a flat bottom composed of Neogene and Quartenary sediments, implying that the poljes were lakes at that time. Cvijić compares the Dinarides of that period with current Alps appearance, emphasizing that "toward the end of that period Bosnia and Herzegovina were an area rich in lakes and glaciers". It was considered, however, that lake products in karst poljes do not have a large thickness.

The results of more recent geological and hydrogeological investigations, combined with geophysical research and deep drilling, completely refuted such opinions. It was found, however, that lake sediments in many karst poljes represent dominant lithologic members and have an important role in their geologic and tectonic structure. Some examples described in detail by J. Petrović in his work "On the Origin of Poljes in the Karst", 1973, will be mentioned.

Neogene products of Duvanjsko Polje have the greatest thickness and most complete development in this area. They are lying discordantly on an ír-regular limestone base, and their overall thickness is about 2,500 m. In the lithostratigraphic column, where marls dominate, several facies were isolated: successive alternation of a number of conglomerates, sandstones, marls, clays, sand and coal horizons.

Neogene lake deposits (strata) in Livanjsko Polje cover the whole area of this gigantic polje, the thickness being in excess of 2,300 m. They are represented by seven different horizons. The uppermost horizon comprises of sandy-clayey marls, marls with coal and sands and gravels with a total thickness of approximately 600 m.

In Glamočko Polje lake deposits have a lesser thickness, some 700 m. Here some of the lake sediments strata found in Livanjsko Polje are missing, but are found in other karst poljes.

The age of lake sediments of karst poljes in Western Bosnia was very precisely defined. According to M. Herak, the floor most important coal-bearing level in all karst poljes basins belongs to Lower Miocene, while the highest levels of the deposits belong to the Pontian. All other lithologic observation points fall within the limits between Miocene and Pontian.

Lake sediments in Eastern Herzegovina karst poljes begin with conglomerates of uniform composition, variable size, well bound with carbonate cement, and are laying directly on limestone paleorelief. In the following series marls and sandy marls alternate with beds of coal, clay, sands and varying gravels. In Gatačko Polje, freshwater Neogene sediments have a thickness in excess of 200 m. The bottom series belong to Oligomiocena, and the uppermost ones to Pliocene. Drillings indicated that the lake strata in all Eastern Herzegovina karst poljes are substantially disturbed by vertical faults. In regard with the lithological composition, they differ from the lake deposits in river Neretva valley, the thickness of which in Bijelo Polje, upstream of Mostar, is more than 600 m.

It is important to note that Tertiary lake sediments are primarily present in the geological structure of the higher and highest karst poljes. They occur in the source sections of all large pre-karst rivers, usually together with older water impervious rocks. In Gatačko Polje the Tertiary basin was formed in the area of high positioned cretaceous flysch.

A major part of Kuprečko Polje consists of Werfenian slates and dolomites overlaped by Tertiary sediments. Also in Glamočko and Grahovačko poljes Werfenian slates and dolomites participate together with other water impervious rocks in the broader area geological structure. All these, hypsometricaly highest karst poljes, lie in the area of topographic divide between the Adriatic and Black Sea watersheds.

In the lower karst poljes Neogene sediments cover a much smaller area and have a lesser thickness. In Western Herzegovina they occur in Posuško, Kočerinsko, Trnsko and Imotsko poljes. Drillings in Imotsko Polje indicated the thickness of Neogene sediments of 145 m. This series of lake sediments begins with sandy clays and clays, followed by alternating marls, clays and sands. In all above poljes, as well as in the open valleys of lower river Neretva course, the lake sediments overlap the Younger Paleogene products, represented by Cosina beds. In the lowest poljes, near the Adriatic Sea, Neogene sediments were not found. This includes Konavosko, Vrgoračko, Dicmo, Dugopolje and Bokanjačko Blato poljes, as well as the cryptodepressions of Skutari (Skadarsko) Lake, Bačinska Lakes and Vransko Lake.

The karst poljes also contain Quarternary sediments. They are usually represented by gravels, sands, deluvial materials and alluvial deposits. Hence, between Livanjsko Polje and Buško Blato larger deposits of pebbly composition are found with a thickness of about 6 m, and in Bučko Blato Quaternary sediments reach even 40 m. The bottom of Cetinjsko Polje in Montenegro is filled with pebbly fluvioglacial (moraine) material with a thickness varying from 8 to 15 m. In many karst poljes diluvial terraces are clearly observable.

Specific functioning of the hydrogeological system is an outstanding feature of karst poljes.

Since by definition typical karst poljes are closed depressions, their drainage takes place by underground routes. Consequently, many poljes are periodically, over a longer or shorter period of time, flooded (in the spring and autumn), because their water balance is not always balanced all year round.

Occurences of surface waters in karst poljes are related to:

- Permanent or periodical alogene river stream flowing into the polje from a larger distance;

- Permanent or periodical stream formed in the polje itself from permanent or periodical springs along one polje boundary (in Dinarides this is mostly the northeastern boundary).

- Outflows of groundwaters from estavelles possibly arranged over the entire polje, but usually nearer to the upstream polje boundary.

Surface waters flow from karst poljes takes place solely through sinkhole zones and sinkholes, usually located along the opposite, downstream polje boundary (in Dinarides this is mostly the southwest polje boundary).

Study of the hydrogeological system in karst poljes resulted in a finding that only one part of the balance waters of its hydrogeological watershed appears on the polje surface, while the remainder, which may be larger or smaller, flows under the polje bottom or around it to the lower drainage step.

In connection with this, some considerations should be noted, supported by marking out the sinkhole zones in karst poljes, which confirm the hypothesis on karst collectors of different generations (older and recent), functioning as a complex hydrogeological system. These facts must be taken into account in relation with the new concepts on the phases, time and method of karst process action under paleoclimatic and contemporary climatic conditions, according to which recent karst morphology was the decisive factor in the formation of the complex hydrogeological system in karst poljes (Bahun 1978). Karst poljes serve as passing local drainage steps for this system, whose absolute erosion base is the Adriatic Sea.

According to presented geomorphologic, geologic-tectonic and hydrogeologic properties of karst poljes, some phenomena may be observed representing common characteristics of most karst poljes and which may be summarized as follows:

1. Karst poljes in Dinarides have a planer and elongated shape, mainly predisposed by regional and geological-tectonic structure of the terrain: they usually strike in the direction of principal tangential structures, i.e. in the NW - SE direction, while the formation of some of them was initiated by land subsidence along fault zones as a consequence of differential movement of individual rock blocks and structures, leading to

deviations both in shape and basic poljes strike direction.

2. Typical karst poljes are topographically closed depressions, i.e. surrounded from all sides by steep or slightly inclined limestone hills and mountains, so that their surface waters may drain only through underground routes - through sinkholes, sinking zones or caves. There are, however, karst poljes open at one end by a recent or fossile valley, somewhat resembling valleys in non-karst areas.

3. Karst poljes bottoms are mainly flat and covered by deposits of permanent or periodical surface stream sediments (usually gravels, but also dolomitic sands, marls, clay and terra rossa), or older Quarternary sediments. Quite frequently lake sediments are found in the base of Quarternary ones, which rarely have a deep dip, and cover either the whole polje, or only one part of it. In some poljes solitary limestone or dolomite hills protrude from the flat bottom, called hillocks (hum).

4. Most of the karst poljes are periodically flooded by waters that, during wet seasons, flow out of the springs and estavelles, or through numerous cracks in their limestone boundary. Poljes with slight above sea levels, or with bottoms below sea level, represent salt lakes (Skutari / Skadarsko Lake / Vransko Lake / Bečinska Lakes, etc).

5. Zonal arrangement and step-like position in the system of Dinaric karst poljes cause complex and specific hydrogeologic conditions of drainage and distribution of groundwaters, of which Adriatic Sea is the absolute erosion base, and karst poljes passing regional or local drainage steps.

3. GENESIS AND EVOLUTION OF KARST POLJES

Even today disagreements exist in interested scientific circles on the genesis and evolution of karst poljes in Dinarides. The disagreements were particularly pronounced in the past when related to the discussion on the erosion cycle and distribution of groundwaters in karst areas carried out at the fall of the 19-th and onset of 20-th centuries among the best known karst reserachers, such as: A. Penck, E. Martel, A. Grund, F. Katzer, J. Cvijić, O. Lehman, M. Malicki, E. de Marton. One of the most eminent among them, J. Cvijić devoted a major part of his field explorations and investigations to the problem of karst poljes genesis. In the study "Das Karstphänomen", for the first time he states the opinion that karst poljes are related to terrain tectonic structure, drawing a conclusion that they are, due to this, depressed (down-thrown) and synclinal.

Later, in his work "Karstna polja zapadne Bosne i Hercegovine" (Karst poljes of Western Bosnia and Herzegovina), published in 1900, Cvijić studied this problem in full detail. He attributes major importance to tectonic predispositions in the formation of karst poljes: notes the occurence of faults following karst poljes boundary, but also tectonic block down-throw, found in all Western Bosnia poljes on the basis of dissturbed deluvial terraces. In Livansjsko polje, for instance, he found that "posthumic movements are also recognized by the varying height of the same terraces along the northeastern and southwestern polje boundaries".

However, in the same work, Cvijić introduces for the first time an entirely new genetic structure, the so called erosion karst polje, formed by the intergrowth of dolains and dolains uvalas, citing as examples Kupreško and Vukuovsko poljes, the bottoms of which are not flat. Uvala is, according to Cvijić, a transition form between dolain and polje.

These original observations were synthetited as an unique concept in his paper "Podzemna hidrografija i morfološka evolucija karsta" (Underground Hydrography and Morphologic Evolution of Karst), 1918, isolating four karst poljes genetic types: 1) Polje tectonic trench; 2) Polje related to a fault; 3) Polje syncline; and 4) Polje of erosion origin, formed by uvala intergrowth. In his capital monograph "Geomorphology", which appeared in 1926 after his death, Cvijić fully maintained this concept on the genesis and development of karst poljes.

Later researchers mainly relied upon Cvijić's assumptions.

Even today it may be stated that Cvijić's basic ideas on the genesis and evolution of karst poljes are valid. It was proved, for instance, that there is a number of karst poljes formed by joining of a greater number of karst uvalas, but only smaller karst poljes may have this origin (Primorski Dolac and Dicmo in Central Dalmatia, a series of smaller karst depressions in limestone anticlinal structures of North Dalmatia, process of uvala joining in karst areas of Katunska Nahija in Montenegro, etc.). Undoubtedly, larger karst poljes may be formed in different ways, but always with visible traces of tectonic action. A conviction prevailed, under Cvijić's influence, that the formation of larger karst poljes was initiated by land subsidence along the boundary faults, and that when subsidence ended - surface waters currents erosion levelled the previously rough polje bottom, leaving on it only isolated undistroyed hillocks. According to Cvijić, this process developed in the following manner: "Tectonic processes enabled the formation of poljes, identically as normal erosion forms valleys, utilizing here and there faults and other tectonic predispositions, but precisely karst erosion gives the final polje shape. The area of a karst rock block lowered in the tectonic trench still does not represent polje bottom; hydrographic phenomena characterizing poljes develop later on under the action of karst erosion. First, dolains and uvalas appear on the surface of that karst block lowered between faults, or inclined along one fault, or lowered into the syncline. Uvalas get widened and deepened. When their slopes intersect caves with streams, karst rivers emerge and level the recess bottom. Gradually the bars dividing the recess disappear and recess intergrowth is completed. In the final stage of development the bars disappear completely; only isolated limestone hillocks, hummocks remain."

This is Cvijić's model of karst polje genesis and development in which he follows three stages of evolution: (1) Lowering of limestone blocks along the fault; (2) Karst erosion action in the lowered limestone mass; and (3) Levelling of polje bottom by the action of surface waters outflowing into the field permanently or periodically. It was considered that deposits over the polje bottom represent only a relatively thin cover, being of practically no geomorphologic importance, and such an opinion on the origin of karst poljes prevailed for a long time among the majority of scientists.

However, we have already seen that numerous and highly detailed geological, geophysical, hydrogeological and enginering-geological investigations completed in the postwar years for the purpose of constructing artificial water accumulation basins in individual Dinarides karst poljes discovered a number of new realizations on the geology, geomorphology and hydrogeology of these karst depressions, resulting in new opinions on their genesis and development, which more or less differ from Cvijić's classic scheme.

B. Stepanović considers that land lowering along boundary faults generally is not a necessary prerequisite for the formation of karst poljes, since "attentive studies of the tectonic structure indicated that such boundary faults do not exist in all karst poljes, and where they exist, their importance is not always decisive as previously assumed" (Stepanović 1963).

It is a fact that the flat bottom of large karst poljes in the Dinarides was not formed, even in a single studied case, by the action of stream erosion, but was levelled by filling, i.e. sediments deposition on very rough original bottom of the karst depressions. Numerous feep boreholes drilled in various karst poljes supplied positive evidence that the thickness of sediments on polje bottoms is ununiform, ranging from a few meters to several hundred meters over larger distances. The thickness of Neogene sediments in Duvanjsko polje reaches even more than 2,000 m. Geological profiles constructed on the basis on numerous deep boreholes prove that the paleorelief of limestone masses under loose sediments on poljes bottom is equally rough - full of side slopes, dolains and sinkholes - the same as present karst highland around the poljes (Stepanović 1963; Petrović 1973).

Therefore, present karst poljes forms - flat bottom and hillocks protruding from it - are not a result of river erosion at that level, but on the contrary, they originated from accumulation of loose sediments carried and deposited by water currents in the lowerest parts of former karst relief right up to the present polje bottom level. Hummocks on polje bottom, hence, are no residual forms of the former karst relief not destroyed by river erosion, but parts of karst paleorelief left uncovered during the deposition of loose sediments (Stepanović 1963).

This leads to a conclusion that the formation of large karst poljes in Central Dinarides is genetically related to the formation of freshwaters Tertiary basins in them, clearly indicating that the karst process was not a sole factor in the genesis and development of the poljes. This fact points to the important role of Neogene lake sediments, which by their very occurence, and particularly by their thickness, essentially affected surface and underground circulation of karst waters, and in turn the genesis and development of karst poljes. In line with this, J. Roglić (1960) emphasizes that closed depressions may be created and developed at the contact partially in non-carbonate sediments and partially in corroded limestones around sinking zones, due to selective erosion. The fluviokarst poljes develop particularly when the contact between limestones and water impervious sediments is marked by a fault, fault zone or isoclinal structure (Roglić 1960). And B. Petrović (1973) sees, in the identity between large karst poljes and Tertiary basins within them, the answer on the issue on the origin of the majority of Bosnian and Herzegovina karst poljes, precisely on the basis of mutual action of karst and fluvial erosion, i.e. selective erosion action in rocks with varying water permeability capabilities. The role of fluvial erosion and denudation was limited to washing-out and removal of eroded materials, and that of the karst process to the creation of most diverse forms of underground collectors - sinkholes enabling removal of the materials from the polje (Petrović 1973).

Due to evident importance of the issues, some synthetic data will be presented, of importance from the hydrogeologic standpoint both for the morphogenesis and evolution of karst poljes and functioning of the hydrogeologic system in them.

Formation of large paleogene depressions in Dinarides is undoubtedly related to the final stage of Dinaric orogene cycle (Laramie and Post-Laramie orogene movements), as well as to the large rupture tectonics, both in internal and especiallly in the external Dinarides, where the vertical deep faults had a decisive role. Basic formation of this carbonatic sceleton took place during Oligocene (Pyrenean and Sava orogene phases), and its activation and calming developed during Neogene tectonics, mainly to the end of Pliocene, when the main sedimentation of Tertiary freshwater products with coal of substantial thickness took place. Oscillations and mainly sinkings in this area continued over the Quarternary too, lasting right up to the present. Here, certainly, one should emphasize the importance of neotectonic vertical movements, which are considered as being large, occasionally in highly limited spaces of even ± 1,000 m (Steyerian, Artinskian and Rhodanian orogene phases - Cicic & Milojević 1977). Mainly differencial block movements are in question, which took place either on old tectonic lines or on younger faults intersecting them. The importance of the role of Neogene and Quartenary tectonics in the uplift of mountain ranges and individual regions is specifically evident in the case of karst poljes and Tertiary basins in the Central Dinarides, which are currently arranged on five principal levels, gradually positioned from the present sea level towards Dinaric karst inland, starting from above sea level + 20 m to above + 1,200 m (Komatina 1975). Flooded cryptodepressions on the Adriatic coastline may be considered as the sixth, lowest neotectonic karst poljes "step" located under the present Adriatic Sea level.

Parallel with the development phases of elevation, rupture and sinking of individual parts of the Mesozoic carbonate series the network of surface streams was formed which was concentrated on all principal directions of above mentioned fractures from which the waters first flows superficially towards former lowest levels within the Dinarides, and then underground over the tranversal fault towards the Adriatic depression. Since the vertical movements of carbonate blocks of this period had a positive sign over a long time, the karstification process had an extremely favorable development. It may be safely stated that over the long period of time which followed immediately after the first larger emersion in the Dinarides, intense highly extensive and continous karstification took place, being constantly stirred up by tectonic and neotectonic dynamics, consisting of differential paleokarst (Triassic, Jurassic, Cretaceous, Paleogene) and dominant Quaternary (recent and sub-recent) karstification.

The process of karstification which, thus, started with the formation of paleodepressions, descended gradually in dependence with the rate of depressions sinking and filling with terrigenous material, being oriented by transversal faults towards the Adriatic depression, which already at the end of Pliocene represented the erosion base for the major part of Dinaric karst, and hence the development of the underground drainage network from the very beginning was generally oriented towards the southwest (Bahun 1978; Jovanović & Avdagić 1981).

4. FUNCTIONING OF THE HYDROGEOLOGICAL SYSTEMS IN KARST POLJES

For the purpose of explaining the development of the underground drainage network over the longlasting evolution of karst poljes, S. Bahun presented a simplified model (reconstruction) of poljes development from Neogene to the present three phases, disregarding the terrain geological structure, i.e. hydrogeologic properties of the rocks and tectonic structure (Fig.6.4). It was assumed that an area is in question composed of limestone-dolomitic rocks for which the classical cycle of karst erosion may be fully applied, starting by surface limestones corrosion, and its movement depthwise with the aid of tectonic and neotectonic ruptures; springs, sinkholes and estavelles are accompanying phenomena of the process (Bahun 1978).

In the case of present position of the principal drainage network, the model places it on a higher hypsometric level in the surrounding karst terrain around the polje, and in the area of the polje itself it is located in the lowered limestone block forming the polje bottom. Consequently, according to the model, underground flow is generally subject to small gradients, which suddenly change up and down in narrow zones around the polje, upstream and downstream (Bahun 1978).

Evidently, this simplified S. Bahun's model is unapplicable to the major part of karst poljes with Neogene terrestric basins, where the hydrogeologic function of clastic sediments plays an important role, both in the morphologic development of the poljes and in the development of the underground drainage network. It is impossible, therefore, from the hydrogeologic standpoint, to identically interprete the genesis and development of karst poljes in Tertiary terrestric basins with substantial thickness of Neogene deposits and in karst depression with relatively thin Quarternary cover having no essential influence on the distribution and directions of groundwaters circulation in the karst polje area.

The hydrogeological factors related to the genesis and development of karst poljes must, therefore, refer equally both to the development of paleodepressions and terrestric basins in them, and to the development of the drainage network in surrounding carbonate rock masses, genetically related to the nectonic and neotectonic movements. All the time this complex system worked on the interaction principle between the purely karst process, surface and underground, in carbonate rocks and fluvial erosion in non-carbonatic rock masses.

Under highly variable paleohydrologic and paleohydrogeologic conditions of Miocene - Pliocene - Pleistocene period, formation of the underground drainage network and functioning of the hydrogeologic system in karst poljes with Neogene terrestric basins developed in several stages in the following manner (Fig. 6.5):

- Tectonic movements at the end of Tertiary were ununiform: elevation of mountain ranges completely disorganized the hydrographic network, favoring further development of paleodepressions and karst erosions within them. The waters originally circulated through underground routes predisposed by faulting tectonic (longitudinal Dinaric and transversal). The springs occurring in limestone blocks on depressions northeastern boundaries flowed superficially or underground into the southwestern limestone block, lowering gradually their streams deeper underground;

- In the stage of accumulation of Tertiary basins, springs in the northeastern block gradually became overflowing ones (more precisely, rising-overflowing), because this part of the karst passes into damed karst; sinkholes were formed on the southwestern boundary, through which particularly during floods, excess water drains out through a well developed system of fracture-karst collectors (Jovanović & Avdagić 1981)

- In the following stages, related to contemporary hydrologic and hydrogeologic conditions, formation of estavelles took place due to unadequate permeability of the drainage system underground, fossilization, as well as the regeneration of paleokarst occurences, right until deep karstification acts below the Neogene basin (Jovanović & Avdagić 1981).

In connection with this, some results of tracing groundwaters in karst poljes should be pointed out, indicating varying values of fictitous rates ranging from a few mm/s to several tens of cm/s, undoubtedly proving the effect of Tertiary basins as partial or permanent underground barriers in the broader karst poljes area. Hence, some sinking zones in higher karst poljes do not communicate directly with all springs in the adjacent, lower poljes, because branching of groundwaters occurs due to the presence of deeper or shallower barriers.

Due to the above mentioned structural relationships between water permeable carbonate masses and water impervious terrigenous sediments, zonal watersheds, regional and local, are formed. With such phenomena in the areas of karst poljes related are bifurcation phenomena of the same order of magnitude, which activate or fade away in dependence of the intensity of water sinking in the poljes. This also implies the process of natural closing of older or opening of new sinking zones, and this has a quite significant effect on the magnitude of hydrogeologic watersheds and water balance in karst poljes.

In line with this, it should be emphasized that the hydrodynamic water regime in karst poljes depends of three basic factors:

- Lithologic composition of the rocks forming the karst polje broader area;

- Hypsometric position of the polje in regard with the lower groundwaters draining steps, and

- Presence or absence of hydrogeologic barriers in the polje.

Analysis of the factors in the largest Dinaride karst poljes lead to a conclusion that the space of karst poljes with Neogene basins represents a highly complex drainage system, which since paleoclimatic conditions, and even currently, essentially affects functioning and complexity of the hydrogeologic system in the karst. The general pattern of the system indicates the possibility of certain simplifications characterized by the following:

- Karst surface and its epidermal part undoubtedly play a crucial role in the linkage between external geodynamic factors and karst aquifers. One should note the high influence of geometric dimensions and karst collectors (cavities) hierarchy on underground waters circulation in this zone;

- Within this zone (subsystem of water unsaturated karst), a specific distribution occurs regarding the position of vertical and horizontal components of underground water flow, particularly apparent in karst poljes area. Namely, transit groundwaters in the karst, on their way to the erosion base change the flow regime when entering the karst polje zone: they either raise towards the springs on the polje boundary, or flow towards the moore deeply lowered drainage network. The waters flowing over the polje surface sink nearly vertically and immediately join this drainage system. This leads to the differentation between primary and secondary drainage streams present in the zone of groundwater table fluctuations, leading to numerous hydrogeologic phenomena in the karst, particularly in karst poljes. This also may be used to explain the phenomena, not unfrequent in karst poljes, that all springs of a single Dinarides hydrogeological watershed do not react silmultaneously after innudation, and some increase their yield only after several successive longer lasting rains (Mijatović 1981);

- The subsystem of water saturated karst contains aquifers in the true sense. In fact, dynamic water reserves are in question, occupying a more or less significant space in the water saturated zone. Other water reserves, mainly belonging to the karst matrix, join the dynamic reserves either laterally or vertically.

According to hitherto study of this problem, it seems that limestone blocks between the karst poljes have no major effect on groundwater hydrodynamic regime, since exactly the karst poljes area is the principal location of underground streams accumulation and distribution in the karst. Here the connection between the primary and secondary drainage zones is realized, which generally exists in the karst, and it may be good, moderate or poor.

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FIGURES

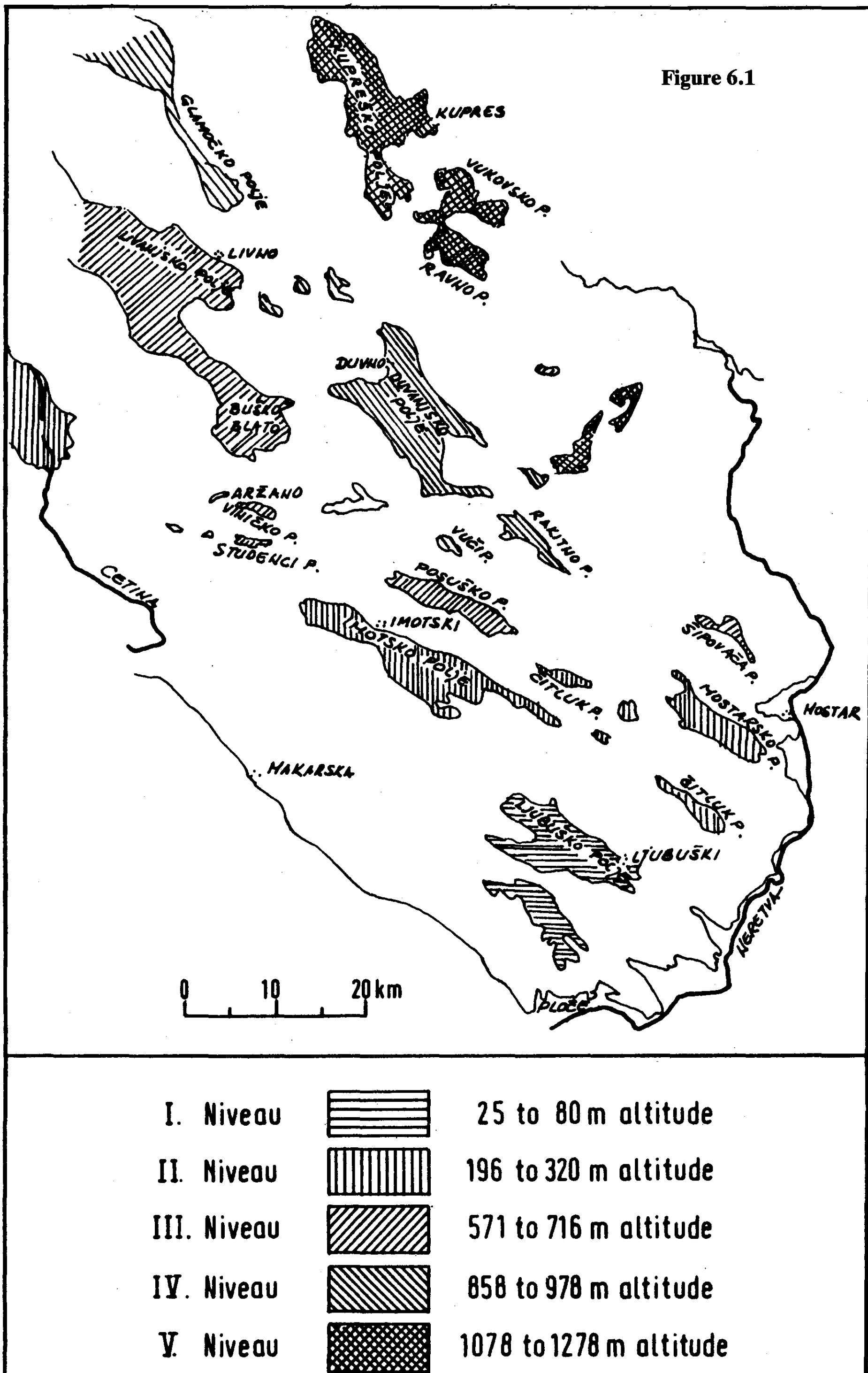
6.1. Zonal level arrangement of karst poljes in Western Bosnia and Central Dalmatia. After J. Vilimononvić (1970).

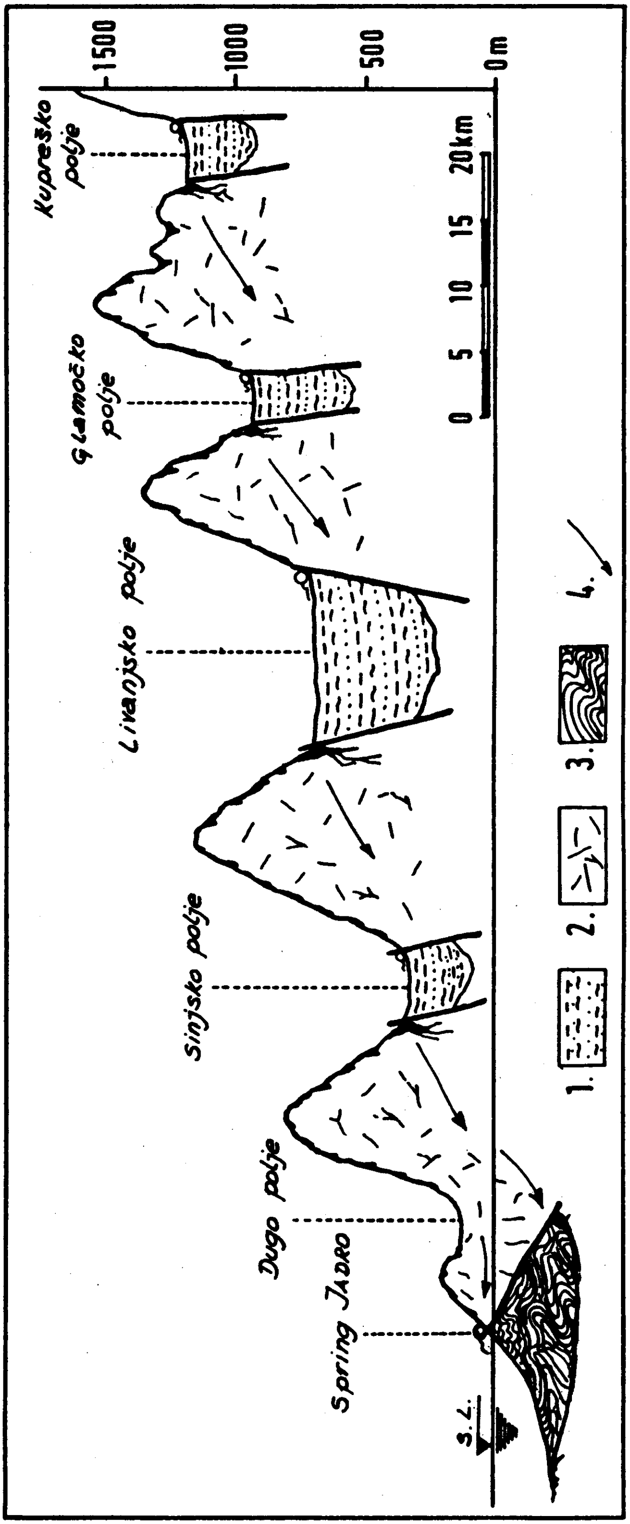
6.2. Schematic synthetic hydrogeological profile through karst poljes of Western Bosnia and Central Dalmatia.
1 - Neogene, 2 - Karstified limestone, 3 - Flysh , 4 - Groundwater flow.

6.3. Schematic synthetic hydrogeological profile through karst poljes of Eastern Herzegovina nad South Dalmatia.
1 - Karstified limestone, 2 - Neogene, 3 - Alluvium, 4 - Cretaceous flysh, 5 - Groundwater flow.

6.4. Model of development of draining net after the basic structures had been definitely formed. After S. Bahun.
I - Start of the karstification after raise of sedimentation basin. Formation of the first concentrated flows towards the erosion basis. Probably at the end of Oligocene - start of the Neogene. II - Neo-tectonic, mostly vertical movements, differential movement of block along normal and vertical faults. Water courses are gradually intersected by faults and even less karstified subsided blocks act as barriers, although being already under formation of inner caves, and waters along faulted zones.
A - raise towards the surface, B - flow deeper to previous, but nowadays deeper level, C - flow downward fault along downstream edge of depression, D - raise upward from deeper parts to unsubsided previous streams, E - make new courses in still unkarstified underground. These processes occured probably in the Younger Neogene and Pleistocene.
Afterwards, due to relative increment of sea water level (F) primary courses come under impounding sea water level and new courses are formed on a level of a younger erosion base. Probably pleistocene - holocene.
III - Supposed present net of undergrounf water connections in areas of karst field after erosion, corrosion and accumulation settling, i - spring, e - estavelle, p - ponor, v - submarine spring.

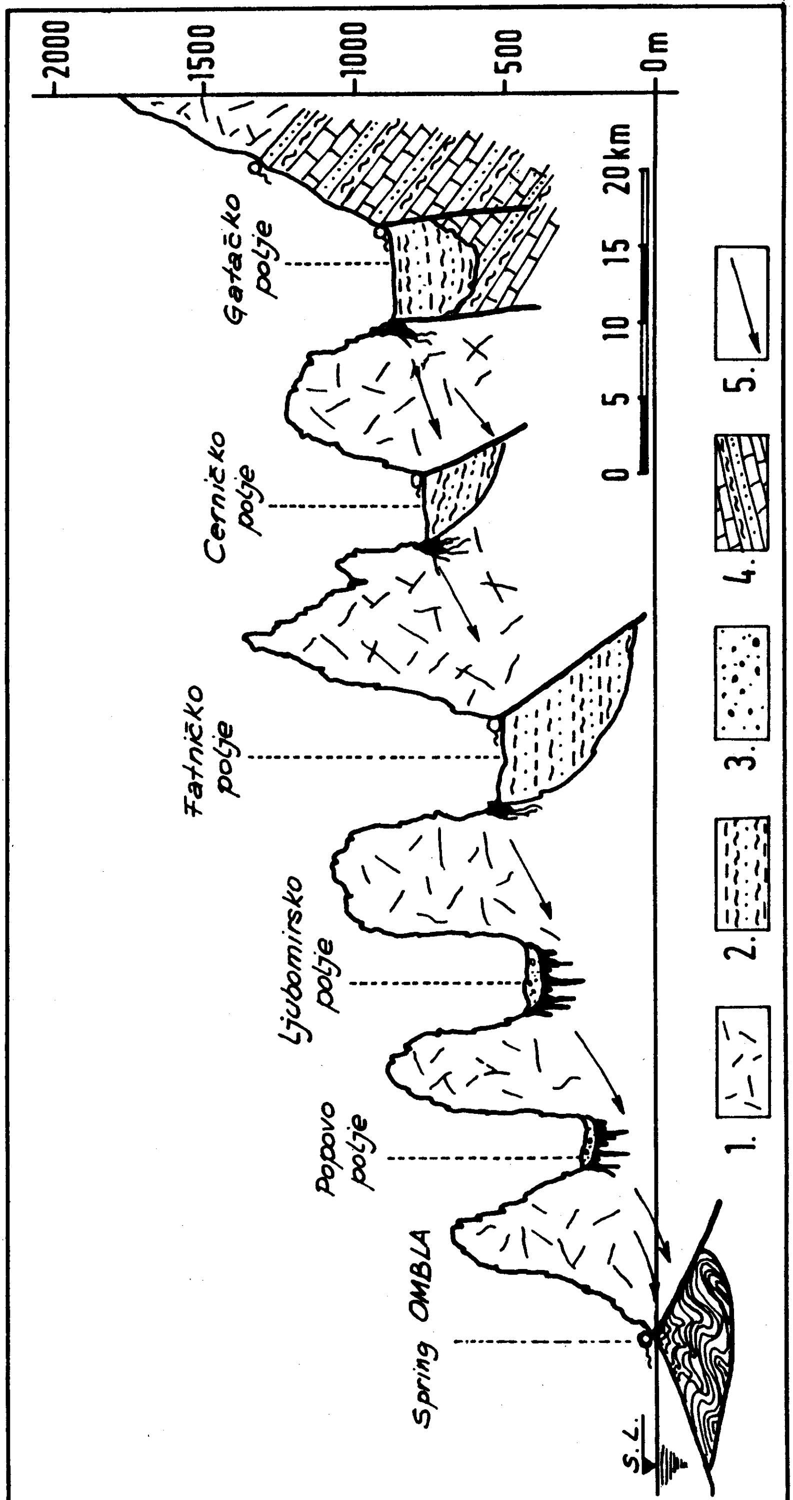
6.5. Schematic Hydrogeological Profile through karst poljes of Dinarides. 1 - karstified limestone, 2 - Neogene, 3 - Alluvium, 4 - Ground-water flow, 5 - direction of ground water flow around the barrier.





1500
1000
500
0 m
Kupreško polje
Glamočko polje
Livanjsko polje
Sinjsko polje
Dugo polje
Spring JADRO
S.L.
0 5 10 15 20km
1.
2.
3.
4.

Figure 6.2



2000
1500
1000
500
0m
0
5
10
15
20km
Gatačko polje
Cerničko polje
Fatničko polje
Ljubomirsko polje
Popovo polje
Spring OMBLA
S.L.
1.
2.
3.
4.
5.

Figure 6.3

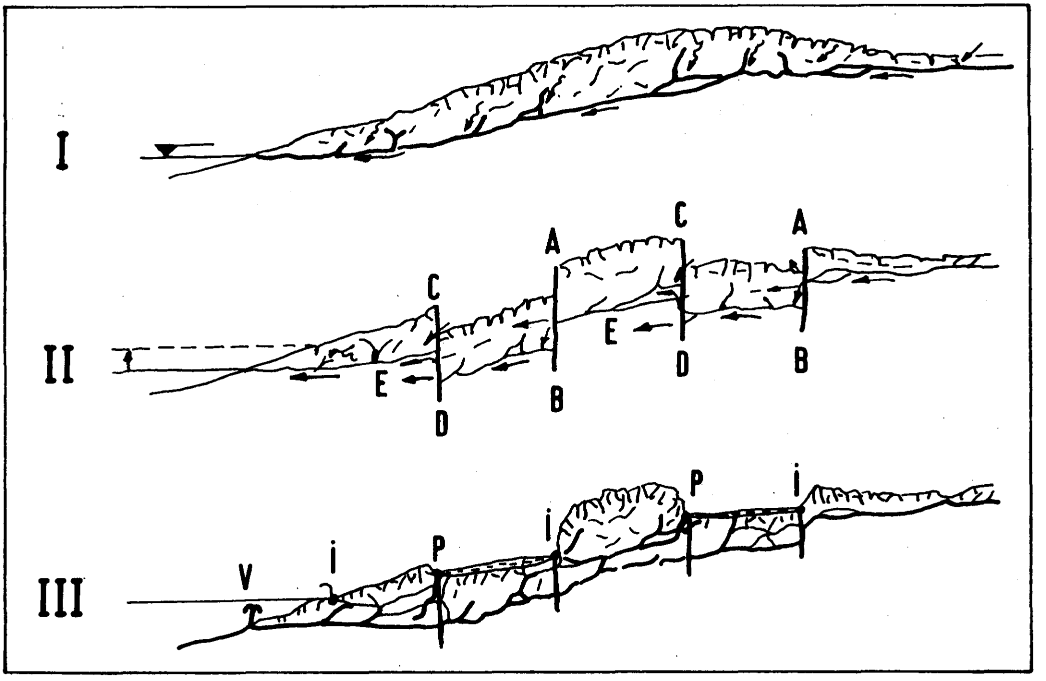


Figure 6.4

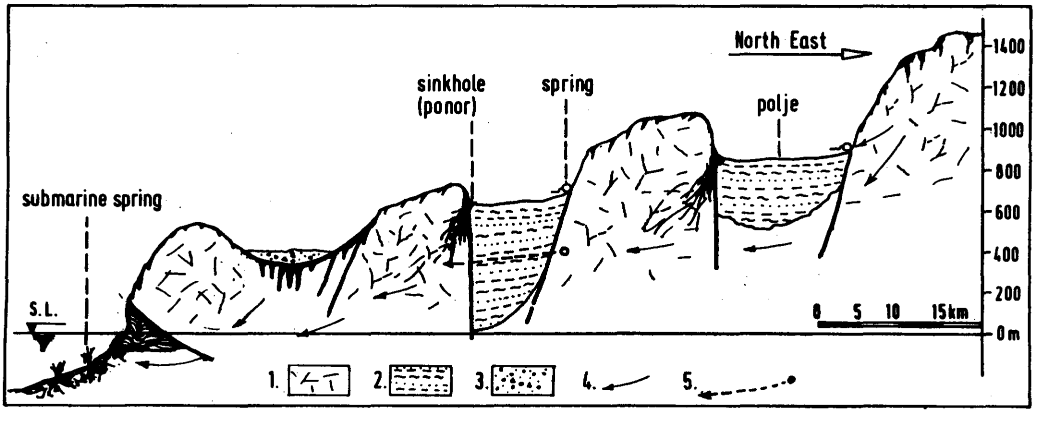


Figure 6.5

TABLES

Table 1: Characteristic pysico-geographic features of some karst poljes in Central Dinarides.

	Polje Name	Area/km²	Height above Sea Level/m
1.	Livanjsko	380	709 - 731
2.	Nevesinjsko	170	870
3.	Glamočko	130	882 - 950
4.	Duvanjsko	127	859 - 932
5.	Sinjsko	115	294 - 326
6.	Kupreško	95	1117 -1165
7.	Imotsko	92	255 - 270
8.	Ljubuško and Rastok	90	57 - 80
9.	Popovo	69	220 - 250
10.	Voskovsko and Ravno	58	1137 -1185
11.	Buško	53	702 - 709
12.	Konavosko	48	60
13.	Gatačko	38	950
14.	Mostarsko	34	225 - 250
15.	Rabarsko	33	470

Table 2: Basic height horizons and sub-levels of karst poljes in Central Dinarides

Level (Horizon)	Level of Above Sea Height Variation	Polje (Polje Elevation)
I	20 - 100	Bokanjačko (20) Vrgoračko jezero (25) Rastok i Ljubuško (57-80) Nadinsko (89-100)
II	169 - 330	Čitluk (196-222) Mostarsko (225-250) Imotsko (255-270) Podkraj (300-320) Mokro (272-280) Sinjsko (294-326) Dugopolje (266) Petrovo (279-330) Kosovo (274-300)

Table 2 (continuation):

Level Horizon	Level of Above Sea Height Variation	Polje (Polje Elevation)
Sub-level		Dicmo (340-370) Vrličko (371-400) Plavno (400-470) Muć (414-472) Drvarsko (459-500)
III	571 - 731	Livanjsko (709-731) Posuško (571-600) Viničko (601) Studenačko (650-660) Šipovača (640-708) Buško blato (702-709)
Sub-level		Grahovsko (780-810)
IV	859 - 980	Duvanjsko (859-932) Roško (890-923) Rakitno (886-917) Šujičko (919) Vučipolje (978) Glamočko (889-950)
V	1078 - 1278	Galovo (1078-1092) Kuprečko (1117-1165) Ravno (1137-1154) Vukovsko (1150-1185) Kruško (1170) Risovac (1205) Trebiševo (1278) Dugo polje (1182-1230)

Table 3: Height karst poljes horizons in Eastern Herzegovina. After P. Milanović (1973).

Horizon	Variation Interval (m)	Karst Polje (Polje Elevation)
I	60 - 86	Gradačko (86) Konavosko (60)
II	220 - 270	Popovo (220-250) Mokro (270)
III	460 - 520	Ljubinsko (470) Ljubomirsko (520) Dobarsko (470) Fatničko (460)
IV	850 - 1080	Cerničko (850) Nevesinjsko (870) Gatačko (950) Lukavačko (1000) Slato (1080)

7

A REVIEW OF SOME SIGNIFICANT PONORS IN SINJSKO AND DUVANJSKO POLJES

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The Sinjski Ponor Zone on the western margin of former Buško blato, i.e. the present Buško jezero lake, was investigated in detail during artificial accumulation realization, and particularly the Požrikoza and Sinjski ponors (Fig. 7.1). During the injection works in this area as a whole it became clear that the morphology of the Sinjski ponor is the most complex one and just because of its complexity this system was treated as the Sinjski ponor zone. The zone consists of formerly known channel of natural hollow and a number of additionally drilled sections divided in sectors.

The Sinjski ponor is provided now with a concrete plug as a partitition in the original hole. From inside the ponor continues as a horizontal canal with gradual but slight elevation. The main canal is approximately 125 m long and its branch is 35 m which altogether makes 160 m in length. The lowerest point of the ponor is only 8.5 m lower than the polje's level. The ponor terminates in the form of a large chamber 40 m long, 20 m wide and 5 m high. The ponor was active in the period of very high waters in the polje.

The Drilled Extension of the ponor was discovered during the works on the grout curtain along the Sinjska jaruga defile. Drillholes helped detection of many sinkings of the ground and as a result access galleries were cut through the drilled space.

Through the gallery 28 m long it was possible to enter the natural extension of the Sinjski ponor and to investigate 280 m of the canals and chambers with active water flow at the bottom. In further drilling and cutting galleries a part of the hollow was discovered in the 7th sector which is closest to the end of the natural canal of the Sinjski ponor. The total length of speleologically investigated canals of the already known section and additionally drilled parts is 470 m. Owing to the concrete plug which was made in the direction of discharge canal, the underground lake which oscillates with water level variation in the nearby accumulation, was formed in a large chamber (48 m long, 15 m wide and 22 m high). The section of the ponor behind the plug is completely dry now, and it is accessible through additionally cut inclined tunnel over 100 m long.

Very complex morphology of the Sinjski ponor and detction of water flow at the lowerest levels of drilled holes indicate uprupt lowering of ground water level at the very margine of the polje. This abrupt water level lowering at high water in the polje (during the period of diluvial abundancy of precipitate) resulted from the erosion power of fissure system and less stable parts of limestone deposits destruction. The space formed by erosion widens later on owing to corrosion activities followed by calcite draining and fallen blocks bonding.

The Stara Mlinica Ponor is the best known and the most important ponor of Buško blato. The ponor is located outside the artifical accumulation on the southwest side of the polje, between the villages Rašeljak and Liskovača. Of all speleologic objects in this area this one is still active, serving for discharge high waters from the accumulation (Fig. 7.2).

The entrance canal of the ponor was concreted and regulated nearly sixty years ago. The ponor hole is 8 m wide and 12 m high with a concrete step 15 m below the entrance.

The subsurface structure of this ponor consists of the main canal 305 m long and an auxiliary canal 85 m long which altogether amount to 390 m. The lowest point in the ponor is 34 m below the surface of the polje. The largest underground space of the ponor is the central chamber 12 m long, 25 m wide and 20 m high. The interior of the ponor is characterized by stone walls with regulated canals which were maintained properly for a long period of time to be of better "porosity" during high water seasons. Low canals in the terminal part of the ponor are filled with drifted wood, sand and other material, but it is obvious that unsearched network of the canals continues through Kamesnica massif.

The Stara Mlinica ponor formation is closely connected with the fractured limestone zone and typical fissures along which water sinks. The erosion power of flooding water from the Diluvial till present days, together with drifted material, effects widening of fissures and canals resulting into existing underground morphology.

The Kovači Ponor in the Duvanjsko polje. Because of its exceptional hole dimension this ponor ranges among the most interesting ones in the entire Dinaric karst region (Fig. 7.3).

The entrance to the ponor has two holes - the eastern and the northern holes, over 20 m wide and high. Water of the Šujica sinking river sinks under the eastern hole where a smaller watermill is erected.

According to the morphologic classification this is a structure with horizontal canals which at a certain distance from the entrance continue in the form of syphon basins. The northern branch of the ponor is mainly dry, with drifted material and a smaller syphon on the end. The southern branch is a canal filled with active water flow which disappears in the syphon at the edge of a larger underground chamber. Search by diving in this syphon discovered continuation of underground canals but they were not investigated in detail later on. The syphon is 40 m long and water is about 10 m deep.

The total length of all investigated underground canals till now amounts to 180 m. Since waters of the Šujica sinking river appear on the outlet above the Ričina cave in the horizon of Buško blato, it is normal to assume that a network of underground canals exists here in considerable length.

Formation of this ponor is in connection with typical faults and fissure systems in folded limestone, along which erosion and corrosion activities resulted in shaping of underground caves system.

FIGURES

7.1. Sinjski ponor and its investigated extension.

7.2. Sinkhole Stara Mlinica.

7.3. Sinkhole Kovači - Duvanjsko polje.

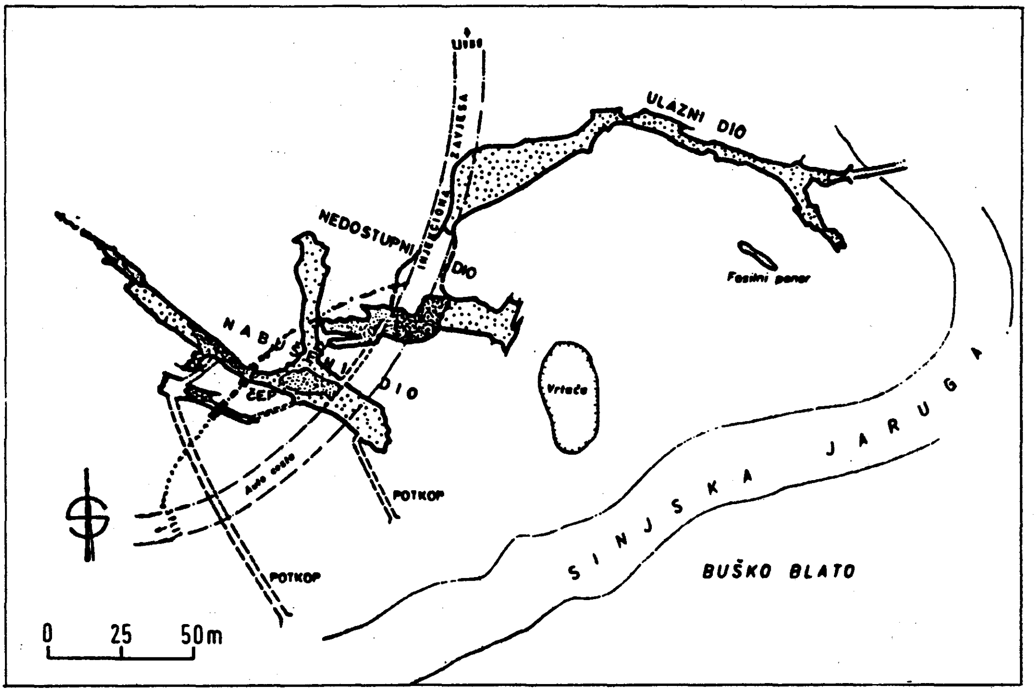


Figure 7.1

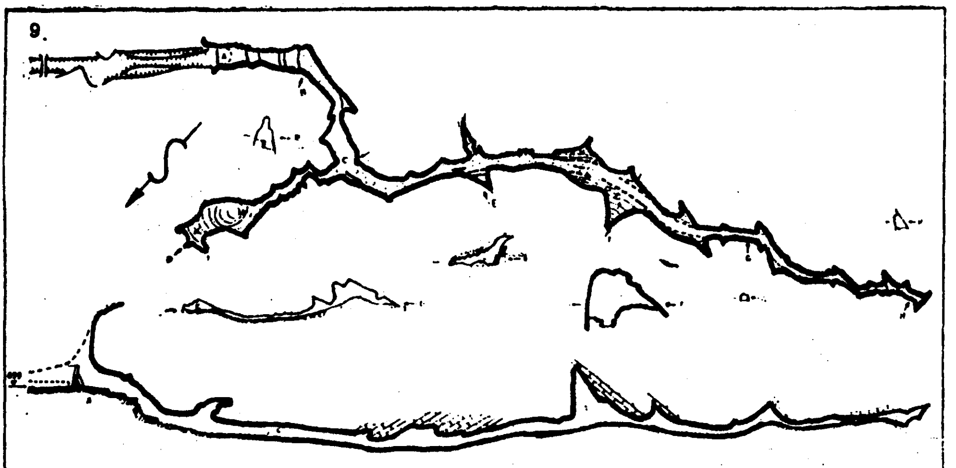
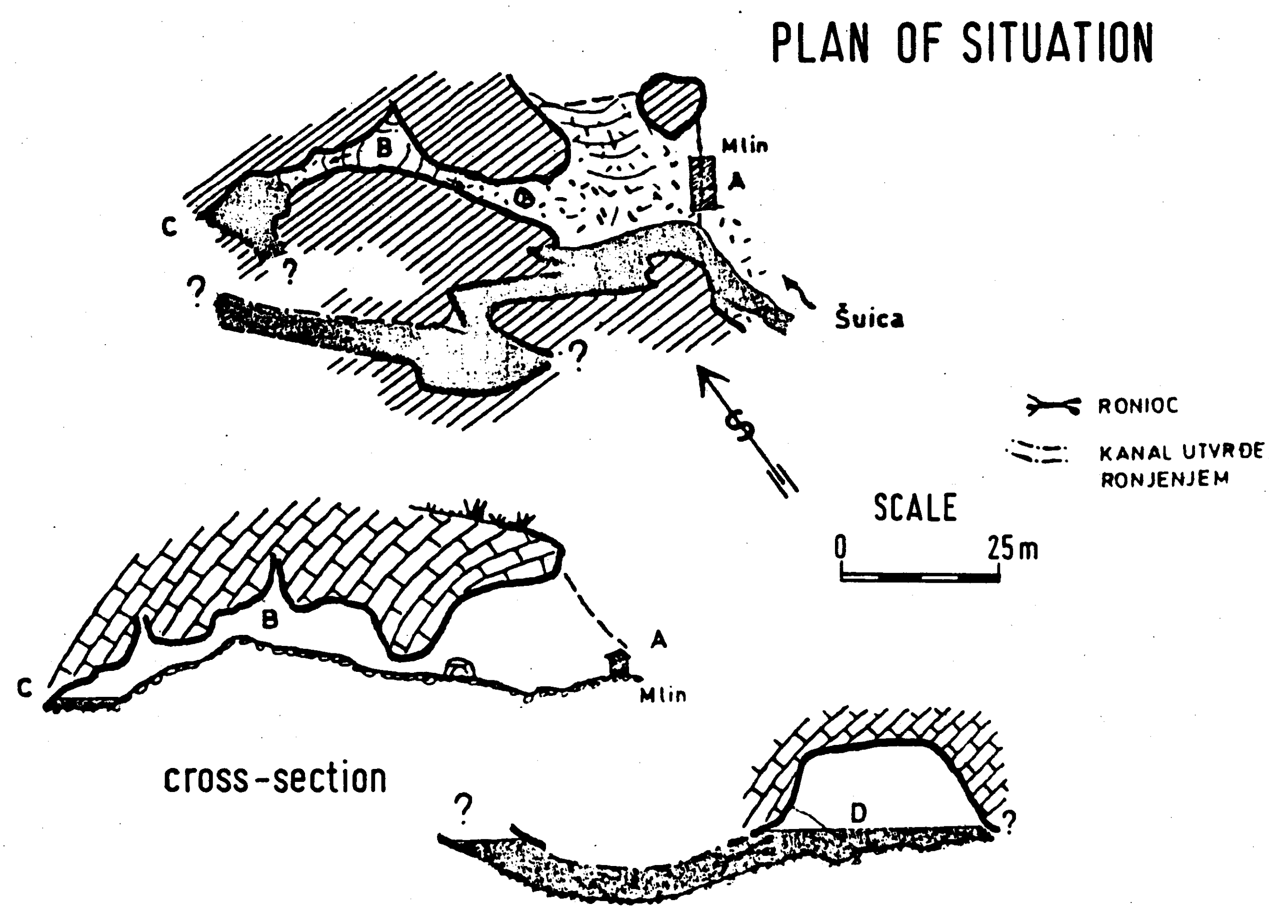


Figure 7.2

Figure 7.3



PLAN OF SITUATION
Mlin
A
B
C
Šuica
RONIOC
KANAL UTVRĐEN RONJENJEM
SCALE
0
25m
A
B
C
Mlin
D
cross-section

8

PROBLEMS OF SEA WATER INTRUSION INTO AQUIFERS OF THE COASTAL DINARIC KARST

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1. BASSIC ASSUMPTIONS

Due to complexity of the problem, many studies have been devoted to exploitation of the coastal aquifers which are in some contact with sea water. Physical aspect of the problem, expressed through the difference in specific gravity of fresh and salt waters based on well known Ghyben-Hertzberger Law, is the main factor whose understanding is often the only and essential thing for successful solution of such problems in practice. This is the case with homogenous intergranular water aquifers (basalt lava on the Hawaiian Islands; Tertiary and Quarternary fine sand at the Netherlands coast, Israel and Florida, etc.) where, strictly speaking, circulation of ground waters is subordinated to Darcy's Law of stationary filtration (aquifers with very low flow gradients of 3.10^{-4} order and smaller) owing to which it can be assumed that fresh water circulating streams are nearly parallel, i.e. that Dupuit's hypothesis is satisfied and that salt water is stationary.

Huber's equation, which takes in consideration circulating stream bending near the coast line, and particularly the equation of Lusczynsky for varying density liquids, will give results of satisfactory preciseness when used for determining fresh water lens thickness and the characteristics of contact interspace which has been formed as a transition diffusion zone between fresh and salt water in an aquifer.

However, the problem of ground water exploitation from captages made in karst coastal aquifers cannot be solved analogously, i.e. on the basis of the known hydraulic gradient of fresh water zone of coastal aquifers and Ghyben-Hertzberger coefficient, regardless general validity of the basic principle of Ghyben-Hertzberger Law.

Therefore, here we have a secondary phenomenon caused by geometrical anisotropy of karst aquifers which has an unfavourable effect on the maintenance of stationary conditions of underground circulation in a longer period of time, that is on balance between fresh and salt water zones in coastal aquifers.

This concerns the retention of an aquifer or retardation of unterground outflow which is, in general, insignificant in karst terrains due to their high and uneven permeability through the privileged directions of drainage.

Hydrogeological evolution of karst aquifers of the Dinaric littoral was decisively effected by the rise of the Adriatic Sea level for about 100 m during the last Interglacial (WÜRM). Direct consequence of this phenomenon was intrusion of sea water into mainland, owing to which all karst aquifers along the present sea coast were filled with sea water included in the permanent dynamic process of ground water circulation. In karst collectors mingling of salt and fresh waters is the result of mechanical convection of both of them, due to which sea water appears during the year at completely different elevations: from the sea level up to several tens of meters above sea level (periodical spring Slanac near Trogir is at el. + 27 m).

In the littoral karst aquifers a transition zone is formed between fresh and salt water, and this zone has no more the structure of the classic contact diffusion zone of small thickness (as it is the case with intergranular homogenous aquifers), but on the contrary it is very wide, irregular in shape, and with brackish water of varying salinity; along the coast this zone fills completely the karst collectors and it is the only ground water there, which results in the ocurrence of brackish and submarine springs whose salinity varies in a very wide range from about 1000 mg/l Cl' up to over 10000 mg/l Cl'.

The major problems in locating captages and evaluation of fresh water resources of littoral karst water bodies, result from inadequate understanding of physio-chemical and dynamic characteristics of this zone. Whereas, for instance, transition diffusion zone in intergranular aquifers is successfully treated by means of electric digital machines, its presence in collectors of typical karst aquifers often makes the quantitative hydrodynamic analysis of water balance and relations between fresh and salt waters unnecessary, and the reliable forecast of their regime in a wider area of the coast.

The problem is rather complex in general for the analytic treatment, because of a large number of different factors which have a direct influence on formation and behaviour of transition or brackish zone.

These are, first of all, different external factors such as natural inflow and outflow of fresh water, artificial discharge of fresh water from the water body by pumping, and intrusion of sea water into mainland, followed by oscillations of high and low tide.

On the other hand, geometrical heterogeneity of collectors and anisotropy of karst aquifers, as the most important internal factors, have a major effect on fresh water zone contamination process, that is on formation of specific forms of transition zone as a dispersion phase between fresh and salt waters (in karst collectors), whose dynamic and physio-chemical properties vary from location to location, gradually or in step-like fashion, depending on variable geometrical features of the aquifers.

Transition zone thickness at any point, will depend on the dispersion coefficient of an aquifer, uneven flow of fresh water, conductivity coefficient and high and low tide situation. However, since occurrence of singular points in the stream circulating field is not rare, because of the local character of ground water circulation and its concentrated outflow, it is impossible to express mathematically, with a precise functional relation, the interrelation of all these factors although they are globally known.

In the natural conditions, therefore, it happens that some captages in a period of pumping are encroached by sea water slowly, while others on the contrary very quickly, say instantaneously, under the influence of brakish zone, what otherwise is not a usual occurrence. True reason of the last phenomenon can not be explained either by existing water levels in captages or by their piezometers.

By systematic study of different examples of salt water instrusion into karst aquifers of the Dinaric coast line we come to conclusion that in solving the above problem particularly important is to know:

- behaviour of a transition or brackish zone in function of mechanism of sea water instrusion, and
- local geological and hydrological characteristics of an aquifer expressed through reliable determination of structural model of the aquifer in question.

Since behaviour of transition or brackish zone in karst aquifers is conditioned directly by mechanism of sea water instrusion, different effects of salt water encroachment upon fresh ground waters can be expected in dependence on whether the aquifer is opened towards the sea or hindered by some barrier. If we take into account also the local geometrical properties of the aquifer, which decisively effect as intensity of sea water intrusion so also dilation of brackish zone in aquifer, then it is evident that complex searching for the causes of sea water intrusion into karst captages and its control cannot be feasible without a good knowledge of local geological and hydrological conditions of the area.

Therefore, it is of high scientific and practical interests to define reliably the limiting conditions (geometrical in the first place), which strictly relate to a certain drainage system of an aquifer in which the natural balance of fresh and salt waters is disturbed.

At the same time this points out the necessity of observing sea and brackish waters migration in the field as well as of constant practical check of the maximum pumping capacity in function of cone influence between brackish and salt water.

Therefore, for solution of these problems the following is understood:

- investigation works,
- choice of an adequate type of rational captage to avoid or lessen the effects of brackish water intrusion into fresh water zone of a karst coastal aquifer, and
- establishment of observation points for brackish water instrusion during exploitation of the captages.

This work contains characteristic examples of sea water instrusion into karst aquifers of different geological and hydrogeological properties in natural conditions as well as the effects of influence of brackish water on fresh water zone during ground water exploitation. On these examples the main principles of fresh ground water captation methods will be defined.

2. CLASSIFICATION OF LITTORAL KARST AQUIFERS ACCORDING TO THE MECHANISM OF SEA WATER INTRUSION INTO THE MAINLAND

When intrusion of sea water into the mainland is considered as the main cause of mixing salt water with fresh ground water then all littoral karst aquifers can be divided into two basic groups, without regard to their geological age and differences in tectonic structure:

I. Aquifers opened towards the sea, in which hydraulic link between ground water and sea water is provided through the contact surface between aquifer and the sea (see Fig. 8.1).

II. Aquifers with incomplete barrier towards the sea, in which the hydraulic link between ground water and sea water is obtained only through localized contact surfaces between aquifers and the sea, in dependence on hypsometric position of an incomplete barrier (see Fig. 8.2 and 8.3).

However, aquifers with complete barrier cannot be the subject of discussion, since they are not affected by sea water intrusion.

In dependence on location and extension of the contact surface between karstified rock and sea (what, in fact, makes geometrical limiting conditions), at coastal karst aquifers with incomplete barrier, different cases of salt water intrusion into fresh water zone can occur. However, only two cases are the basic ones:

- aquifers with incomplete barrier in the sea, in which sea water intrusion occurs above the barrier (see Fig. 8.2), and
- aquifers with hanging barrier in which sea water intrusion occurs below the barrier (see Fig. 8.3).

By detailed study of the cited characteristical and typical examples we can get some useful hydrogeological criteria for setting a calculation scheme of an aquifer. Aim is to contribute to the more rational design of captation structures in litoral karst on the basis of field observations and investigations for the optimum utilization of fresh ground waters.

3. EXPLOITATION OF FRESH WATER ZONE

Before any locating of a captage in terrains of the litoral karst, certain compatible hydrogeological investigations are carried out.

After completion of preliminary investigation including:

- mapping of a terrain,
- inventory and levelling of existing ground water outcrops,
- indication of salt water and brackish water intrusion into collectors of karst aquifer, mainly by geoelectric and exploratory drilling,
- circulation of fresh water balance and evaluation of their resources based on studies of an aquifer recharge and drainage conditions through a study of a rainfall regime, level oscillations in piezometers, test pumping, and yield of springs.

The most important question put before the investigation project is, selection of an adequate type of captation and control system for observation of brackish water migration effects during exploitation of fresh water.

3.1. AQUIFERS OPENED TOWARDS THE SEA

In aquifers opened towards the sea exploitation from fresh water zone always cause disturbance of the original equilibrium and establishment of a new one manifested by extension of a transition zone, i.e. by brackish water intrusion into fresh water zone. In general, intensity of this disturbance is less if the distance between the captage and sea is bigger.

Regarding this problem, two cases are possible:
- karst aquifer is represented by dissoluble-fissure system of collectors,
- karst aquifer is represented by its system of isolated flows.

In the first case, at small flow gradients and fictive flow speeds of up to 1 mm/s rate, the difference in densities of salt and fresh waters allows the interrelation of these two fluids in the fissure network to be analysed by use of the following equation:

$$\Delta p = (H + h) \cdot \rho \cdot g - H \cdot \rho_s \cdot g \qquad (1)$$

However, it is wrong to assume that there is no salt water pressure drop towards the mainland and that both the salt and fresh waters are steady.

It is possible therefore to derive an expression which would take into account the dynamic state of these fluids, by piezometric level derivation in each of these fluids. In this way, dynamic equation can be obtained for more proper expression of equilibrium conditions near the coast line (Fig. 8.4).

$$H = \frac{\rho_s}{\rho_s - \rho} \cdot h_s \frac{\rho}{\rho_s - \rho} \cdot h \qquad (2)$$

Thus the depth to the salt waters can be defined by pressure and density.

Calculations based on the equation (2) and at a distance from the coast also on the equation (1) are acceptable under conditions of nearly all aquifers of dissoluble-fissure type, since brackish zone is not considerable disturbed either by daily or seasonal oscillations of ground waters, because of relatively slow underground circulation. Here, as by the rule, mechanical convection is excluded in formation of a transition zone, and concentration gradient gradually changes from salt to fresh water. This is the case, for instance, with littoral karst of the South Italy (Puglia), where dissoluble-fissure aquifer was discovered by means of a number of drill holes, draining towards the Adriatic and Ionian Sea. For the value of last water density ρ_s = 1.028 g/cu. cm and fresh water ρ = 1.0028 g/cu. cm, the ratio H = 40 for theoretic depth to salt water was obtained. With precise measurements in the largest part of the water body it was found that up to 4/5 H depth the total salinity varied from 0.6 to 5 g/l (the highest values were found in the lowest sections of the water column). Near the end of the last, fifth section of theoretical depth, the total salinity increased rapidly to 20 - 30 g/l, what undoubtedly indicated transition into the coastal zone.

Exploitation of fresh water from dissoluble-fissure coastal aquifers is most often done by means of drilled wells of large diameter, due to their relatively good yield and simple, not expensive and fast construction.

Pumping from water well causes withdrawal of brackish and salt waters and this critical depth to the salt cone is nearly equal to the product of Ghyben-Hertzberger coefficient and obtained decrease of water level in the well.

We shall concentrate ourselves on examination of this phenomenon under steady conditions, when the transition zone is reduced.

At H depth the pressure (Fig. 8.5) is:

$$p = (H + h) \cdot \rho \cdot g, \qquad \text{i.e. } p = h + h$$

Since H = f(h), at pumping of water and when h value decreases, H will also change; if a level lowers down for Δh the coastal zone pressure will increase. In this way the salt cone intrudes the fresh water zone. The newly created pressure of fresh water at pumping point will be:

$$p = (H + h - \Delta h) \cdot \rho \cdot g, \quad \text{i.e.}$$

$$p = H + h - \Delta h$$

and thus the new depth of fresh water zone in the analysed cross section:

$$H_s = \frac{\rho}{\rho_s - \rho} (h - \Delta h) \tag{3}$$

Discontinuity of fresh zone will appear when, from the conditions of limiting value:

$$\lim H_s = \lim \frac{\rho}{\rho_s - \rho} (h - \Delta h)$$

Height of intruded salt water cone into fresh water zone is:

$$z = H - H_s = \frac{\rho}{\rho_s - \rho} h - \frac{\rho}{\rho_s - \rho} (h - \Delta h) \quad (4)$$

$$z = \frac{\rho}{\rho_s - \rho} \cdot \Delta h$$

Since $\frac{\rho}{\rho_s - \rho} > 1$ then $z > \Delta h$ which means that the salt cone is intruded into the fresh water zone faster than pressure lowering from which it results. Here we have dilation of a transition zone and appearance of a brackish "protuberance" for which the Ghyben-Hertzberger coefficient is relatively fast rising. The first manifestations of salt water rising can occur very soon in water of a well, if pumping capacity is considerable higher than fresh water inflow.

In that case, the only effective protection against salt cone instrusion to the bottom of a well will be establishing of sufficiently high overpressure of fresh water at the point where intrusion of brackish water is wanted to be blocked. This protection, however, cannot be a long lasting one, if pumping rate is not compatible with natural feeding conditions of an aquifer. On the contrary, it causes exploitation of limited fresh water reserves.

Obviously, complete breakage or reduction of water pumping enables efficient observation of salt and brackish waters intrusion.

In the open type littoral aquifers of dissoluble-fissure collector systems, in which contamination of fresh water during exploitation period mainly occurs by vertical penetration of brackish water from the bottom, as in general, location of several captages in some area of an aquifer or a battery of wells of smaller capacity may represent a good and efficient solution for "surface" exploitation of littoral water tables.

Theoretically, if we want to prevent intrusion of salt water into the bottom of a well, then it is necessary to have limited drawdown h, which according to the equation (4) is

$$\Delta_h = \frac{\rho_s - \rho}{\rho} \cdot z \frac{\rho_s - \rho}{\rho} H - \frac{\rho_s - \rho}{\rho} H_s,$$

always less than piezometric level of the water table i.e. $\Delta h >> h$.

Since theoretical depth to salt water must not be taken as reliable, due to the presence of transition zone, it is necessary to introduce an additional reduction coefficient (b) for real depth ($Hr = b \cdot H$); it usually varies between values 1/2 and 4/5 if the contents of 300 mg/l Cl is taken as the upper limit of transition zone. In that case:

$$\Delta h \frac{\rho_s - \rho}{\rho} b \cdot H - \frac{\rho_s - \rho}{\rho} Hs, \text{ i.e.}$$

$$\Delta h = b \cdot h - \rho \cdot H_s \qquad (5)$$

If we put that

$$\frac{\rho_s - \rho}{\rho} = \Delta\rho$$

for a coastal aquifer in the Cenomanian-Turonian dolomites of the town Šibenik hinterland, which are partially covered with Quaternary sands to the sea shore, then equation (5) can be written in the following form:

$$h = 0.8 \cdot h - 0.02 \cdot H_s$$

since a reduction coefficient b, as calculated, represents the mean value between 0.6 and 0.98 and that ρ_s = 1.020 g/cm^3 and ρ = 1.000 g/cm^3.

The nomogram shown in Fig. 8.6 was constructed according to the above formula, with the difference that value of a limited drawdown was divided by 2 ($\Delta h_s = \frac{\Delta h}{2}$) in order of better securing of the captage.

Since allowed limited drawdown is a function of depth to the salt cone below the sea level, $\Delta h_s = f(H_s)$, in water pumping during exploitation of the captage there is undoubtedly a certain "optimum" for H_s, which corresponds to the most rational exploitation of fresh water. So, for instance during a pumping period in summer of 1963, at the piezometric level of + 1.00 m, the allowed limited drawdown could not be more than 0.30 - 0.35 m per well to obtain H_s vaule of about 25 m. Under such conditions, in the defined aquifer zone, salt and brackish waters do not intrude into the pumping regime was disturbed by a higher rate.

In Marinski Bay, near Trogir, at a distance 3 km from the sea shore, fresh water is pumped from captage of a gallery type which is located at depth of 27.5 m (el. 0.90 m) and perpendicularly on flow direction towards the sea, 20 m in length. On the basis of pumping during summer 1960, it was found that at piezometric water level + 2,50 m in the captage at pumping rate of 5 l/s drawdown of 0.40 was obtained, in which case salinity of water does not rise over 150 mg/l Cl. According to testing of piezometer B-3, located nearest to the captage by el. - 60 m, it was found that intrusion of salt water into captage from the bottom advanced rather slowly.

Varying of Cl (mg/l) contents in water column of the observation piezometer B-3, during test and exploitation pumping of the captage in the Marinski Bay, at an average pumping rate of Q = l/s.

In this way, at pumping rate of 5 l/s from a drainage gallery in the Marinski Bay, not only the permanent exploitation of fresh water from this aquifer is secured, but also blocking of salt water at considerable depth below the pumping structure (more than 50 m) (Bibliography 6, pp. 1-62). A drainage gallery thus ensured very efficient "surface capture of fresh ground water zone".

Table 1

Date	Depth of piezometer (m)	26 (-2.0)	30 (-1.5)	40 (-11.5)	50 (-21.5)	60 (-31.5)	70 (41.5)	80 (-51.5)
16.09.1960		58	56	119	149	146	127	135
18.09.1960		116	122	145	145	156	154	150
20.09.1960		103	101	145	130	142	153	146

Problems of exploitation of fresh ground waters from the coastal aquifers represented by systems of isolated ground flows, can not be equalized with the problems of water exploitation in described examples, because of a very strong influence of geometrical anisotropy of aquifers onto the mechanism of sea water intrusion and dynamic regime of ground waters.

All experiences, so far, in Yugoslavia and in the world, have pointed out great difficulties in determination of allowed drawdown at water pumping from the captages in such aquifers. There are examples, particularly on islands, that even insignificant drawdowns of only some centimeters can cause intrusion of salt water into the wells.

Due to the privileged directions of underground circulation and concentrated drainage through collectors of larger size, which are opened towards the sea, very close ties between sea water and fresh ground water are established. Under such conditions spreading of the brackish zone can be considerably accelerated by oscillations of tides. Any lowering of natural water flow through the collectors can effect propagation of brackish water in the reverse direction from fresh water flow. In these aquifers intrusion of salt and brackish waters in the form of characteristic cone (caused by pumping) does not run only from the bottom, below the pumping point, but also along the entire contact surface between the transition and fresh water zones (Fig. 8.7). Which of these salt cones will become the most harmful for the captage, it will primarily depend on the position towards the captage of those low-levelled collectors opened towards the sea, whose proper profiles are the largest. If, for instance, the captage K-1 on the island of Brac is pumped at a rate of q = 1 l/s, the Cl content in water starts rapidly to rise even over 500 mg/l, only after few hours of pumping, although without any lowering of water level in a captage. In such cases, obviously, the equation (5) cannot be applied for calculation of H_s depth to the salt cone. And since it is impossible to localize all collectors which have a more significant role in a wider zone of captages, the usual approach is then in locating a captage at a bigger distance from the coast line.

Capture of ground water from karst aquifers which are mainly represented by systems of ground water flows with concentrated drainage at the sea level and below it, is connected with many risks, both in respect of captured water quantities and quality of water, and especially if that represents a system of drilled water wells. However, it was proved that captages consisted of horizontal drainage galleries, provided not only the maximum water capturing by intersecting of ground water flows, but also weakening of salt water effects during a period of fresh water exploitation by regulation of a pumping rate or by radical intervention on the ground flow itself (by construction of an artificial barrier perpendicularly on direction of water circulation).

This twofold positive role of a drainage gallery as a rational type of ground water capture from karst aquifers with systems of underground flows has been noted in several areas of the Dinaric littoral karst.

3.2. AQUIFERS WITH INCOMPLETE BARRIER TOWARDS THE SEA

In littoral karst aquifers with incomplete barrier towards the sea, as shown schematically in Fig. 8.2, sea water intrusion was localized to that part of the aquifer found in interval between the present sea level and the contact surface of the aquifer with the impermeable barrier (point A in Fig. 8.2). The longer interval, the weaker effect of sea water intrusion into the mainland.

Presence of salt water in an aquifer is not linked with the sea water intrusion under the present conditions and therefore structure of the coastal zone is different from that of the aquifers opened towards the sea. Here, coastal zone was formed by gradual filling of aquifers with sea water already during the older Quarternary and even earlier, so that zone of fossil, salt water, was formed by time, whose salinity in the deepest sections of an aquifer exceeded salinity of sea water, because of the steady conditions ($\rho_s > \rho_m$). Connection between this zone and sea water, which is established through a small contact surface between aquifer and sea, under present conditions, cannot have any stronger effect on change of its chemical composition, since stationary conditions have been established. The fresh water zone, however, effects the motion of salt water towards the sea, but the barrier prevents mingling of most of coastal ground waters with sea water. As the consequence of such situation, during filling of aquifers with infiltrated waters, the coastal zone is disturbed and this results into its fluctuation instead of into an accelerated run towards the sea.

From the physical point of view, this phenomenon is completely clear and can be explained by analogue phenomenon of oscillations of water masses and hydraulic stress in a water supply system.

So, for instance, ground water collectors of characteristic apophyge shape (with expressed vertical dimension), which are laterally weakly connected, in geometrical sense, are similar to various types of U-pipes, which at the bottom keep salt water in steady conditions (Fig. 8.8). In case of disturbance water level it comes to its oscillatory movement, the more expressed as dist bance is stronger. When applied to littoral aquifers, such situation may appear in case of any proportionally higher infiltration of atmospheric waters into aquifer. Since moved coastal zone can not eavenly discharge to the sea due to the applied pressure and it comes to whirling of all waters contained, to mixing of salt and fresh waters based on mechanical convection. This phenomenon is in no way effected by the sea water (except the immediate contact zone between aquifers and the sea, which is local). The examples from practice prove this phenomenon.
Very instructive is the example of the Boljkovac spring at Zadar which yields fresh water all through summer months, why it is connected to the city water supply system from June till September each year, while during the rainy season it is mainly brackish.

Ground water of the captage at Bol in the Island Brač, are brackish during winter, containing 600 to 900 ml/l Cl', while in summer, during pumping period, their salinity never exceeds 450 mg/l.

At Orebić, by exploration drilling, it was found that in deeper sections of an aquifers (below the sea level) brackish and salt water occur, what was well indicated also by geoelectric surveys. Test records of these drillholes are very interesting. On the grounds of these explorations, and also later on by encountering karst collectors in a gallery type captage, it might be concluded that under natural conditions, all through a year, fresh water zone extends to a depth of -20 m in a wide area of the captage, which is 1,6 km far from the sea. Belt between fresh water zone and coastal zone is in fact, a brackish zone, which already at such depths reacts to any abrupt change of the pressure in fresh water zone. Such changes, resulting only from a sudden change of water level, that might be caused by any heavier rain, lead to already described unsteady circulation through karst collectors which contain, not only fresh water, but also brackish and salt waters, due to their deep penetration into aquifer. Therefore, fresh water zone is periodically intruded by salt water.

However, if ground water does not occur, which is the case of correct recession conditions in aquifer discharge, i.e. during rainless period, then circulation runs mainly in fresh water zone and is slowed down nearly to stationary conditions; natural water flow through aquifer does not essentially effect a boundary in a vertical structure of fresh and salt water. During this period, pumping of water from the captage, at a rate approximately equal to that of natural ground water flow through aquifer, cannot cause a rapid rise of salinity in pumped water.

If, in the meantime, a water level is disturbed by rainfall, rapid intrusion of salt water occurs not only into captage, but through the whole aquifer as far as hydraulic stress reaches. This phenomenon was registered on August 20, 1972, as clearly shown in Fig. 8.9. On a diagram it can be seen that recovery could be attained in 7 to 10 days, if there were not new disturbances.

To avoid penetration of salt water into captage, it is necessary to stop pumping at any sudden disturbance of water level or to increase the piezometric level of fresh water over the minimum critical water level, at which naturally distrubed water level in aquifer would not produce syphon-like withdrawal of salt water from deeper sections of an aquifer. This complete protection of captage can be provided by erection of an artificial barrier close to the sea shore, to prevent, or considerably lessen a loss of fresh ground water from an aquifer.

In a system of karst aquifers with hanging barrier towards the sea (Fig. 8.3) any efficient protection against sea water intrusion is not possible, if captage is tried in the very zone of a coastal spring by means of artificial lifting of spring overflow level. This was the case, for instance, with coastal spring Pantan near Trogir where experimental works were undertaken for desalination of the spring by means of artificial lifting of an overflow level during summer 1973, but with negative results. Namely, although the spring overflow level was raised for 1,4 m, i.e. from +2.5 to 3.9 m, the salinity of water descrased from 7800 mg/l Cl' to 5500 mg/l. Apparently, mechanism of salt water intrusion operates from considerable depths and that contacts of low collectors with salt water are directly connected with fresh water collectors at the spring level.

In such cases captage of fresh ground waters is possible only farther inland from the spring, at the proper distance from a direct sea influence. So, for a karst aquifer of the Pantan spring it was found, on the basis of complex hydrogeological investigations, than most appropriate location of a gallery type captage would be at a distance of 1.6 km from the spring.

In general, in coastal karst aquifers with hanging barrier toward the sea, gallery type captages are undoubtedly more convenient than water wells, particularly when isolated ground water flows dominate.

4. CONTROL SYSTEM AS A COMPONENT PART OF PROTECTIVE MEASURES IN EXPLOITATION OF WATER FROM A CAPTAGE

To protect captages during their exploitation against intrusion of salt water it is necessary, in order of due interventions, to install a control system for observation of brackish and salt waters migration into a wider influence zone of a captage towards the sea. In this aim, a network of observation boreholes - piezometers is located for observing the brackish zone, both in its horizontal and vertical profile.

Disposition and number of piezometers depend on structure of the aquifer subjected to water exploitation as well as mechanism of sea water intrusion into low karst collectors.

In setting a system for observation of fresh water zone contamination effects, in the process of water pumping from captages, it is necessary to identify as precisely as possible:

- conductivity of an aquifer in the area between the captage and the sea;
- coefficient of water potential or effective porosity of an aquifer in the same area;
- vertical component of an aquifer conductivity along profile from fresh water to salt water, based on measuring the vertical gradient of water salinity in piezometers;
- evolution of salinity in all piezometers and the captage on the basis of simultaneous stationary testing of water column;
- location and structure of transition (brackish) zone;
- depth to effective circulation zone of ground waters.

Applied methodology, which must be respected in all these measurings and tests, is determined in dependence on particularity of the geological conditions of the area.

Symbols and Marks

p	- prassure
Δp	- pressure variation
H	- depth to coastal zone, reckoned from the sea level (m)
h	- heigth of fresh water, reckoned from the sea level (m)
h_s	- salt water pressure drop towards the mainland, reckoned from the sea level (m)
H_s	- depth to salt cone, reckoned from the sea level (m)
Δh	- drawdown in fresh water zone (m)
$z = H - H_s$	- height of salt cone (m)
$H_r = b \cdot H$	- reduced depth to transition zone reckoned from the sea level (m)
ρ_m	- sea water density (g/cm^3)
ρ_s	- density of salt water in aquifer (g/cm^3)
ρ	- fresh water density (g/cm^3)
g	- gravity acceleration (m/s^2).

5. SOME FRESH WATER CAPTAGE EXAMPLES

The coastal karst region from Split to Šibenik is characterized by typical development of flattened structures - anticlines and synclines - with slight bending of typical Dinaric trend of layers in east-west direction (Hvar bending of layers). Limestone and dolomite of the Upper Cretaceous age make the major part of the terrain, and in some elongated depressions the clastites of Eocene flysh are isoclinically intruded in block overthrust structures of carbonate beds by tectonic effects. Hydrogeologic role of the flysh impervious sediments (mostly marles and scarcely sandstones) has been very significant in karst coastal region, as it protects underground karst waters along the sea coast from direct mingling with sea water. This is the situation in the ample Split - Kašteli flysh synclinal structure, which owing to isoclinal structure of carbonate material (flysh overthrust) prevents intrusion of sea water in karst collectors. Due to the above situation the contact overflow springs appear in tectonic contact layer of flysh and limestone, which is the case with well known spring Jadro which serves for supply of water to Split and Trogir, and also the spring Žrnovnica. At the western end of Kašteli syncline, the flysh sediments are considerable reduced owing to tectonic activity and erosion, so that in hydrogeologic sense they do not represent the barrier for sea water penetration to coastal karst collectors. This is the reason why we have so many brackish and submarine springs in the bay at Trogir and from Trogir down to the Marinski Bay many others coastal brackish spring.

Northwest from Marinski Bay and Rogoznica there are also a number of bigger and smaller brackish water springs because of direct mingling of fresh and salt waters in karstified limestones. Here the flysh sediments are completely absent along the coast line and therefore intrusion of sea water into karst collectors reaches rather far into the mainland. In some karst valleys the influence of sea has its effects even 2 km far from the coast line. Because of that the hydrogeologic works on capturing the underground karst waters in these terrains are linked with many difficulties and risks.

Captation Works in the Area of the Pantan Spring

At the western end of the Kaštelanska Riviera, near Trogir, the strong permanent brackish spring Pantan, periodical spring Slanac and two submarine springs in its vicinity (whose total minimum yield reaches over 1.0 cu. m/s at the end of dry season) were the subject of detail and complex hydrogeologic surveys (Fig. 8.10) which were periodically undertaken during the recent 10 years.

From the geologic point of view it concerns the limestone anticlinal structure sinking under the Eocene flysh. Owing to its tectonic dissection and very low position in relation to the sea level, at the contact line between flysh and limestone, the permanent brackish spring Pantant and periodical brackish spring Slanac appear, as well as two submarine springs little bit farther in the sea (Fig. 8.11).

The Upper Cretaceous limestones, with intensive fissures and tectonically damaged and karstified, are under effect of strong underground circulation which was in the process of development during the entire Quarternary, explain why at present the Pantan spring is 11 m below the sea level and two submarine springs are at 37 m below the sea level.

The Pantan spring is connected to well expressed diagonal fault (in relation to anticlinal structure) which is extensive and which was identified by photogeologic survey and geologic mapping and later on by captage works as well. According to the surveys performed so far, this fault is supposed to represent the main privileged direction of underground circulation towards the Pantan spring.

The explorations so far have explained completely the mechanism of sea water intrusion to karst collectors. The explorations included detail geoelectric sounding of the terrain, drilling of exploration boreholes and long term observation of piezometric level of karst water bodies in the function of hydrometric survey of the Pantan spring, exploration of submarine springs in the sea during the fresh water level rising and sea water sinking in such submarine springs etc. The purpose of all these explorations was to find the most appropriate location for fresh water captage in the background of the Pantan spring. For realization of this significant Project the following was done until now:

- It is found that intrusion of salt water into the Pantan spring comes from the direction of submarine springs and from the periodical spring Slanac; evolution of changes in the fresh salt water system was recorded in function of precipitation regime in the catchment area and oscillations of water level of the aquifer in piezometers;
- Captation structure consists of vertical mine shaft 67 m deep with a horizontal water collecting gallery directed towards west at 260° bearing, at the bottom; its purpose is intersecting of the fault zone and capture of underground karst flow. Up to now the gallery penetrated through in the length of 45 m but it would be necessary to extend it for about 100 m more to encompass the complete fault zone i.e. ground water collector. A preliminary horizontal exploration borehole, which was completed during summer 1981, entered into waterbearing caverns of the fault zone, enabling thus tracing of water by means of sodium-fluoresceine before gallery extension. Three days after, the tracer emerged at the Pantan spring proving the presupposed role of the fault zone as a collector of the main drainage system of the Pantan spring.

Continuation of works in the captation gallery is expected for 1983, in which way supply of fresh water of Q_{min} = 200 - 250 l/s will be provided during dry season of the year.

Figs. 8.12 and 8.13 are schematic presentation of fresh and salt waters circulation, based on piezometric pressure in the rear of Pantan spring during winter 1975 and summer 1976.

As it can be seen from the above, the karst aquifer is located in the anticlinal limestone structure and it is tectonically divided in two blocks: block A and block B. During the period of high water levels, the underground karst waters flow through both blocks towards the Pantan and Slanac springs, that is towards the sea and submarine springs. During the period of low water levels, in summer season, the fresh water circulates only in the block A and towards the Pantan spring, while in the block B the brackish water inverse circulation occurs, what is the main cause of encroachment on the Pantan spring.

"The Roman Well" Captage in the Gustirna Uvala

In one karst uvala, north of the Marinski Bay, there is a captage named the Roman well, which is permanently connected to a separate water supply system since 1982, to supply the western part of Trogir Commune with fresh water.

The hydrogeologic surveys began in 1967 already, with exploration of coastal brackish springs in the Poljica Bay (Fig. 8.14). Later explorations which included geologic mapping, photogeologic treatment of the terrain, geophysical surveys and exploration drilling have shown optimum conditions for fresh water catchment in the Gustirna uvala at a distance of 2 km from the coast line.

Works on the captation started in 1969 and were completed in 1972. During 1975 the works on the water supply system had started and were completed in 1981 and in this way the supply of water for the whole area was ensured.

The captage consists of vertical access shaft, 82 m deep (the shaft bottom is at $\pm$ 0 level), and a horizontal water catchment gallery in the total length of 270 m (at the level +1.5 m and +2.5 m). This captation is shown in Fig. 8.15.

The horizontal underground gallery, as it can be seen intersects five zones of karst collectors (of tectonic origin) - reservoirs and conductors of ground waters, enabling thus exploitation of captured water. The results of test water pumping during summer 1971 and in 1975 show that pumping capacity of about 120 l/s can be provided during the hydrologic minimum. The outstanding results of this captage are not only in relative high quantity of water which can be pumped from the access shaft, but also in good quality of water having Cl content of about 250 mg/l, during pumping period, is maintained within the limits of +2.5 m level and +1.5 m minimum, which ensures proper protection of the captation from sea water penetration into the karst collectors. Evolution. i.e. development of salt cone is observed through a satellite piezometer, installed in captation area and reaches to 30 m below the sea level. In this way a specific control of salt cone development is provided and also the possibility of higher intrusion of salt water into the captage is prevented during the exploitation period. This probably could not be possible if vertical drilled wells were used instead of this gallery for fresh water exploitation.

Horizontal drainage gallery offers favourable conditions for eventual artificial intervention in individual collector zones as well, to lessen underground discharge of fresh water and improve the accumulation balance of karst aquifer and its quality in respect of Cl contents in water.

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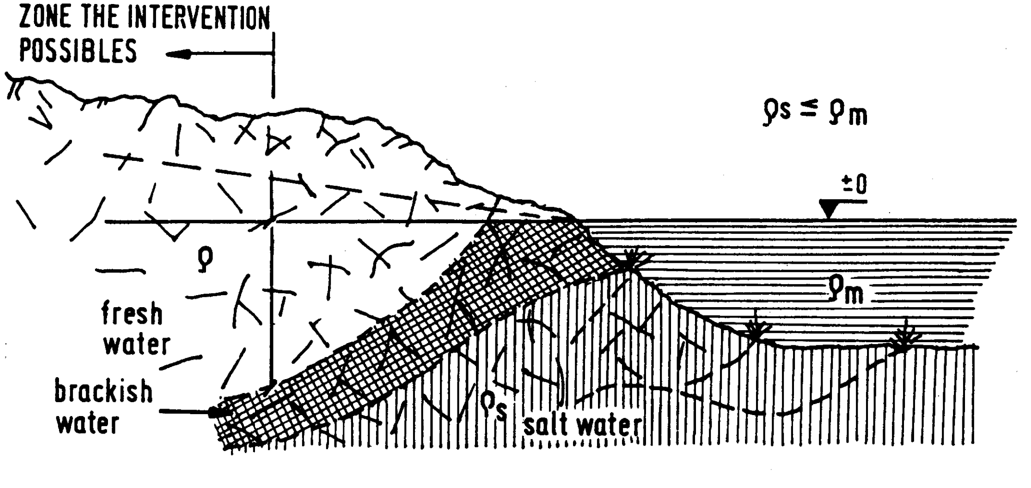
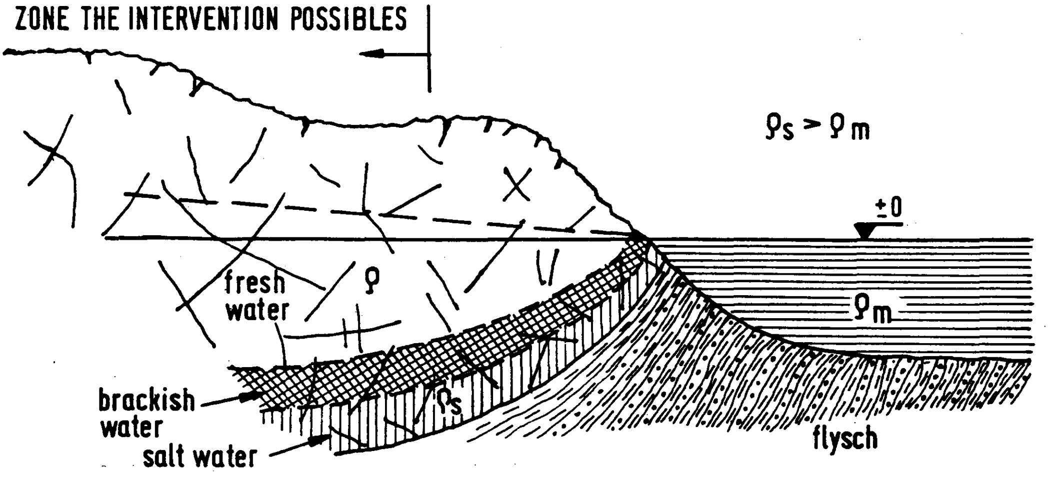


Figure 8.1



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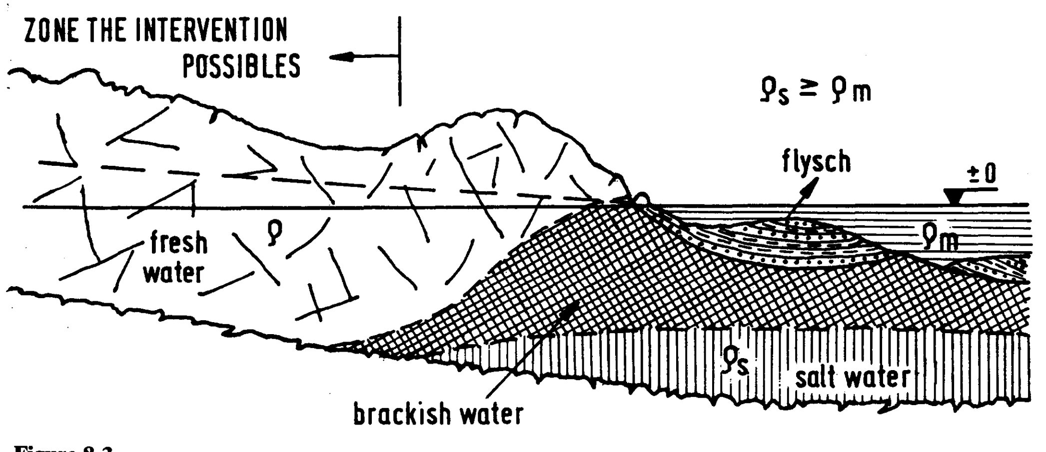

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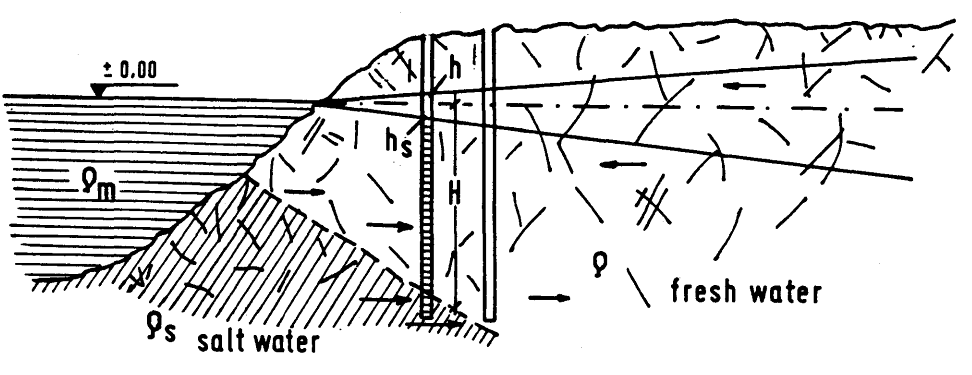

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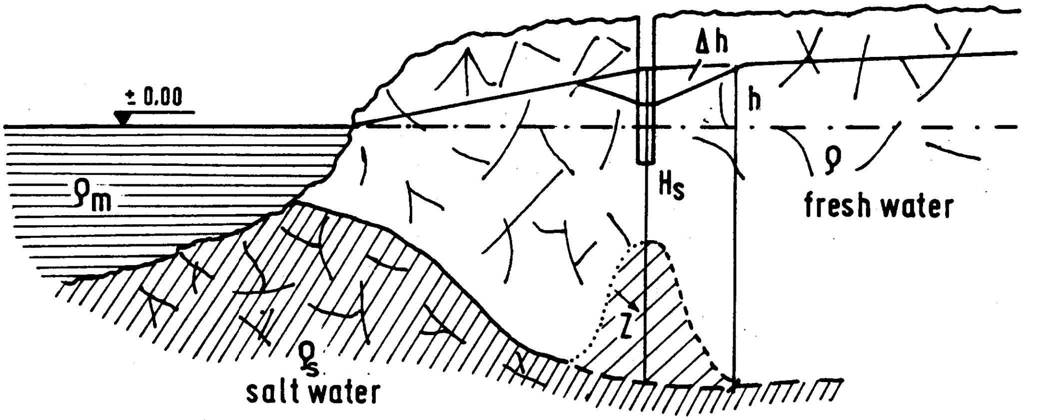

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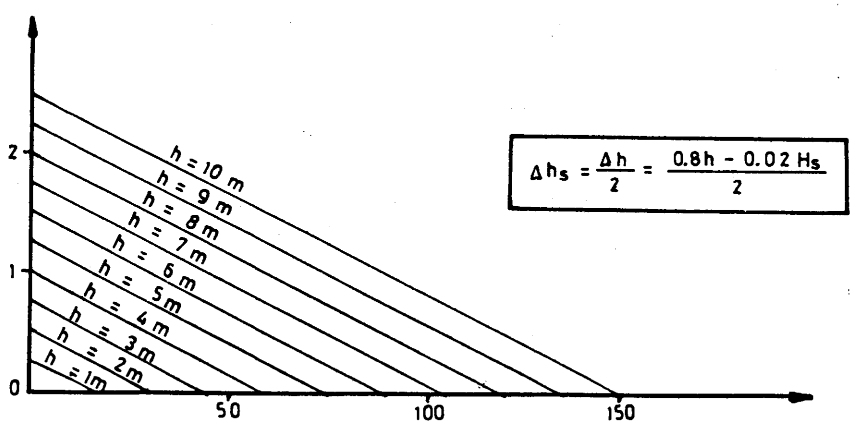

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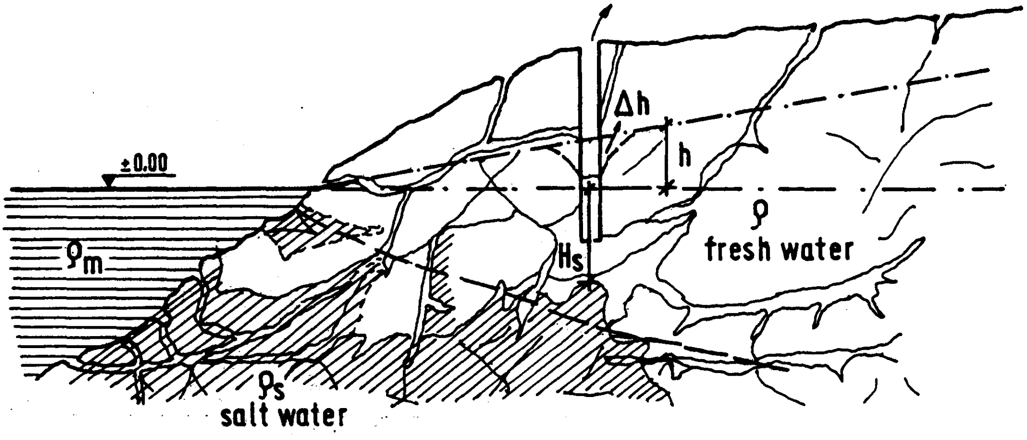

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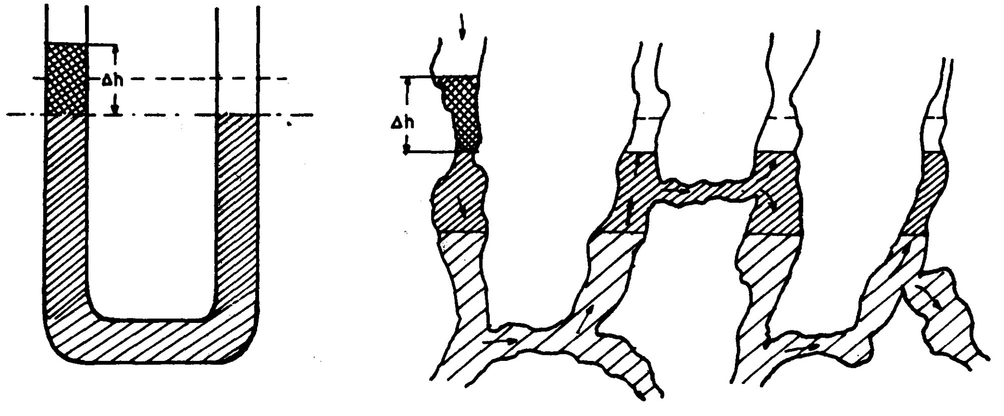

Figure 8.8

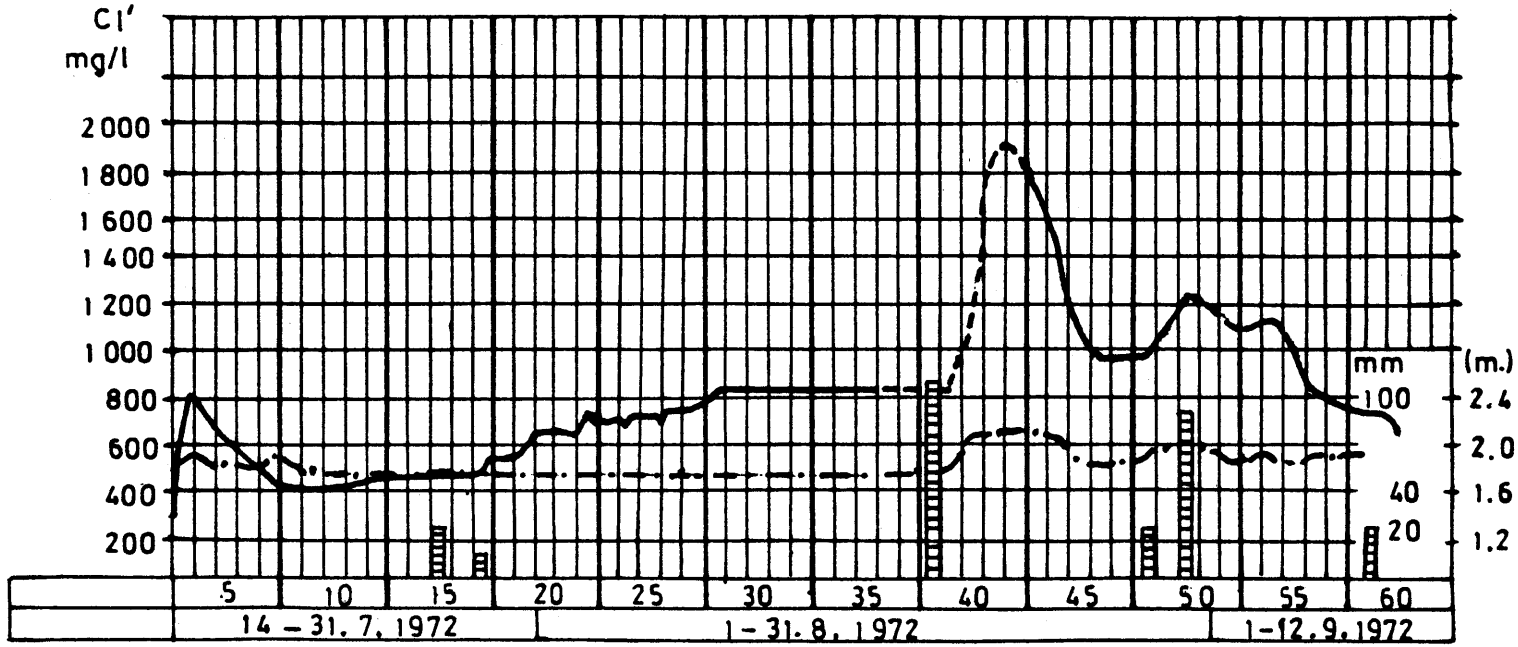
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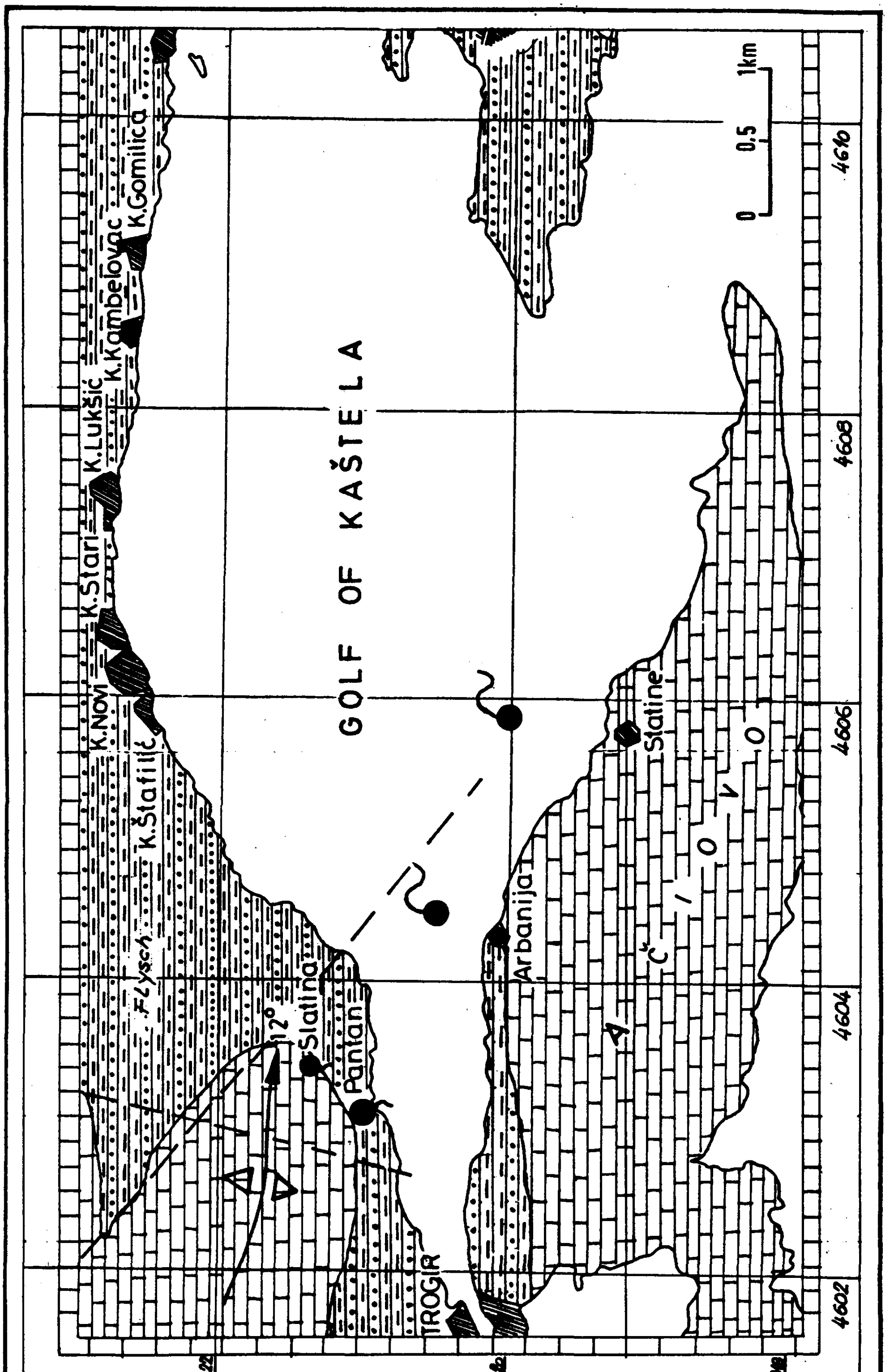
Figure 8.9



GOLF OF KAŠTELA
K.Novi
K.Stari
K.Lukšić
K.Kambelovac
K.Gomilica
K.Štafilić
Flysch
12°
Slatina
Pantan
TROGIR
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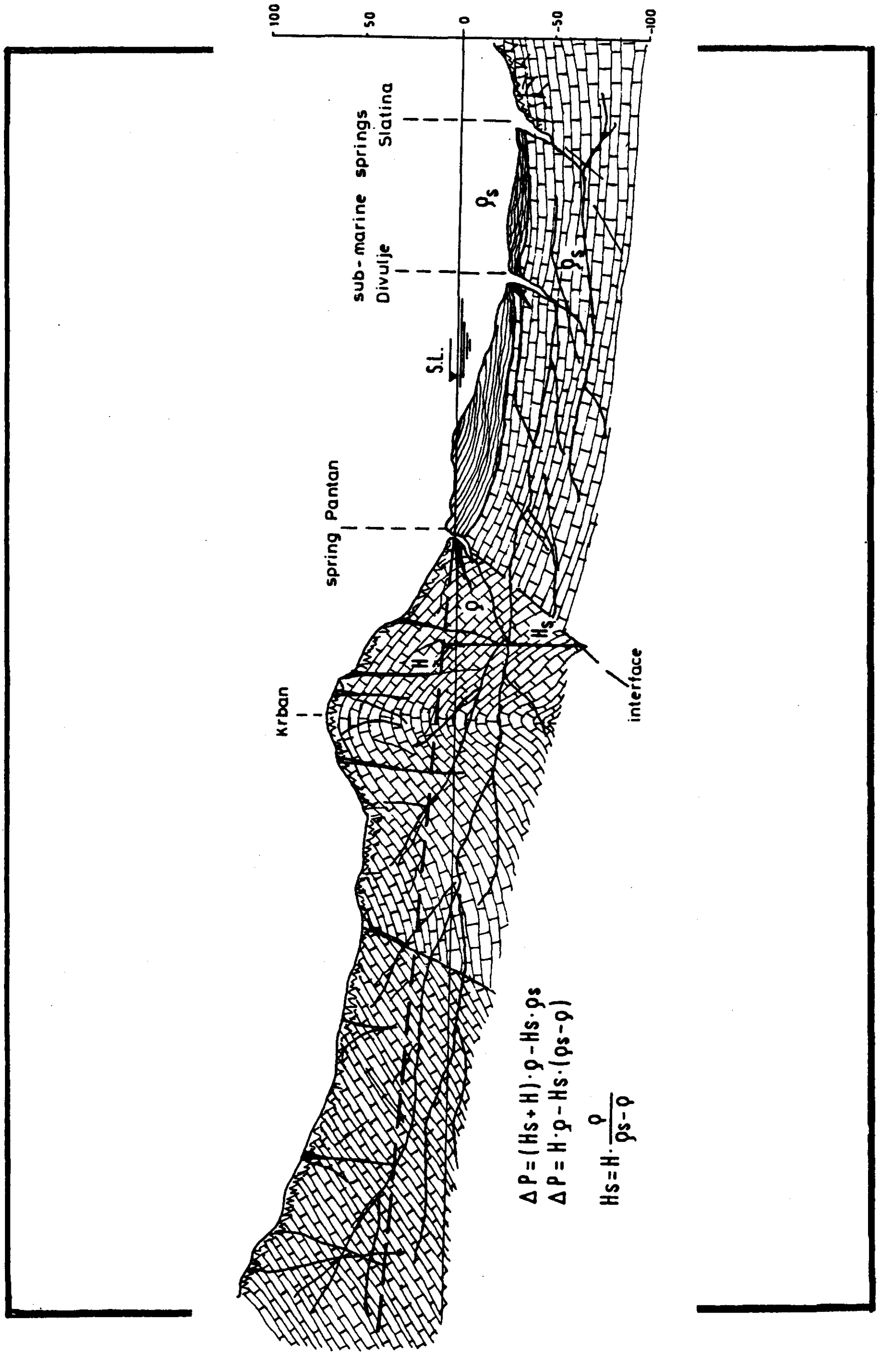
Figure 8.10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sub-marine springs
Divulje
Slatina
S.L.
spring Pantan
Krban
interface
ρ_s
ρ
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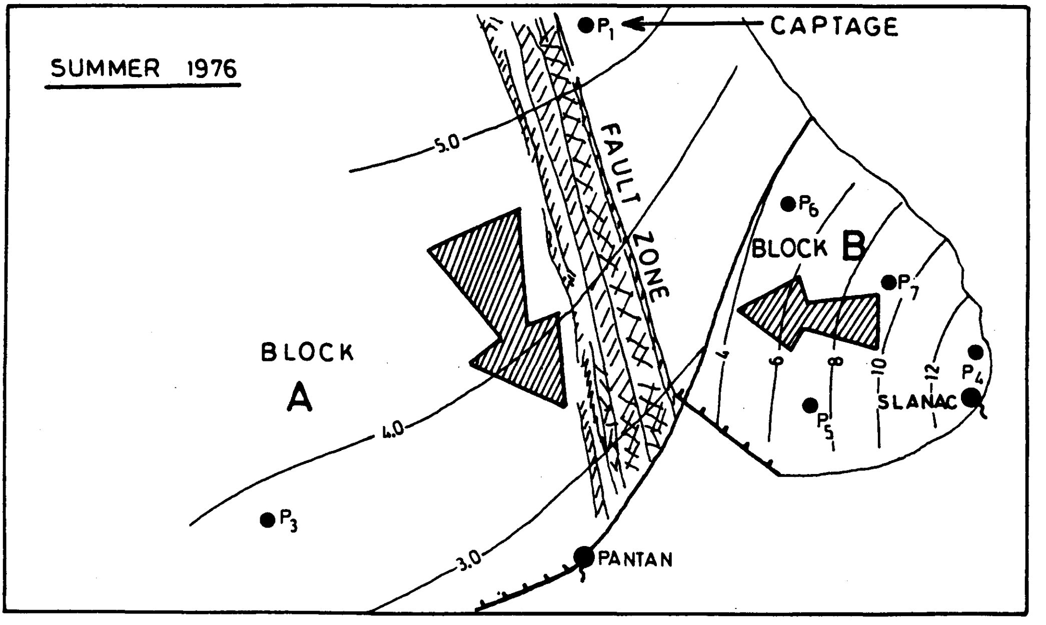
H_s
$\Delta P = (H_s + H)\cdot\rho - H_s\cdot\rho_s$
$\Delta P = H\cdot\rho - H_s\cdot(\rho_s - \rho)$
$H_s = H\cdot\frac{\rho}{\rho_s - \rho}$

Figure 8.11



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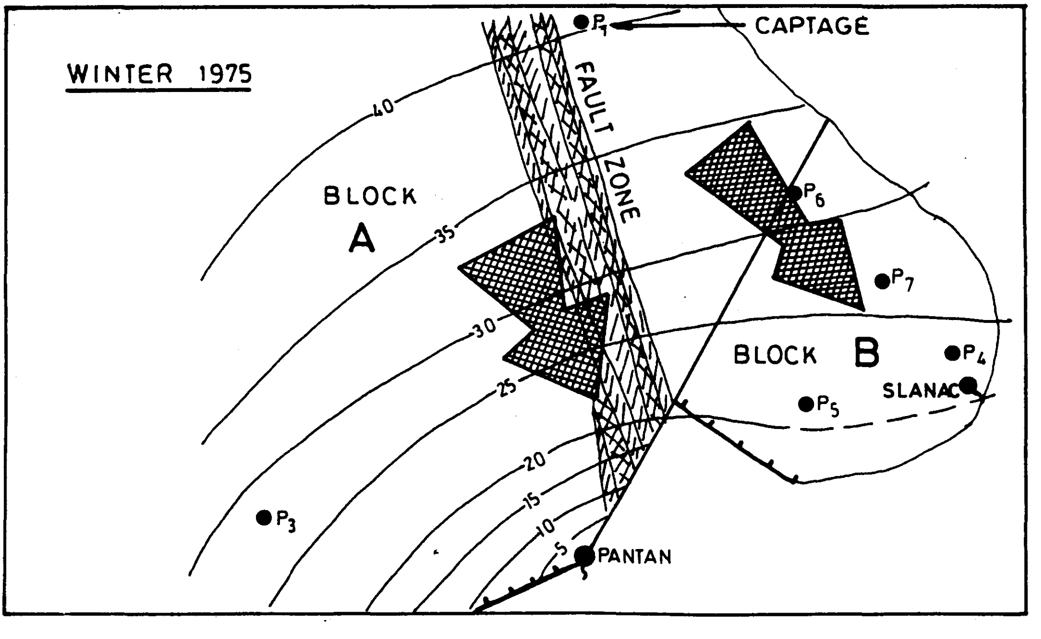

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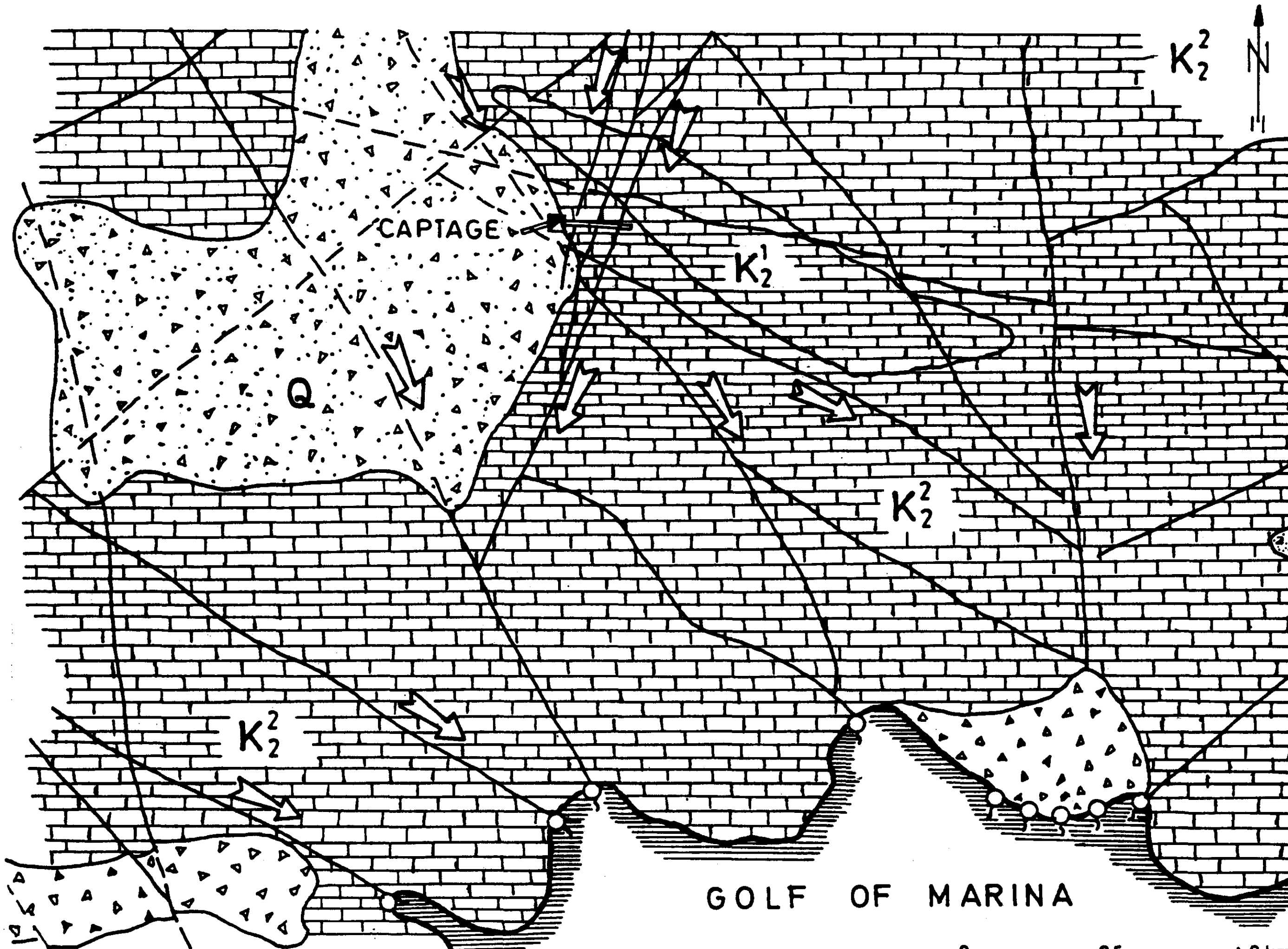
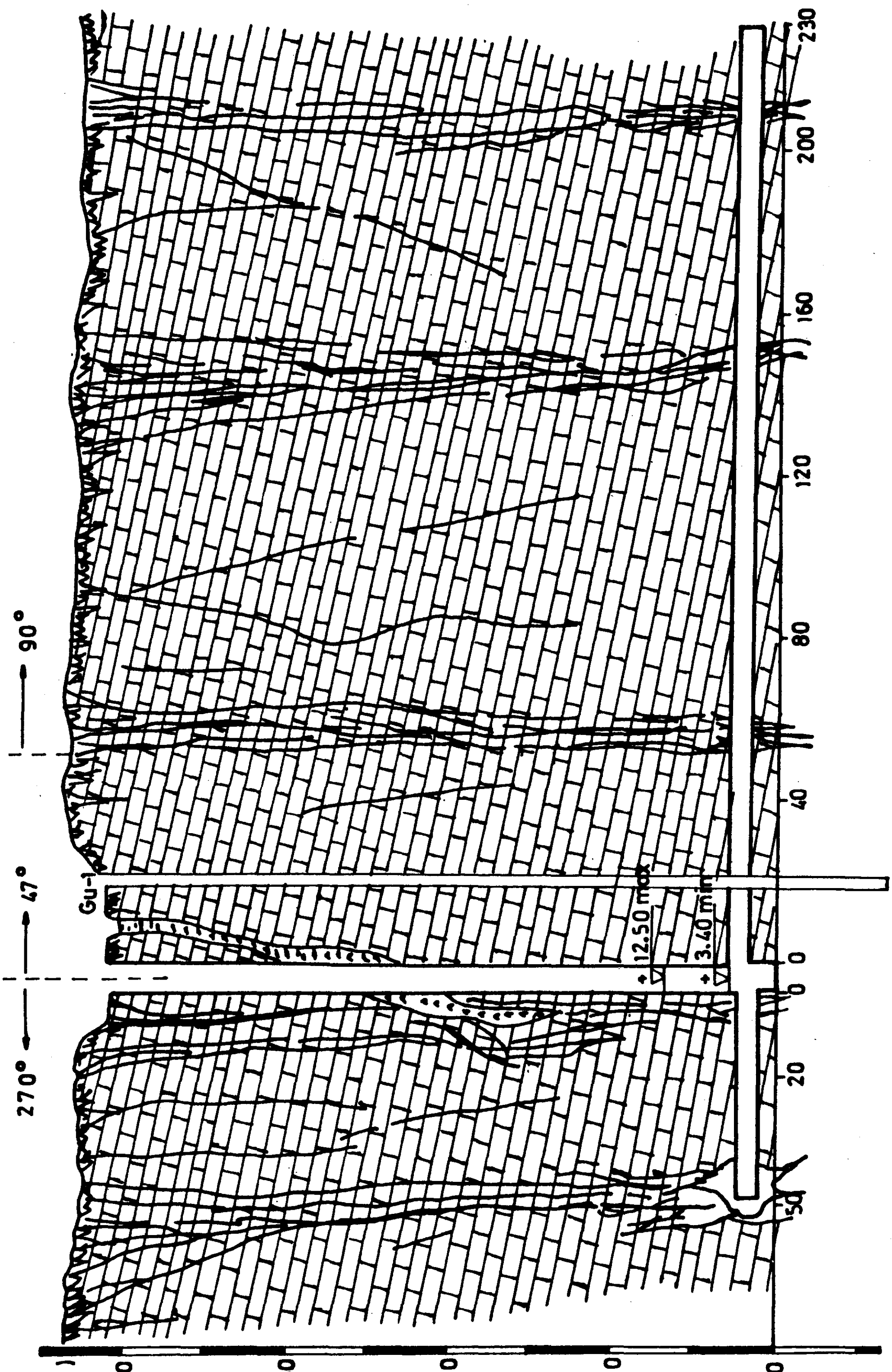


Figure 8.14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160
200
230

Figure 8.15

9

APPLICATION OF GEOPHYSICAL METHODS TO HYDROGEOLOGICAL PROBLEMS IN DINARIC KARST OF YUGOSLAVIA

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Geophysical methods play a particular part in extensive hydrogeological and engineering geological investigation of Yugoslav karst areas. The scope and variety of their application constantly increase. Because of their advantages, such as high efficiency, accuracy, low coast, etc., it can be said that geophysical methods became one of the main components of general and detailed engineering and hydrogeological investigation in the karst.

Of all geophysical methods applied, most useful informations were assembled by the electrical and seismic methods, viz.:

(a) Electrical sounding method;
(b) Electrical mapping method;
(c) Mise à la masse method;
(d) Seismic refraction method;
(e) Ultrasonic impulse method;
(f) GEOBOMB method, and
(g) Well-logging method.

The electrical methods are almost exclusively applied in the field of engineering geology and hydrogeology, while the seismic refraction method and ultrasonic impulse method are used primarily in engineering geological and geotechnical investigations. GEOBOMB method - a new original and very specific geophysical method - is used in hydrogeological investigations.

Applicability of electrical methods in Dinaric karst is based on the fact that determination of electrical parameters of karst rocks and their adequate interpretation yields a clear insight into engineering-geological and hydrogeological problems, thus leading to correct solutions. Of the numerous electrical parameters - resistivity is most often determined because it can most safely be related to definite engineering-geological and hydrogeological characteristics in a karst massif. It is on account of their efficiency, that the electrical sounding and electrical mapping are dominantly used in this kind of work.

In a general sence, electrical resistivity of karst rocks depends on several factors and varies with them. Of these, the most important are: porosity, tectonic fracturing and karstification. The nature of material with which karst fissures are filled (water, clay, air) has a special effect. The more intensive karstification of rocks with water- or clay-filled fissures, the lower resistivity, and vice versa.

Applicability of the seismic refraction and ultrasonic impulse methods in the study of geotechnical properties of karst rocks relies on the fact that elasticity and deformation modulus can be calculated from elastic wave velocities.

To put it simply, the velocities in compact, slightly karstified rocks will be high, and so will also be the values of the elasticity and deformation modulus. On the other hand, in karstified, cracked, and tectonically damaged rocks velocities will be considerably lower. Percentage of the velocity drop is a function of size, distribution and orientation of the porosity (karstification, tectonic fracturing) and the character of the fissure-filling material (clay, water, air, grout mass).

Geological problems encountered in realization hydrotechnical projects and construction in karst, to which geophysical methods are applicable, can be classed into three main groups:

A. Hydrogeological,
B. Engineering-geological, and
C. Geotechnical.

By the application of corresponding, geophysical methods, or their combination, the following basic hydrogeological problems in Dinaric karst were solved:

(1) Determination of depth of the karstification base, i.e. the boundary between intensively karstified and unkarstified rocks (limestones or dolomites);
(2) Determination of the position of intensively karstified and tectonically broken zones in karstified limestones;
(3) Delimitation of the intrusion of salt-sea water and its water table;
(4) Recognition of boundaries of the part of the terrain with fresh water in a brackish karst areas;
(5) Study of the intensity of karstification and position of water-bearing zones in boreholes;
(6) Detection of potential or existing groundwater flows;
(7) Determination of direction and rate of groundwater flow by a single well;
(8) Estimation of prosity and permeability of karstic rocks.

Of many problems by which engineering geology is faced in Dinaric karst, the following are most often solved by geophysical methods:

(1) Thickness and character of alluvium and detritial material in the river valley and on banks;
(2) Discovery and delineation of unstable parts of rock which may be involved in landslides, or may readily break off;
(3) Detection of underground caverns and cavities;
(4) Determination of major direction of the most intensive karstification;
(5) Seismicity of the area;
(6) Disvovery of suitable building material (gravel, sand, clay) as close as possible to the construction site.

The role which geophysical methods play in geotechnical investigation of karstic rocks consists of:

(1) Estimation of the modulus of deformation and modulus of elasticity, and in
(2) Determination of the degree to which the modulus of elasticity of rocks was improved after grouting.

The following will be a short survey and explanation of a few cases illustrating the approach to hydrogeological, engineering-geological and geotechnical problems in Dinaric karst.

MARINA-STUPIN VALLEY NEAR TROGIR belongs to the coastal zone of Dinaric karst. It is built up mainly of Cretaceous karstified limestones covered by a three-meter thick layer of terra rossa.

Systematic exploration aimed at a realistic evaluation of prospects for the utilization of groundwaters as a water supply source included geophysical exploration by the resistivity method.

These exploration proved that karstification along the whole length of this valley reached far below the sea level. The most intensively karstified zones were delimited and in these exploratory and later exploatation borings were located. The areas of karstified limestones saturated with salt water were also delimited and thus excluded from further exploration. The depth of salt water table was established over entire valley. Figure 9.1 shows the results of electrical exploration and exploratory boring along the section running through the center of the Marina-Stupin valley. Further exploratory works confirmed the results of electrical exploration and considerable amounts of fresh water floating above salt water were established in this area.

OKO SPRING NEAR TREBINJE. Oko Spring is located about 5 km upstream of Trebinje. It is the strongest perennial karst spring in the valley of Trebišnjica River and is utilized for the water-supply of Trebinje. Because of the construction of the Dubrovnik water power plant, i.e. the creation of a storage reservoir in Trebišnjica valley, this spring has to be flooded thus causing considerable trouble and complication in the Trebinje water supply system. This made it necessary to determine the groundwater flow of Oko spring so that a water supply source could be secured in the immediate proximity. By applying mise â la masse method the potential gradient were measured along several profile lines. From the geometric position of points of sign change and extreme points of potential gradient, the position of groundwater flow was predicted (Fig. 9.2). By drilling, that followed immediately after, groundwater flow of Oko spring was found in the predicted zone and a new water supply system was constructed in the most economical way.

FATNIČKO POLJE IN HERZEGOVINA belongs to the broader hinterland of the famous storage reservoir "Bileća" (Trebišnjica water power plant). Many hydrogeological problems in this area were solved by the application of geophysical methods. The karstification base in limestones and the thickness of flysh sediments in the Polje has been determined. Figure 9.3. shows the results of electrical resistivity exploration i.e. structural contours of the karstification base, and the resistivity map. Predicted direction and possible communications between groundwater flow in intensively karstified or tectonically broken zones are also shown. The information assembled proved that the formerly assumed groundwater divide between the drainage systems of Trebišnjica and Bregava is not present here and the levels of the karstification base were lowered even below +400 m (maximum pool-water level).

DETERMINATION OF THE DIRECTION OF GROUNDWATER FLOW by the single-well method has become common practice in the karst. The method gives quite good results especially if the groundwater flow is not too deep below surface of the terrain. It consists in dumping a sodium chloride solution into the well or swallow hole in which a groundwater flow has been established and of a subsequent application of mise â la masse method. The direction of groundwater flow is determined by study of the electric field on the surface around the well or sinkhole. In figure 9.4. are shown two field examples.

STORAGE RESERVOIR "BILEĆA". To make a detailed study of the engineering geological and hydrogeological properties of karstic rocks in and around storage reservoir, especially in its western and southern parts, a complex electrical exploration program was designed primarily to determine the karstification base, as well as the position of intensively karstified and tectonically damaged zones. To solve these problem, an area of over 120 km^2 was studied with more than 750 electrical soundings and 180 km^2 of electrical profiling. Up to now this is the largest program of electrical karst investigation executed in the world.

On the ground of the results of electrical soundings a contour map of karstification base was constructed (Fig. 9.5). The map permits a plausible assumption that the water tightness of the storage reservoir (impounding level +400 m), i.e. of its western part is in all probability satisfactory. The whole of this part is completely "closed" due to comparatively high karstification bases, exceeding the elevation of the impounding level designed.

THE DAM SITE "GRANČAREVO". Extensive geophysical exploration has been done and is still being done at the sites of constructed or planned dams in Dinaric karst. These exploration have proved highly adventageous, so that nowdays one could not even think of constructing a karst dams without applying geophysical exploration to a larger or smaller extent.

The dam site "Grančarevo" is located in the Trebišnjica canyon, where a 124 m high arch dam has already been constructed, very extensive and diverse geophysical exploration was done, not only during its designing stage, but also during its construction.

Electrical sounding and mapping was done over a wide area around the dam site on the basis of which contour lines of karstification base and resistivity map were plotted. The results obtained pointed to a number of engineering-hydrogeological problems and greatly contributed to their adequate approach and resolution.

The results of electrical sounding along the axis of the left bank of the dam site, greatly governing the design of the grout curtain, are shown in Fig. 9.6. The same figure shows the section through the curtain, it is noticeable that the curtain and the karstification base reach to almost equal depths.

Figure 9.7. shows the results of seismic exploration by means of cross-hole shooting from 6 boreholes conveniently spaced along the dam site axis. It is readily noticeable that the velocities increase with depth along the entire profile investigated, i.e. that the elastic properties of rock mass have been improved.

THE DAM SITE "SKLOPE". Very extensive electric and seismic exploration were done at this dam site in the Lika River valley, in the Dinaric

karst. Their results greatly contributed towards and adequate insight into numerous engineering-hydrogeological problems, which made it possible to select the correct type of dam and the appropriate extent of consolidation works. A detail, characteristic of these exploration, is presented in Figure 9.8. It refers to the prognosticated to geological cross-section along the dam axis plotted on the basis of results of electrical sounding.

THE DAM SITE "MRATINJE". The 220 m high concrete arch dam "Mratinje" has recently been completed in the Piva River canyon. Because of the size and type of the dam, as well as the fact that it is situated in locally karstified and tectonically damaged limestones, geophysical explorations were wide in scope and extent. The seismic and ultrasonic explorations were most extensively used to determine geotechnical properties of rock mass at the dam site. In conformity with the exploration procedure decided on, the rock mass was investigated down to one-meter depth by ultrasonic impulse method, and down to 100 m depth by the seismic refraction method (cross-hole and gallery shooting). Figure 9.8. shows obtained results along the dam axis. On the ground of mean velocities, several zones with given elastic properties were recognized. The all-over estimate of the dam site "Mratinje" - based on seismic exploration - indicated that the elastic properties of rock mass were very good. Such an estimate, along with other data obtained by the exploration of the dam site, was a significant contribution towards the most advantageous design and execution of consolidation works and the dam site itself.

GEOBOMB USED IN TRACING A GROUNDWATER FLOW IN KARST. The idea of using geobomb method for the determining the position of groundwater flows in karst resulted from geophysical investigation of highly developed Dinaric karst which has a remarkable large number of underground water channels resembling underground rivers.

Therefore, the determination of their space location is attractive not only from theoretical point of view but also has an immense practical interest. These were the reasons for initiating the first practical field experiments with geobomb in the karst region of Yugoslavia.

In short, the concept of applying geobomb method is as follows: a time-bomb (geobomb) inserted into a swallow-hole is carried down the groundwater flow where it explodes at a predetermined time (Fig. 9.9). Elastic seismic waves initiated by the explosion are transmitted to the earth's surface where they are detected by the adequately arranged geophones that are connected to a standard seismic recording instrument. The coordinates from the epicentre and hypocentre of the explosion can be calculated by applying the appropriate graphic or analytic methods, and finally, the location of the groundwater flow may be ascertained.

In conclusion, it could be pointed out, without exaggeration that the geophysical study of karst phenomena in most cases greatly contributes towards an efficient solution of engineering-geological and hydrogeological problems. There is hardly any karst problem to which geophysical exploration methods could not be applied, and not only as auxilliary methods, but very often as principal methods of research.

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FIGURES

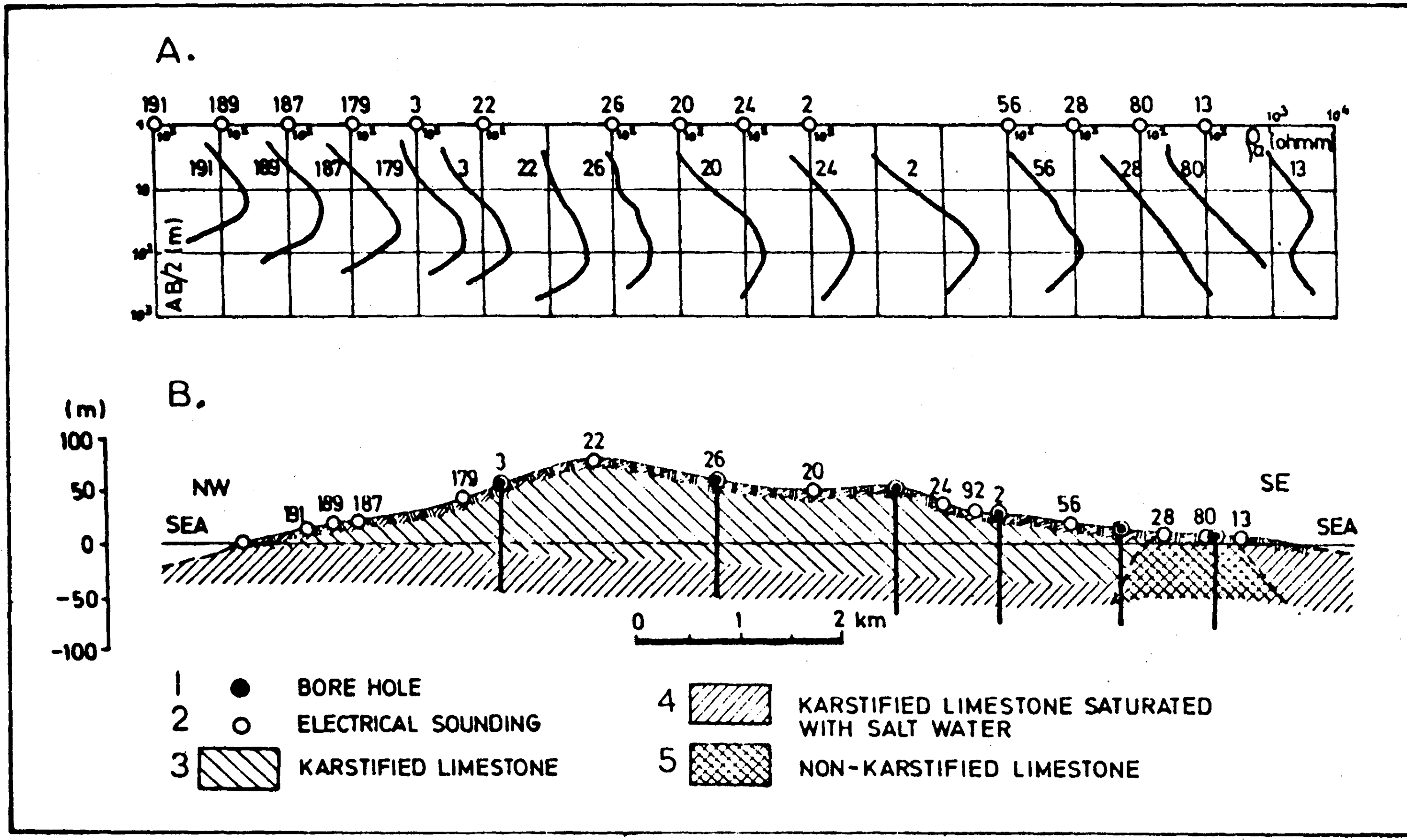

A.
191
189
187
179
3
22
26
20
24
2
56
28
80
13
AB/2 (m)
ρa (ohmm)
B.
(m)
100
50
0
-50
-100
NW
SEA
SE
SEA
0
1
2 km
1
BORE HOLE
2
ELECTRICAL SOUNDING
3
KARSTIFIED LIMESTONE
4
KARSTIFIED LIMESTONE SATURATED WITH SALT WATER
5
NON-KARSTIFIED LIMESTONE

Figure 9.1

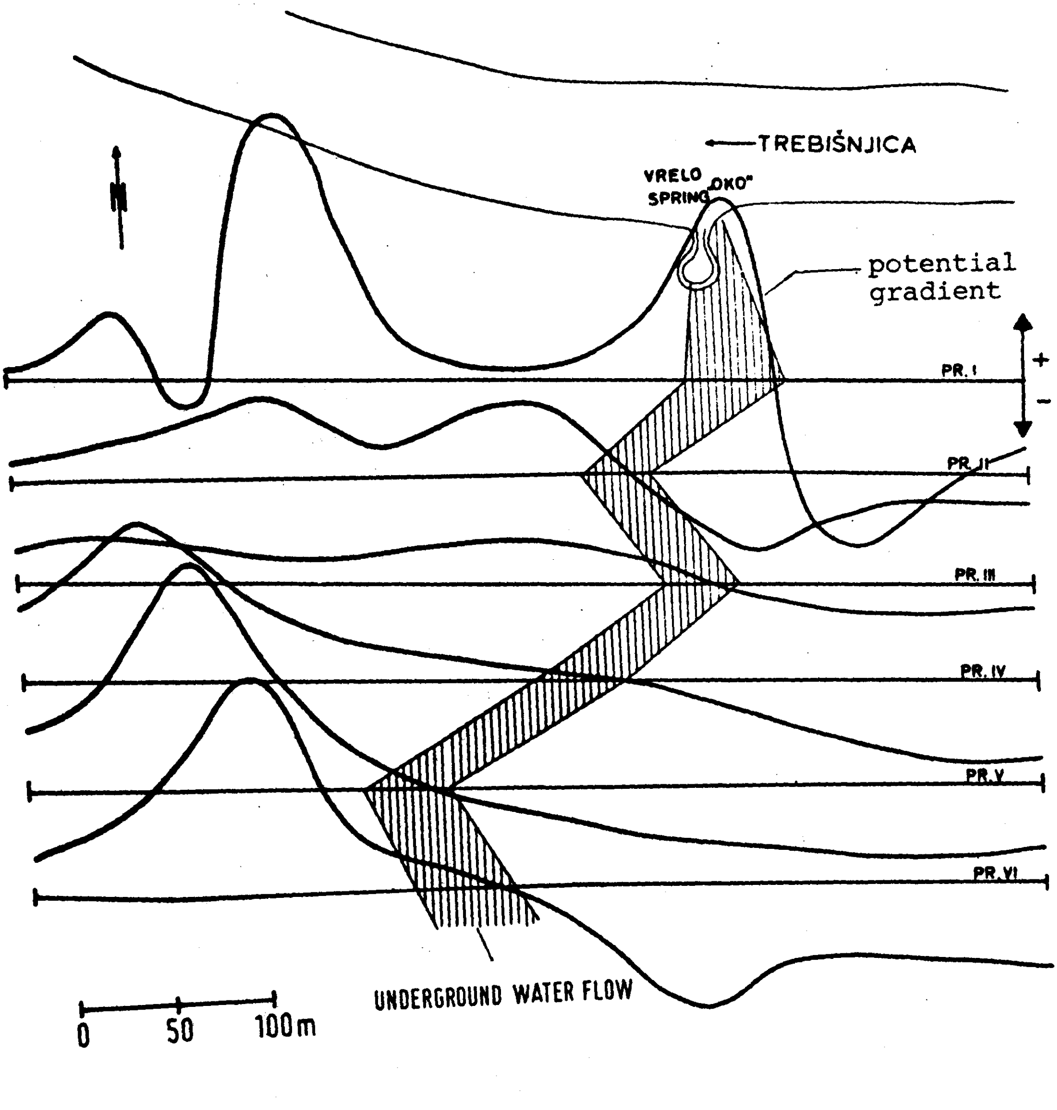

TREBIŠNJICA
VRELO
SPRING
„OKO"
potential
gradient
+
−
PR. I
PR. II
PR. III
PR. IV
PR. V
PR. VI
N
UNDERGROUND WATER FLOW
0
50
100m

Figure 9.2

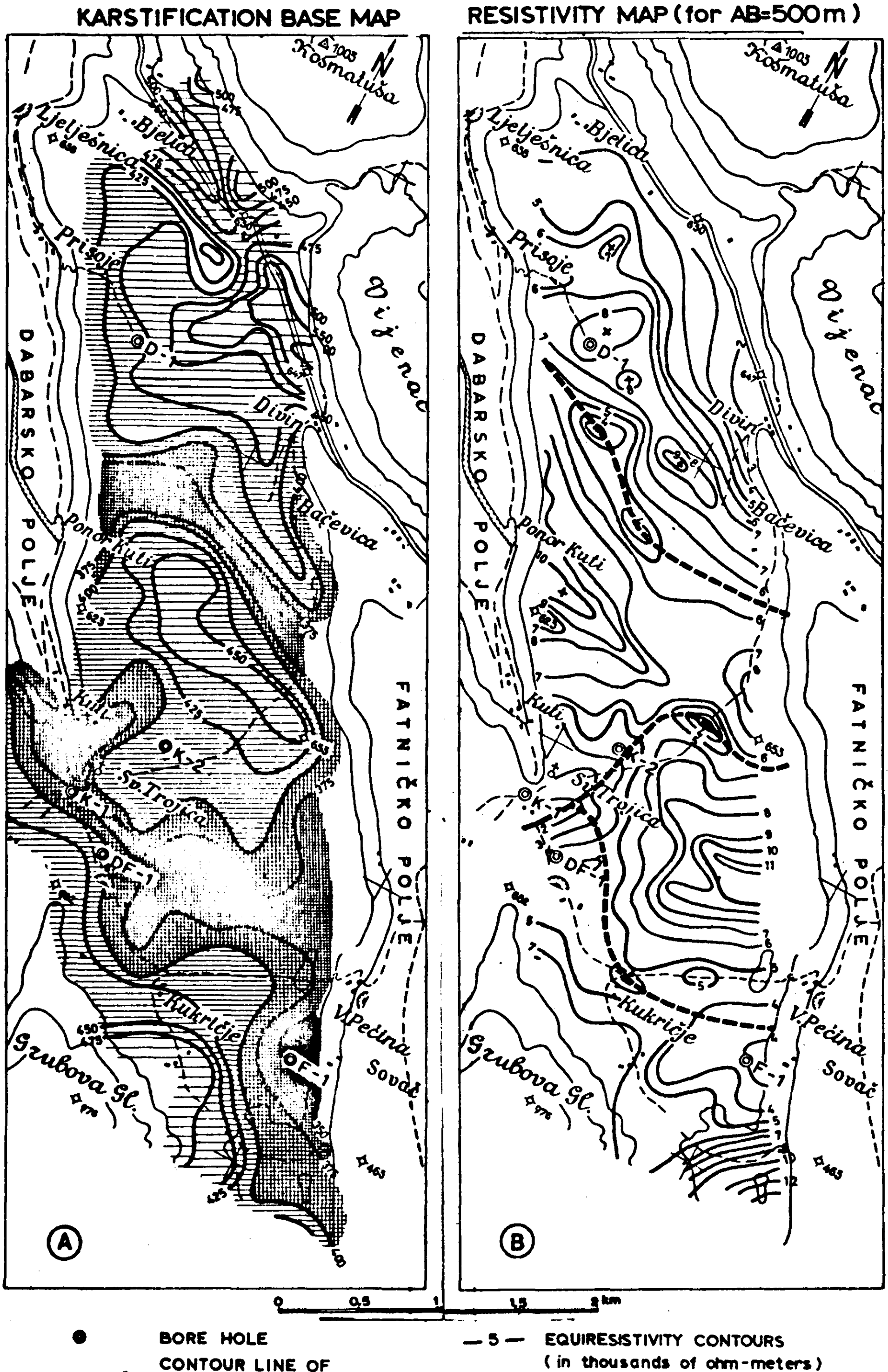

KARSTIFICATION BASE MAP
RESISTIVITY MAP (for AB=500m)
Kosmatuša
Ljelješnica
Bjelica
Prisoje
D-1
Vijenac
Divin
Bačevica
DABARSKO POLJE
Ponor Kuli
Kuli
K-2
K-1
Sv. Trojica
DF-1
FATNIČKO POLJE
Kukričje
V. Pećina
Grubova Gl.
F-1
Sovač
A
B
0 0.5 1 1.5 2 km
BORE HOLE
—350— CONTOUR LINE OF KARSTIFICATION BASE
—5— EQUIRESISTIVITY CONTOURS (in thousands of ohm-meters)
AXIS OF LOW RESISTIVITY ZONES (intensively karstified zones)

Figure 9.3

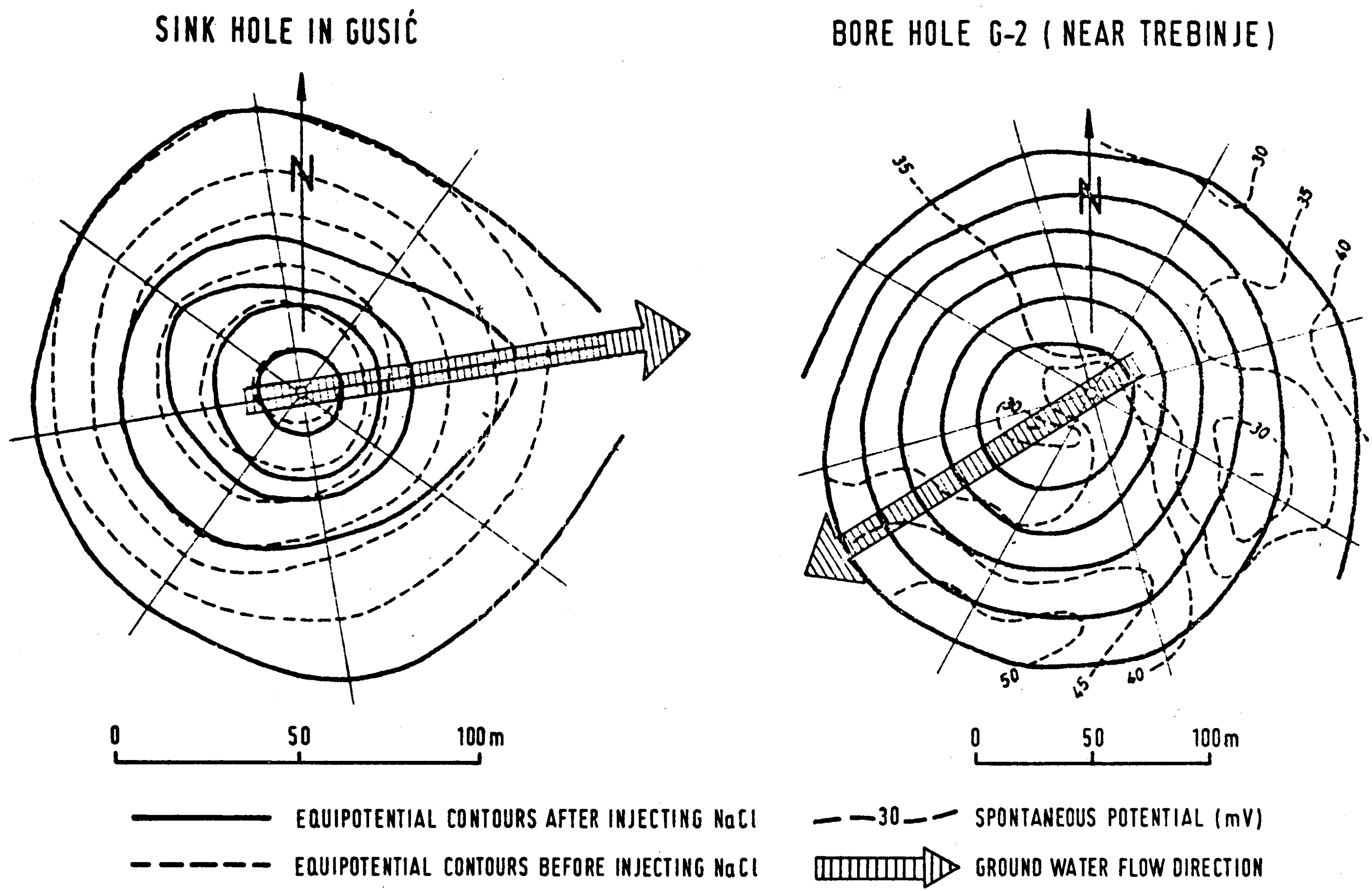
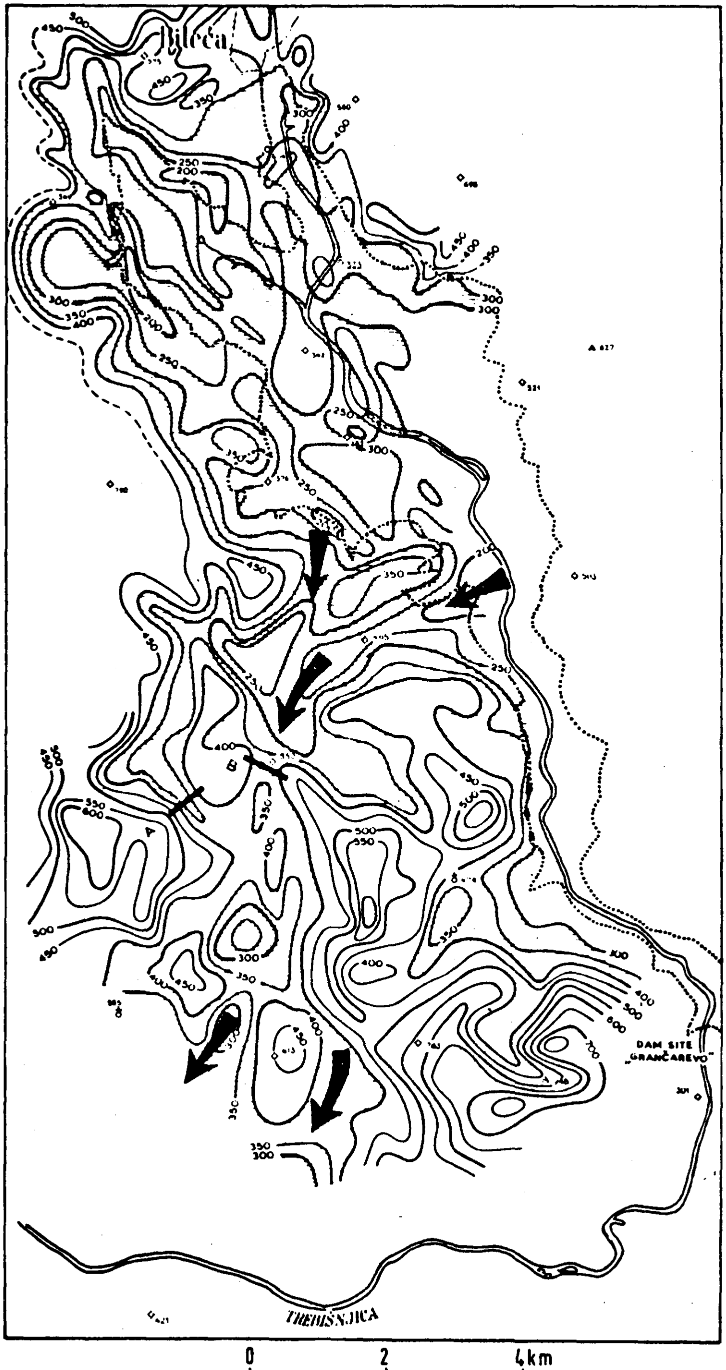

SINK HOLE IN GUSIĆ
N
0
50
100m
BORE HOLE G-2 (NEAR TREBINJE)
N
35
30
35
40
30
30
50
45
40
0
50
100m
EQUIPOTENTIAL CONTOURS AFTER INJECTING NaCl
EQUIPOTENTIAL CONTOURS BEFORE INJECTING NaCl
30
SPONTANEOUS POTENTIAL (mV)
GROUND WATER FLOW DIRECTION

Figure 9.4



1 —400— CONTOURLINE OF KARSTIFICATION BASE

2 .... BOUNDARY OF THE STORAGE RESERVOIR (ELEVATION OF +400m)

3 ⟵ DIRECTION OF ASSUMED SEEPAGE LOSS

4 ▬ FAVOURABLE PLACES FOR GROUTING WORKS

Figure 9.5

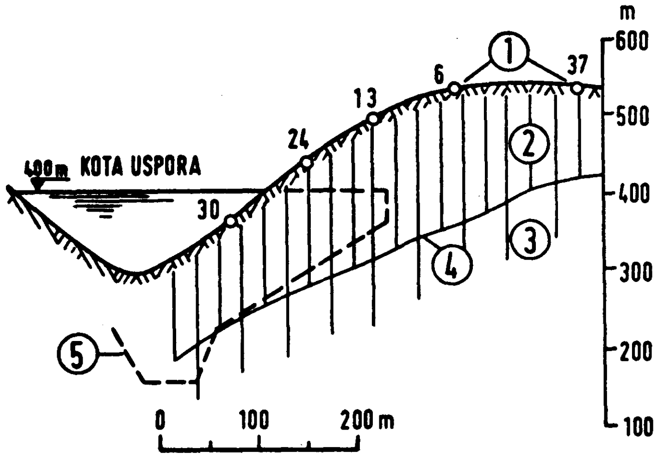


Figure 9.6

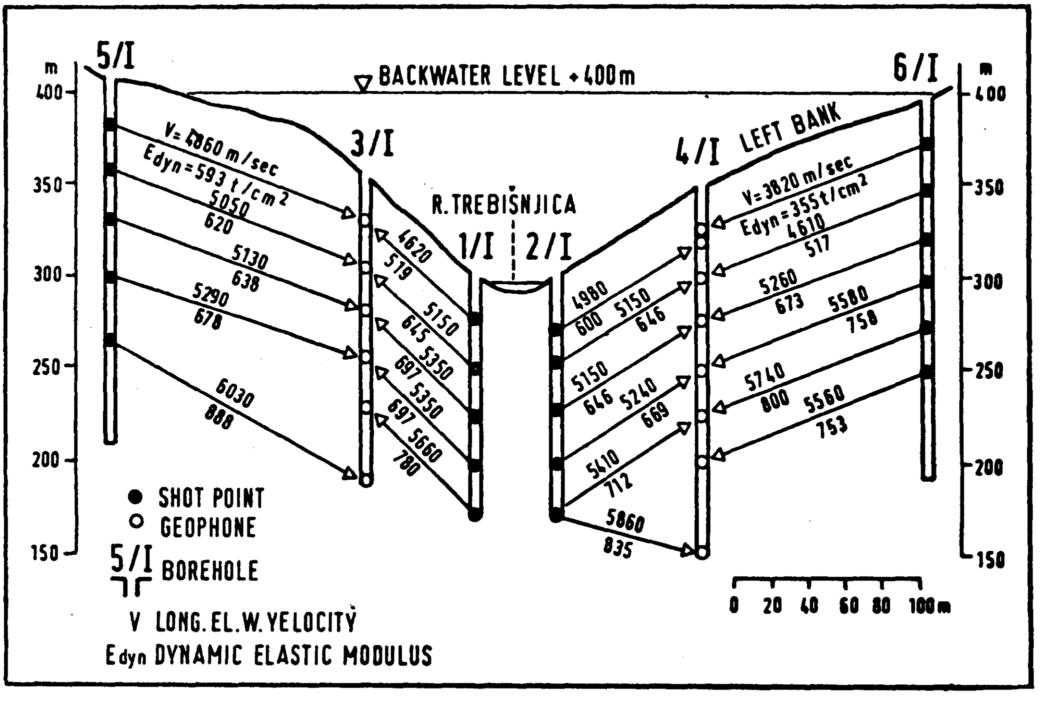


Figure 9.7

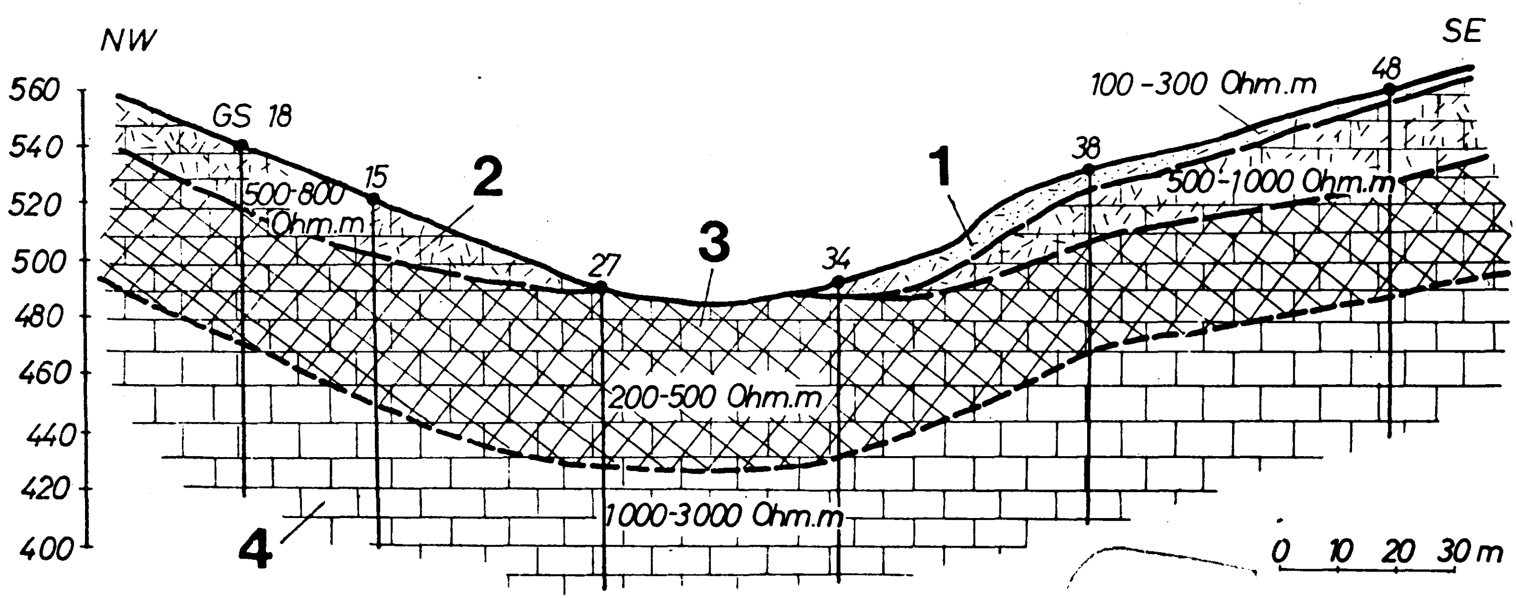
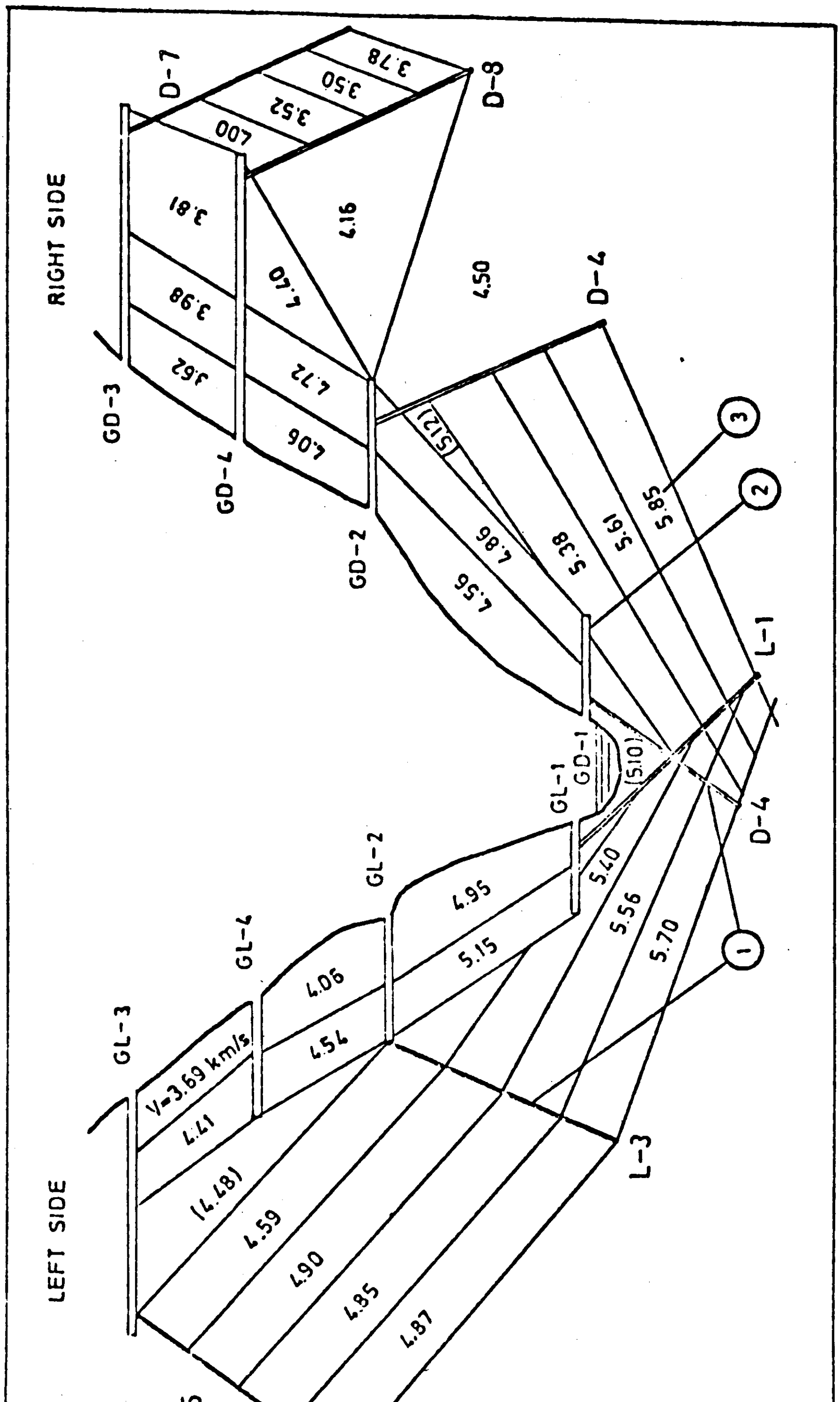

NW
SE
560
540
520
500
480
460
440
420
400
GS 18
15
27
34
38
48
1
2
3
4
100 -300 Ohm.m
500-1000 Ohm.m
500-800 Ohm.m
200-500 Ohm.m
1000-3000 Ohm.m
0 10 20 30 m

Figure 9.8



RIGHT SIDE
LEFT SIDE
D-7
D-8
D-4
GD-3
GD-4
GD-2
GD-1
GL-1
GL-2
GL-4
GL-3
L-5
L-3
L-1
D-4
1
2
3
3.78
3.50
3.52
4.00
3.81
4.16
4.40
4.50
3.98
3.62
4.72
4.06
(5.12)
4.86
4.56
5.38
5.61
5.85
(5.10)
5.40
5.56
5.70
4.95
5.15
4.06
4.54
V=3.69 km/s
4.17
(4.48)
4.59
4.90
4.85
4.87

Figure 9.9

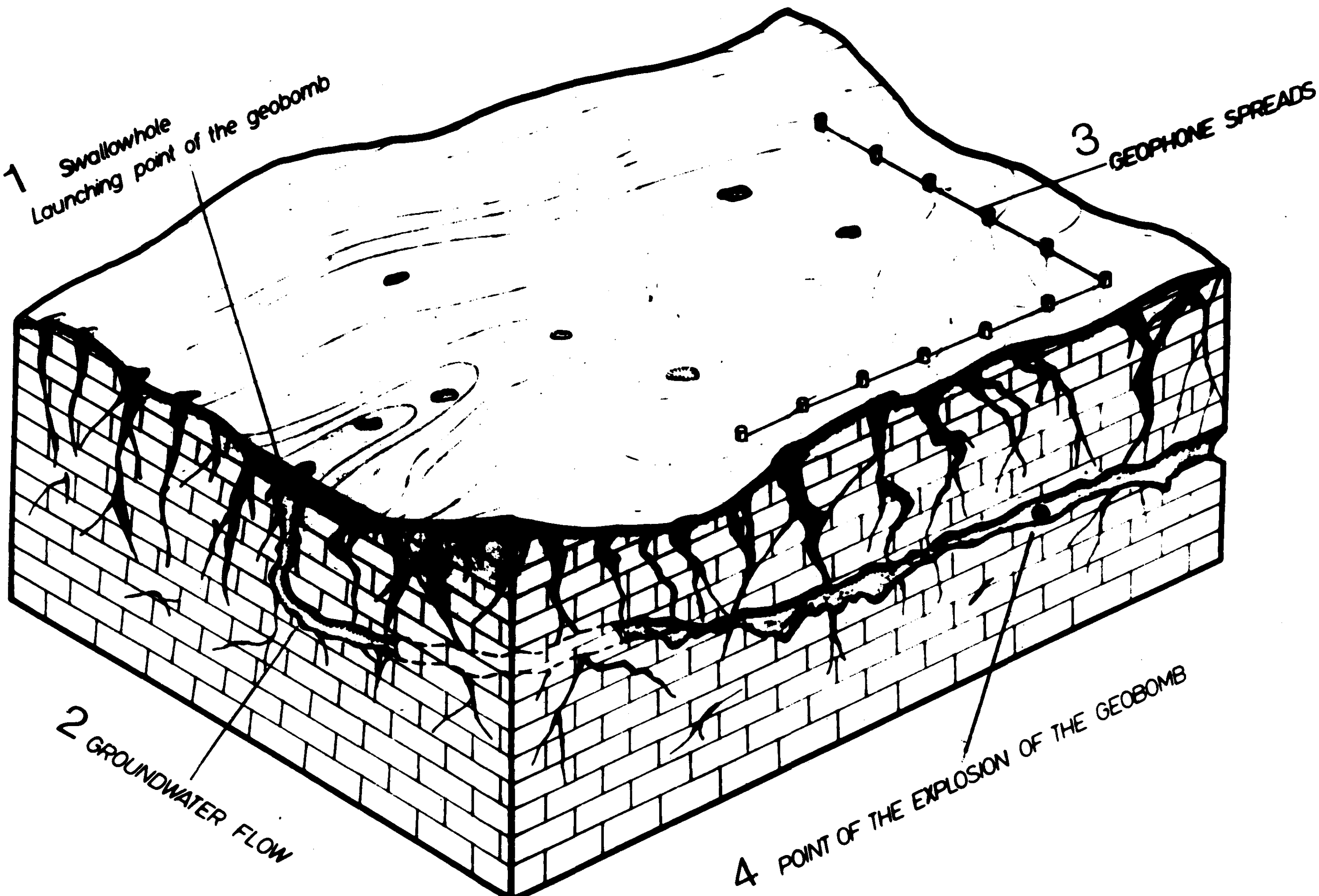

1 Swallowhole
Launching point of the geobomb
2 GROUNDWATER FLOW
3 GEOPHONE SPREADS
4 POINT OF THE EXPLOSION OF THE GEOBOMB

Figure 9.10

SOME METHODS OF HYDROGEOLOGIC EXPLORATION AND WATER REGULATION IN THE DINARIC KARST WITH SPECIAL REFERENCE TO THEIR APPLICATION IN EASTERN HERZEGOVINA

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1. REVIEW OF THE EXPLORATION METHODS

The modern concept of multipurpose utilization of water potential had a decisive influence on the exploration orientation. With the optimum application of the most modern exploration methods available, many new and very specific methods in the field of hydrogeology have been developed. Of the numerous exploration methods, only the most significant ones, will be discussed herewith.

1. Based on the most contemporary principles of the geology, many different geologic, hydrogeologic and engineering-geologic maps were prepared for the requirements of selection of damming profiles location, determining of storage reservoirs characteristics, captures, land reclamation and similar projects erection. Within this extensive job ground registers of numerous specific karst phenomena like springs, ponors, estavellas, caves and pits were prepared.
2. Speleology, as a specific exploration method, was used in solving the problems of hydrogeologic and engineering-geologic nature, for erection of hydro power projects water supply, drainage of periodically inundated fields, and in the process of paleontologic explorations with the purpose of utilization of caves for tourist purposes. Very hazardous diving speleology was used for special purposes (Herceg-Novi - the Opačica spring canal; the Popovo Polje - the Doljašnica, Žira and Crnulja ponors and the discharge tunnel of the "Čapljina" HE Power Plant).
3. For the clarification of geologic, hydrogeologic and engineering-geologic characteristics of these regions, some 1000 exploration boreholes were made. The major part of these boreholes is equipped with zink plated perforated pipes for the observation of ground water

levels (GVL). The GVL oscillations in some of the boreholes are already 20 years under observation.

4. Due attention has also been paid to the development of instruments for automatic measuring of water body head oscillations and electronic record and storage of the data. So, for instance, a digital water level gauge was developed for continual observation of GVL oscillations, consisting of a sonde, recorder (tape recorder) and electronic data reader.

5. For caverns and canal exploration in the process of drilling, usually a TV camera and stereo-photo sonde were used. TV camera was also used for checking the efficiency of regulation (injection) projects in the zone of the damaged tunnel lining.

6. Particular attention has also been paid to solving one of the most complex karst exploration problems - determining of the privileged directions of underground circulation and special position of underground karst canals. Because of that, the special attention was paid to tracer technology development. In these regions, about 150 different tracing experiments were made, using different types of tracers: Na-fluorescein, radioactive isotopes bromide-82, iodine-131, chrome-51 and tritium; additionally activated isotopes; environment isotopes; licopodium spores, and the analysis of some others very specific methods application was made, among which the hydrobiologic method, as well.

7. For the requirements of spęcial position of subsurface water flow defining, a completely new exploration method of geobomb was developed. This method, which is a seismic method in essence, is based on the fact that the subsurface water flows use canals of such dimensions which enable moving of ball shaped body 10 - 15 cm in diameter. In addition to high detonating explosive, the geobomb also contains a very precise clock mechanism which is provided to ignite the explosive at wanted moment. The elastic wave produced by the explosion is recorded on the ground surface by very sensitive seismometers (geophone) and the explosion point i.e. location of the subsurface water flow is determined by calculation. After a number of experiments in the Popovo Polje and the Fatničko Polje, the geobomb was improved considerably as compared to the prototype. The results achieved so far, prove that this method is a very perspective one.

8. The geophysical methods have also very significant role in exploration of the zones in which the subsurface water flow development is possible. Such methods, in the first place the geoelectric methods and different kinds of coring, have been successfully applied more than 20 years in the Trebišnjica hydro system region. In this period more than 50 geophysical projects were realized, within which about

400 sq.m. of terrain were explored, about 50 km of tunnel route locations and a number of damming profiles. In execution of these works, significant experiences were obtained in respect of the applicability of the geophysics in karst regions.

9. For aeration zone exploration the application of gas tracer was tested. Extremely good results have been achieved with the gas (smoke) tracer, and particularly in the exploration of cavernous space around the Čapljina HE power plant tunnel.

10. In new explorations the remote detection methods are more and more applied. In addition to the classic and already routine analysis of aerial photography, data collected by means of satellites are intensively studied.

11. Due attention has also been paid to the seismotectonic activity of these regions analysis, particularly to the earthquakes caused by water accumulation. For this purpose a network of seismologic stations has been established which permanently collect data required for design and construction of future storage reservoirs and estimate of seismic risks coming from natural and artificial earthquakes.

2. DESCRIPTION OF THE REGION

In karst areas of Montenegro, eastern Herzegovina and coastal area of Dubrovnik the presence of explorers has been evident for more than a hundred years, and they have studied this unique, geologic phenomenon from different scientific points of view. This period can be divided in two phases characterized by different exploration methods.

The first phase begins in the second half of the past century and lasts, generally speaking, up to forties, of this century. This is the phase in which karst exploration is dominated by individual explorers. They introduced numerous theories on ground waters circulation rules, based on their field observations. Of exploration methods applied, the speleology ranges among those which, at least to some extent, enable a more significant search of the subterrain. But even speleology is poorly technically equipped. Technical projects are really rare. And in spite of the fact that already in early twentieth century the possibilities of exploitation of this only resource of this region - the water potential, have been studied and the ideas, as by the rule, have stayed unrealized.

The second phase begins with the end of the Second World War. This is the phase in which the development of these regions is closely connected with exploitation of the most significant resources of the Dinaric karst - the water potential. The features of karst have become the only barrier for exploitation of these resources. The necessity of interdisciplinary approach to karst exploration has been imposed as an imperative for successful searches and "demistification" of karst phenomena. Investments in power generating projects have enabled both the quantitative and qualitative different approaches in relation to the earlier phase. New methods and new technology now are offered to the explorers. Successfully completed projects of water storage basins at: Liverivići, Krupac and Slano in the Nikšićko polje; Bileća, Gorica and Hutovon in the Trebišnjica catchment area, and Piva on the Piva river, justified capital investment and research efforts and the karst phenomenon was brought within the limits of geologic environment for which the term "phenomenon" is less and less applied. However, successfully realized projects as mentioned above, point out some insufficiently analysed characteristics of karst as in regard of its sensitivity to the changes of natural water regime. Because of that the problems of water economy have become the primary ones. The ideas of multipurpose utilization of waters with as less as possible negative effects on the environment are accepted as time passes as the only possible alternative.

Realization of the programme in the Nikšićko Polje started with 1951 and the first water project in the Trebišnjica river catchment area was completed in 1954. The extensive programme of performed exploration works resulted, in a very short period of time, a lot features and new experiences were obtained in the field of capital investment hydro-engineering projects. Many of the realized projects were estimated by a large number of eminent domestic and foreign experts as technically infeasible until recently.

Apart from the above cited projects of regional importance a number of smaller projects for different application were also realized like those designed for water supply, water drainage, irrigation and so on.

BASIC ELEMENTS OF THE EVOLUTION OF KARST AQUIFERS

The evolution process of karst water bodies of these regions is very complex one, characterized by numerous discontinuities in time and space. According to its effects and role in forming real hydrogeologic characteristics of many complex karst water bodies, the evolution process of karst collectors can be divided in two global stages:

1. Pre-Savian and
2. Neotectonic, with two periods:

- the Pliocene-Pleistocene period, and
- the end of Pleistocene - the recent period.

The pre-Savian phase of karstification was of insignificant influence on the present status of karst collectors in this region. The relicts of this karstification phase exist within the framework of the recent karst collector in the form of karst fossils (bauxite). This phase terminates with orogeny movements of Middle Alpine orogeny phase which is characterized by expressed application and rupture forms and emersion of carbonate masses. They participate in the karstification process during the neotectonic phase of the development. Tectogenetic process was initiated with the Laramian phase and it culminates at the end of Eocene, when elements of the recent structures are formed (Fig. 10.1). The faulting surfaces of the Dinaric direction are formed, along which the vertical and subvertical-reverse movements of blocks occur. These movements bring the Mesozoic sediments into reverse position in relation to the Eocene flysh. Numerous explorations (drilling, geophysical surveys) proved that relative emergence of northeastern blocks had appeared along the discontinuity whose inclination towards northeast was always more than 55°. The narrow flysh zones along these discontinuities are participating by an insignificant percentage in the total lithomass of the region, but with regard to their position in the structure they are of high hydrogeologic significance. Those are narrow and long zones of the Dinaric trend whose depth increases (perpendicularly to the trend) from the southwest edge towards the reverse contact. To mention, as an example, the depth of these sediments in the Fatnicko polje reaches 200 m and in the Cernicko polje 120 m.

The tectogenetic phase is the next one, in which the vertical component of movement dominates, because of big difference in movement of individual tectonic units. Differences in vertical movement of some neighbouring blocks reach even 1.500 m.

Tectonic movements in the Pleistocene play a very important role in forming the recent structure in evolution of the karst process. The entire carbonate massif is exposed to the effects of erosion base of the Adriatic Sea (whose level in some periods was much lower than the present one) and of many bases of the lower order like those as river valleys and tectonic ditches in which karst poljes are formed. Well developed surface network disappears and the privileged directions of subsurface circulation are dominating in the process of evolution.

The continuity in formation of tectonic structure runs without interruption during the recent time. This is proved by the activity of numerous seismogenic focuses, from Montenegrin and Dubrovnik littorals, through the seismogenic zone of Stolac up to the Nevesinje epicentral zone.

THE BASIC HYDROGEOLOGIC PARAMETERS

Systematization and analysis of a great number of exploration works have enabled generalization of essential hydrogeologic features and basis hydrogeologic parameters which can be accepted as the representative for the entire region.

T h e o u t f l o w s c o e f f i c i e n t is very high, ranging between 0.70 and 0.80, due to rapid sinking and decreased influence of evapotranspiration.

P o r o s i t y of karstified rock masses, ranges between 0.79 % (Gornja Zeta catchment area); 1.20 % - 1.50 % (the Trebišnjica river catchments area), and 1.40 % - 3.50 % (the Obla river catchment area). In some particularly karstified zones like those as the limestone beam Budos - Kunak in the Niksičko polje, or limestone beam between the Dabarsko and Fatnicko poljes, the porosity may reach even 6 % to 10 %.

D e p t h o f k a r s t i f i c a t i o n . The analysis of many records shows that karstification of rocky mass decreases as by the rule along the depth. The most karstified is surface zone to 15 m in depth. The greatest number of karst caverns was recorded to 150 m in depth. Generally speaking, the basis for karstification lies at the depth of 250 m. Below 200 m the karst forms are scarce and mainly connected to fault zones.

Presence of karstification was encountered locally at big depths as well. A deep drillhole in the Niksička zupa penetrated the forms which indicate the presence of karstification at a depth of 2236 m. Numerous submarine springs in the Bay of Kotor in the direction Janska - Bistrine signalize presence of extremely developed karst forms, deep below the present sea level.

O s c i l l a t i o n s of ground water level are fast and with large amplitudes. The maximum rising of the level recorded was 90 m/24 h, i.e. 375 cm/h. The maximum amplitude of karst water body fluctuation which was recorded for the Nevesinjsko polje was 312 m. The maximum recorded amplitude for the Niksičko polje was 94 m; in the rear of the Ombla river 198 m; in the Fatnicko polje 117 m; in the Plana area 123 m; at the marine of the Cernicko polje 124 m. The most often the amplitudes range between 20 and 80 m.

C i r c u l a t i o n s p e e d of underground waters varies in a wide range between 0.002 and 55.2 cm/s. Most often speeds (average) of subsurface flows are in a range of 0.5 to 0.9 cm/s. In a large number of karst water bodies particularly in those with limited catchment area, circulation during the dry seasons completely disappears.

I n f i l t r a t i o n z o n e s . Although all terrains of this region, which are composed of carbonate rocks, represent water permeable medium, the karst poljes and river valleys represent typical infiltration zones. The infiltration zone of the Nikšićko polje consists of 880 and of the Popovo polje of over 500 recorded ponors and estavellas, in addition to countless widened fissures along the edge, and soil failure zones in the alluvial cover which is impossible to identify properly in the field. Maximum infiltration capacity of the Popovo polje is higher than 200 cu. m/s; of the Nikšićko polje 160 cu. m/s; of the Gatačko polje 160 cu. m/s; of the Fatničko polje 120 cu. m/s and of the Dabarsko polje 43 cu. m/s. The greatest concentrated infiltration locality, in the form of a single orifice only, is the Bigrad ponor in the Nevesinjsko polje. "Swallowing" capacity of this ponor is over 100 cu. m/s. Then follow: the Slivlje ponor in the Nikšićko polje (70 cu. m/s), Srdevići in the Gatačko polje (65 cu. m/s), Doljašnica in the Popovo polje (55 cu. m/s) and at least twenty more ponors whose "swallowing" capacity ranges between 25 and 3 cu. m/s.

D i s c h a r g e z o n e s . Numerous water bodies of this region are discharged through a large number of concentrated discharge zones. Among them with their maximum yieldingness dominate: the water source zone of the Bay of Kotor (about 300 cu. m/s); the Perućica spring (170 cu. m/s); springs fo the Trebišnjica River (300 cu. m/s); Buba with Bunica (300 cu. m/s); Ombla (160 cu. m/s).

Between Trebinje and the Fatnicko Polje the Dinaric structure trend are dominated. The most interesting structure forms along the Dubrovnik litoral is huge tectonic zone following the coast. This is the front of the high karst overthrust named "celo navlake visokog krsa" (the High Karst Overthrust) (Fig. 10.9). The reverse wing of this structure, composed of carbonate complex of Triassic, Jurassic and Createaceous dolomite and limestone, is thrust over the sediments of the Eocene age (flysh and alveoline and nummulitic limestone). Contact of the Eocene flysh and Triassic dolomite has been discovered on the road and can be seen along the edge of the Dubrovacka Zupa by kilometers far. Water impermeable deposits of flysh have the role of hydrogeologic barrier in this structure owing to which, along this contact, a larger number of springs of different yield appear. The settlements in this area are mostly located along this contact line.

Farther on, towards Trebinje the series is monoclinic in general with 20^{o} - 35^{o} dip towards the northeast. The Mokro Polje is periodically flooded karst depression filled with fluvial-glacial gravel and sand. Westward, this polje extends to the Trebinjsko Polje and karst cover of the Trebinjska šuma forest.

The most significant structure of this region in the hydrogeologic sense is the "Lastvanska anticline" whose lake is composed of water impervious Triassic dolomite (Fig. 10.9). Owing to the hydrogeologic characteristics and suitable special position, this structure had the decisive role in the "Bileća" reservoir forming in the widened valley of the Trebišnjica river, having all characteristics of the Dinaric karst. This accumulation volume is 1.3 cu. m and it is 18 km in length. The greatest depth of the accumulation is 100 m. Before entering Bileća the marchroute passes along submerged springs of the Trebišnjica River (Fig. 10.4). When the water level of the lake reaches the maximum level, the main spring (the Dejanova pećina cave) is submerged, covered with 76 m high water column.

THE FATNIČKO AND DABARSKO POLJES

Both the Fatničko and Dabarsko Poljes are formed along the steep reverse fault extending along the northeastern border of the poljes. Those are limestones of the Cretaceous age, thrust over the Eocene complex composed mainly of flysh and sporadically of alveoline-nummulitic limestone as well. The flysh extends also below the Fatničko Polje where it reaches to 200 m in depth. The central part of the northern edge of the Dabarsko polje is composed of sediments of the "Promina Series" consisting of conglomerate deposits over 1000 m in depth.

The poljes are separated by extremely karstified limestone beam (limestone ridge), about 2 km wide. Those are closed karst poljes without the possibilities for surface runoff. The common characteristics of both poljes is that along the northeastern edge numerous permanent and periodic springs appear, while ponors appear along the southern edge of the poljes. Compared to periodic springs, the permanent springs are of negligible yield. The most significant source zones in the Fatničko Polje are Obod and Baba pit (Fig. 10.3), and in the Dabarsko Polje the Vrijeka and Ljelješnica zones. The maximum yieldingness of the Obod reaches about 60 cu. m/s and of the Vrijeka about 25 cu. m/s. There are many periodic springs in both poljes with a lower yieldingness compared to the above mentioned.

The only permanent water course in the Dabarsko Polje is the Vrijeka river. Its length is about 2.5 km (from the Vrijeka spring up to the

Ponikva ponor), and the minimum flow through is about 150 l/s. In the rainy period another water course is formed in the northwestern part of the Dabarsko Polje, flowing towards the central part of the polje where it overflows flooding the polje. The periodic water course which is formed in the Fatnicko Polje (Fig. 10.10) lasts very short, since this polje is quickly flooded.

Floods in the Fatničko Polje may last 79 to 213 days in a year. The maximum level of the flood reaches 28 m when 228 cu. m of water accumulates in the polje. In the Dabarsko Polje only the southeastern part is flooded and the maximum recorded flood level was 13.7 m.

The summary swallowing capacity of the ponor zones of the Fatničko Polje amounts to 120 cu. m/s and of the Dabarsko Polje 43 cu. m/s. The largest of the single ponors is Pasmica in the Fatničko Polje with swallowing capacity of 25 - 30 cu. m/s. A part of the ponor zone of the Fatničko Polje lies in the watershed bifurcation area so that waters from this polje discharge underground towards the Trebišnjica River source (about 85 %) and towards the Bregava River sources (about 15 %).

Waters of the Dabarsko Polje discharge towards the Bregava River sources. To control the activities of the most significant ponor of this polje i.e. the Ponikva ponor, detail field and model explorations and tests were made. This ponor consists of two holes which are impounded. The input canals are slightly inclined i.e. they are nearly horizontal. For continual control of speed change under the conditions of complete inundation of the ponor, each hole is provided with a velocity measuring unit at one point (Pit tube). For mean velocity defining, i.e. for determining the velocity at different point of the input profile of the canal, the laboratory models of both holes are used. For determining the coefficients required for mean velocity calculation on the basis of the measured velocity, models with large hole were tested using water, and those with smaller hole by means of air current. After two years of continual measuring it was found that the swallowing capacity is highly variable value which only under concrete conditions depends on the water level in the field. The maximum swallowing capacity amounts to 15 - 20 cu. m/s and in certain periods discharge through the ponor was at a minimum although the ponor was impounded.

THE BREGAVA RIVER

The Bregava River valley is composed of the Cretaceous and Paleogene sediments, covered with debris and inrush breccia in the canyon, and downstream from Stolac with the alluvial deposit (the Vidovo Polje). Faults of reverse type and the plication forms of the Dinaric trend give tectonic character to this area. The most rugged tectonic element is the anticlinal form in which the canyon section of the water course is cut through (Fig. 10.11). The anticline is broken by a fault which imposed forming of the canyon valley from the source close to the Stolac settlement.

In the geologic period preceding the karst process development, the Bregava River drained the large catchment area. Its catchment area extended from the uppermost upstream sections of the Zalomka River to include extensive areas of the Nevesinjsko, Slato, Lukavačko and Dabarsko poljes. Intensive karstification and its effects, i.e. very fast evolution of the karst process, destroyed the surface network and now only its relicts can be met, mainly in the form of periodic water courses (Fig. 10.12). With appearance of ponors and intensification of underground circulation in the area of the highest horizons of this catchment area (the Slato and Lukavačko poljes) the Zalomka River loses its surface tributaries so that part of waters of the Lukavačko Polje discharges subterrane towards the Dabarsko Polje. Across many ponors in the Nevesinjsko Polje the underground circulation towards the Buna and Bunica rivers had appeared. In this way the Zalomka River loses a large part of the Nevesinjsko Polje catchment area. Finally, the Zalomka itself loses one part of its catchment area, discharging through karst canals towards the Bunica River. The Biograd ponor has become a dominant infiltration point. A part of the Zalomka water course between Biograd and its mouth to the Bregava turns in a dry valley.

The evolution process of karst water body continues and reaches deeper and deeper. The surface outflow from the Dabarsko Polje through the Bregava River is replaced by the underground circulation through the infiltration zones of the Dabarsko Polje (the most significant are the Ponikva ponors and the Kutske jame pits). The springs Veliki Suhavić and Mali Suhavić are formed as well. By rising the terrain in the area of Prijevor, the surface runoff ceases completely and the evolution process reaches even deeper into the limestone masses owing to which the Veliki Suhavić and Mali Suhavić springs lose their function of permanent springs. Downstream, the present source of the Bregava River is formed. Upstream, the dry river valley will remain in which a water course will be formed periodically, only in the direction between the Suhavić springs and the present permanent springs.

The evolution process is not limited to the source area only. Karstification is intensive in the downstream part of the course as well. This part of the water course (downstream Stolac) is under strong influence of Deransko Blato. Here ponors are formed through which water discharge towards springs along the edge of Deransko Blato. During the dry season this part of the Bregava River course is dry as well. The permanent course function was retained by the central part of the course only, from the source zone up to Stolac. The permanent course is 12 km long. Only in the period of intensive rainfalls the river flows in its total length of 33 km.

The karst process evolution of this karst water body has not been completed. The karstification basis and the karst water body did not reach the phase of complete adjusting to the erosion basis of Deransko Blato. The influence of this basis on the Debarsko Polje is more and more direct. At the same time, however, the influence of the Bregava basis weakens. This process is partially slowed down due to the Alb-Cenomanian member position in the anticlinal structure and the fault which intersects the river bed at the permanent springs of the Bregava River (Bitunje). The predominant dolomitic composition of this member imposes the function of a relative hydrogeologic barrier. Waters flowing out of the Dabarsko Polje are retarded by this barrier and forced to appear on the surface. Passing over the barrier, water comes again into an environment which is deeply engaged by the karstification process and sinks again. With further lowering of the karstification base the role of the above mentioned hydrogeologic barrier will be less . The Gregava River shares the fate of many water courses in the Dinaric karst. This river is losing the characteristics of a permanent water course therefore.

The thickness of drift in the river bed ranges between 4 and 23 m. Drift deposits rise fastly with the construction of a smaller dam upstream from Stolac. The limestone below the drift is highly karstified and water permeable. Here and there they are so porous that their structure looks like a sponge. The ground water level is deeply below the river bed.

The source zone yieldingness is about 2 cu. m/s at its minimum and the maximum measured flow through reaches 139 cu. m/s.

A part of the permanent water flow still exists owing to well deposited river drift through which a relatively small quantity of water percolates so that the permanent course disappears only downstream the Stolac settlement.

THE POPOVO POLJE

The Popovo Polje is an exceptional example of the karst phenomenon. It is divided into the corrosion karst surface without continual alluvial cover (the area of Trebinjske Šume forest) and the Popovo Polje in a narrower sense. This part of the Popovo Polje is shaped as a narrow valley whose trend coincides with the Dinaric trend of the structure. It is slightly inclined northwestward. The alluvial drift thickness increases in the direction of the polje incline. At the beginning the drift thickness is 1 to 2 m, to reach 15 - 25 m in the narrowest part.

The karst plateau of the Trebinjska šuma forest was formed in the Crateceous limestone which is intersected by a thick network of faults. Particularly rugged are the faults in the north-south direction (Fig. 10.13). In this part the Trebišnjica River cut through its bed along the northern edge of the plateau.

The alluvial cover area of the Popovo Polje is 68.4 sq. m. The width of the polje varies between 1 and 2 km.

More than 500 ponors were recorded in the polje, together with estavellas and periodic springs. The largest ponor is the Doljašnica ponor having the swallowing capacity about 55 cu. m/s.

Among larger ponors with the swallowing capacity from 10 and 3 cu. m/s are Crnulja, Ponikva, Žira and some others.

The most significant cave in the Popovo Polje is the Vjetrenica cave. It has been the subject of interest of the explorers since 1872. Up to now the total of 4.500 m of canals were explored and the phase of detail exploration of this cave system is planned. Apart from its tourist aspects this cave is particularly interesting from the biologic point of view since it represents a true preserve of endemic fauna.

Under natural conditions the Popovo Polje comes in the group of periodically inundated poljes. According to some old data there were floodings in the narrowest part of the Popovo Polje in the past, whose level reached 40 m in height. One of the heaviest floods, during the period of floods control by means of the observation stations, was recorded on March 1, 1941. At the time the maximum level was at the level 261 above sea level i.e. 38 m above the lowest part of the polje. About 7.500 ha were flooded then. In the average the floods last 253 days in a year. The longest floods were recorded in 1915, lasting 303 days, and the shortest in 1930, lasting 209 days. At maximum flood levels about 1 billion cu. m of water accumulates in the polje.

It may happen that the Trebišnjica River in its course through the Popovo Polje disappears in the length of 50 km during the summer period. In rainy seasons the river bed is often too narrow to receive all waters which inflow with the Trebišnjica and those which appear through a large number of estavellas and periodic springs in the polje alone. The maximum flow through at the profile downstream from Ravno may reach more than 1.400 cu. m/s, which exceeds considerably the capacity of all ponors (250 - 300 cu. m/s).

The relation between underground and surface waters in this confined karst polje is a specific one. In dependence on this relation the polje can be divided in three parts (Fig. 10.4). The lowest part (A) is characterized by the ponors; the central part (B) by estavellas and the uppermost part (most upstream) (C) by its large number of strong karst springs.

The lowest part of the polje (A) is encircled from three sides with erosion basis. Since the difference in elevation between the basis and the polje is more than 220 m, the subsurface circulation branches in many directions, nearly radially, under the influence of high gradients. Such position influenced the draining system forming with a high capacity of ground water discharge. The capacity of this draining system is much bigger than that of all ponors in this zone owing to which even at the highest levels of inundation the ground water level does not come in contact with the surface. Observation of drillholes which penetrate the karst canals shows that some of the canals discharging towards the erosion basis are not filled with water up to their full profile, even when inundation in the polje reaches 20 m level. These canals lie at about 110 m below the inundation level. Apparently the water quantity q flowing through them could be much larger as compared to the summary capacity of the ponor zone through which water sinks towards the canals (Q = 15 - 20 cu. m/s) in addition to infiltration waters quantity q_2, and other waters which are coming underground from other catchment areas.

Ground to surface waters ratio in the central part (B) is of specific feature and it is manifested on the surface by numerous estavellas. Dolomitic zone in between the polje and the sea, i.e. between the local erosion basis and the absolute basis had a big influence on such relations. In this way the direct hydrogeologic connection between these two basis was prevented along this line. This zone acts as a barrier enabling thus rising of ground water level in the background. High inflow of ground waters q_1 and waters of direct infiltration q_2 is much higher than discharge capacity (q) and therefore the water body level will rise. Since the upper surface of the water body is inclined towards the absolute erosion basis, it establishes contact with the surface along that edge of the polje which is farther from the erosion basis. Along this edge the estavellas appear as springs. One part of waters reach the surface of the local basis (q_3). The water body level at the profile b-b is marked with (1). A part of these waters disappear on the other side of the polje through estavellas which are now in the role of the ponors. At heavy rainfalls, when the water body level comes into the position (2) these estavellas will be turned into springs which results in faster flooding of the polje.

The zone (C) is characterized by periodical springs and ponors. The springs appear along the northern edge of the polje and the ponors mainly in the river bed or around it. When the water body level rises, the springs are activated and a part of the water body discharges (q_3). The major part of waters discharge underground (q_1) in the direction of the erosion basis. Discharge is regulated by the discharge canals capacity q. The water body level variation speed will depend on (q) as well. The discharge canals capacity is such that ponors always may function without any disturbance. Furthermore, the surface runoff in the polje is always oriented towards the lowerest part of the polje.

The specificity of the ground water to surface water ratio in the above cited three zones can also be noted in the levels diagrams shown in Fig. 10.14.

In case A, the water body level does not reach the level of the polje at any moment, even when floods are highest. Inundation in this part of the polje occurs (point E in the diagram) under the influence of waters which run in this part of the polje over the surface.

The case B characterizes the ground-surface water ratio of the majority of karst poljes. After heavier rainfalls the piezometric levels reach fastly the level of the polje influencing directly the faster flooding of the polje. After rain falls stopping, the piezometric levels in estavellas zone usually decrease faster than the level of the flood. The diagram of this zone levels shows that the level of the zone, which was higher than the flood level, rapidly goes down, intersects the flood line at G point and then goes down rapidly below the level of the polje. At that moment the inflow to the polje ceases completely. The estavellas are in the role of ponors. The phase of pure discharge of the polje occurs and terminates at H point when the polje is completely clear of water.

In the region C, the levelgram of oscillations in piezometers of the spring zone (thick line) and the levelgram of oscillations in piezometers of the ponor zone (dotted line) are apparently different. The piezometric level of the ponor zone behaves similarly to the piezometric level of the region A. It never reaches the level of the polje. The water body level in the background of this spring zone (thick line) behaves similarly to the level of the estavellas zone in that part of the polje designated with B. The periodic springs will be active when the piezometric line in the background reaches the level of the polje.

THE BUNA RIVER SPRING

The springs of the Buna and Bunica rivers are concentrated zones of discharge of large karst body formed in the massif under the Nevesinjsko Polje and partly under Velež Mountain. Both springs are at the level 35 m above sea level while the main infiltration zones of the water body lie at the edge of the Nevesinjsko Polje at the levels 800 and 850 m above sea level. The springs are about 4 km apart (Fig. 10.15).

The Buna River spring is formed on the reverse tectonic contact along which the carbonate sediments of the Cretaceous age are thrust over the narrow zone of the Eocene flysh. This contact, in the length of 13 km and approximately of the Dinaric trend represents the hydrogeologic barrier which causes discharge of the unique water body through two separate concentrated springs.

The minimum measured flow through of the Buna River is 3.7 cu. m/s and of the Bunica River 0.8 cu. m/s. The total maximum yield of these two springs ranges between 300 and 320 cu. m/s.

The water body of the Buna and Bunica rivers are characterized by extremely high amplitudes of ground water level fluctuation.
The maximum recorded amplitude is 312 m (Fig. 10.16). And the speed of circulation in the individual parts of this water body is much higher than the average speeds of underground circulation in the Dinaric karst reaching 33 cm/s. The largest infiltration zone is the Biograd ponor in the Nevesinjsko Polje with the measured swallowing capacity of 86 cu. m/s. The maximum capacity could not be precisely determined since at maximum capacity the ponor is impounded. The analysis of the discharge curve of the natural accumulation formed over the ponor shows, as an estimate, that the maximum swallowing capacity of this ponor is higher than 110 cu. m/s.

3. SOME EXAMPLES OF EXPLORATION AND WATER REGULATION PROJECTS

CLOSING OF THE OBOD ESTAVELLA

The Obod estavella is located in the Fatničko Polje. Because of its position and complex hydrologic-hydrogeologic characteristics, this polje represents an extremely significant erosion basis of the local character in this part of the eastern Herzegovina. It lies between the Cerničko Polje and the Trebišnjica River spring. The Cerničko Polje is a hypsometric higher cascade (by about 350 m) within the Fatničko Polje catchment area. Springs of the Trebišnjica River are by 130 m lower than the Fatničko Polje. Through them the large catchment area, including both the Fatničko and Cerničko poljes, is drained.

The Fatničko Polje is hydrologically active only during the period of high waters when it is inundated. The inundations may last between 79 and 213 days a year. The maximum inundation water level is 38 m. This is a bifurcation area from which waters discharge in the direction of the Trebišnjica River sources (85 % approximately) and in the direction of the Bogava River source (about 15 %). The most significant ponor is Pasmica ponor (25 cu. m/s) whose waters discharge towards the Trebišnjica River sources.

The Obod estavella lies in the Upper Cretaceous limestone at the contact with the Eozene flysh sediments. This contact is a reverse fault whose trend goes along the northeastern edge of the polje, and at the spot where the estavella is formed there are two fractures perpendicular to the contact direction. When appearing as the spring the yield of the estavella amounts to about 60 cu. m/s and when appearing as a ponor it receives and swallows about 2 cu. m/s. The reason for such variation in the yield is in very high levels of ground waters in the periods when the estavella "works" as the ponor which causes retardation of discharge.

Long ago it was noted by the local people, that the day before the Obod ponor turns into the spring the muffled sounds resembling explosions can be heard followed by periodical ground vibrations. Because of that a seismograph (only the vertical component) was installed above the ponor. Results of one year observations have proved the reality of the local people's observations.

To lessen inundation of the Fatničko Polje and losing of a part of waters from the Trebišnjica River catchment area by their outflow to the Bregava River catchment area, in 1964 the experiment of sealing the Obod estavella was proposed. After speleological explorations sealing of the estavella was undertaken (Fig. 10.2). The intention was to "force" a part of waters outflowing into the polje to continue their underground flow towards the Trebišnjica River sources.

A massive concrete plug was made (according to the Energoinvest of Sarajevo design), 10 high and 3.5 m wide in average. At the top, a hole

1.53 x 1.40 m was left, covered with a reinforced concrete slab containing 10 kg of explosive. The plug was calculated for the pressure of 40 bar. The pressure behind the plug was controlled through a built in pipe which was extended to a place outside the inundation waters area, with a pressure gauge on that end.

The experiment was planned to last one hydrologic year. However, on October 11, 1964 an extremely heavy rain occured in the Obod catchment area. Precipitation in this catchment area was over 100 mm in average. Some rain gauges showed even 230 mm of precipitate. During the night between 11th and 12th October, above and around Obod the springs appeared. The highest ones appeared at the levels which were by 80 to 100 m above the Obod estavella level (Fig. 10.3) and some springs appeared in the houses, 80 m above the Obod level. Measuring of yieldingness and estimates showed that the total yield of newly formed springs was about 11 cu. m/s. On the same day, in the morning, the pressure gauge showed 7.0 bar and at 6 p.m. the pressure was 9.25 bar. Roars and strong strikes were heard from the underground. On the first day five stronger and a greater number of smaller strikes were noted. These strikes were recorded the next day as well, and also the increase of the pressure on the gauge. The road over the Obod estavella started sliding. The highest pressure was read on the gauge on October 10, 1964, reaching 10.6 bar.

Yieldingness of the second largest spring in this part of the Fatničko Polje, the Baba pit, belonging to the source zone of the same catchment area as the Obod, increased due to the pressure rise by 5 cu. m/s. Under natural conditions this spring starts working always at least half a day after the Obod.

Mining of concrete slab of the plug was done on October 18, 1964 at 11 a.m. The water level at the overflow (exit) rised in 5 minutes from 14 to 130 cm. Hypsometrically highest springs ceased working at 12 a.m. and at 13.45 p.m. the springs above the road became dry.

Explosion of mining destroyed the intake pipe for the pressure gauge and as the result the pressure could not be possible to control any more. All springs above the Obod, even those at the highest levels stopped working during the next 3 to 6 hours, which showed the rapid pressure drop in the underground. The road surface settled by 50 cm in the length of 30 m, and a number of houses on the slope above the Obod, at the distance of 250 to 300 m, were damaged.

Heavy rains effected the experiment to a great extent. Instead to last one complete year, the experiment was interrupted one week after the first heavy rains. Quantities of water accumulated in the zone of dynamic reserves of the catchment area and in the aeration zone were insignificant. The result of hydrologic analysis (B. Petrović, 1965) allows the supposition that about 30 cu. m/s of water was prevented to discharge into the Fatničko Polje.

The increased pressures and the activation of aeration zone caused many problems on the surface of this terrain. As the result is was clear that expected effects of sealing were not achieved under the geologic and hydrologic conditions which exist in the Fatničko Polje ("transit" erosion basis in the bifurcation area with hanging barrier which act as a retarder but only in the period of very high water body heads) and under the geologic conditions like those in the direct background of the spring. Under such hydrogeologic conditions forming of a subsurface accumulation is not possible.

Such a conclusion comes out from two basic reasons:

(1) accumulation is possible only in the period of water body high heads, which lasts very shortly, and
(2) accumulation volume of this part of the water body is insignificant.

Sealing of the estavella, with the only reason to prevent discharge of water into the Fatničko Polje and to force its underground flow towards the Trebišnjica sources, is linked with big problems and harmful manifestations on surfaces whose scales could hardly be foreseen. The expected energetic gains do not justify such a risk.

SUBMERSION OF THE TREBIŠNJICA RIVER SOURCES

With the construction of the Grančarevo Dam and with the "Bileća" accumulation forming, the Trebišnjica River sources were submerged with 76 m high water column. The source zone is at 324 m above the sea level. The exploration drillings and electric trial boring showed that in the rear of the springs the rocky mass is highly karstified, approximately up to 300 m level. Together with the Čepelice spring, which is a part of discharge zone of the same water body, the Trebišnjica River sources have Q_{mean} = 80 cu. m/s. The main spring is the Dejanova Pećina cave. It is the terminal of the karst canal system which is partly explored in speleologic sense.

The question is whether submersion of these sources would have possible effects on the direct background of the sources and their wider catchment area, and to what extent. During the period of 14 years of this accumulation operation, some phenomena were under observation and studied, in connection with the accumulation forming and springs submersion.

1. Observations by means of the piezometer in the right hand wing of the accumulation and in the background of the source zone showed that an underground accumulation exists whose volume is estimated to about 15 % of the surface accumulation volume.
2. When the level of the accumulation is below 360 m above sea level then the natural regime rules over the water body. Above the levels of 360 - 370 m above sea level the influence of the accumulation is noted only in the water body in the immediate background of the source. When the accumulation is above 370 m above sea level it effects activities in the water body of the deep background (Fatnica - Plana area), i.e. it effects the rise of maximum inundation levels in the Fatničko Polje. In such caes, the difference in elevation between the Trebišnjica River sources and the Pasmice ponor zone in the Fatničko Polje decreases from 130 m to 64 m.
3. The water body head in the immediate background of the source zone, i.e. in the Bilećko Polje area depends on two essential elements:
   (1) level of the accumulation, and
   (2) precipitation in the catchment area which can be expressed by means of previous rainfall index or as the inflow to the accumulation.

   When the level of the accumulation is at 400.00 m above sea level and the inflow greater than 125 cu. m/s, a part of the Bilećko Polje will be inundated (Fig. 10.4). The critical inflow for the level 397.00 of the accumulation, at which the water body head reaches the level of the Bilećko Polje and floods it, is 220 cu. m/s.
4. Because of the aeration zone activation, in the immediate background of the sources and due to "clearing" of a number of inactive and plugged karst canals at that period, the outflow zone is enlarged. In addition to the Dejanova Pećina cave karst system (level 324 m above the sea level) a new point of outflow at the level 363 m above sea level was formed.
5. Submersion of the spring zone has changed the hydraulic conditions of flows through the karst canals. The important element of natural hydraulic status change is the rapid change in the accumulation water level. These changes resulted from seismic effects which are divided in two groups:
   (1) induced earthquakes due to rising the level of the accumulation and variation of rocky mass equilibrium, and
   (2) hydraulic and air stresses as the consequence of releasing the confined air in the karst caverns and canals during the sudden changing of the underground space.

6. Observation and analysis of water body head oscillations in the watershed zone towards the Bregave River catchment area have confirmed that impounding of the accumulation up to the level of 400 m above sea level and submersion of the Trebišnjica River sources had not effected the position of the watershed. All doubts as regards loosing of water from the "Bileća" underground accumulation, in the area of the watershed zone south of the Fatničko Polje, were declined.

HYDROGEOLOGIC PROBLEMS OF THE "HUTOVO" ACCUMULATION

Water imperviousness of the accumulation basins, river beds and damming profiles is one of key hydrogeologic problems of the Dinaric karst. Seldom happens that accumulation basins are located under such hydrogeologic conditions which enable accumulation of water without regulation works. Of the accumulations formed in the southeastern Dinarides region, the "Slano" accumulation in the Nikšičko Polje and the "Hutovo" in the Popovo Polje are specific ones regarding the complexity of hydrogeologic problems. They were realized only after extensive exploration and water regulation works on the surface and subterrain .

The "Hutovo" accumulation represents the upper compensation basin of the "Čapljina" HE power plant. It is located in the northeastern wing of anticline structure of the Cretaceous Age, whose lake is composed of the Lower Cretaceous dolomite (Fig. 10.5). This structure has the function of the hydrogeologic barrier against the erosion basis of the Adriatic Sea.

The accumulation area is covered with alluvial deposits whose thickness increase from the flanges towards the centre where it reaches to about 30 m. Paleorelief has all characteristics of typical karst (dolines, clint and ponors). The exploration drilling along the northern edge confirmed presence of the ponor zone at a depth of 50 m below the polje's surface (Fig. 10.6).

Hydrogeologic activities of this zone are manifested on the surface in the form of the biggest group of deep alluvial ponors in this part of the polje. Other alluvial ponors in the "Hutovo" accumulation basin area are connected mainly to the bordering part of the polje in which alluvial cover is not more than 10 m thick.

In spite of a high contents of clay component in the Alluvial deposit, it is highly water permeable under natural conditions, although according to the granulometric data it belongs to water impervious environment. The reason for such high permeability is in the pseudoloess structure of these sediments. This structure resulted as the consequence of clay material settling (in the period of polje flooding) at the bottom covered with low vegetation. During the excavation works on a shaft 10 m deep in one of ponor zones, numerous cavities in the shape of tubes were visible across the entire profile, whose diameter was 1 to 2 mm. These cavities appeared as the result of weeds and brushwood decay after their covering with clay mud.

The ground water level in the karstified limestone, below the alluvial cover, seldom reaches the level of contact of these two environment. In the oscillation zone of the ground water level, the draining karst system of high transmission efficiency was developed. This system has such a capacity that all sinking waters of this part of the polje (Fig. 10.7) can be evacuated. The discharge capacity is limited by the capacity of underground discharge system. The most significant ponor of this zone, the Ponikva ponor, is isolated according to design solution and it is outside the accumulation.

The analysis of complex exploration works results (geologic mapping, exploration drilling, geophysical exploration, dyeing, tracing by means of radioisotopes, speleologic explorations, observation of ground water level oscillations) confirmed the position of dominant drains in the accumulation zone (Fig. 10.7) and the general directions of underground circulation of regional scales (Fig. 10.8).

Two possibilities to make the accumulation basin water impervious were analysed:

- closing of underground drains (grouting and sealing), and
- regulation of the surface together with appropriate interventions underground.

Having in view the alluvial ponors genesis (soil failure process, effects of air under pressure and combination of these two mechanisms) it was necessary to take care about the air evacuation as it was certain that planned improvement of the water imperviousness of surface layer would effect concentration of the pressure of confined air at some localities. To enable timely evacuation of confined air from the aeration zone, the introduction of aeration pipes was foreseen through the Alluvial cover up to the ponor system in the Paleorelief. Tops of these pipes were set above the maximum expected levels of water in the accumulation area. One of these aeration pipes was introduced after excavation through the Alluvial deposit up to the karst canals in the Paleorelief while the rest were introduced in the boreholes of large diameter set in ponor zone up to the Paleorelief. At sudden rise of ground water level in the karst water body beyond the polje, it was found that air circulates even at some piezometers installed in the basin area. At abrupt rise of the ground water level the air stream from the piezometric pipe was reaching the character of pulsation consisting of expelling out and sucking of air. The period between the maximum value of expelling out and sucking of air ranged within 17 to 35 minutes. These pulsations were recorded only when ground water level as rising but never when it was going down.

By means of the gas (smoke) marker the supposition about a good communication within the karst system of the aeration zone below the alluvial cover was confirmed.

The area of accumulation was losing water under natural conditions through 75 registered ponors in alluvial cover and by smaller part through karstified Carbonate flanks and by filtration through the alluvial deposits having pseudoloess structure of porosity. The loss ranged between 7 and 10 cu. m/s.

To make the accumulation basin impervious, several different sealing methods were applied. The flanks were protected with sprayed concrete, the bottom was compacted and marginal parts of the field (alluvial deposit) were covered with PVC foil. The ponor zones in the alluvium were filled with soil and the surface compacted and covered with the foil, provided sporadically with valves which in case of uplift could discharge water or air.

Regulation of the most significant ponor zone, which lies 50 m below the surface was ensured by means of grouting of the karstified Paleorelief (Fig. 10.6). Pressure grouting with cement mixture was provided from the surface.

Since its putting into operation all changes at the basin bottom have been recorded every year, and the newly formed ponors in the alluvial cover were closed by pouring the clay-cement mixture into their holes.

The number of newly formed ponors ranged by years as follows: in 1975 - 38 ponors; 1977 - 44; 1980 - 36. After that time appearance of new ponors was not recorded. This does not mean, however, that the process of new ponors appearance definitely came to the end, but it is for sure, that a great number of them was successfully closed and that the selected method is proper.

Inspection of the accumulation bottom in 1976/77 showed a new phenomenon - appearance of fissures in the alluvial cover. The fissure width ranged between 1 and 10 cm and, the length from a few meters up to several tenths of meters. Sporadically the width of individual fissures increased up to 20 and even 30 cm. Sections of individual fissures consisted of two close cracks 10 to 30 cm apart and a portion of the mass between them was sagged from 2 to 0.5 m. Fissures were found even under the PVC foil. The visible depth of fissures ranged from a couple of decimeters up to 5 or 6 meters. On some of these fissures new alluvial ponors were formed. Those are ponors of smaller dimensions in general, having crater diameter from 0.3 to 1.0 m and mainly they appeared at the points of two fissures intersection.

The fissures were noted already when the basin bottom was covered with water which means that fissures did not appear as the consequence of material contraction due to drying process. The fissure edges are sharp leading to the conclusion that water erosion was absent.

Fissures were sealed with clay-cement mixture by pouring.

Inspection of the basin bottom in 1980 showed that some of sealed fissures opened at the contact of the natural material with grouting mixture and that new fissures also appeared. The total length of newly appeared fissures was 930 m. These fissures were sealed by using the same methods as for the previous ones.

The water regulation works which were undertaken on the "Hutovo" accumulation (including also sealing of fissures which appeared in the sprinkled concrete at the flanks) resulted in lowering the losses after each intervention and finally were reduced to only 1.0 cu. m/s.

To provide satisfactory water imperviousness of the accumulation basins in such terrains with above cited hydrogeologic characteristics it is necessary to perform permanent inspections and periodical regulation works. It is practically impossible to detect and eliminate all defects in the Alluvial deposit and below it, without regard how extensive the regulation works are. Forming of water impermeable accumulation of good sealing properties in karst terrain is a long lasting process, and proper understanding of hydrogeologic relations is the essential element for a successful execution of the project.

4. INFLUENCE OF THE TREBIŠNJICA HYDRO-SYSTEM ON THE KARST AQUIFER AND SOME ECOLOGIC EFFECTS

Any change in the natural regime of surface waters results in positive or negative effects on a karst aquifer. Depending on their diversity, massiveness and unforeseenableness these effects may occur as accompanying phenomena in construction of large hydro-engineering projects and water economy systems. The erection of large storage reservoirs, regulation of underground courses, artificial drainage of periodically inundated fields and the like, may to a large extent effect the water regime of the karst aquifer. By regulation of many infiltration zones the natural conditions of sinking and discharge have been changed and by submersion of water source zones the water circulation regime in a part of aquifer have been effected. And, instead to drain through natural surface water courses and through subsurface karst canals water accumulates on the surface, directed to flow through tunnels and concrete river beds.

In addition to the above effects the effects of ecologic and sociologic character are evident. Flooding of cultural-historical objects and natural rarities, jeopardizing of endemic varieties and particularly the complex social-economic problems appearing in connection with removal of settlements from submerged areas are only a part of the problems, resulting as the consequence changing water regime.
Construction of the first phase of the Trebišnjica Hydro-System has changed to a great extent the regime of surface and underground waters in eastern Herzegovina region and in Dubrovnik littoral belt with the Neretva River valley. Hereinafter we shall discuss some of more significant influences of this system and the positive and negative effects noted so far.

1. In the typical dry region with only one permanent surface water course - the Trebišnjica River, whose length could reach only 30 to 35 km in summer period of the total length of 90 km and the flow at most 2 to 3 cu. m/s in the same summer period, a large accumulation called "Bileća" was formed with an area of 27.6 sq. km, containing 1.3 billion cu. m of water and with the permanent water course of the Trebišnjica River 65 km in length with a minimum water flow of 8 cu. m/s. Within this system there are three additional smaller accumulations: compensation basins "Gorica", "Hutovo" and "Svitava". In this way this waterless region was enriched with more than 40 million sq. m of water surface in the form of a lake. The periodical water flow of the Trebišnjica River was turned into a permanent water flow covering the surface, which depending on the flow capacity, ranges between 1.2 and 1.9 million sq. m. The influence of this water surface on the micro-climate was noted. These micro-climate changes have improved conditions for vegetation development around the accumulation areas.
2. About 5.000 hectares of the Popovo Polje is protected against inundations, which under original conditions have allowed minimum utilization of the polje for agricultural production. Earlier, inundations lasted 253 days per year in average which prevented development

of any type of infrastructure in the polje itself, forcing the inhabitants of this area to organize their settlements under extremely unfavourable conditions, in unapproachable, steep rocky slopes over the level of flooded soil. Now, however, only in one village (Orašje) some 30 buildings are erected at the level of the polje, and people leave their old houses on the rocky slopes, high above the level of floods, since they are unsuitable and non-economic for living.

3. Prevention of long-lasting floods in the Popovo Polje has been manifested on a number of periodic springs and underwater springs in the area of Janska - Malostonski Zaliv bay - Bistrina in the form of considerable shorter duration of water issuance. Because of that extensive searching of this phenomenon effects has been undertaken, particularly on living conditions of oysters in the Malostonski Bay and in Bistrine.
4. After the analysis of regional hydrogeologic characteristics under natural conditions, based on a large number of tracing experiments, the possible influence of changing the natural regime of waters in the water catchment area on the yieldingness of numerous springs in the littoral belt and in the Neretva River valley was estimated. Because of that, the so called zero status, was recorded at 64 selected springs and permanent control of their yieldingness was organized. It was determined for sure that the structures of the system effected some more important springs (Robinzon, Zavrelje, Ombla) in such a way that minimum flows were increased (Ombla) or mean annual flows (Robinzon, Zavrelje). Karst water bodies which discharge through these springs are steadely fed by percolating waters which disappear from the compensation basin. "Gorica", from a part of the river bed downstream of the Gorica Dam, and from 16 km long tunnel connecting the compensation basin with the power plant at the coast.
5. Owing to the accumulation of water at the lowest part of the Popovo Polje, the quality of the Doljani spring in the Neretva valley was improved. In natural conditions the area of the accumulation basin represented the most important infiltration zone of ground water body which discharged through a number of springs in the Neretva valley among which the Doljani water source zone as well. The minimum water quantities of this water source have been increased manifold. Only during short periods of inspection and eventual regulation undertakings the basin is discharged and then restauration of the natural state occurs in this karst water body.
6. Numerous estavellas along the northern margin of the Popovo Polje in the line of 12 km (from Dračevo to Strujića) lost partly their functions which classified them in this group of hydrogeologic features. After Grančarevo Dam erection these estavellas have mainly the role of periodic springs with the maximum yield of 70 - 80 cu. m/s.

Since this part of the polje is protected from inundation waters, the sinking function of estavellas was brought to an insignificant minimum.

7. Recharge of water bodies through the largest concentrated infiltration zones of the Popovo Polje (ponors of Doljašnica, Crnulja, Provalija, Žira and Ponikva) was deduced to scarce and short hydrologic periods. Sinking to the water body through numerous ponors along the river bed (under natural conditions up to 63 cu. m/s) has been completely prevented. The fact is, that the karst water body, whose main infiltration zone is the extensive area of the Popovo Polje, has been impoverished for an average recharge of 105 cu. m/s in the long range. This means that the available water mass which under natural conditions recharged this water body looses more than 3 billion cu. m of water annually owing to artificial capture. Impoverishment of water body for such a water mass resulted in the change of karstification process intensity, in the area of dominating drains of underground circulation. Possibilities of floating and drag detritus movement through karst canals have been lessened as well. And particularly lessened is the activity of those parts of drainage systems which have the highest gradients and through which turbulent flows are of highest speed.

This shortage in recharge of aquifers has undoubtedly influenced renewal of dynamic reserves. Replenishment of such reserves is deduced to short periods, and consequently the function of those parts which receive water in individual key drains is reduced to a minimum.

8. Disturbed natural regime of surface and underground waters in the Popovo Polje has the negative effect on endemic varieties and their existence whose living environment is in the zone of water body dynamic reserves. A large number of localities (37) at which the presence of well known Proteus reptile was determined, were destroyed with erection of different kinds of building structures. The changeable regime of underground waters seriously endangered the existence of the Proteus in other locations as well. Such changes imperil seriously the existence of some other endemic varieties as well, whose living environment is exclusively karst subterrane.

The similar situation is with the well known inhabitant of syphon lakes in the karst subterrane, the endemic specie of paraphoxinus ghetaldi fish. This fish, 10 to 17 cm in length, used to live during the dry period in the syphon lakes and during the flooding season of 6 to 7 months in the periodical lake of the Popovo Polje.

Appearing in a large mass this fish as of particular importance for the population as a kind of food as well as for salmonoid fish species (before all the trout) living in karst rivers of Eastern Herzegovina. Since the estavellas were the main communication for the p a r a p h o x i n u s g h e t a l d i fish, i.e. for its exit and return to the underground, the change of estavellas function into periodic springs endangered the existence of this endemic specie.

9. The Aeolian erosion process in the Popovo Polje has been intensified. Earlier, in the period of strong winds, the polje was inundated and its surface covered and protected with grass. Now the large surfaces of the polje are ploughed over in the season of strong winds owing to which the Aeolian erosion comes highly to expression.
10. There is no more sedimentation which earlier used to occure during inundations, enriching the polje with a new layer of fertile soil every year.
11. Recharge and discharge of the "Bileća" accumulation caused changes of natural seism in wider area of the accumulation. During the period of the first six years of this accumulation operation, about 8000 earthquakes were recorded, each of which released the energy in the range of $n \cdot 10^{6}$ erg to $n \cdot 10^{16}$ erg. The largest number of earthquakes was recorded in the periods of maximum water levels of the accumulation. These levels coincide with the highest energy release.

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FIGURES

10.13. Photo-geological analysis of the infiltration zone Kocela - Dobromani in Popovo Polje. 1 - Fault (defined and assumed); 2 - Zone of the pronounced tonal variations (lineament); 3 - Beding trace; 4 - Edge of the cutoff; 5 - Direction of the underground circulation; 6 - Ponor (swallow-hole); 7 - Estavelle; 8 - Intermittent spring; 9 - Sinkhole (Doline).

10.14. Schematic representation of relationship of surface and groundwaters in Popovo Polje. 1 - River and Marsch sediments; 2 - Karst Polje; 3 - Dolomite; 4 - Ponor; 5 - Estavelle; 6 - Intermittent spring; 7 - Permanent spring; 8 - Direction of groundwater circulation; 9 - Ponor and spring zone (on the cross section); 10 - Riverbed of the Trebišnjica River; 11 - The poljes flood levels; 12 - Hydrograph of piezometer level in the spring-estavelle zone; 13 - Hydrograph of piezometer level in the ponor-estavelle zone; 14 - Flood level hydrograph; 15 - Bottom of the polje; 16 - Part of level hydrograph during the extremely high aquifer table; 17 - Spring-estavelle zone; 18 - Ponor-estavelle zone.

10.15. Simplified hydrogeological map of the Buna spring drainage area.

10.16. Fluctuation of the water table within the Buna spring aquifer.

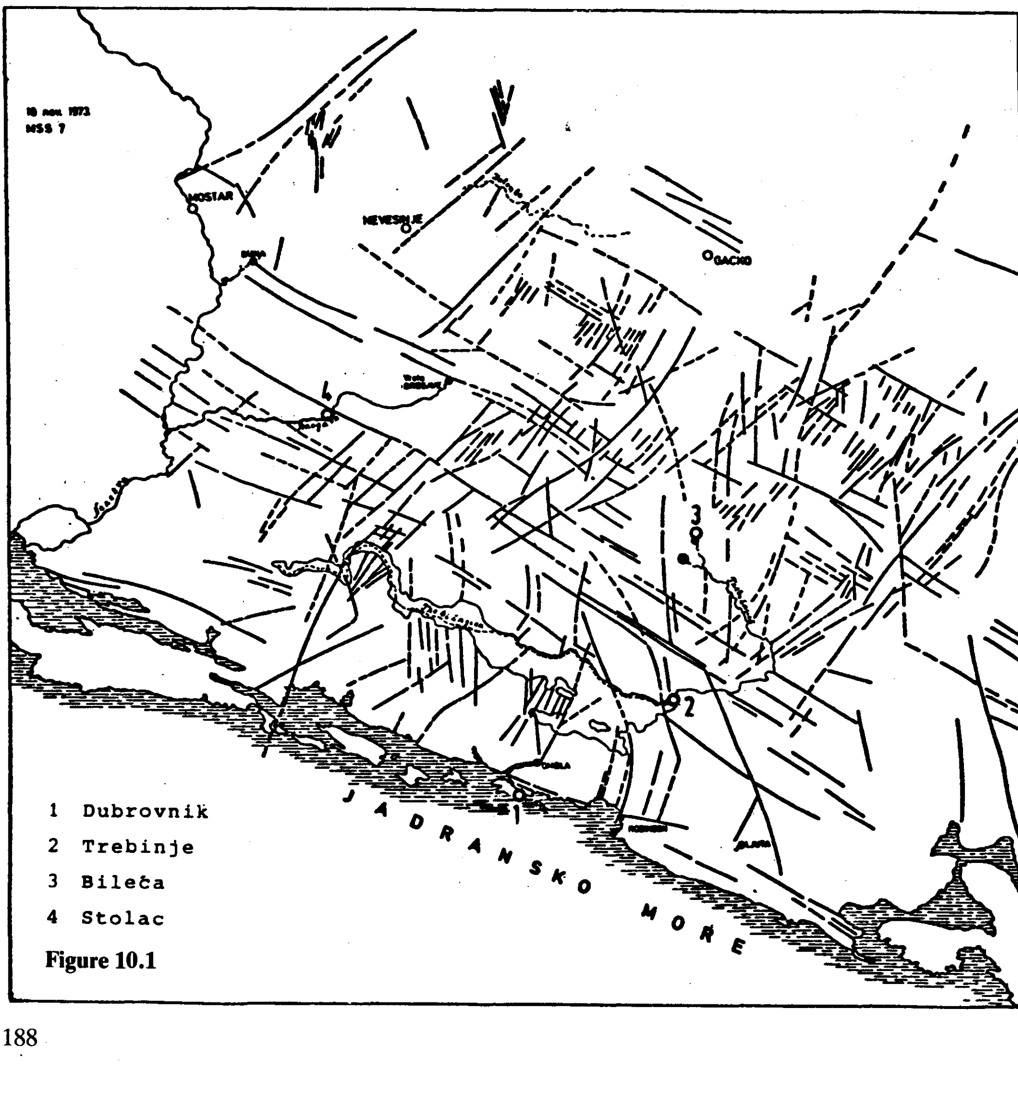


Figure 10.1

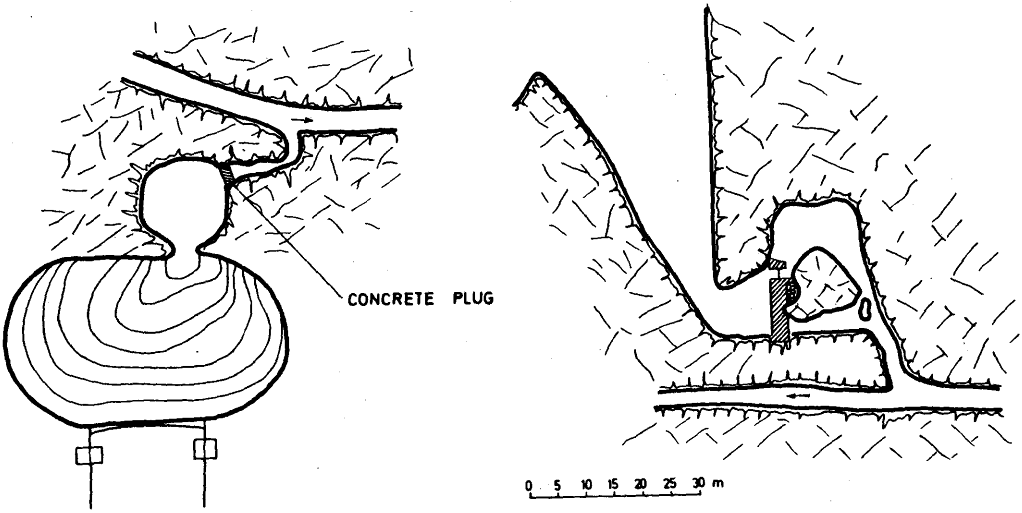
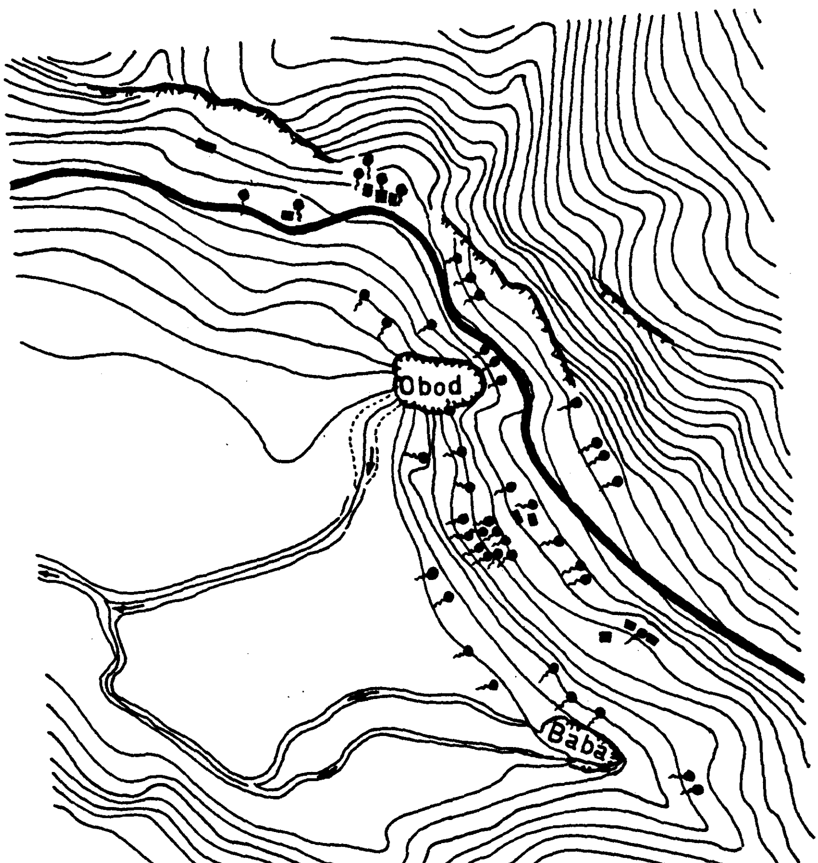


Figure 10.2



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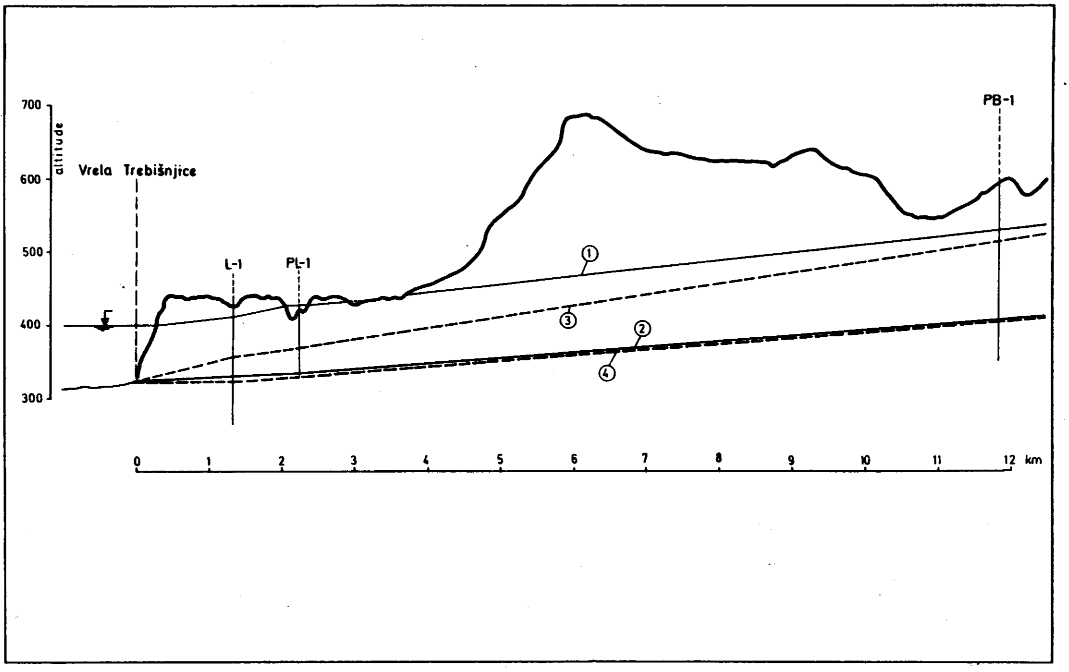

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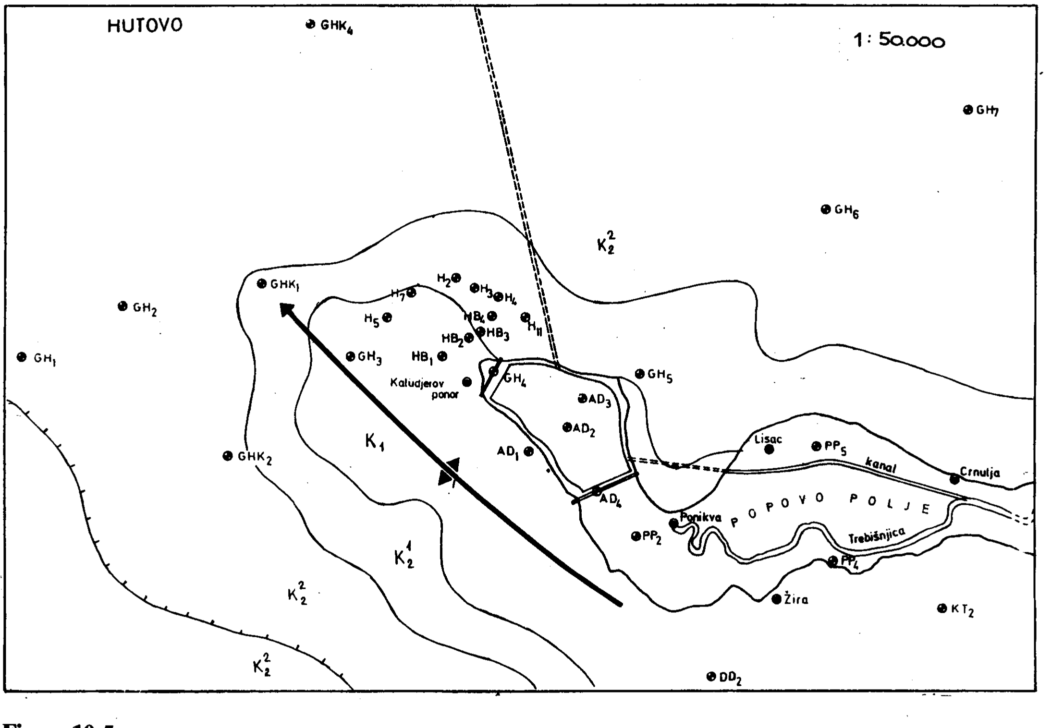

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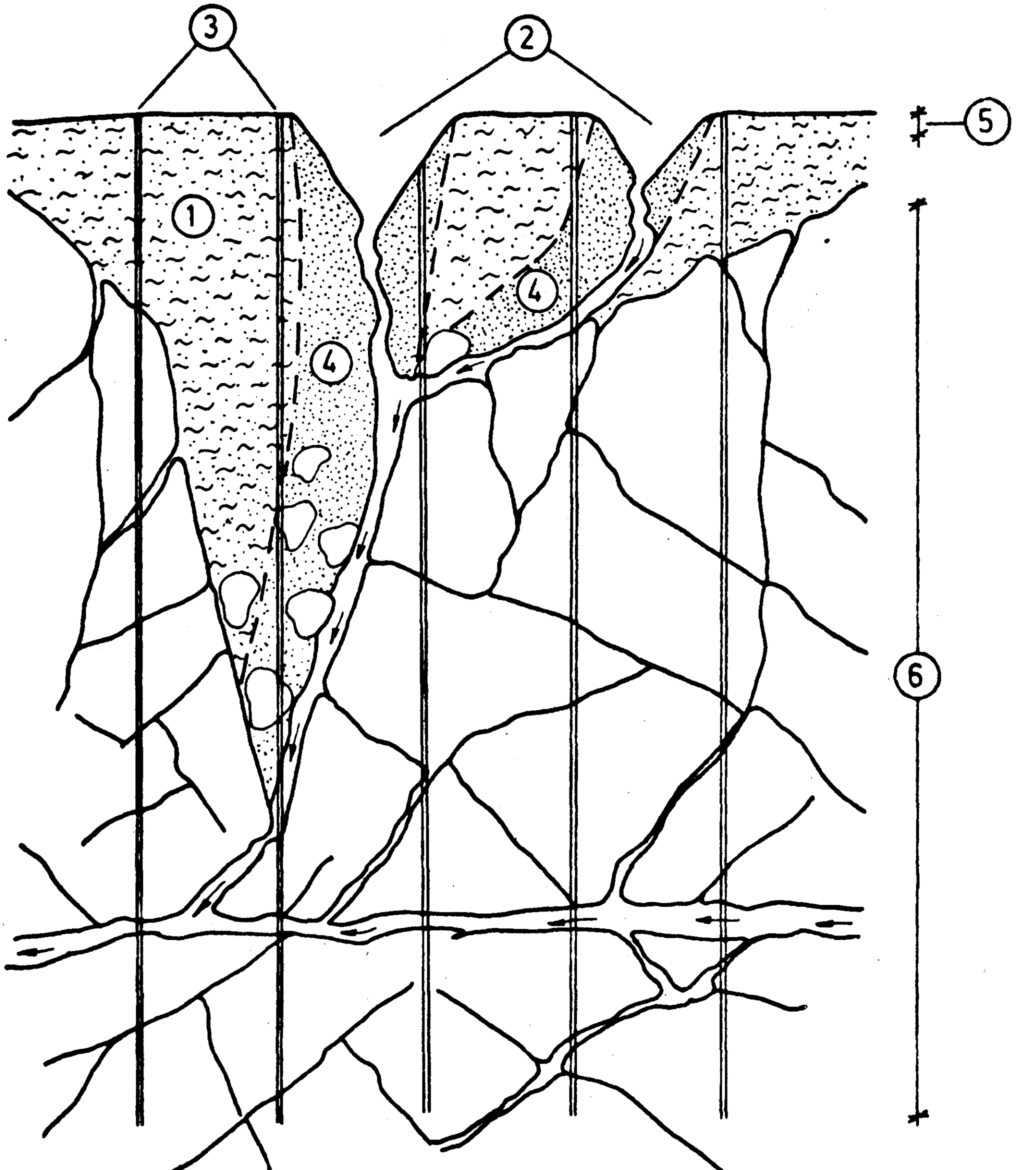

Figure 10.6

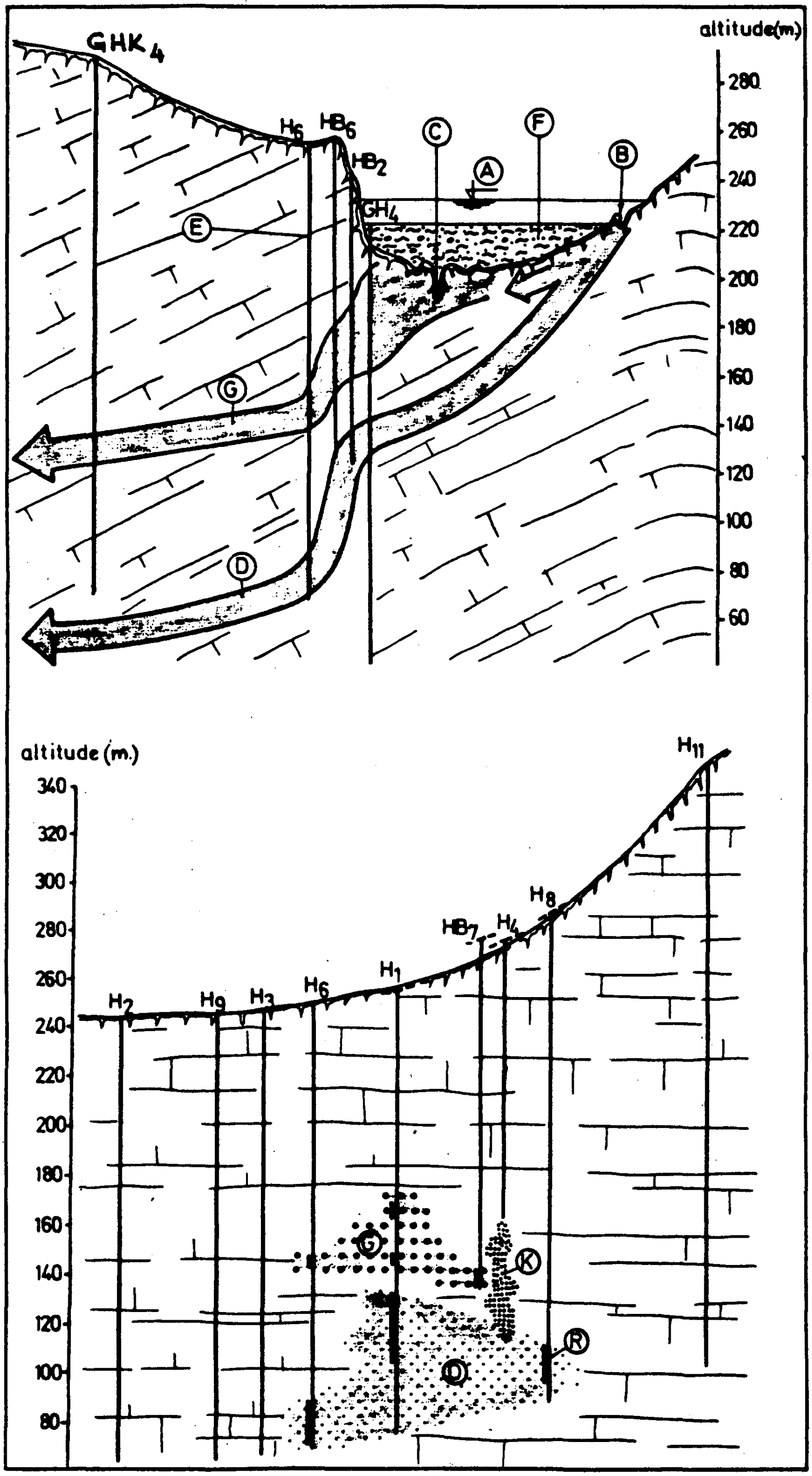
GHK4
altitude(m)
280
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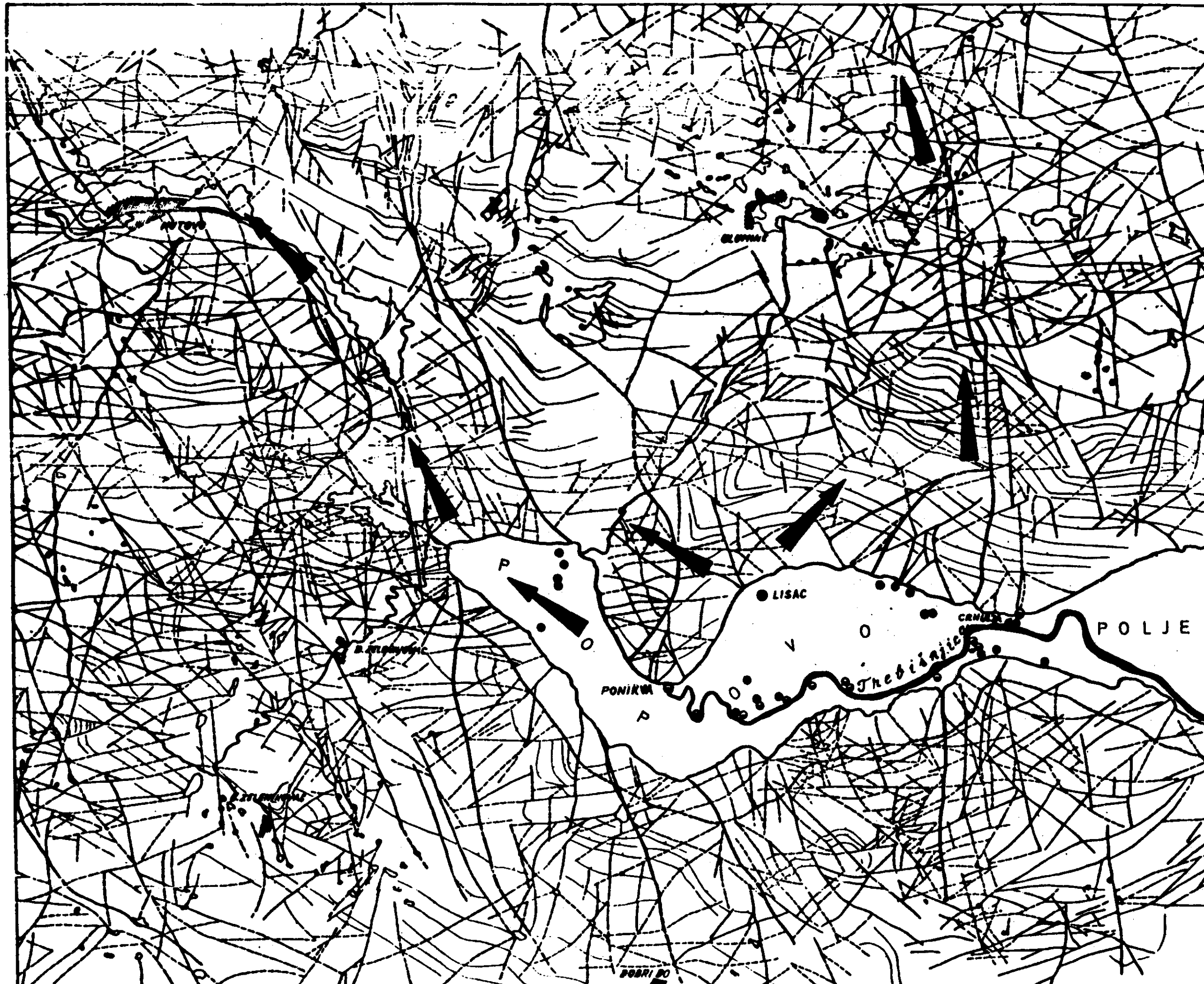
Figure 10.7



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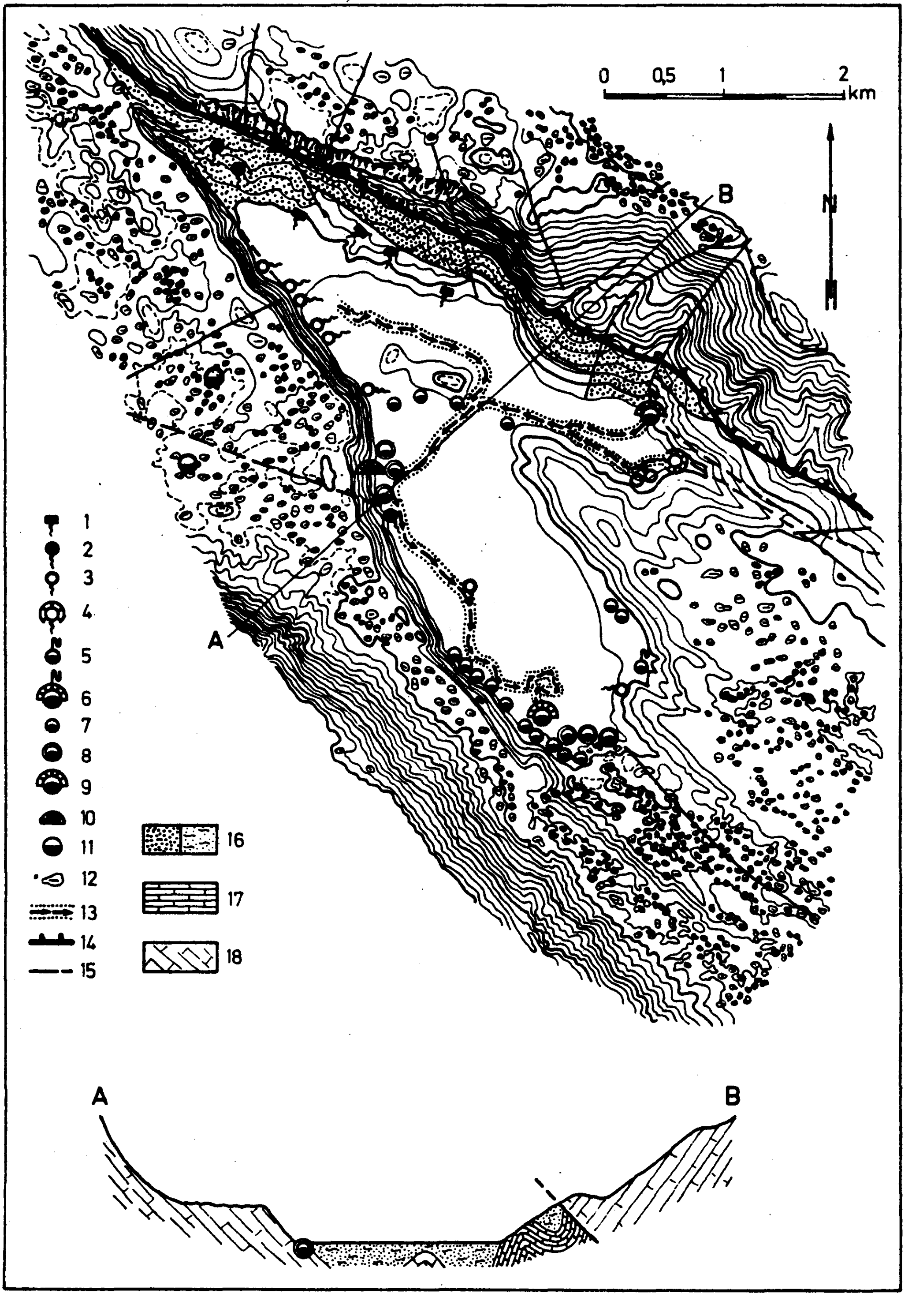
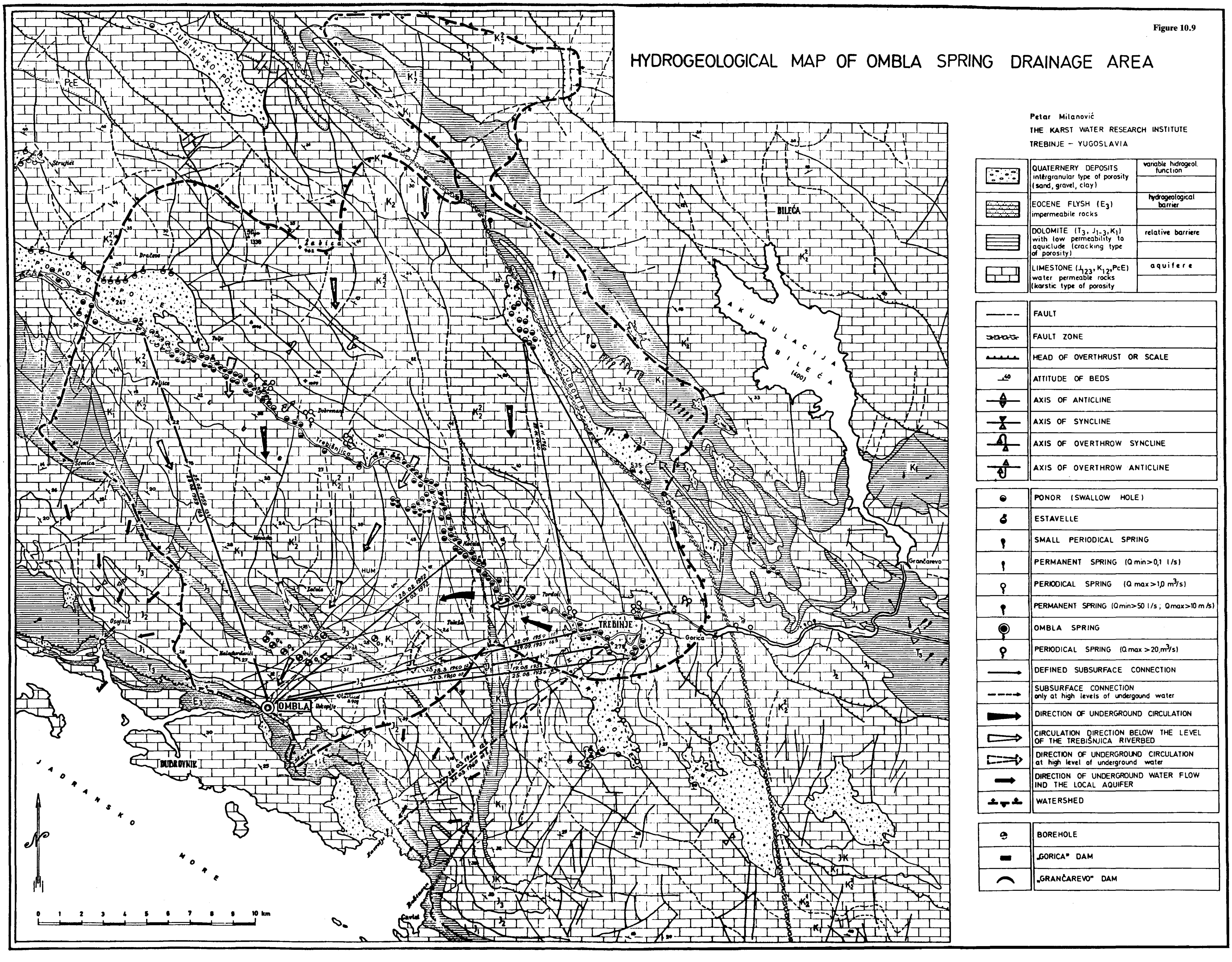
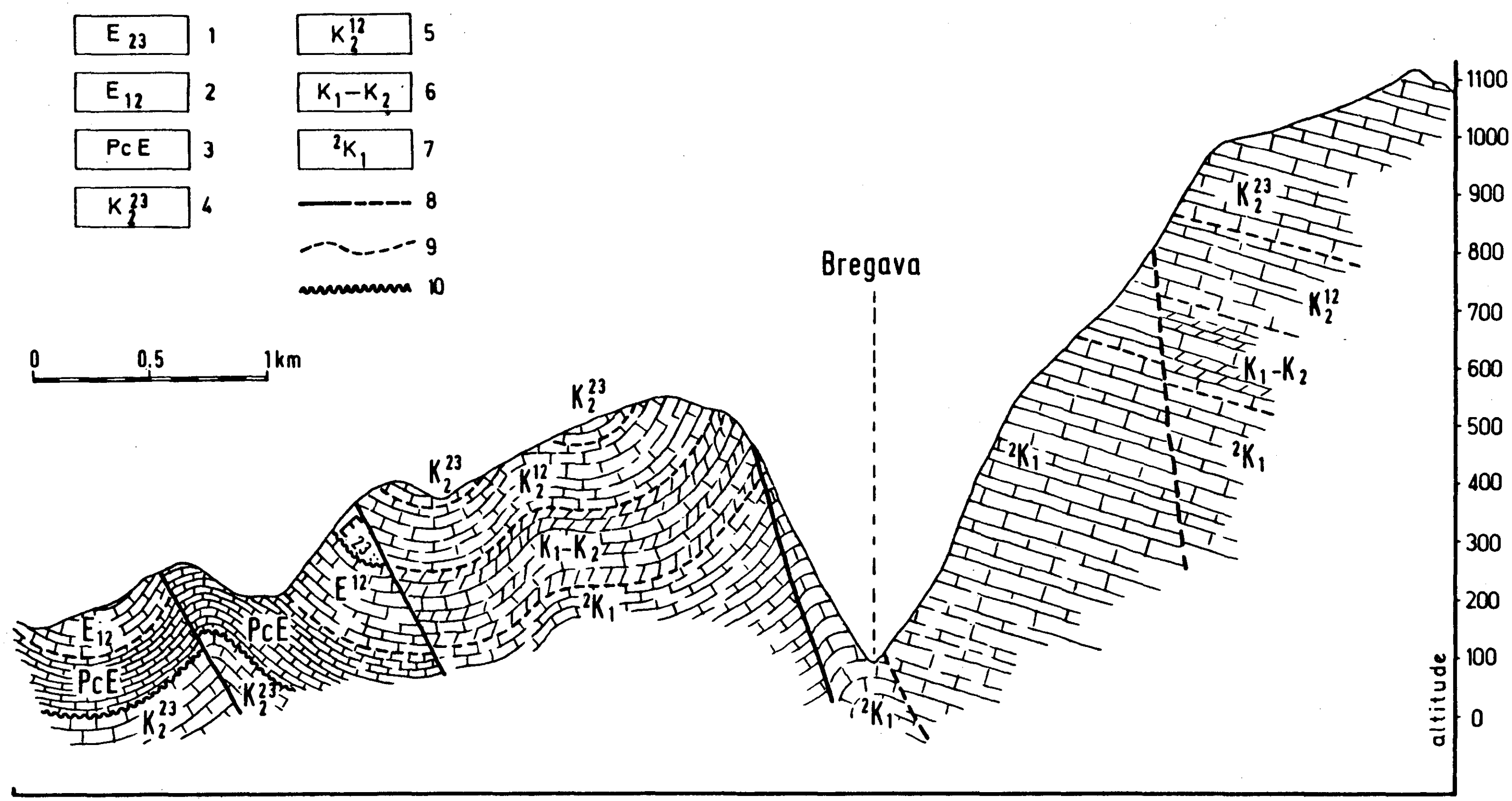


Figure 10.10

Figure 10.9


HYDROGEOLOGICAL MAP OF OMBLA SPRING DRAINAGE AREA
Petar Milanović
THE KARST WATER RESEARCH INSTITUTE
TREBINJE - YUGOSLAVIA
QUATERNERY DEPOSITS intergranular type of porosity (sand, gravel, clay)
variable hidrogeol. function
EOCENE FLYSH (E3) impermeabile rocks
hydrogeological barrier
DOLOMITE (T3, J1-3, K1) with low permeability to aquiclude (cracking type of porosity)
relative barriere
LIMESTONE (J123, K12, PcE) water permeable rocks (karstic type of porosity)
aquifere
FAULT
FAULT ZONE
HEAD OF OVERTHRUST OR SCALE
ATTITUDE OF BEDS
AXIS OF ANTICLINE
AXIS OF SYNCLINE
AXIS OF OVERTHROW SYNCLINE
AXIS OF OVERTHROW ANTICLINE
PONOR (SWALLOW HOLE)
ESTAVELLE
SMALL PERIODICAL SPRING
PERMANENT SPRING (Q min>0,1 l/s)
PERIODICAL SPRING (Q max>1,0 m3/s)
PERMANENT SPRING (Qmin>50 l/s; Qmax>10 m/s)
OMBLA SPRING
PERIODICAL SPRING (Q max>20,m3/s)
DEFINED SUBSURFACE CONNECTION
SUBSURFACE CONNECTION only at high levels of undergound water
DIRECTION OF UNDERGROUND CIRCULATION
CIRCULATION DIRECTION BELOW THE LEVEL OF THE TREBIŠNJICA RIVERBED
DIRECTION OF UNDERGROUND CIRCULATION at high level of underground water
DIRECTION OF UNDERGROUND WATER FLOW IND THE LOCAL AQUIFER
WATERSHED
BOREHOLE
„GORICA" DAM
„GRANČAREVO" DAM
LJUBINJSKO POLJE
POPOVO POLJE
AKUMULACIJA BILEĆA (400)
BILEĆA
TREBINJE
OMBLA
DUBROVNIK
JADRANSKO MORE
HUM
Gorica
Grančarevo
Trebišnjica
0 1 2 3 4 5 6 7 8 9 10 km



E 23 1
E 12 2
PcE 3
K 2 23 4
K 2 12 5
K1–K2 6
2K1 7
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0 0.5 1km
Bregava
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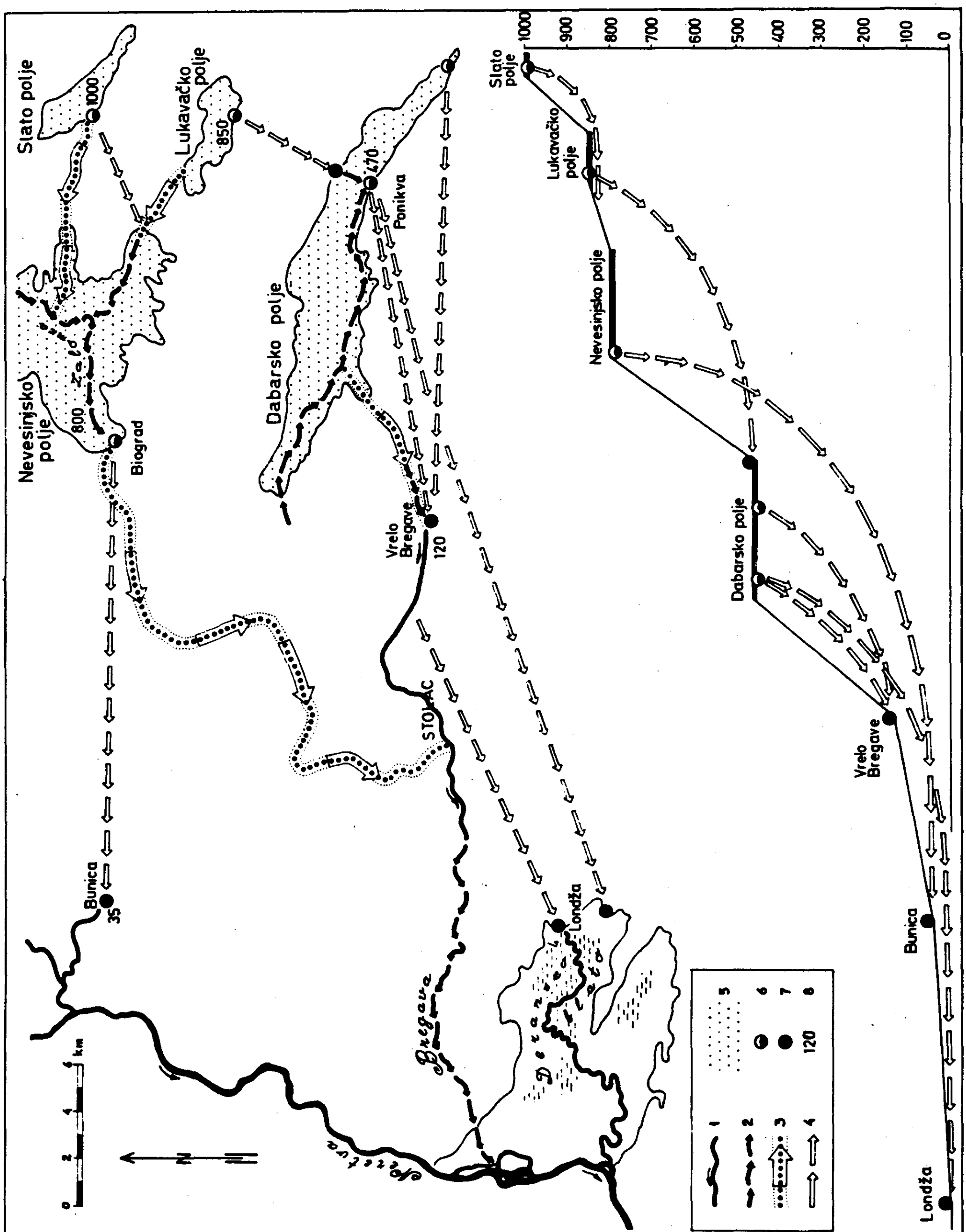
Figure 10.11



Slato polje
1000
Lukavačko polje
850
Nevesinjsko polje
800
Biograd
Dabarsko polje
470
Ponikva
Vrelo Bregave
120
Bunica
35
STOLAC
Londža
Bregava
km
1
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Slato polje
Lukavačko polje
Nevesinjsko polje
Dabarsko polje
Vrelo Bregave
Bunica
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Figure 10.12

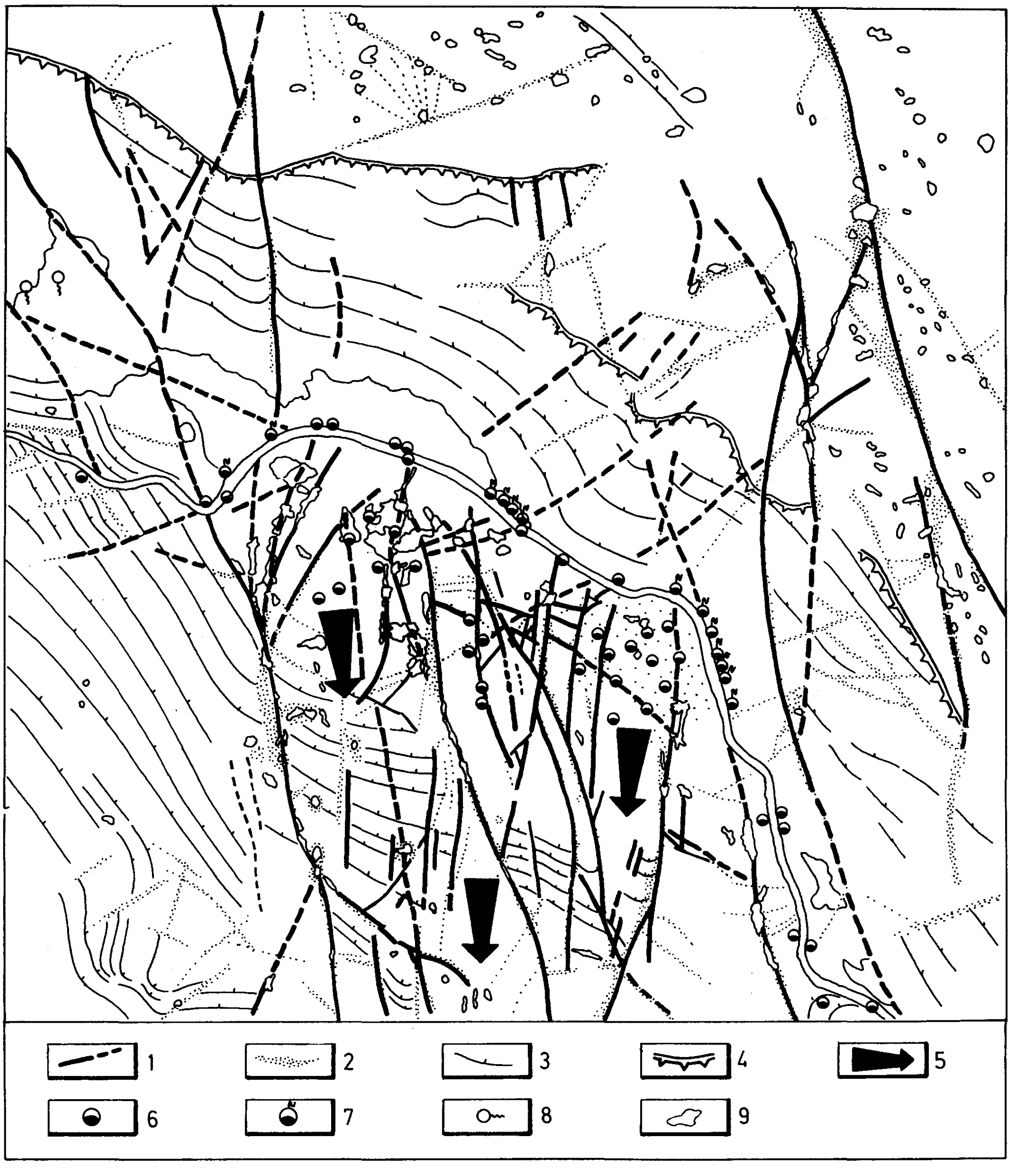
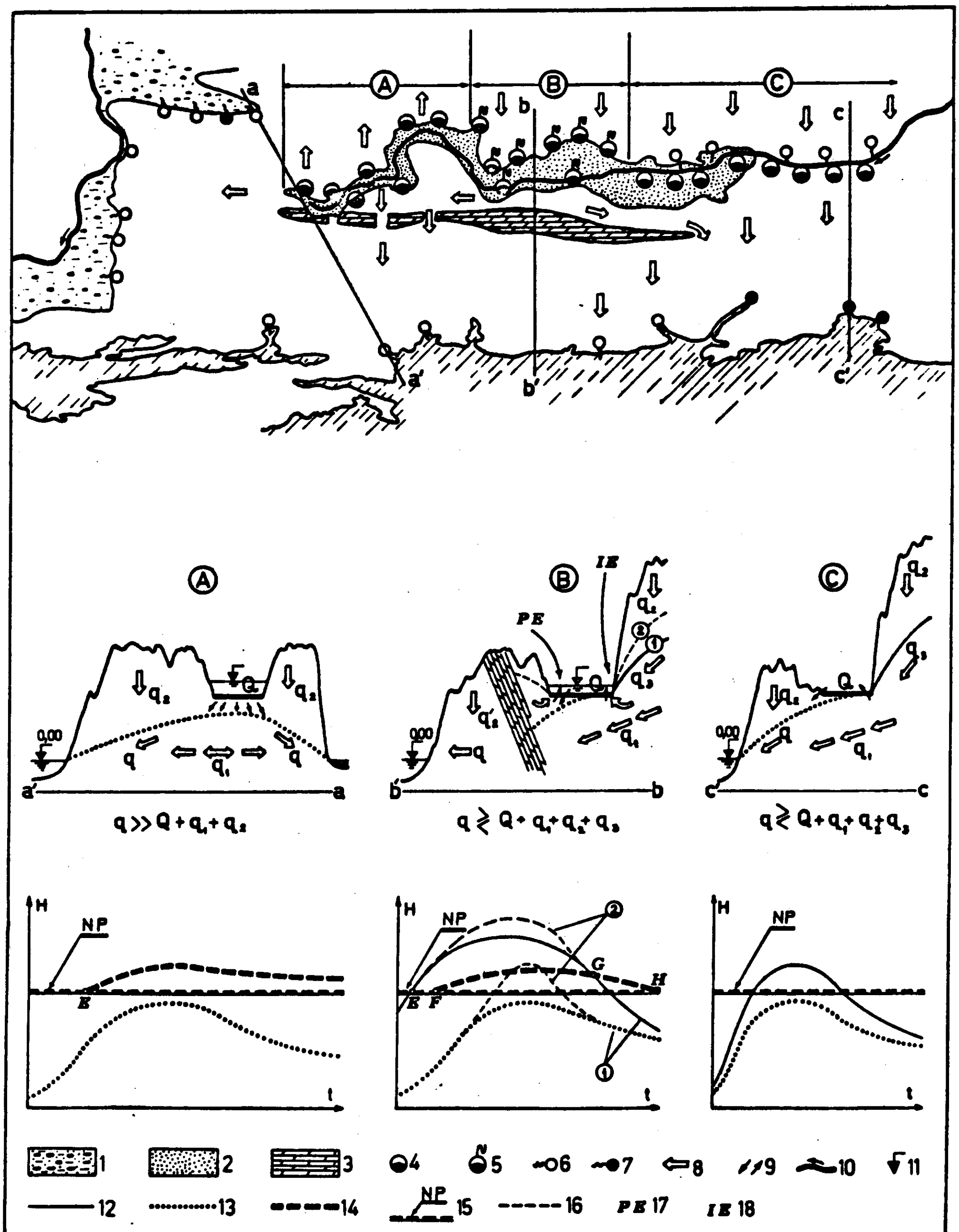


Figure 10.13



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PE 17
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Figure 10.14

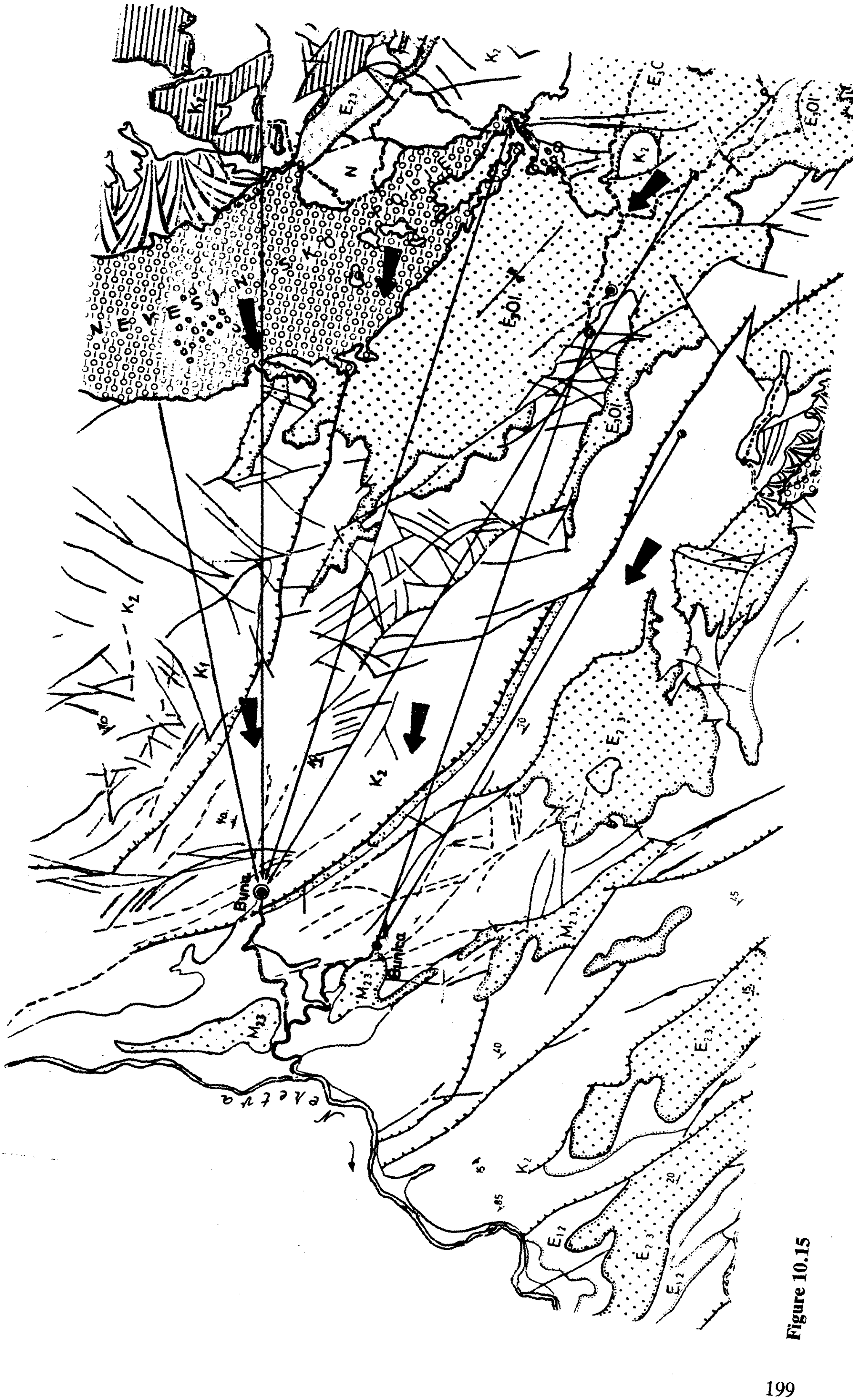
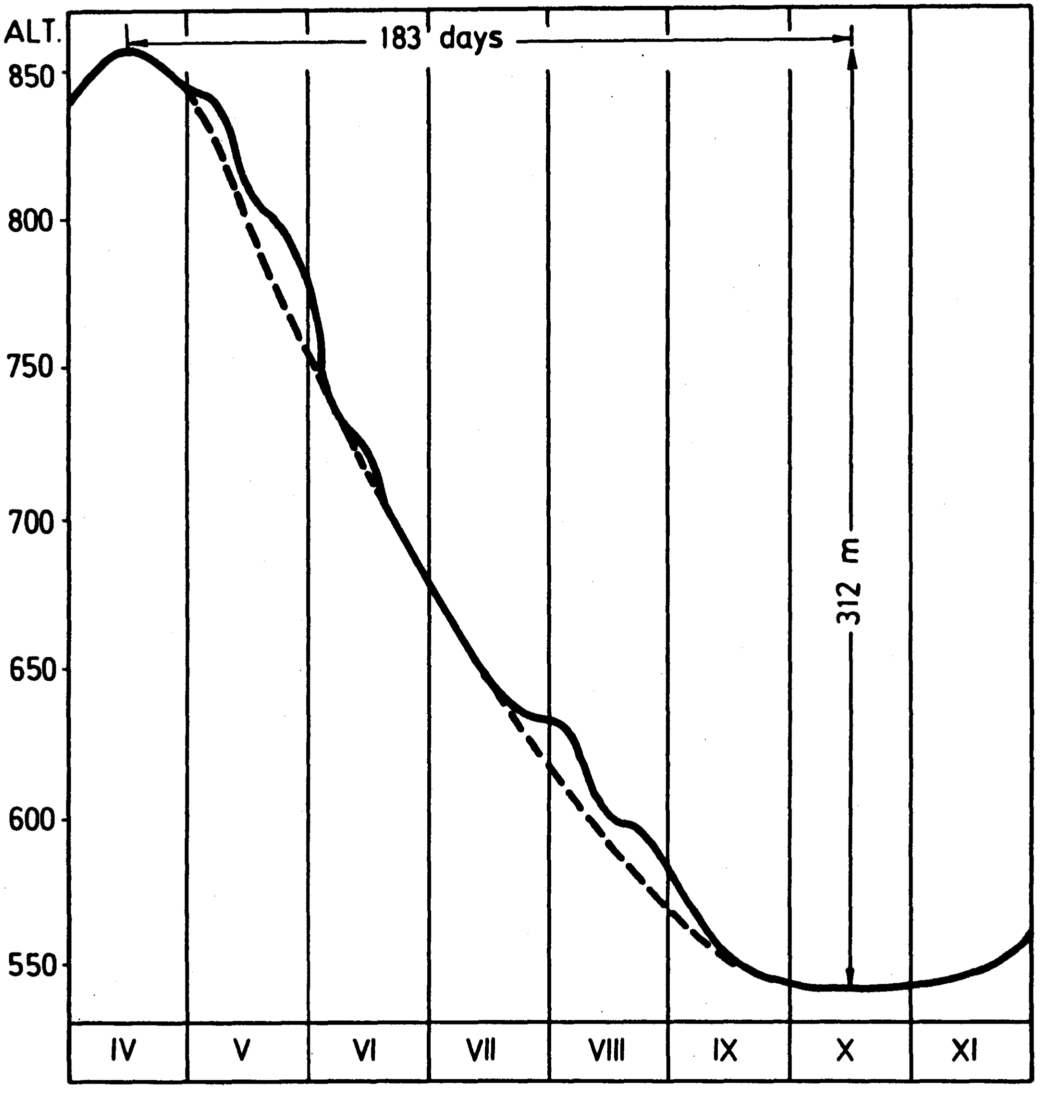


Figure 10.15


ALT.
850
800
750
700
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183 days
312 m
IV
V
VI
VII
VIII
IX
X
XI

Figure 10.16

11

HYDROGEOLOGIC FEATURES OF TYPICAL KARST TERRAINS IN MONTENEGRO

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These terrains represent parts of well known geotectonic units of the outer Dinarides:

a) High karst zone
b) Cucali zone
c) Adriatic folds system.

Locations of the above mentioned geotectonic units are clearly seen in the attached geotectonic reonization of Montenegro (Fig. 11.1) and the geologic profile across Skadarsko jezero (Scuttari Lake) catchment area along the line: Adriatic Sea - Rumija - Prekornica - Maganik - Sinjajevina (Fig. 11.2).

The high karst zone mainly consists of the Mesozoic limestone and dolomite but there are also, spread out subaltern, Younger Palaeozoic schistous-argillaceous marl layers, Lower and Middle Triassic slate, marl, sandstone and conglomerates as well as Middle Triassic porphyrite, quartzporphyrite, dacite and andesite. In addition to the above, in two narrow zones across the entire territory of Montenegro, from the southwest towards southeast, there appear Upper Cretaceous - Paleogene sediments of flysh, represented by marl, argillite, sandstone, breccias and conglomerates.

The major part of the territory of Montenegro belongs to the high karst zone which is very complex. This complexity is manifested through the presence of more anticlinorium and synclinorium, imbricated structures, and more folding and fractional structures. Within the high karst zone the anticlinorium of old Montenegro is particularly noted, as well as synclinorium of the Zeta river valley, Nikšićko polje and Duga gorge, then anticlinorium of Žiljov, Prekornica and Maganik and synclinorium of the Morača, Tušina and Vrbnica river.

Terrains of cucali zone are composed of numerous stratigrafic-lithologic members, starting with Permo-Triassic up to the end of the Eocene. Such are terrains that form the Montenegrin coastal area with Crmnica in the rear, in which a number of facies were classified, among which particularly noted are:

- flysh-clastic facies of the Lower Triassic;
- flysh facies of the Middle Triassic;
- eruptive facies of the Middle Triassic;
- sediment-volcanic facies of the Middle Triassic;
- carbonate facies of the Triassic, Jura, Cretaceous and Paleogene, and
- flysh facies of the Paleogene.

Terrains of the cucali zone are confined between the high karst zone in the north and northeast and the Adriatic folds complex in the south and southwest.

The Adriatic folds complex consists of carbonate and flysh facies. The carbonate facies consist of limestone, dolomite-limestone and rarely of dolomite of the Upper Cretaceous and Eocene, while flysh facies consist of claystone, marl, sandstone, breccia and conglomerates of the Eocene age.

HYDROGEOLOGIC FEATURES OF THE TERRAIN

Tectonic history of the Nikšićko polje and its surrounding is characterized by still epirogenic development and relatively short orogeny phases, i.e. by the youngest rising and formation of mountains around it. Rocks of this region are folded and intersected by faults.

Although the Nikšićko polje with surrounding represents a system of bigger and smaller folds in tectonic sense, in general it represents the syncline which in the direction of the northeast turns in anticline of Vojnik and Prekornica and in southwest direction in the anticline of old Montenegro. The general trend of beds in this region is Dinaric.

Surveys have confirmed that the territory of the Gornja Zeta catchment area is composed of rocks of the Palaeozoic, Mesozoic and Cainozoic age.

Palaeozoic rocks as the oldest occupy a small area. In the terrains of the Gornja Zeta catchment area the largest space is occupied by the sediments of the Mesozoic in all three periods: Triassic, Jura and Creteceous. The Triassic is present in all three beds: the lower, middle and upper, in the entire catchment area in broken sections. Jurassic sediments occupy relatively large area in all three phases: the Lower, Middle and Upper Jura.

Cretaceous sediments occupy the major part of the catchment area and are found in both periods - the Lower and the Upper Cretaceous.

The Cainozoic sediments are noted at more localities in the catchment area but they occupy small space.

Igneous rocks occupy a narrow zone and they are inadequately studied in the petrographic sense.

In this terrain there are significant deposits of white and red bauxites. They are not only of the economic but also of the stratigraphic importance. Bauxites serve as a relatively reliable point for drawing of geologic boundary in the monotonous limestone series.

The terrain of the Nikšićko polje is composed of Quarternary sediments which extend rather widely. They include mainly the plane of the polje. The Glacial sediments in the polje are represented by clays, gravel, sand, conglomerates, sandstone and limestone blocks. The basic mass is composed of clay, gravel and sand. This material was drifted by surface waters; firstly rough than fine material settled. Composition of sediments in the polje has been proved by making a large number of geologic drillholes and by geomechanic exploration.

The sediments in the Nikšićko polje vary between 12 and 18 m in depth.

It is speculated that these sediments could be formed during the Diluvial only. However, they were transferred in the geologic recency - the Alluvium.

Alluvial sediments are of relative low thickness and they appear along river beds, cut in the Diluvial sediments.

Humus bed covers Diluvial sediments and belongs to the Alluvium.

Hydrogeology of the Nikšićko polje and surrounding area is heterogenous. This heterogenousness is characterized by occurence of waters on the surface in the form of springs and sources, their short flow and by their sinking into ponors to reappear in new springs.

Of the total water balance of the Nikšićko polje, 80 % inflow during autumn and spring seasons while the rest inflow in winter and summer time.

Catastrophic waters, according to the calculations, are those having inflow of 600 cu. m/s. Up to now recorded inflow were of 300 cu. m/s.

The above data are obtained from hydrologic and hydrometeorologic stations in the Nikšićko polje catchment area on the basis of observations performed during the past 40 years.

The Nikšićko polje has been periodically flooded in autumn and spring seasons and natural water level can reach 615.0 m above the Adriatic Sea level. In such situations about 3.000 ha could be inundated with creation of lake containing 300 million cu. m. of water in volume.

Such lake dissapears with big waters inflow lowering and their sinking through numerous ponors along the southern edge of the polje.

This sinking and emerging and vice versa follow in sequences, beginning with the northeast end of the Nikšićko polje i.e. with the Gornja Zeta catchment area up to the Zeta River spring in the area of Glava Zete. The catchment area of the water flow of the Nikšićko polje belongs to karst terrain in general. Here there are many dolines+) pits, fissures, faults and the like which makes sinking of surface waters possible in many ways. In this terrane, except in the Nikšićko polje, the permanent springs are very rare, and there are not permanent surface waterflows as well, except those along the Nikšićko polje, sink in it and appear again at the lava Zete, while the occurs underground. In this circulation the ground waters partly appear in the Nikšićko polje, sink in it and appear again at the Glava Zete, while the other part flows directly towards the Glava Zete.

Such circulation of waters makes the hydrogeology of the Nikšićko polje the complex one, but at the same time it is very interesting for study. Such hydrogeologic relations have been conditioned by the geologic composition of the karst terraine.

The hydrogeologic catchment area of the Nikšićko polje, except for a small area in Nikšićka Župa with narrow zones of Tertiary flysh, is mainly composed of the Mesozoic limestone and dolomite among which the limestone dominates. Because of that the topographic and hydrogeologic catchments do not coincide in this terraine.

In the anticline of Vojnik and Prekornica mountains and in the anticline of Old Montenegro the Triassic dolomites predominate, in the base of

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+) The Yugoslav term for doline is vrtača(e).

younger beds, and they serve as the hydrogeologic barrier which directs water circulation towards strata dip. Because of that the waters from both anticlines gravitate towards the Niksićko polje and Donja Zeta, in the direction of so called Glava Zete area.

The underground interconnection of ponors and springs has been proved by many explorations and tests, by means of dye tracers and piezometric drillholes.

Ground waters which feed the rivers of the Nikšićko polje have very important role. These waterflows of the Nikšićko polje, after their short flow in the polje disappear in ponors. In this way the underground waters flows on one hand, and on the other, after sinking, recharges the underground flows reaching in this way to karst water bodies. Karst aquifer oscillates during the year having the minimum level at the end of summer season. These oscillations of karst water table result in opening of ponors in drifts of the Nikšićko polje. And this process of ponors opening lasts even today.

NIKŠIĆKO POLJE

From Nikšićko polje to Titograd, the terraine belongs to the synclinorium of the Zeta river valley, Nikšićko polje and Duga gorge. This synclinorium structure consists of limestone, dolomite-limestone and rarely dolomite of the Jurassic and Cretaceous age, with the Upper Cretaceous limestone dominating.

In addition to the above, in a number of zones which are confined in a narrow space, along reverse faults - scales intergrown like fingers, appear claystone, marl, sandstone, breccia and conglomerates of the Upper Cretaceous-Paleogene age (flysh facies). In the Bjelopavlićka plain, which lies at an average altitude of about 50 m, there are limnetical-glacial clay, sand-clay and argillite-sand gravel. Floors of these sediments contain Upper Cretaceous limestone and Cretaceous-Paleogene flysh layers.

Synclinorium limestones of the Zeta valley are tectonically well damaged and very carstic. Those are cavernous limestones owing to which terrain is highly water permeable. These terrains are characterized by nearly all typical phenomena of the holokarst from uvalas and dolines+) through defiles, scrapes, clints, jamas (pits) and caves with or without water,

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+) The original Yugoslav term for doline(s) is vrtača(e).

and the like. Those are terrains abundant with dispersed karst water bodies. High abundancy of these water bodies comes from high cavernousity of the limestone and the catchment area of the Bjelopavlićka plain. Along the edge of this plain there are numerous permanent and periodical karst water springs and even estavellas.

Some parts of this terrain consisting of Upper Cretaceous-Paleogene flysh layers are practically impermeable for surface and ground waters. Those are hydrogeologic barriers. They are mainly hanging barriers due to their geotectonic position and elevation, but for small waters they represent floor barriers.

At the farthest northwest edge of the Bjelopavlićka plain there is very abundant periodical karst spring known as Perućica as well as two others, Glava Žete and Oboštničko oko. From these karst sources the Zeta River is formed (The Lower Zeta). Perućica, Glava Zete and Oboštničko oko sources yield minimum over 6 cu. m/s and maximum about 250 cu. m/s of water (average in several years). However, the annual average amounts to about 55 cu. m/s. The Zeta River meanders through the Bjelopavlićka plain and after a course of about 17 km long in the straight line feeds the Morača River, north of Titograd. In the long-term average the Zeta River feeds the Morača River with 110 cu. m of water in a second. The difference between 110 and 55 cu. m/s the Zeta River compensates from periodic and permanent karst springs and sources at the edge of the plane which charge the river.

At the northeast edge of the Bjelopavlićka plain there are the following well-known karst springs: Dobropoljski springs as permanent ones and a number of periodical springs among which the most abundant are: Podkrajska jama, Lakića jama, Vujića jama, Brajovića jama, Zarića jama, Vukovića jama, Straganičko oko, Jama Djukića i Jama Markovića. In rainy seasons these karst springs provide some cu. m/s of water. During dry seasons they are pits water wells. However, the last three jamas i.e. Straganičko oko, Jama Djukića and Jama Markovića for a shorter period can appear as estavellas. This happens when after a long dry period heavy rains come suddently charging the bed of temporary river Šaralija, until water level in dispersed karst water tables rises water level in the above mentioned jamas. In such situations the Markovića jama, Djukića jama and Straganičko oko swallow the waters of the temporary Široalija river.

Along the northeast edge of the Bjelopavlićka plain, at higher levels, and at the contact level of the Upper Cretaceous Paleogene flysh layers in the floor and the Upper Cretaceous limestone in the roof, there are numerous periodical and permanent springs. It seldom happens that yield of these springs rises over 10 l/s during dry seasons of the year. Among these springs particularly abundant are: Vrela, Studenac, Orovik, Žurim, Djemas, Slatinski spring, Gospodina voda, Studeno, Dubovik, Odim, Medunac etc.

Along the southwest edge of the Bjelopavlička plain the well known are the following permanent and periodical karst springs: Svinjička vrela, Milojevička vrela, Vidoštak, Dobrik, Smrdan, Tamnik as well as estavellas called Šatovo oko, Gurgurovo oko, Modro oko and Oraška jama.

Perućica, Glava Zete and Oboštinsko oko, and to some extent the Svinjička vrela as well, receive waters from the Nikšićko polje. Those are waters which sink at the south and southeast edge of the Nikšićko polje in numerous estavellas and ponors along the Budoški fault as in a series.

Periodical and permanent springs and sources along the northeast edge of Bjelopavlička plain are fed with waters from extensive karst terrains of Prekornica mountain (1926 m above sea level).

Periodical and perennial karst springs at the southwest edge of the Bjelopavlička plain are fed with waters from ample karst terrains of old Montenegro.

Westward from Titograd there is a spring known as spring Mareze. The minimum yield of this spring is about 2 cu. m/s while the maximum seldom rises over 10 cu. m/s. This spring receives waters from terrains southeast from the Bjelopavlička plain. This means that Upper Cretaceous-Paleogene layers of flysh of th Bjelopavlička plain and its edge are hanging barriers under which waters of the Prekornica massif penetrate towards Mareze spring.

Concentration of population in the Nikšićko polje and development of industry in this area resulted in pollution of the soil and underground waters further on it is transferred to waters of the Morača and through it to Skadarsko jezero. This pollution increases owing to the effects of waste waters from Danilovgrad and Titograd areas.

During the rainy seasons the area of the Bjelopavlička plain may be heavily inundated which causes lot of damages. This is one of issues which have to be solved parallel with water control problem solving.

TERRAINS OF OLD MONTENEGRO

Terrains from Titograd through Cetinje and Lovćen mountain, up to town Kotor, belong to the anticlinorium of old Montenegro. This anticlinorium is composed of the Upper Triassic dolomite, limestone dolomite and dolomitic limestones, and limestone; Lower, Middle and Upper Triassic limestones; Lower Jurassic marl, dolomite and cherts (Lovćen - Ledenik facies) and Lower and Upper Cretaceous limestone and dolomitic limestone. In addition to these rocks, from Titograd towards Cetinje the plains are composed of glacio-fluvial sand and gravel of carbonaceous origin. Those are parts of extensive Zeta plain which stretching towards south and southeast continues into the basin of Skadarsko jezero and further the Skadarska plain.

From Titograd, i.e. from the Zeta plain synclinorium towards Cetinje we find more older Mesozoic carbonate sediments, starting with the Upper Cretaceous in the immediate vicinity of Titograd up to the Upper Triassic dolomites around Cetinje. In this direction the Mesozoic limestone and dolomite are highly fractured and carstic. Those are terrains of many different shapes, phenomena and processes characteric for holokarst. There are many uvalas (transition form between dolina and polje), dry - hanging valleys and dolines, throughs, clints, scrapes, pits, caves, etc. Those are terrains without surface waters but containing a large, water rich karst aquifer of old Montenegro, discharging through many periodic and perennial karst springs and subsurface springs along the northwest edge of Skadarsko jezero. Among these permanent and perennial karst springs and subsurface springs the following are particularly noted: Vučje Studence, Oko Matice, Čista Jama and Pogana Jama at the southwest edge of Lugovo westward from Titigrad; Golač, Šutinska Jama, Lisica, Kaludjerovo Oko and many other eyes - underwater springs along the edge of Malo Blato; Volač, Karuč and many other eyes - underwater springs in the valley of Bazagurska Matica; Grab and many other eyes-underwater springs in flooded valley of the Crnojevića Rijeka river and finally the spring of the river Crnojevića Rijeka.

In the direction from Titograd to Cetinje the most popular among caves and pits is the cave Lipska Pećina which is shown in its plan and profile in Fig. 11.4.

Cetinje itself is located in the Cetinjsko polje. The Cetinjsko polje is by its size the largest karst polje in Montenegro after Nikšićko polje. It is about 3.8 sq. km in area having an average altitude of 635 m. However, the levels of this polje reach here and there even up to 750 m above sea level. The polje itself strikes firstly towards west-northwest in slope, and from the centre it strikes and trends towards south-southeast. In this broken direction it is about 5 km long and its average width reaches to some 800 m. The catchment area of this polje consists of the Mesozoic carbonate sediments and the polje itself is rich at the edges with glaciofluvial and glacial gravels and sands. Thickness of such sediments is seldom more than 10 m. The polje was formed in hanging valley of the Cetinjska River and it is predisposed by the fault along the east edge of the polje.

From Titograd - Cetinje road, at several points, the view Skadarsko jezero is wonderful. This is the largest lake in the Balkans. Depending on a water level its total area varies between 350 sq. km (4.7 m above sea level) and 500 sq. km (about 9.8 m above sea level). With its major part the lake lies in the territory of the Socialist Republik of Montenegro and with the smaller part in the territory of the People's Socialist Republic Albania.

The lake receives more than 60 % of water from the Morača River while the rest comes from numerous periodical and permanent rivers and brooks, permanent and perennial sources and springs and from a great number of underwater springs, mainly along its edges. The best known and most abundant with water are those underwater springs along the southwest and northwest edges of the lake. The Ruduško oko underwater spring is the best known one, with its bottom below the middle of the lake (at about 6.76 m above sea level) for approximately 60 m, which means that it lies below the sea level for about 53 m.

The lake is emptied by evaporation and through the only effluent the Bojana River. Discharge through the Bojana River to the Adriatic sea, in a long term, amounts in average about 240 cu. m/s.

Notable vertical fluctuation of water level of Skadarsko jezero, over 5 m, average in a long term, results in flooding of rather vast areas of Donja Zeta. This is one of major problems in littoral regions of Skadarsko jezoro.

Apart form the issues linked with inundation caused by lake waters the problem of lake water pollution has also appeared. This pollution comes from polluted waters of the Morača catchment area which receives waste waters from Nikšić, Danilovgrad and Titograd, as well as the waste waters from the Crnojevića Rijeka river catchment area and Cetinje city. As it is known, Cetinje is a closed karst polje and all waters from its catchment area disappear by sinking into numerous ponors mainly along its southeast edge. Waters of these ponors appear at the spring of the Crnojevića Rijeka river and this river is the biggest feeder of the lake from its southwestern side. The largest part of this river makes at present the inundated valley, which results from tectonic dipping during the Neogene and Quarternary.

From Cetinje and further on over the coastal massif Lovćen, down to Kotor there is hydrogeological watershed, between the catchment area of Skadarsko jezero on the southeast and the catchment area of the Montenegrin littoral on the southwest. These terrains are composed of the Mesozoic limestone and dolomite which are highly karstic and waterpermeable. Those are terrains without surface waters but with vast and water abundant karst water bodies which drain partly towards Skadarsko jezero and partly towards the Bay of Kotor. Here and there, in these terrains, you can find periodical and perennial springs, the yieldingness which rarely extends 2 l/s. Such is, for instance, the spring called Ivanova Korita on Lovćen mountain. These springs appear due to presence of smaller sections of layers of the Lovćen - Ledenik facies (marly limestone, dolomite, chert) or due to sounder sections of the Upper Triassic dolomites which are considerable less waterpermeable as compared to surrounding limestones.

Terrains from Cetinje to the Bay of Kotor represent parts of old Montenegro as those above mentioned, with typical holokarst features. These terrains fully contain karst phenomena as are Cetinjsko polje, Njeguško polje, uvalas, dry valleys, dolines, troughs, clints, scrapes, pits, caves etc.

The Njeguško polje and its catchment area belong to the catchment area of the Bay of Kotor. It is of eliptic shape with longer axis in the northsouth direction.

In this direction it extends for about 1200 m in length and in the eastwest direction about 600 m. An average level above sea level ranges between 840 and 845 m. The catchment area of the Njeguško polje and its basic highlands are composed from Mesozoic limestone and dolomite and covered with glacio-fluvial and glacial gravel, sand and clay. Formation of this polje and of other poljes in karst terrains of Montenegro had been predisposed by rugged faults, and its present appearance was shaped by the surface forces.

In the vicinity of the Njeguško polje there is a well known and one of the deepest pits in Montenegro, called Duboki Do. This pit has been explored for several times until now. Plan and profile of this pit is shown in Fig. 11.5 and the geological profile, from the Crnojevića Rijeka river over Lovćen to Kotor, is shown in Fig. 11.6 in which hydrogeological features of these terrains can also be noted.

The best and shortest evaluation of hydrogeological features of karst terrains from the Trebišnjica River through the Nikšićko polje and old Montenegro to the Adriatic Sea was made by the well known Yugoslav explorer J. CVIJIĆ (1926, p. 434) as follows: "There is no deeper and more complete karst than that of Herzegovina and Montenegro, between the Lower Neretva river, Skadarsko Blato and the Adriatic Sea."

LITTORAL KARST OF MONTENEGRO

From Kotor to Herceg-Novi terrains belong to the well known Boka Kotorska Bay type of terrains. In formation of this bay the high karst zone participated to a lesser degree while the Cucali zone and the Adriatic folds mainly.

In formation of this complex bay the lithostratigraphic composition and tectonic structure of the terrain were particularly noted with the appropriate influence of external forces. This bay was formed of several smaller bays and troughs. It opens with the entrance trough between Oštri Vrh, Glavica and Kobila in the west and the Arza and Suštica headlands. The entrance into the Boka Kotorska Bay, is known as the Boka Katorska Gate. It is 1500 m wide at its entrance and about 1375 m at the exit. Water depth of the trough reaches 60 m. There are also two smaller islands called Mamula and Mala Gospoja in this trough. Immediately after the exit from the Boka Kotorska Gate, northwestward, there is the Toplanski Bay and eastward the Kumbor trough opens. The Kumbor trough is narrower than the Boka Kotorska Gate but it is longer. It is over 3 km long. The Kumbor trough extends towards east and southeast into the Tivat Bay and northward the next trough so called Verige, open. The Verige trough is situated between the Vrmac massif (786 m above sea level) in the east and the Devesilja massif (781 m above sea level) in the west. While the Boka Kotorska Gate trough and the Kumbor trough belong to terrains of the Adriatic fold system and Cucali zone, the Verige trough belongs to terrains of Cucali zone. The Verige trough has an entering width of 500 m and after some 2.250 m it is wide only 300 m. From the Verige trough, towards northwest there is a wider opening of the Morinski Bay, and towards east, southeast and south the Kotor Bay spreads out.

Then complex of the bay continues into the Risan Bay and northward from the Kotor Bay there is the Orahovac Bay. As we can see from the above, the Bay of Boka Kotorska is a complex consisting of a number of bays as: Toplanski, Tivat, Morinski, Risan, Orahovac and a number of troughs like: the Boka Kotorska Gate, Kumbor and Verige (Fig. 11.7).

Terrains of the Boka Kotorska Bay are composed of many stratigrafic and lithologic members, from the Middle Triassic to the Quaternary. Among these rocks, from the hydrogeological point of view, there are many different kinds and this is why these terrains are of different and specific features. In this area some parts of the terrains are completely water permeable while the others are completely impermeable. Such differences influenced the formation of pits, caves and other karst features without water and on the other side resulted in occurences of springs, sources, brackish springs and even the submarine springs.

The best known springs along the edges of the Boka Kotorska Bay are: Gurdić and Škurda springs near Kotor, Ljuta spring at Orahovac, Spilja spring at Risan, the Morinski springs at Morinje, Opačica at Herceg-Novi and Plavda at Tivat, while Sopot is the best known among the submarine springs at Risan.

South of Kotor Fortress, in its immediate vicinity, there is the main spring, Gurdića spring, on the beach. Its precipice is under the sea level for over 20 m. Through this spring, vast and up to now inestimable underground water quantities, coming from the Lovćen massif, discharge. This is a brackish spring containing Cl ions in the concentration which prevents its use as potable water. In exceptionally dry years it can happen, as it was noted, that sea water sinks into the Gurdića spring precipice. However, it happens once in 10 years in average, although it does not occur as a rule.

Northward from Kotor, also in the immediate vicinity, there is a karst spring called Škurda. This is a brackish spring in fact. This spring serves for supply of potable water to the city of Kotor, although its water is intruded by salt waters. Cl ions concentration in the Škurda spring water increases rapidly when the Gurdić spring acts as a ponor. In this case even water of the Škurda spring is not proper for use as potable water. To Škurda spring, the same as to Gurdić spring, vast quantities of water from extensive and water abundant karst aquifers of Lovćen mountain and of old Montenegro discharge.

South of Orahovac there is a brackish spring called Ljuta. This spring has also its catchment area in the karst of Montenegro. This is really abundant brackish spring whose yield ranges from 0.1 cu. m/s to over 170 cu. m/s.

Gurdić, Škurda and Ljuta springs are at such points where high karst limestones come in direct contact with the sea. Those are such locations at which, owing to penetration of such waters, the water impermeable Paleogene barrier Škaljari - Dobrota - Orahovac is eroded up to the level below the sea level.

Close to Risan is a periodic karst spring called Spilja. This is also brackish spring but in spite of that is serves for supply of nearby inhabititans with potable water. This spring is fed from the vast and water abundant catchment area of old Montenegro, in the direction of north and northwest up to the Grahovsko polje (Fig. 11.7).

Southwest from Risan there is the best known submarine spring in the Montenegrin coast, called Sopot. When the sea is quiet, at any part of the year, it can be noted how this submarine spring "works". Its catchment area belongs to the same one as that of the Spilja of Risan (Fig. 11.8). In the Morinski Bay there are few brackish springs called the Morinski springs. Their catchment area is extensive and is situated in the area of Orjen, in both parts of the area, i.e. in that one which belongs to the High Karst zone and one which belongs to the Cucali zone. Cl iones concentration in the Morinja springs reaches over 1000 mg/l owing to which they are unsuitable for use as potable water.

In the Kutsko polje, near Herceg-Novi, there is a well known periodical karst spring named Opačica. Within the very spring there is a pit which was searched up to nearly 30 m in depth. Up to the recent time this spring was the main source of water supply of Herceg-Novi (Fig. 11.10).

In the close vicinity of Tivat there is the Plavde spring. This spring is only some 50 meters far from the sea water and its catchment area is in the terrains of the cucali zone of the Vrmac massif. This is a brackish spring. During the dry season of the year the concentration of Cl iones increases in this spring, but not to such an extent to make it unusable as potable water. This spring serves mainly for water supply of Tivat city.

Inhabitants of Tivat, Kotor, Orahovac, Risan, Herceg-Novi live all along the edges of the Boka Kotorska Bay. In this area many industrial, tourist and other capacities have been built. The population of the Boka Kotorska Bay is well known for longer time by their activities in the field of maritime economy. And all such activities cannot be without negative effects of waste waters and other materials which are the result of these activities, causing pollution of the coastal soil and underground waters in these terrains and waters of the Boka Kotorska Bay in general.

In spite of water abundancy all along the edges of the Boka Kotorska Bay the well known fact is that the population of this area suffers from inadequate supply of fresh water (which affects also the activities of the economy of this region) due to the lack of required quantities of qualitative potable waters. This is a paradox, however, if one has in mind the size of the catchment area of the Boka Kotorska Bay and the quantity of precipitation in it, which according to the long term average is on top in Europe. The rainfall measuring station "Crkvice" on Orien mountain, the measured precipitation reaches over 5.000 sq. mm per annum as a long term average, but from year to year it can reach even more than 8.000 sq. mm per annum.

And while there is a lack of qualitative potable waters during dry seasons of the year all along the periphery of the Boka Kotorska Bay, on the other side, during the rainy seasons, the abrupt discharge of ground waters from dispersed karst water bodies produces remarkable damages. This is particularly noted in Kotor, and especially within the old city of Kotor, which is proclaimed by the international organizations as the cultural heritage of the mankind.

FIGURES

11.1. Geotectonical zones of Montenegro

11.2. Geological profile across Skadarsko jezero along the line the Adriatic Sea - Rumija - Prekornica - Maganik - Sinjajevina. 1 - Quarternary sandstone and gravel - Zeta plain; 2 - Neogene clay and sandstone - Zeta plain; 3 - Paleogene claystone; marl, sandstone, conglomerates and breccia of the Adriatic folds (flysh); 4 - Upper Cretaceous - Paleogene claystone, marl, sandstone, conglomerates and breccia of Zeta plain synclinorium (flysh); 5 - Upper Cretaceous claystone, marl, sandstone and rarely Adriatic folds dolomite; 6 - Upper Cretaceous claystone, marl, sandstone, limestone, conglomerates and breccia (Durmitor flysh); 7 - Cretaceous limestone, rarely dolomite; 8 - Jurassic limestone, rarely dolomite; 9 - Triassic dolomite and limestone; 10 - Sinjajevina Triassic; 11 - Middle Triassic eruptives: dacite, andesite, keratophyre and quartz-keratophyre; 12 - Younger Palaeozoic and Lower Triassic heterogenous schist, claystone, sandstone, conglomerates, marl and limestone; 13 - Mesozoic and Paleogene claystone, marl, sandstone, conglomerates, breccia limestone, dolomite, chert, tuffite, bentonite, dacite, andesite, keratophyre and quartz-keratophyre of cucali zone. N - Dislocation of 1st degree, overthrust; K - Dislocation of 2nd degrees, block overthrust; R - Dislocation of 3rd degree, fault.

11.3. General geotectonic map of Nikšić field.

11.4. The Lipska Pećina cave.

11.5. Duboki do - Krstac (profile).

11.5a. Plan of the cave Duboki do Krstac.

11.6. Geological-tectonic profile (Gurdić - Lovćen - Obodska cave).

11.7. The Boka Kotorska Bay, 1 : 100.000.

11.8. Cave

11.9. Schematic profile of vrulja Sopot. 1 - Mesozoic limestones; 2 - Eocene marles, slates and sandstone; 3 - Scale front.

11.10. Layout of spring cave "Opačica" - Herceg Novi. a) (1) - control borehole BB; Legend: ● Water depth in relation with sea level; 0^{o} - Change of direction in relation with magnetic compass direction; m' - length of the distance covered by the diver; b) Profile of spring cave "Opacica" - Herceg Novi. 1 - pebbles; 2 - gravel and sand with coarse fragments; 3 - gravel and sand containing some clay; 4 - white large pebbles Ø 5 - 7 moved during high waters; Legend:▼Water depth measured according to sea level. Dimensions in horizontal direction designate orthogonal projections of the true distance covered by the diver in meters.

11.11. Karst spring called Oboštničko oko (northwest edge of the Bjelopavlićka plain).

11.12. Karst spring called Glava Zete (northwest edge of the Bjelopavlićka plain).

11.13. Estavella called Straganičko oko serving as a well (northwest of the Bjelopavlićka plain).

11.14. Estavella called Straganičko oko when occurs as a karst spring (northeast edge of the Bjelopavlićka plain).

11.15. The mouth of the Zeta River to the Morača River in the season of low water level.

11.16. The mouth of the Zeta River to the Morača River in the season of high water level.

11.17. Folds in the Upper Cretaceous limestones along the edge of Skadarsko jezero (Malo blato).

11.18. Kaludjerovo oko spring when occuring as a spring.

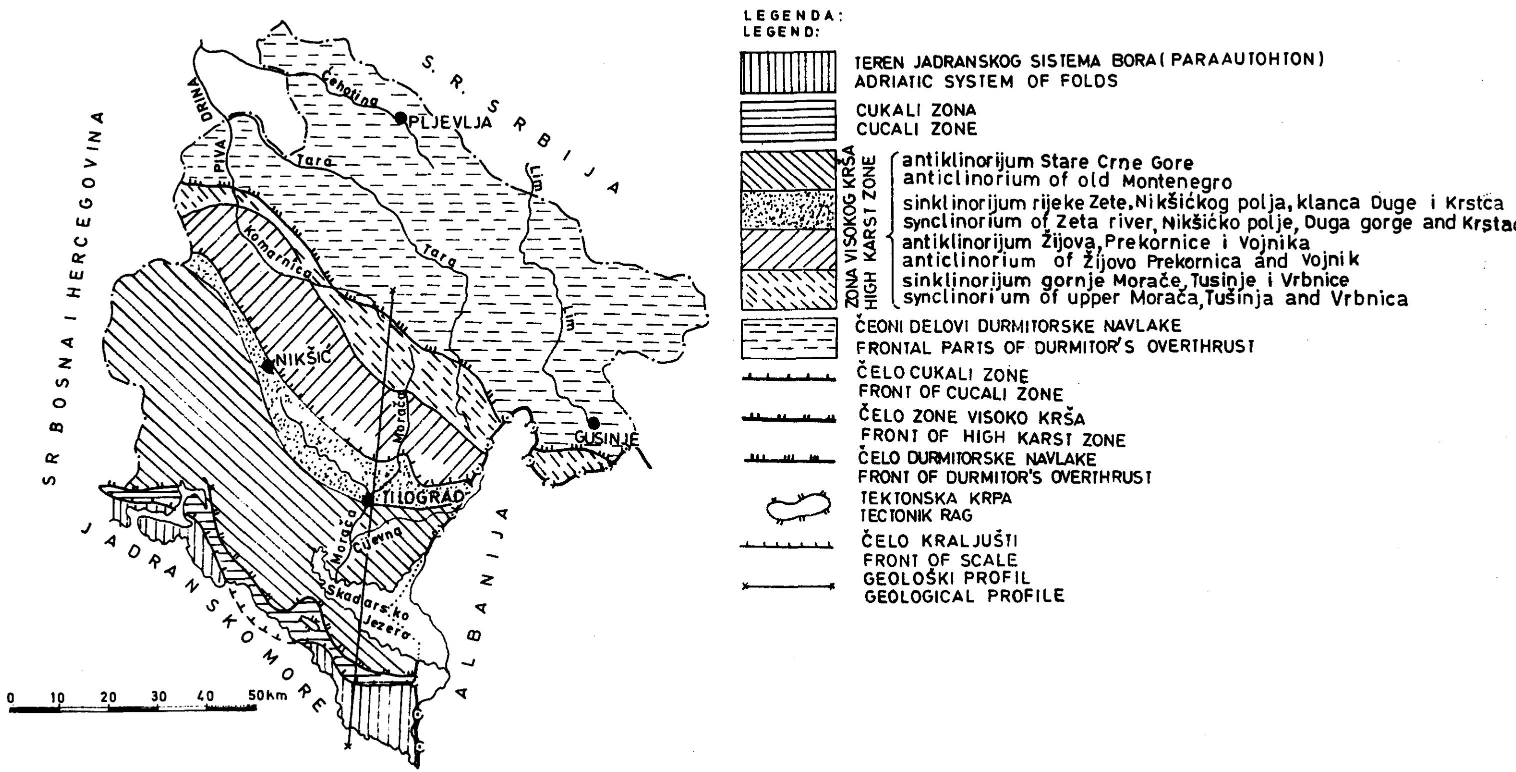

S. R. SRBIJA
SR BOSNA I HERCEGOVINA
JADRANSKO MORE
ALBANIJA
PLJEVLJA
NIKŠIĆ
TITOGRAD
GUSINJE
DRINA
PIVA
Tara
Ćehotina
Lim
Komarnica
Morača
Cijevna
Skadarsko Jezero
0 10 20 30 40 50km
LEGENDA:
LEGEND:
TEREN JADRANSKOG SISTEMA BORA (PARAAUTOHTON)
ADRIATIC SYSTEM OF FOLDS
CUKALI ZONA
CUCALI ZONE
ZONA VISOKOG KRŠA
HIGH KARST ZONE
antiklinorijum Stare Crne Gore
anticlinorium of old Montenegro
sinklinorijum rijeke Zete, Nikšićkog polja, klanca Duge i Krstca
synclinorium of Zeta river, Nikšićko polje, Duga gorge and Krstac
antiklinorijum Žijova, Prekornice i Vojnika
anticlinorium of Žijovo Prekornica and Vojnik
sinklinorijum gornje Morače, Tušinje i Vrbnice
synclinorium of upper Morača, Tušinja and Vrbnica
ČEONI DELOVI DURMITORSKE NAVLAKE
FRONTAL PARTS OF DURMITOR'S OVERTHRUST
ČELO CUKALI ZONE
FRONT OF CUCALI ZONE
ČELO ZONE VISOKO KRŠA
FRONT OF HIGH KARST ZONE
ČELO DURMITORSKE NAVLAKE
FRONT OF DURMITOR'S OVERTHRUST
TEKTONSKA KRPA
TECTONIK RAG
ČELO KRALJUŠTI
FRONT OF SCALE
GEOLOŠKI PROFIL
GEOLOGICAL PROFILE

Figure 11.1

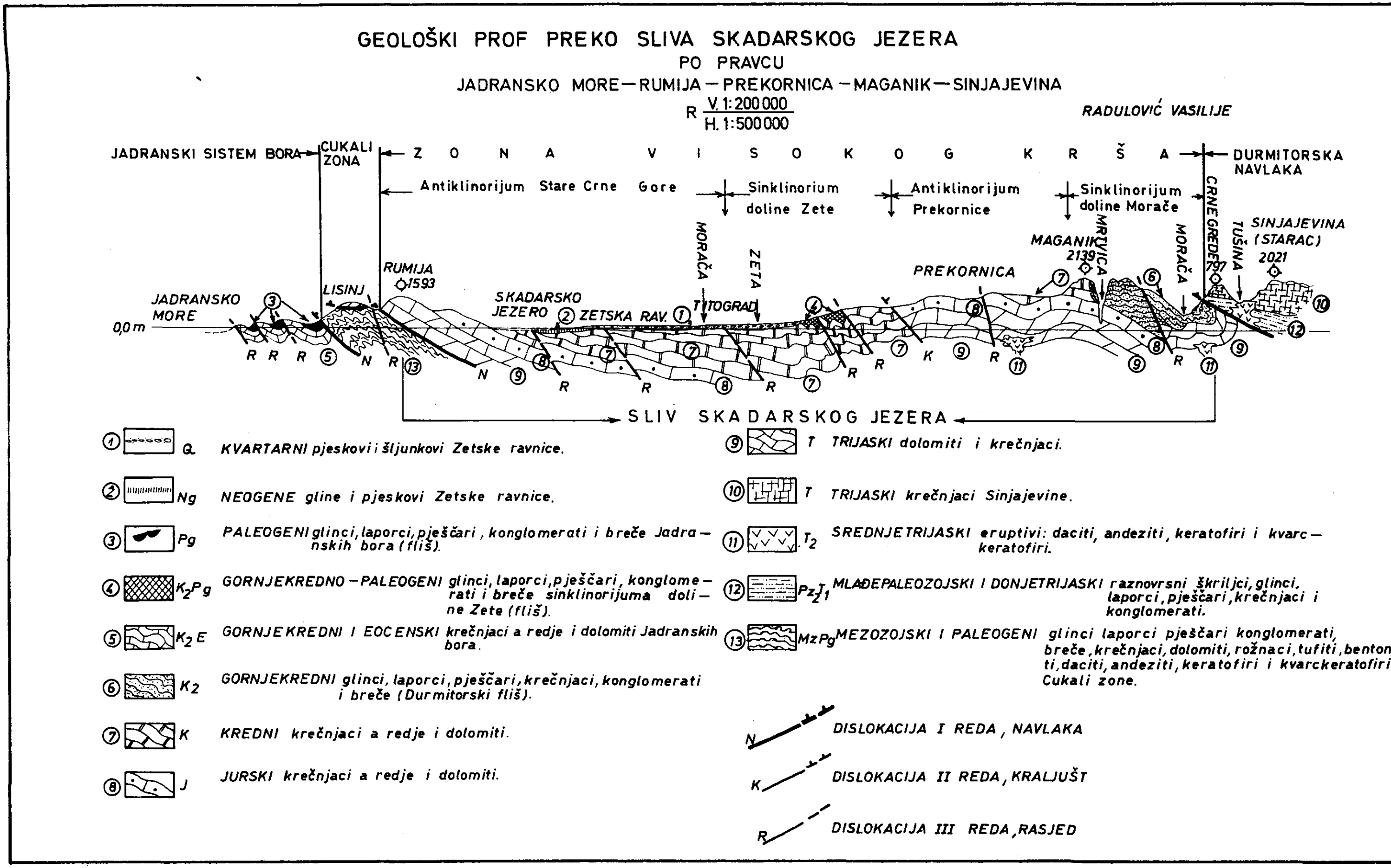
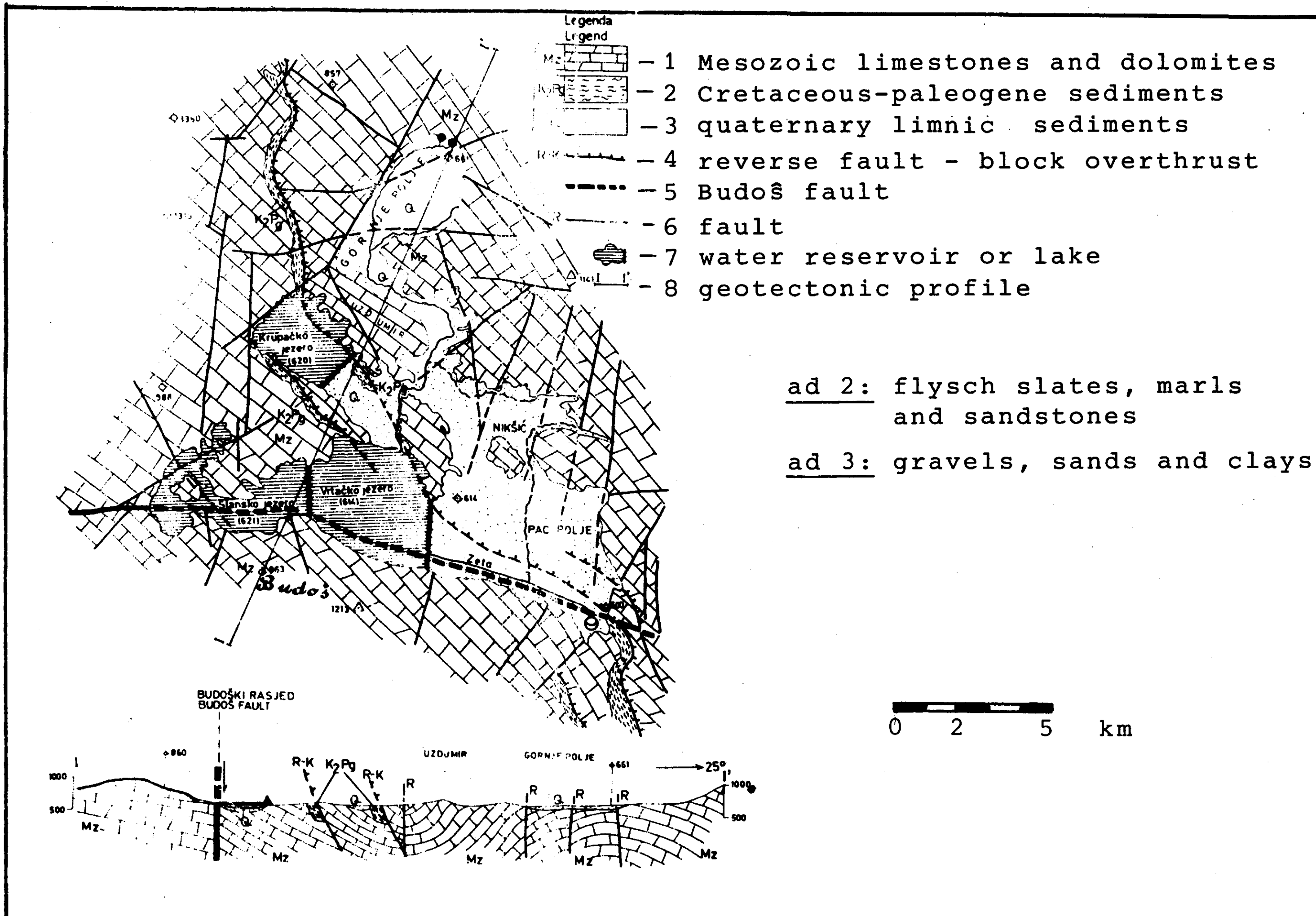

GEOLOŠKI PROF PREKO SLIVA SKADARSKOG JEZERA
PO PRAVCU
JADRANSKO MORE—RUMIJA—PREKORNICA—MAGANIK—SINJAJEVINA
R V. 1:200 000 / H. 1:500 000
RADULOVIĆ VASILIJE
JADRANSKI SISTEM BORA
CUKALI ZONA
Z O N A V I S O K O G K R Š A
DURMITORSKA NAVLAKA
Antiklinorijum Stare Crne Gore
Sinklinorium doline Zete
Antiklinorijum Prekornice
Sinklinorijum doline Morače
0,0 m
JADRANSKO MORE
LISINJ
RUMIJA 1593
SKADARSKO JEZERO
ZETSKA RAV.
MORAČA
ZETA
TITOGRAD
PREKORNICA
MAGANIK 2139
MRTVICA
MORAČA
CRNE GREDE 797
TUŠINA
SINJAJEVINA (STARAC) 2021
SLIV SKADARSKOG JEZERA
1 Q KVARTARNI pjeskovi i šljunkovi Zetske ravnice.
2 Ng NEOGENE gline i pjeskovi Zetske ravnice.
3 Pg PALEOGENI glinci, laporci, pješčari, konglomerati i breče Jadranskih bora (fliš).
4 K2Pg GORNJEKREDNO-PALEOGENI glinci, laporci, pješčari, konglomerati i breče sinklinorijuma doline Zete (fliš).
5 K2E GORNJEKREDNI I EOCENSKI krečnjaci a redje i dolomiti Jadranskih bora.
6 K2 GORNJEKREDNI glinci, laporci, pješčari, krečnjaci, konglomerati i breče (Durmitorski fliš).
7 K KREDNI krečnjaci a redje i dolomiti.
8 J JURSKI krečnjaci a redje i dolomiti.
9 T TRIJASKI dolomiti i krečnjaci.
10 T TRIJASKI krečnjaci Sinjajevine.
11 T2 SREDNJETRIJASKI eruptivi: daciti, andeziti, keratofiri i kvarc-keratofiri.
12 PzT1 MLAĐEPALEOZOJSKI I DONJETRIJASKI raznovrsni škriljci, glinci, laporci, pješčari, krečnjaci i konglomerati.
13 MzPg MEZOZOJSKI I PALEOGENI glinci laporci pješčari konglomerati, breče, krečnjaci, dolomiti, rožnaci, tufiti, bentoniti, daciti, andeziti, keratofiri i kvarckeratofiri Cukali zone.
N DISLOKACIJA I REDA, NAVLAKA
K DISLOKACIJA II REDA, KRALJUŠT
R DISLOKACIJA III REDA, RASJED

Figure 11.2



Legenda
Legend
— 1 Mesozoic limestones and dolomites
— 2 Cretaceous-paleogene sediments
— 3 quaternary limnic sediments
— 4 reverse fault - block overthrust
— 5 Budoš fault
- 6 fault
— 7 water reservoir or lake
- 8 geotectonic profile
ad 2: flysch slates, marls and sandstones
ad 3: gravels, sands and clays
0 2 5 km
Krupačko jezero (620)
Vrtačko jezero (641)
Slansko jezero (621)
NIKŠIĆ
PAC POLJE
Zeta
Budoš
GORNJE POLJE
UZDUMIR
BUDOŠKI RASJED
BUDOŠ FAULT
Mz
Q
R-K
R
25°

Figure 11.3

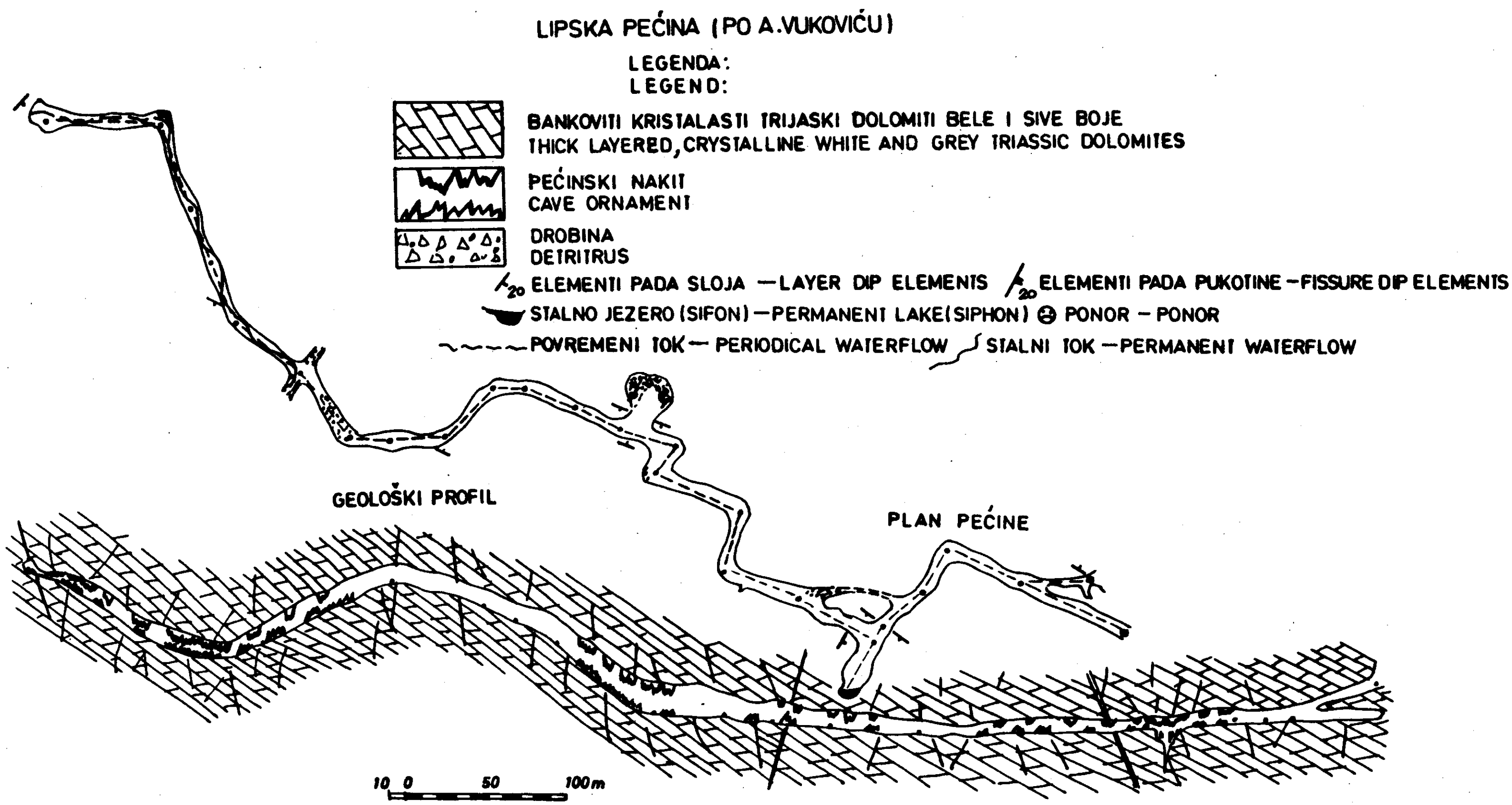

LIPSKA PEĆINA (PO A.VUKOVIĆU)
LEGENDA:
LEGEND:
BANKOVITI KRISTALASTI TRIJASKI DOLOMITI BELE I SIVE BOJE
THICK LAYERED, CRYSTALLINE WHITE AND GREY TRIASSIC DOLOMITES
PEĆINSKI NAKIT
CAVE ORNAMENT
DROBINA
DETRITRUS
ELEMENTI PADA SLOJA — LAYER DIP ELEMENTS
ELEMENTI PADA PUKOTINE — FISSURE DIP ELEMENTS
STALNO JEZERO (SIFON) — PERMANENT LAKE (SIPHON)
PONOR — PONOR
POVREMENI TOK — PERIODICAL WATERFLOW
STALNI TOK — PERMANENT WATERFLOW
GEOLOŠKI PROFIL
PLAN PEĆINE
10 0 50 100m

Figure 11.4

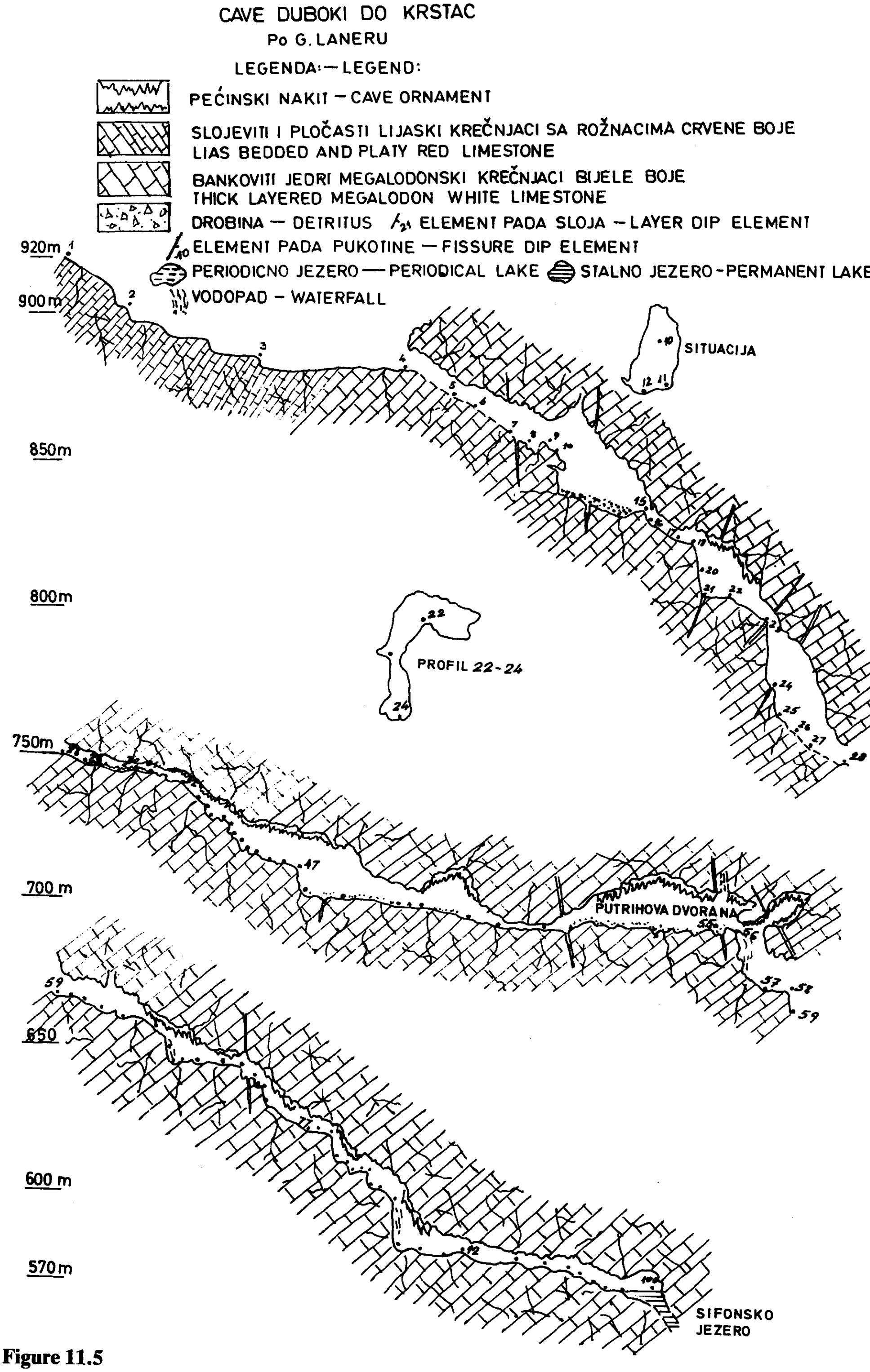

CAVE DUBOKI DO KRSTAC
Po G. LANERU
LEGENDA:—LEGEND:
PEĆINSKI NAKIT — CAVE ORNAMENT
SLOJEVITI I PLOČASTI LIJASKI KREČNJACI SA ROŽNACIMA CRVENE BOJE
LIAS BEDDED AND PLATY RED LIMESTONE
BANKOVITI JEDRI MEGALODONSKI KREČNJACI BIJELE BOJE
THICK LAYERED MEGALODON WHITE LIMESTONE
DROBINA — DETRITUS
ELEMENT PADA SLOJA — LAYER DIP ELEMENT
ELEMENT PADA PUKOTINE — FISSURE DIP ELEMENT
PERIODICNO JEZERO — PERIODICAL LAKE
STALNO JEZERO - PERMANENT LAKE
VODOPAD - WATERFALL
920m
900m
850m
800m
750m
700 m
650
600 m
570m
SITUACIJA
PROFIL 22-24
PUTRIHOVA DVORANA
SIFONSKO
JEZERO

Figure 11.5

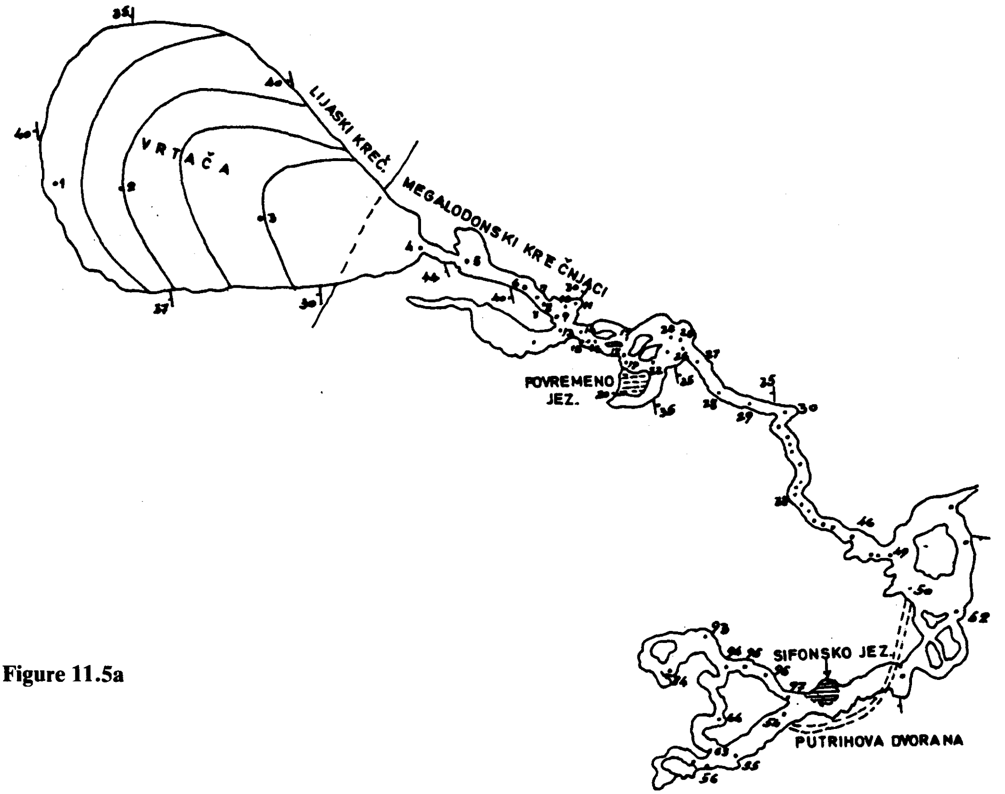
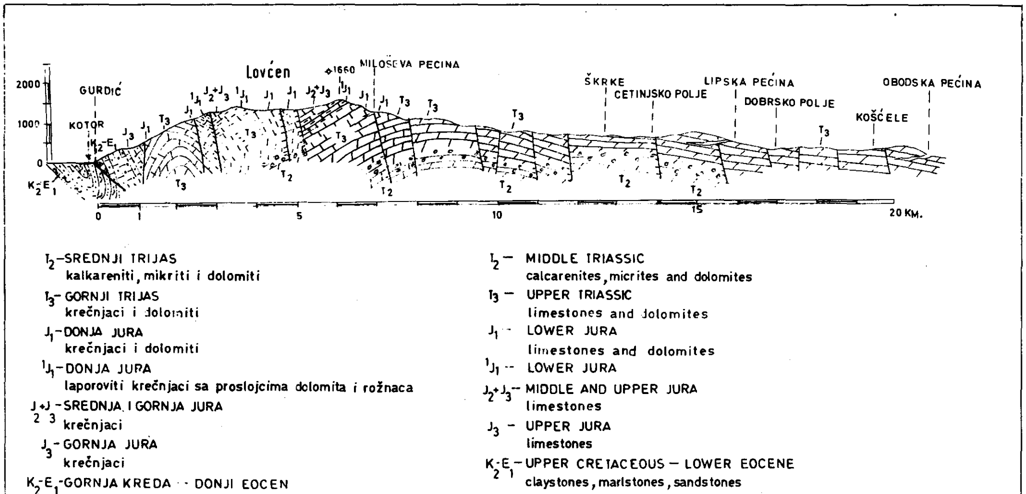


Figure 11.5a



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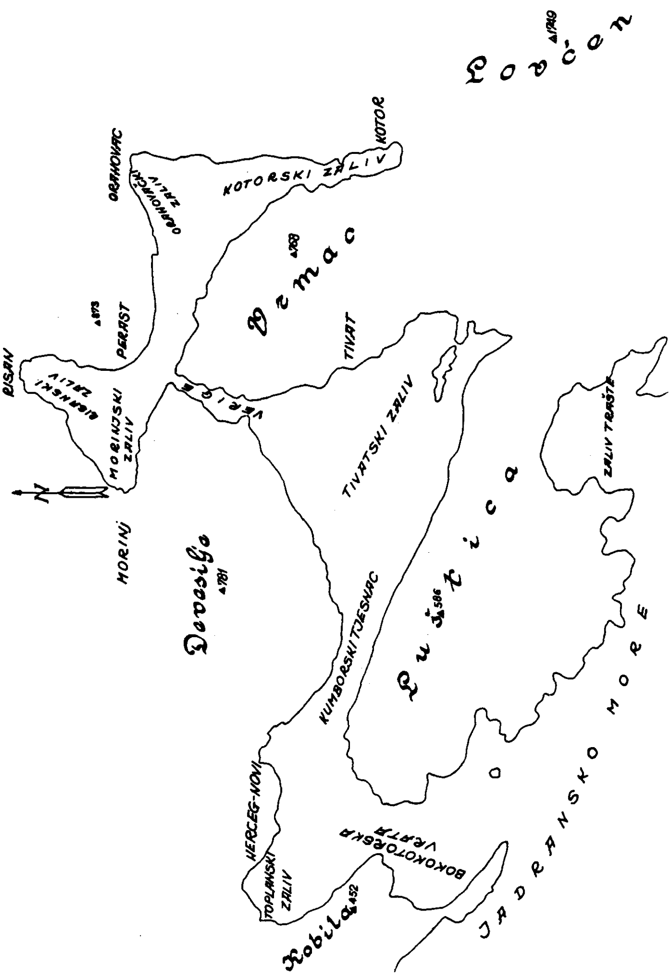


Figure 11.7

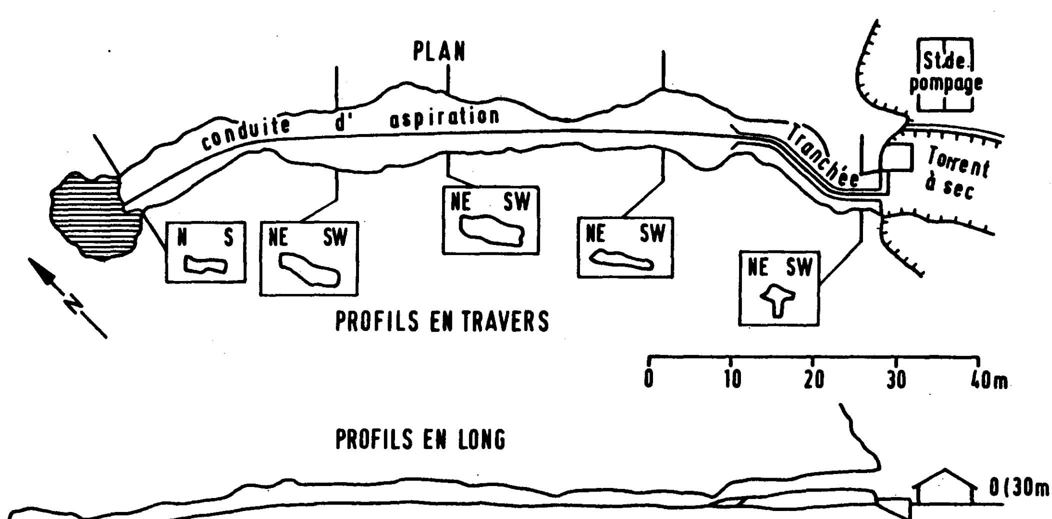


Figure 11.8

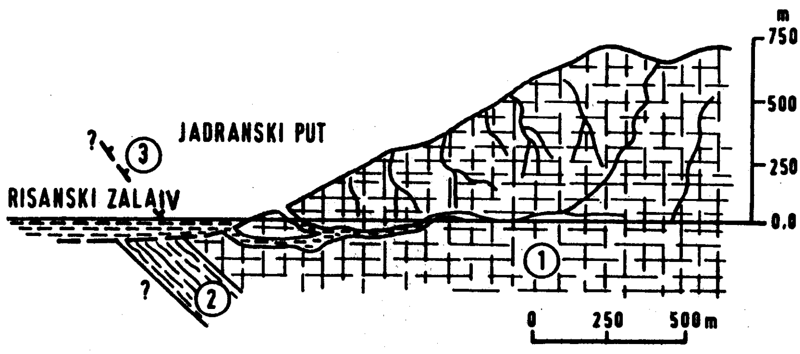
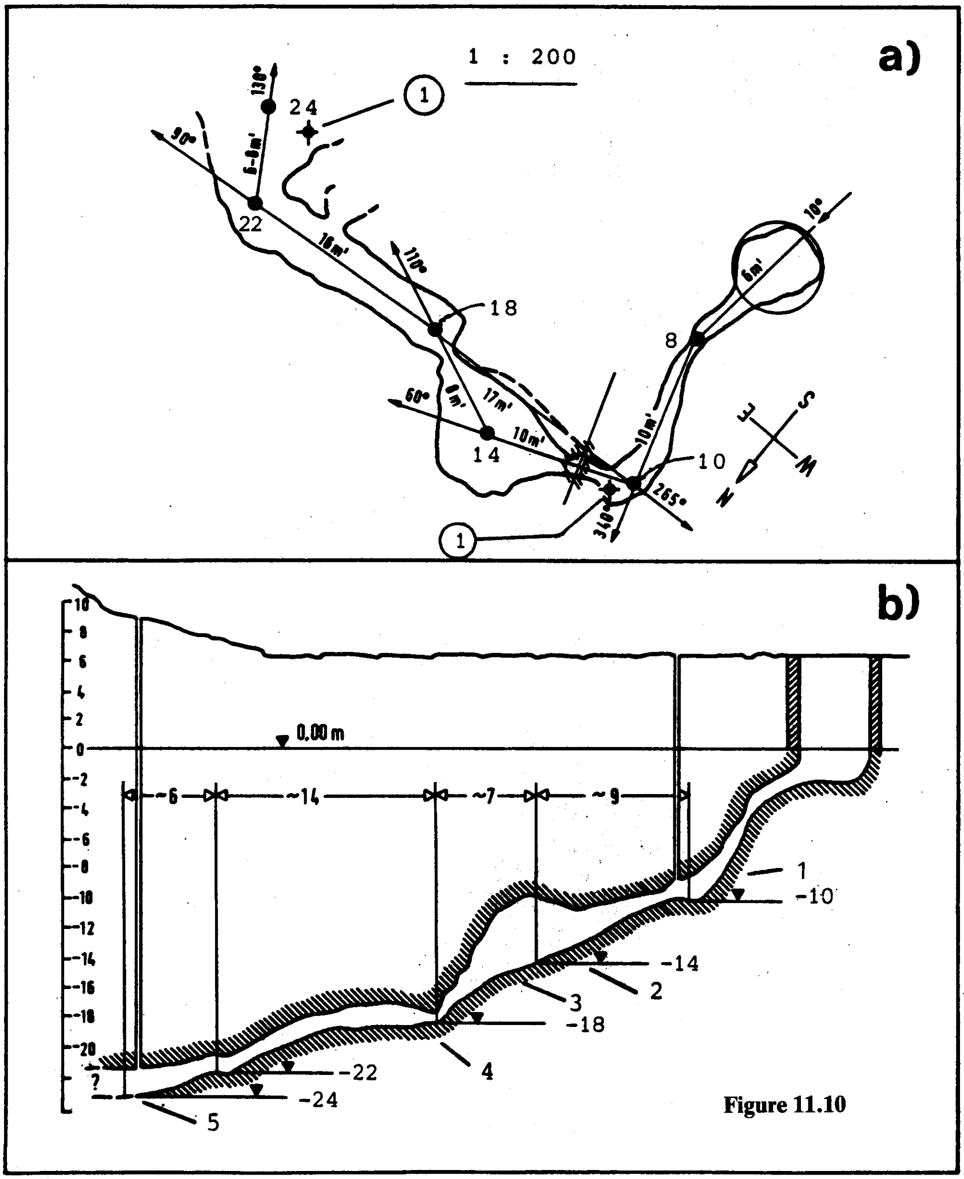

m
750
500
250
0.0
JADRANSKI PUT
RISANSKI ZALAIV
0 250 500 m

Figure 11.9


a)
1 : 200
b)
0.00 m
Figure 11.10

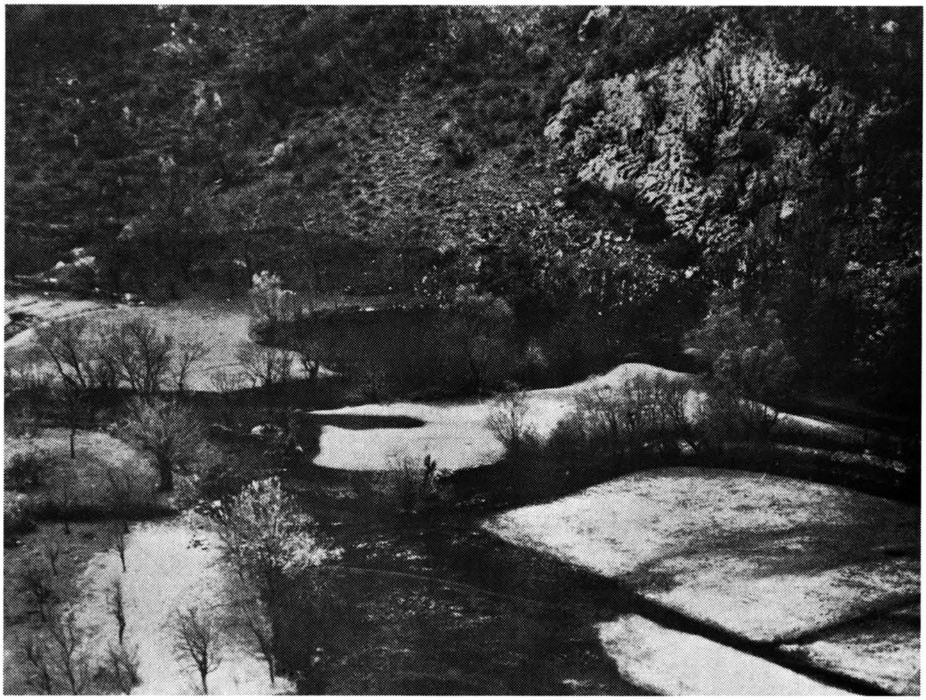


Figure 11.11

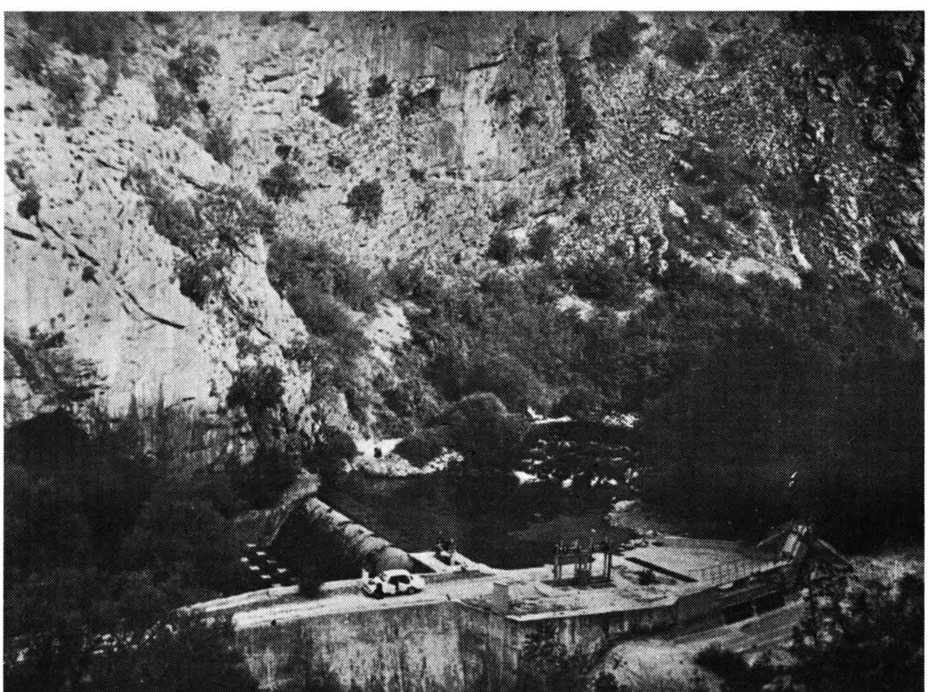


Figure 11.12

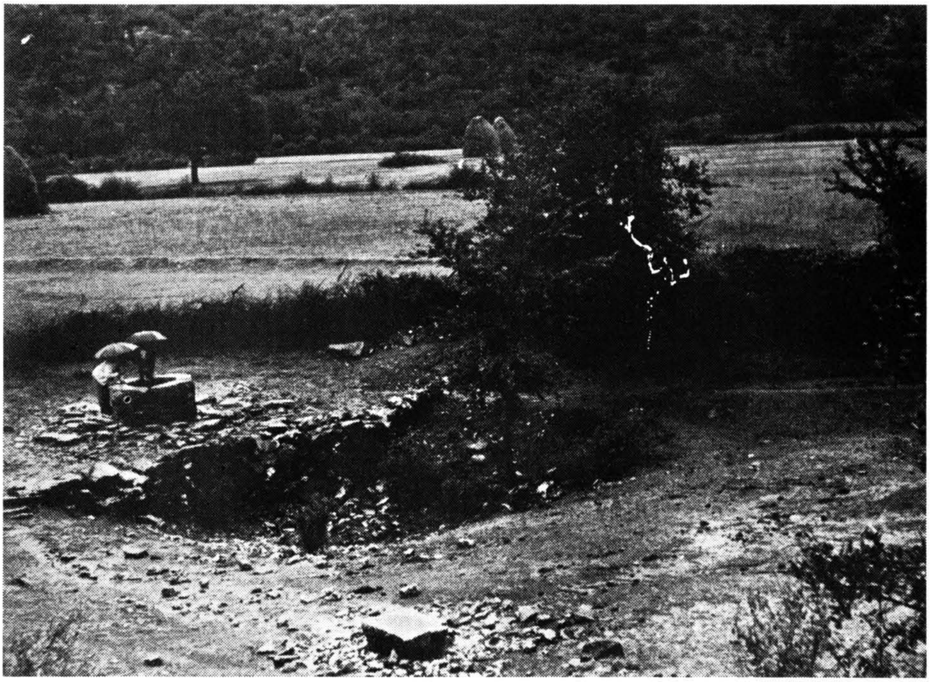


Figure 11.13

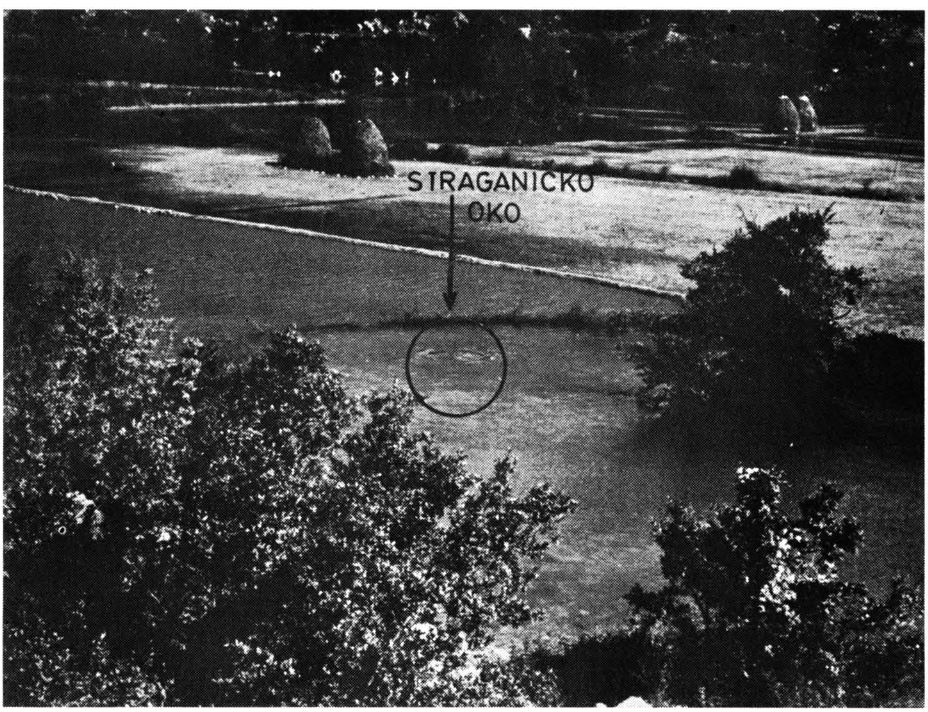


Figure 11.14

Figure 11.15

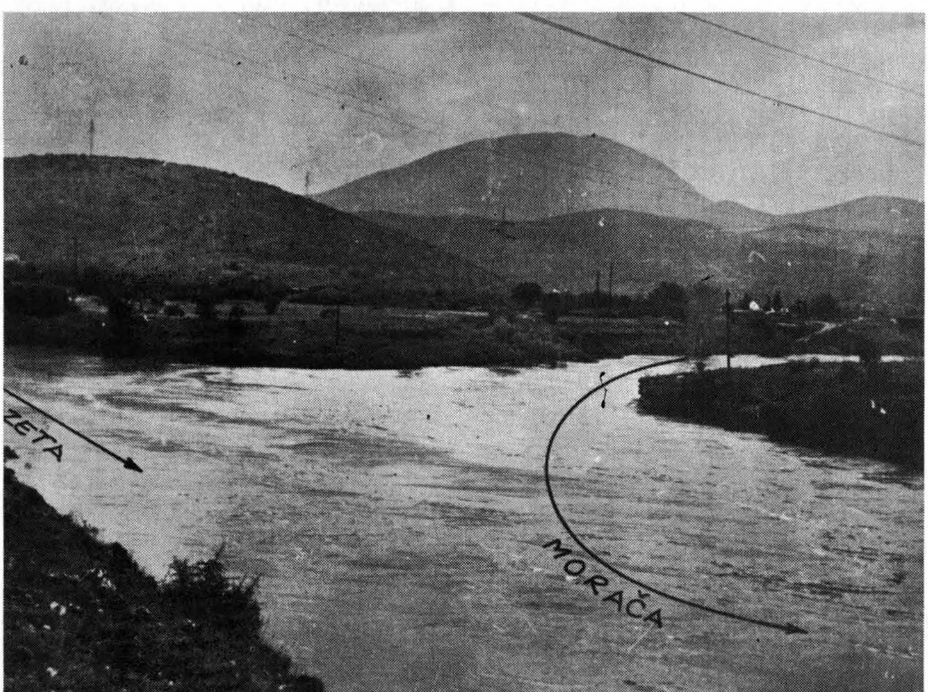


Figure 11.16

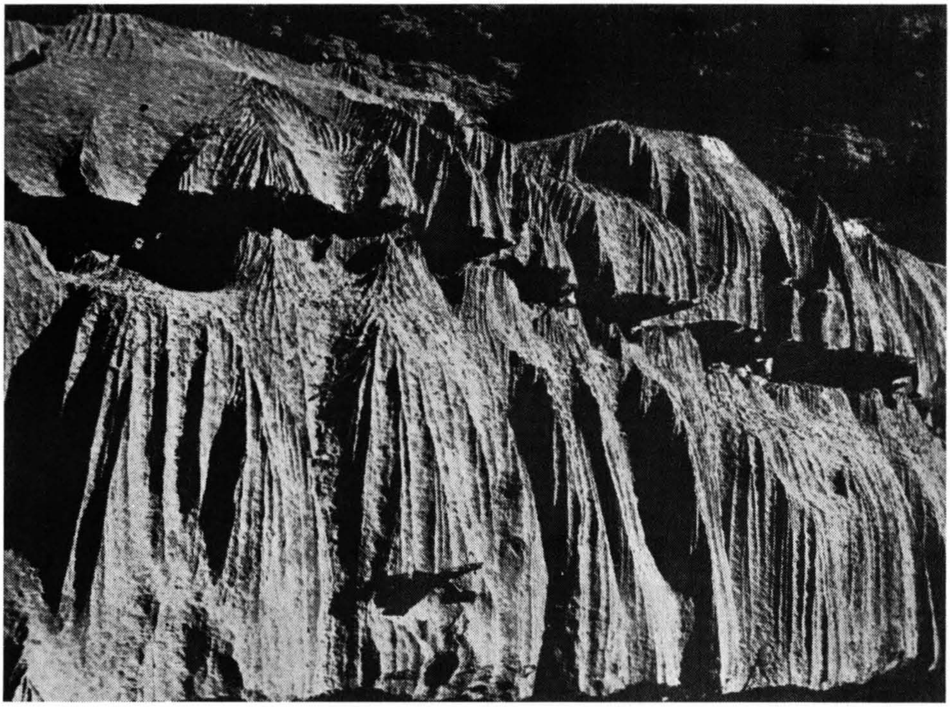


Figure 11.17

Figure 11.18

12

HYDROGEOLOGIC FEATURES OF SOME NORTHERN DALMATIA LITTORAL KARST PARTS, LIKA AND CROATIAN LITTORAL

Franjo FRITZ - Institute of Geology, Zagreb; Stjepan BAHUN - University of Zagreb, Božo BIONDIĆ, Anton POLŠAK, Željko VULIĆ, Srećko BOŽIČEVIĆ and B. PAVLIN - Institute of Geology, Zagreb

DESCRIPTION OF THE REGION

This is the region of Ravni Kotari, low coastal region characterized by specific hydrogeologic relations, belonging to so called Orogenski karst (HERAK, 1977). This terrain is composed of a series of parallel folds of northwest-southeast trends. Cretaceous carbonate deposits (except dolomites in the anticlinale cores) and Eocene foraminifere limestone make a permeable complex of deposits. They appear in cores and limbs of anticlines. Through them practically all ground waters which could be used for water supply are circulating.

The Middle Eocene flysh as a whole is water impermeable. Although it appears in the syncline cores, it reaches rather deep in relation to the uttermost erosion base - the sea, and most often has the function of true barrier for surrounding karst underground waters. Because of that the majority of karst underground waters run in between two barriers northwestward or southeastward. Only where flysh (syncline) and dolomitic (anticline) barriers disappear, which are of primary importance for ground waters circulation, the transversal and diagonal faults appear, most frequently used by ground waters as the shortest ways to the erosion base.

For ground water circulation understanding, and for understanding karst features development and fresh water intrusion by salty waters in the coastal area, it is neccessary to analyse fluctuation of sea level in this coastal area (the erosion zone), particularly during the period of the past 25.000 years in which the sea level raised gradually from about 100 m in depth up to the present level.

In Ravni Kotari the inverse relief developed owing to which the crests are most often of synclinal and valleys of anticlinal structure which can be clearly seen from the bus, travelling, from Zadar towards Obrovac. In rainy seasons periodical lakes appear in the valleys and Vransko jezero is the permanent lake.

Northward from Obrovac (Velebit mountain and Lika region) the marchroute enters into so called accumulated karst zone (HERAK, 1977) which is characterized by big primary thickness of the carbonate sediments, mostly of the Jurassic and the Cretaceous, and by their secondary tectonic bedding up to several thousands meters. Water impermeable deposits of the Paleozoic and Lower Triassic are relatively deep which enables occurence of deeper water connections from the inland regions towards the sea. The part of Velebit mountain, between Jablanac and Gračac (where the water impermeable rocks are lifted), about 70 km in length, represents the morphologic and hydrogeologic barrier for direct water link between the mainland and the sea, and in that part Velebit mountain is the local surface and subterranean watershed. Because of that all waters on the northeast side of Velebit mountain flow along its body towards the northwest (the Jadova and Lika rivers), i.e. towards the southeast (the Ričica river). Surface courses disappear on both longitudinal ends of the barrier into ponors, and together with other ground waters (including also waters from the Gacka catchment area), reaching the coast, appearing in the northwest between Senj and Karlobag in the form of submarine springs i.e. in the southeast in the form of springs on the right bank of the Zrmanja river.

The marchroute from the Plitvice Lakes towards Senj at the Babin potok brook, crosses the watershed between the Adriatic and the Black Sea catchments. Owing to this watershed, waters of the Krbavsko polje, the Plitvice area and Mala Kapela, flow towards the northeast. Althought the gradients are considerable lower here than that on the southwest side of the watershed, here also occur deep underground water connections (for instance under Plješevica, in the direction Krbavsko polje - Bihaćko polje).

The Kruščica accumulation is located in typical karst area in the morphological sense, without direct hydrogeologic influence of older clastic water impermeable sediments. However, in this area, the Velebit barrier hinders indirectly the outflow towards the sea, while deposits of the Jelar formation (Tertiary limestone clastites with marly elements), which are of lower permeability as compared with the carbonaceous environment, ensure satisfactory water imperviousness of the accumulation together with technical solutions applied.

From Senj towards Rijeka the one passes through the carbonate area of uniform structure up to Novi Vinodolski. This is southwest wing of anticline form, of Velebit Kapela, mostly with limestone development of sediments striking in slope towards the sea in general. In hydrogeologic sense those are well permeable rocks, and supposed confirmed flows of ground waters are parallel to sediments and main faults trends. The highest concentration of sources from the carbonaceous subterrane is the Novljanska Žrnovic which is located in a deep gorge between Klenovica and Povil along the sea coast.

From Novi Vinodolski towards Rijeka the structural relations vary to a great extent and also the hydrogeologic situation. The anticline composed of carbonate rocks extends along the coast line, but it is bordered from the northeast with flysh barrier and therefore the underground waters from the deep carbonate rear do not reach the sea coast in this area. Scarce coastal springs and submarine springs are of local character.

In the Bay of Bakar the above mentioned flysh barrier is submerged into the sea and its hydrogeologic function reflects on the northeast coast of the Bay where three captions for potable water supply are provided of considerable capacity.

From the Bay of Bakar towards Rijeka town, we pass again through the carbonate anticline with flysh barrier in the rear, while in the coastal area there are not significant springs and submarine springs. Entering Rijeka we come to the first larger concentration of springs which is connected with the extensive karst area behind Gorski Kotar. This is the Martinšćica source. In the central part of the town, towards the sea, the Rječine gorge passes through the carbonaceous terrain, and along the right hand bank there are many karst springs captured or being under the process of capturing for water supply requirements of Rijeka town. The water storage "Zwir II" is located in this area.

VELEBIT MOUNTAIN - BIOGENETIC PRESERVE OF EUROPE

The Velebit massif extends 145 km, from Senjska draga bay to the upper course of the Zrmanja river, bordered by the Adriatic sea on one side, and the Ličko polje and Gačko polje on the other.

Velebit mountain is characterized by specific karst morphology with numerous surface and subterrane phenomena. As concerns its flora, the side of the mountain turned towards sea differs from the inland side, while the vegetation of the karst area is specific with many endems. Fauna is also specific which is conditioned by may endemic features dating from the Diluvial period. Human influence in this mountain was more expressed in the past because of intensive cattle breading and many permanent settlements. Nowadays we have more expressed exploitation of forests in this mountain and more intensive tourism activities in some parts of the mountain.

Canyons of the Velika Paklenica and Mala Paklenica rivers and the Bezimenjača river valley in the southern part of Velebit were put under protection of the state as the National Parks in 1949, while the area of Rožanski and Hajdučki Kukovi, with the Štirovača river, was declared as true preserves of the Nature. A part from the above the flooded valley Zavratnica at Jablanac and the Tulove grede complex above Obrovac represent a real morphologic specificity of this region.

Because of all these specificities, Velebit Mountain was declared by the United Nations Organization (programme of Man and Biosphere) in 1978 as the part of the International Network of Biosphere Preserves. According to the said Programme Velebit mountain has become a "typical protected region of the Yugoslav mainland in which the interrelation between the human being and the nature appears in varied forms both in space and time".

VRANJSKO JEZERO AT BIOGRAD n.m.

The lake Vranjsko jezero has an area of about 30 sq. km. It is 4 to 5 m deep. It is recharged with waters from the periodical flow of the Kotarska river and a number of periodical and permanent karst springs along the northeast edge of the Vransko polje, upstream the river. During the rainy period, water of the lake is fresh water containing in total 1.000 mg Cl/l. To prevent inundation of arable soil of the Vransko polje with waters from the lake, the embankments were erected and a drainage channel was dug to provide discharge into the sea.

The lake is partitioned from the sea by a mountain-ridge composed of the Cretaceous and Eocene limestone. Now the explorations are under course for damming the lake at its narrowest part (1.2 km) to retard the waters upstream from the dam by about 2 m. In this part of the lake the above mentioned ridge is only about 1 km wide. By studying the geologic structure, karstification and lake depression development it was evaluated that the ridge was impervious, since there was no underground connection between the lake and the sea in the past and there are no such connections even now, neither they are expected after water retardation. This evaluation is based on the earlier positive role of present submerged barrier composed of impermeable rocks of Eocene flysh (in the lake directly along the ridge). In addition to this barrier the ridge imperviousness is supported by the Cretaceous anticline whose axis trends nearly parallel with the presentday coast line since its core contains dolomite. Damming of the lake to get a part with fresh water and another with brackish water will enable development of fresh water and sea fishing. But it is even more important that such a project will enable desalination of the present brackish spring in the Vransko polje, bringing under control practically all waters of this water abundant catchment area, and providing in this way water supply to the near and farther surroundings.

THE "OBROVAC" HYDRO POWER PLANT

This hydro power plant, which is now under construction will be of reversible type. For this plant, waters of three karst sinking rivers will be utilized, whose waters will be directed into the "upper basin" at the elevation of about 520 m. The power house and the lower basin will be located in the Zrmanja river valley at the elevation of 5 - 6 m. This section of the Zrmanja we shall see travelling over the road from Obrovac to Gračac (from Dalmatia through Velebit mountain to Lika). The "upper basin" will be located in a part of karst polje where the Upper Triassic clastites are structured in degraded anticline, having the function of a hydrogeologic barrier. Other parts of this karst polje (Štikada - Gračac) are composed of rather broken Middle Triassic limestones and dolomites which through many ponors swallow waters of the mentioned sinking rivers of Lika. Within this travelling we could visit the Tučić ponor, one of the most remarkable ponors into which waters sink during the most part of the year, and then the caves Cerovačke pećine, which sometimes in the past were a sinking system serving for discharge of waters from this karst polje when its elevation was higher than now.

TUČIĆ PONOR

Tučić Ponor is in the southeast part of the Štikadsko polje. The location of the ponor is in the most southern end of the Ričica water course and it "swallows" flooding waters during rainy periods. The ponor hole is formed in the succession of Triassic limestones and dolomites in the protracted fissure of north-south trend, with vertical extensions up to the stairs at depths of 30, 60 and 90 m.

Morphology of the ponor is typical for such karst phenomena formed along expressed and perpendicular fissures through which water disappears in the subterrane. At the intersection of widened fissures some staira are formed and the vertical channels turn round shortly. This ponor was searched so far up to 145 m in depth but it is anyway deeper than that. For a man it is impossible to reach deeper because of tuffaceous deposits covered with drifted material.

At present the river bed in front of the ponor is regulated and cut in deeper for easier water outflow, preventing floods in the polje.

PLITVIČKA JEZERA

The Plitvička jezera lakes are located in the Dinaric karst at the junction of Kapela mountain and Lička Piješevica mountain and they represent a unique natural phenomenon. They are far and wide known by their beauty, and extremely attractive for scientists of many different branches, and have been properly declared as the National Park since 1949.

In the area of the Plitvice National Park, deposits of the upper Triassic were discovered as well as of the entire Jura and the Lower Cretaceous, and some parts of the Upper Cretaceous. All these deposits are nearly completely of carbonate structure (limestone and dolomite) while other sediments appear only scarcely.

Of the Quarternary sediments the most significant in this area is tuffa. It contains barriers over which water from one lake overflows into another. The rock is of greyish yellow colour, cavernous and porous. In some barriers it is over 200 m thick. Tuffa was mostly formed by incrustation of mosses from the Bryum and Cratoneuron genera of Bryaceae family. Some of tuffaceous barriers are submerged.

In the area of the Plitvice National Park fault tectonic structure is dominating. Only sporadically relicts of older folded structures are more expressed. Major tectonic units strike in the northwest-south-east directions.

HYDROGEOLOGIC RELATIONS

Since detail hydrogeologic explorations were not undertaken till now we shall comment here only the main characteristics of hydrogeologic relations based on the existing geologic data.

The Upper Triassic dolomite belt represents a true hydrogeologic barrier and in this connection the concordant deposits of the Lower and Middle Lias. This belt extends through the central part of the Park towards northwest-southeast. It could be said that this belt represents the skeleton of the hydrogeologic regime of the Park. Dolomite in this terrain has the role of impervious rocks. It results from the impermeable clayish deposits of karnik which lay in the immediate floor of the Upper Triassic dolomite. These impervious deposits prevent circulation of ground waters in depth owing to which the fissure structure of the Upper Triassic dolomite is saturated with water which drains through a series of bed and fracture springs. Because of terrain impermeability this area is characterized by having many surface water courses. Such hydrogeologic situation suits best for larger hydro-accumulations. From this reason only this belt of the Park was suitable in the hydrogeologic sense for larger lakes forming, like that as the Upper Lakes. The sound hydrogeologic barrier in the bed prevents any loss of water from these lakes and their sinking underground. This barrier ends with Lower and Middle Lias deposits whose water impermeability is even more stressed with the presence of marl and chert layers.

Retardation function of this Triassic-Liassic barrier comes particularly in expression at the contact with higher permeable deposits. In connection with fault contacts with waterpermeable Dogger and Malm carbonate deposits here there appear strong ascending springs.

Another significant sound barrier is composed of a horizon of impervious plate-like and laminated marly limestone of the Upper Turonian. This horizon which is 30 to 50 m thick extends along the border with Senon water belt limestone and it is particularly well developed in the area from Poljanak to Ličko Petrovo Selo. These sediments strike southwestward in general and make this floor permeable in the deep karstified Senon water belt of the limestone in the area of Plitvički Klanac - Medvedak.

This water impervious horizon contributed forming of water accumulations of lower lakes called Donja jezera forming. Water permeable deposits of Dogger-Malm dolomite are incomplete barrier in the wider area of Kik-Crni Vrh. This barrier is connected with the strong spring of the Bijela Rijeka river.

Water permeable zones are present in the major part of the Park. They consist mostly of thick successive layers of limestone and dolomite of the Lias, Dogger, Malm and Lower Cretaceous, and of Upper Cretaceous limestone from the water belt.

The water permeable zones represent at the same time the main water catchment zones which "feed" the hydrologic system of the Plitvička jezera lakes. Because of that such zones, although without visible surface water flows, require a particular kind of protection.

THE KRUŠČICA ACCUMULATION BASIN

The Kruščica accumulation basin with retardation of 80 m (up to the level 554, above sea level) contains 140 million cu. m of water and serves for water leveling of the rivers Lika and Gacka, for their utilization in the hydro-power system and in agriculture.

The area of the Kruščica accumulation basin, on the Lika river, together with the neighbouring areas of its tributaries, is called Lička visoravan (highland of Lika) separated from the sea by Velebit massif. The anticlinal cores of Velebit whose waterpermeability is rather weak because of their composition consisting of the Paleozoic and Triassic clastite and dolomite, are separated and dammed by the Kruščica accumulation basin catchment area towards the sea. This natural impervious barrier prevents outflow of surface or ground waters towards the sea, from the Kruščica accumulation basin catchment area which is composed of Paleogene and Mesozoic limestone deposits.

The Kruščica accumulation bed is formed in the limestone deposits which are of dominated Paleogene age and to a smaller extent of the Cretaceous age.

Morphogenetic studies of this accumulation area development in addition to utilization of extensive exploration results have enabled clarification of hydrogeologic relations in the limestone zone of this accumulation which in the surface zone is extremely karstified. This also helped to come to the conclusion that this accumulation can be realized and that technical solution should be found appropriately.

High ground water heads in limestone layers, laterally from this accumulation, have proved that its flanks are weakly permeable, although their surface is highly karstified.

HORVATOVA AND POLJAKOVA PEĆINA

Horvatova and Poljakova Pećina cave, on the left and right flanks of the dam prove extreme karstification of Promina deposits in this part of Lika. Tectonic fracturing of deposits caused penetration of water into rocks in which erosion and corrosion activities resulted in formation of underground cavities. Discovered caves prove intensive surface karstification in Jelar deposits in this area as well as on the surface itself. By formation of present bed of the Lika river in shaped cavities, the period of stalactites and stalagmites forming appears, and such structures reach up to twenty meters in height and over five meters in diameter. Traces of cracked dripstone columns (of stalagmites and stalactites), and of complete parts of cave chambers point out more intensive caving or younger tectonic movements in this part of Lika.

Both cave systems have been unknown up to the recent time and they were discovered when drillings for the grouting curtain were undertaken at the underground space and work in it. Owing to steady supervision of works in that space underground injecting works were successfully completed, as well as on the grouting curtain section in the cave zone.

The Horvatova pećina cave, at the left hand flank of the Sklope dam, was searched in the length of about 500 m of underground canals and chambers. One part of inaccessible and unsearched canals is filled with injecting compound. The Poljakova pećina cave on the right side of the dam was searched 220 m in length.

PERINKA PONOR

Perinka Ponor at the Donje Švičko jezero lake is one of present active ponors in a series of twenty ponors in this area. The zone of ponors extends over 4 km in length, cutting in the northern slopes of Velebit mountain.

Before the realization of the hydro-power project on the Lika and Gacka rivers in this area a part of sinking river Gacka waters was swallowed. Nowadays, owing to newly built channel and the Gornja Švica - Marsi tunnel, waters of the Gacka river are fully used within the Senj Hydro Power Plant.

The Perinka river ponor has round and funnel-like shaped orifice which was formed in the Quarternary sediment, below which widened fissures of Jurassic limestone can be met.

The ponor is searched up to 40 m in depth, but underground canals continue to greater depths. The lower part of the ponor is filled with a thicker drift of tuffaceous masses which have covered drifted logs and other material.

Nowadays the ponor is active only when due to temporary overhaul of the main tunnel of the Senj HE Power Plant the surplus of water is discharged into the old bed of the sinking river Gacka.

SUBMARINE SPRINGS AND COASTAL SPRINGS AT JURJEVO

In the coastal part of the Croatian Littoral, at the foot of the northern Velebit, the most abundant coastal and submarine springs appear south of Jurjevo, in the line of about 4 km long. The capacity of submarine springs is not known and water salinity in May 1974 ranged between 18.000 and 20.000 mg Cl/l.

By dyeing of sinking rivers of Lika, the Lika and Gacka, the greatest apparent speeds of flow were determined, towards the above mentioned springs. The sinking waters of Lika (Markov ponor) flow mainly in the direction west-northwest, along the parallel faults zone Lipovo polje - Oltare, Volarice - Jurjevo, which separates Velebit mountain from Senjski mountain ridge. This fautl zone is intersected nearly perpendicularly by another fracture zone at Volarice, used by sinking waters of the Gacka river in their underground flow towards Jurjevo and Lukovo, and downstream of Volarica it enables the ground waters of the Lika river to turn southward towards Lukovo which is mainly the case in the season of mean and high waters.

More northward from the spring zone at Jurjevo (up to about ten km behind Senj) and more southward (up to Klada), in the hydrologic minimum water does not appear at all. Namely, the precipitation waters which infiltrate in the western side of the Senj mountain ridge, relatively rapidly flow out after the rains, through a series of periodically active coastal springs and submarine springs.

Relatively low present minimum yieldingness of water springs at Jurjevo is effected by the HE Power Plant Senj, which since 1967 has been exploiting practically all mean and low waters of the Lika and Gacka rivers.

According to the above said, the fault zone Oltava - Volarice - Jurjevo represents an expressed trend of recent flow of ground waters and the Senj mountain Ridge and the northernmost Velebit are the local underground divides.

THE BAY OF BAKA (THE BELVEDERE ON THE SOUTHWEST SIDE)

The area of the Bay of Bakar represents a part of the Paleogenic Syncline Klana - Novi Vinodolski. The syncline trends northwestnorth - southeasteast. The core contains the Eocene clastic deposits and the wings contain the Eocene and Cretaceous limestone, dolomite and breccia. The Eocene clastic rocks (flysh) have the function of barrier while the carbonate rocks (limestone, dolomite, breccia) serve as the collector of ground waters.

In carbonate rocks a series of longitudinal reverse faults are noted, whose trends are broken at many points by transversal and diagonal faults. Combination of faults at the contact of water permeable carbonaceous and impermeable clastic rocks resulted in tectonic forms which are of importance for hydrogeologic relations.

In the area of Bakar place, by solving tectonic and hydrogeologic relations, the underground water was captured by means of a shaft and gallery. Trial pumping (14 days) proved the capacity of 280 l/s without variations in the salinity (5 - 15 mg Cl/l). The springs at the distance of 350 m downstream issued at that moment about 100 l/s water.

At nearby locations Dobra and Dobrica 60 l/s and 180 l/s of water were captured respectively and the efficient protection of direct source has been provided.

WATER CATCHMENT ZWIR II

Water catchment Zwir II in the city of Rijeka was designed on the basis of results obtained through hydrogeologic explorations which were carried out in this city area from 1974 till 1977. This project was designed for catchment of water from the springs on the right bank of the Rjecina river of previously defined catchments areas. The springs flow out freely to city sewerage system and their catchment "in situ" is not feasible because of mixing with waste waters. The total minimum capacity of the spring is 768 l/s and the maximum 3054 l/s.

The spring catchment area is composed of carbonaceous karstified rocks with the direct influence on the chemical composition of water (calcium-hydrocarbonaceous type).

The water storage is provided in the carbonaceous background of spring zone in the form of a tunnel 400 m long, in the zone above minimum and mean ground water levels. High level waters reach over the levelling point of the tunnel and are drained towards the outlet in the Rječina river. The main idea of ground water catchment in the background of the spring was to reach the underground water through dug wells. It should be noted, however, that very weak horizontal circulation of the ground water as observed in the visual zone and that inflows towards the springs are very deep, and hardly catchable from the surface. By pumping water from the drilled wells in heavily karstified surrounding, the piezometric level of water was deformed and inflow of ground water from deep karst flows towards the springs initiated. Trial pumping resulted in determining pumping capacity of 260 l/s at the minimum and the planned additional works which are in the course will enable considerable increase of the total capacity. The quality of water under dynamic conditions meets standards of potable waters.

FIGURES

12.1. Cave of Tučič.

12.2. Cave of Perinka.

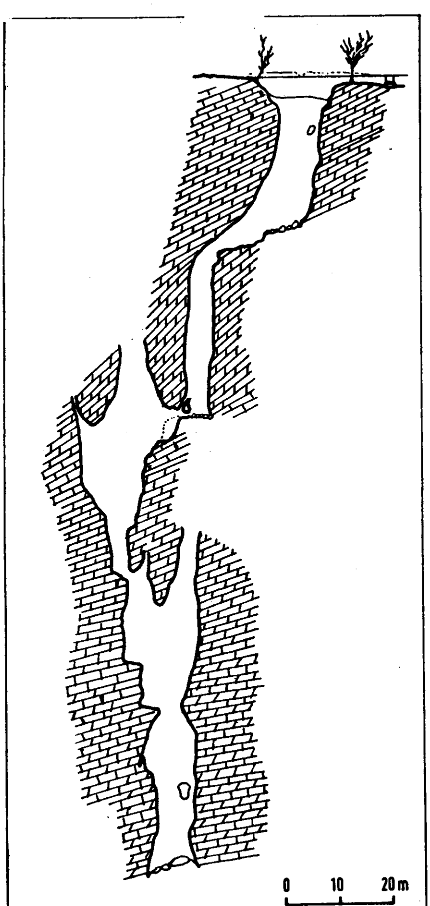


Figure 12.1

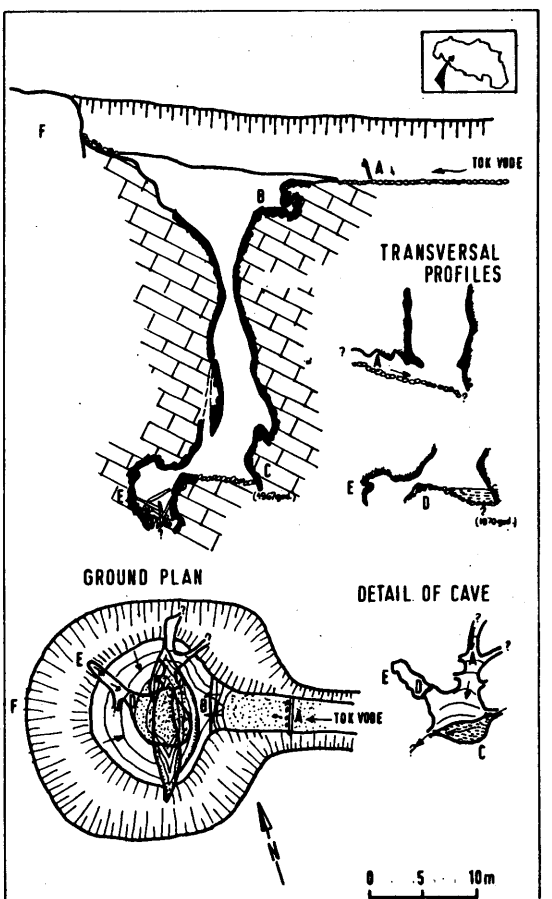


Figure 12.2

13

HYDROGEOLOGIC FEATURES OF SOME KARST PARTS OF SLOVENIA

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REGIONAL PRESENTATION

The field trip is going through Dinaric and Alpine karst of NW Yugoslavia, on the territory of SR Slovenia, bordering on the west to Italy and on the north to Austria. In this region the geologic structure and hydrogeologic units of Dinaric karst become more narrow and northwestwards they disappear under alluvium of Furlania, the Po valley respectively, while on the other side begins alpine karst of Julian Alps, forming a part of Southern Carbonate Alps.

The Kvarner and Koper bay on the Adriatic Sea encompass the low carbonate-flysh plateau of Istria peninsula, which reaches in the northern border of Čičarija its highest peak Učka (1396 m) and then it turns into dry Matarsko and Brgudsko karst valleys. This region with typical morphology of contact and transverse karst is built by fractured folds and imbricate structure of limestone and flysh of Cretaceous and Paleogene age. Northwards, above this 100 - 600 m high Littoral karst, there are plateaus, cones and depressions of High karst (Snežnik 1796 m, Nanos 1313 m, Trnovski gozd 1496 m). Its karstified Mesozoic limestones and dolomites are overthrusted to flysh towards southwest, while on the northern part they are covered by nappe of Triassic carbonates and clastites of prealpine zone and Inner Dinarides. This zone covers Julian Alps (Triglav 2863 m) where in Uppertriassic reef limestone expressive phenomena of Alpine karst developed. The valley of Upper Sava river separates the Julian Alps from Paleozoic and Mesozoic of Karavanke Mts.

The superficial and underground watershed between the Adriatic and Black Sea could be followed from Kvarner bay on the south up to Julian Alps on the north. From Littoral karst the waters flow underground south and westwards to Adriatic Sea. Hydrographic net is composed by several sinking streams, forming morphologically characteristic blind valleys on the border of Eocene flysh and limestones. The biggest sinking river is Notranjska Reka, starting with karst spring of Bistrica and sinking in Skočjan Caves in socalled Classical karst.

The waters from High karst appear in karst springs of Vipava, Hubelj and Lijak, composing together with superficial tributaries the Vipava river, which partly sinks in lower part of the valley near the outlet to river Soča thus enriching the underground waters of the Classical karst.

Headwaters of alpine river Soča are in Julian Alps. Its upper part is fed by Soča and Boka karst springs and partly by karstic Tolminka and Idrijca, its lower part is fed by karst springs of western part of Trnovski gozd, where the most important spring is Mrzlek. Near Gorica Soča leaves the yugoslav territory and near Trbiž (Monfalcone) in Italy empties into Adriatic Sea. The precipitations falling on Julian Alps and High karst are flowing also towards east and north into Sava, Danube tributary. Specially known Sava tributary is karstic Ljubljana, gathering the waters from karst poljes and High karst plateaus among Vrhnika, Cerknica and Postojna. Hydrographic net and Adriatic-Black Sea watershed as well as hydrogeological properties of High karst are adapted to complicated geologic structure of this part of Dinaric karst. In nappe and fracture structures and in limestone, dolomite and clastite blocks marginal, partial and hanging hydrogeological barriers developed, reaching differently deep into the underground. Karstified zones are somewhere shallow, elsewhere deep thus the karst waters are easy to be reached in the karst polje areas and at the karst springs but mostly inaccessible in deep karst.

Typically developed superficial and underground karst phenomena, relatively high humidity (up to 2.500 mm) as well as economic reasons accelerated different hydrogeological investigations. In spite of numerous researches the hydrological systems are not yet well known. Regarding the research methods the direct and indirect underground water tracing is the most estimated. On the treated region the direct (speleological) methods have almost two centuries tradition. The cavers followed the streams, sinking on karst poljes into the underground; in potholes on karst plateaus they searched underground flows and karst streams. They successfully used diving and drilling methods. The gathered data show that the caves in through-flow karst developed mostly on the level of karst rivers; regarding the form and function we can distinguish the caves in three hydrographic zones according to Katzer and Cvijić hypothese.

The zones of shallow and deep karst and corresponding hydrological systems were proved by indirect water tracing methods. In 1910 already these methods were used during hydrological investigations by G. Timeus; he stated the connection of Notranjska Reka with Timavo springs. From 1913 onwards the fluoresceine as a tracer was used on the karst poljes of the High karst for the first time. Among numerous tracing tests we must accentuate a combined water tracing experiment using 13 tracers, achieved in 1975 in the background of Ljubljanica karst springs; the results were treated on the 3rd International symposium on underground water tracing in 1976 in Bled.

NOVOKRAČINE BLIND VALLEY

Above Opatija the relief steeply elevates to 400 m of altitude, passing to dry Brgudsko karst valley, continuing towards NW oriented Matarsko karst valley. In these karst valleys holokarst phenomena developed in form of deep potholes and remains of karst caves with Pleistocene sediments.

On the passage of Eocene flysh to Paleocene and Cretaceous limestones developed several, morphologically charateristic blind valleys. At western and southern border of flysh Brkini there 16 of them, the biggest is blind valley near Novokračine (Fig. 13.1). In blind valleys sinking streams disappear into caves and inclined potholes from where the water flow underground to Kvarner and Koper bay. Anyway this connection is not yet proved by water tracing. The blind valley of Novokračine developed in two levels, ponor cave was surveyed 800 m in length.

ILIRSKA BISTRICA - PIVKA BASIN

From flysh Brkini the waters flow to Rečina, to Brkini sinking streams and to sinking river Notranjska Reka. The valley of Notranjska Reka is morphologically the most expressive, being fed beside the superficial brooks also by karst springs of High karst in Ilirska Bistrica.

Above Ilirska Bistrica there is 200 m high upward step on overthrust contact of High and Littoral karst. Overthrust border goes southwestwards to Pivka, loosing the property of high tableland in Pivka basin, but appearing again at the foot of Nanos (1313 m) and Trnovski gozd 1496 m). The nappe of Mesozoic limestones near the overthrust border is rather thin, flysh basement is inclined synclinely, proved by flysh tectonic window near Knežak and Zagorje. The underground bifurcation between karst tributaries of Notranjska Reka (Bistrica, Podstenjšek) and upper Pivka is connected to this tectonic structure. Eastwards, in region of Snežnik (1500 m) the flysh base deepens, Mesozoic cover becomes more thick; here we find deep cone and dale karst of karst Pivka valley with low eastern border at the foot of Javorniki, characterized by periodical lakes and karst springs and shallow, through-flow karst as far as Postojna. From western flysh border superficial brooks are flowing into Pivka, having torrential character. In Pivka valley the water conditions are very changeable, the low waters flow underground northwards, therefore, specially in summer, the valley is dry, while the high waters flood the surface. Thus drought and floods cause numerous water economic nuisances.

In lower flow Pivka reaches the basin near Postojna. Its meandros river bed passes above Pleistocene alluvium, covering the structural relief in Eocene flysh, Pivka sinks into Postojna cave system.

On the northern border of the Pivka basin there are sinking streams near Strane and Šmihel near Predjama and Belsko disappearing into limestones and dolomites of Hrušica and reappearing in Vipava karst springs. Even on the western part of the basin near Sajevče the brooks from flysh sink into karst of Vremščica and flow underground towards Notranjska Reka. Thus Pivka basin presents a hydrographic roof from where the waters flow towards Adriatic and Black Sea.

POSTOJNA CAVE SYSTEM (Fig. 13.2)

Near Postojna, touristic town with 10.000 inhabitants, Pivka river sinks into karst underground called Postojna Cave System. System is composed by active and fossil ponor channels on the Postojna side (about 14.600 m of surveyed gallieries) and by spring channels in Planina Cave (about 6.000 m of surveyed channels) near Planina polje.

In rich history of speleological investigations the year 1818 is extremely important; in this year the native from Postojna Luka Čeč discovered the upper level of concretioned galleries. With this discovery the modern karst tourism in our places began. Touristic development was accompanied by further development of discoveries and investigations. The first cave plan was composed by A. SCHAFFENRATH (1824), first scientific study about the cave was written by F.v. HOHENWART (1830 - 32). In the period 1850 - 1858 first "hydrogeological" investigations of the underground started. For the first time the Pivka river was followed in the underground (SCHMIDL, 1854), and thus rendered possible for later investigators to know the majority of water channels which were reached by boats (F. KRAUS, 1894; E.A. MARTEL, 1894; A. PERKO, 1910). After hydrological signs they were sure that Pivka reappears on the surface of Planina polje and this was finally proved in 1928 by E. BOEGAN and A. PERKO (use of funghi and fuxines) and definitely by I. AVDAGIĆ, N. PREKA and N. PREKA-LIPOLD (1976); the latter used NaCl and studied the autopurification capacity of Pivka. In the period 1948 - 1959 the further water channels were discovered (I. MICHLER, 1960), between the years 1975 and 1981 the divers successfully passed through several siphons and thus connected some, till now separated, water channels. But all the channels connecting Postojna and Planina part of the underground system are not yet known.

In the last twenty years several new geological, geomorphological, hydrological and speleogenetical properties were studied; thus Postojna cave system can be considered as one of the best studied underground worlds in Dinaric karst.

POSTOJNA CAVES developed in Uppercreataceous, Planina cave in Lower Cretaceous limestones. Accessible ponor channels are situated in southwestern limb and in Postojna anticline crest, while the intraversable siphons and blocked channels in northeastern limb of this fold. The channels mostly developed at bed planes, traversing the strata also at joints and faults. Cave breakdowns are connected to crushed zones as well as to depressions and dolines on the surface. The direction of Planina cave is mostly connected to faults NW-SE and NE-SW directions. Cave system is composed by upper dry galleries, where sediments and flowstones from Middle and Younger Pleistocene are preserved and lower, water channels, with unequal inclination from 3 - 5 %, where Holocene sediments are preserved (R. GOSPODARIČ, 1976). As such sediments are preserved on Pivka basin and Planina polje too, we can conclude, that the cave system developed concordantly with karst poljes on both sides. Postojna cave system is typical for through-flow type of Dinaric karst.

UNDERGROUND PIVKA AND KARST LJUBLJANICA (Fig. 13.3)

The channels of underground Pivka are hydrogeologically the most interesting. At the beginning they are only one kilometer distant from flysh-limestone contact, at Otoška jama they move off this contact and they are oriented northeastwards to Pivka jama. There Pivka river deepens into 25 m deep siphon; on the other side the divers have found only 500 m long section ending by siphon again. From there to inflow siphon in Planina cave Pivka flows in the distance of 2 km altitude difference of 10 m through unknown channels. In Planina cave Pivka bifurcates with waters from Cerknica polje and reaches Planina polje under the name of Unica. From this polje it flows underground to Ljubljanica springs.

Pivka underground channels have several siphons and roof-falls, where the water is dammed, when it is high. Limited permeability of the channels causes before the cave and in the Pivka basin frequent, short-lasting floods. One of more important water economic problems is the abolition of these floods.

ŠKOCJANSKE JAME AND DIVAČA KARST

Among the folds of Eocene flysh of Brkini and Vipava valley the anticline of Uppercretaceous and Paleocene limestones of Trst and Komen outcropped, named Classical Karst. This is rocky pavement without superficial flows, with numerous karst caves and underground water flows. From there the name "Kras" spread all over the world, designing the regions with similar morphological and hydrogeological properties (Fig. 13.4).

The greatest natural curiosity of this classical Karst are the Caves of Škocjan near Divača (length 5.100 m, depth 352 m). Beside speleological and karstological importance these caves have important cultural-historical, touristic-economical and water economical importance. In hydrogeological point of view the Skocjan caves with vicinity present a typical example of deep, contact karst, where superficial streams sink into carbonate rocks. In our case Notranjska Reka sinks, gathering the superficial and partly karst waters from High Karst and Brkini having 1 m^3/s of minimal and up to 200 m^3/s of maximal discharge. It belongs to the biggest sinking streams in the world.

Until Notranjska Reka flows on the flysh it has a normal relief and about 3 % inclined river bed, on the limestones in the canyon with almost 100 m high walls the inclination is 4,5 ‰. The Reka canyon continues from the ponor (325 m) almost 2,5 km far in the underground westwards to the final siphon (173 m) the underground river bed is inclined for 6,3 ‰. At minimal discharge all the greatness of the underground can be seen, at maximal discharge the water floods the underground canyon to the roof. Notranjska Reka was traced in the Timavo springs near Devin (Duino) in Trieste bay by the help of marked eels and HCl in 1910, and in 1962 by tritium and fluoresceine. By speleological investigations its flow was discovered under the surface of Classical Karst in Kačna jama (length 8.500 km, depth 330 m) and in Labodnica (depth 329 m).

Speleogenetical studies showed that in Škocjanske jame there are several fossil water channels being active in Pleistocene. The weathering of these levels and origin of big collapse dolines is connected mostly by deepening of ponor channels in Würm glacial and Holocene. Karst surface above the cave is composed by remnants of normal relief from Pliocene and older Quaternary when the precursor of Notranjska Reka flowed on the surface northwards.

LIPICA

The settlement Lipica belongs to important natural and touristic curiosity of Classical Karst. In green grass oasis with numerous, hundred years old oak-trees, a special species of white horses - lipizaner is grown and bred for 400 years already. Favourable natural conditions for breeding of Lipica horses are given by relatively thick and permanently humid soil above less karstified Paleogene limestones. They cover Senonian limestones, which are very karstified. Among superficial karst phenomena we know the entrances to several deep potholes and long karst caves (f.e. Lipiško brezno, Vilenica and other caves). In Senonian limestone here and there are thicker layers of reef limestone with numerous rudists remnants. The rock is convenient for freestone being exploitated in the near quarry.

In morphological point of view the levelled surface of Lipica presents a composing part of Nabrežina valley, geologically it belongs to Brkini-Reka sinkline. As elsewhere on Classical Karst the lack of water is felt here too. At first the water supply was connected to precipitation water and numerous pools, now the settlement has its regional water supply.

KARST GROUNDWATER NEAR BRESTOVICA

The lack of drinking-water on Classical Karst accelerated the hydrogeological investigations in geologically favourable structures. The karst area among Sezana, Komen, and Brestovica (NW part of Dinaric karst) was studied in the last time. In Uppercretaceous limestones, encompassed by impermeable flysh and Uppercretaceous dolomite and alluvium of Furlania it was expected to find accumulated allothonous and autothonous karst water.

By universal geologic studies were located several bore-holes, deep from 70 - 190 m; water levels were observed in them and testing pumping was achieved. The results showed that hydrological system developed in heterogeneous karst aquifers, composed by drainage zones (water caves, open joints and different underground channels) with big transmissivity ($T > 10^{-2}\ m^2/s^{-1}$) and small storage and fractured blocks with small transmissivity ($T < 10^{-5}\ m^2/s^{-1}$) and bigger water storage (P. KRIVIC, F. DROBNE, 1980). This hydrogeological structure is connected to lithological and tectonical composition of Uppercretaceous limestones, while their different karstification in depth to geomorphological development of this extreme NW part of Dinaric karst.

The bore-holes and pumping tests were extremely successful near Brestovica where from the drilled well, the water was pumped not lowering the groundwater level essentially. The oscillations are influenced mostly by ebb tide and flood tide of the near Adriatic coast. Pumped water is composed by allothonous and autothonous water, not knowing their mutual rate. Allothonous water probably flow from Vipava and Soča, these waters partly sink in the northern part of this karst and flow under it to Adriatic Sea.

MRZLEK KARST SPRINGS

At the foot of high karst among Idrijca, Soča and Vipava rivers there are important karst springs (Vipava, Hubelj, Lijak, Divje jezero - Podroteja) caught for water supply of near lying settlements. Regarding traffic and density of population the catchment area of Mrzlek is the most exposed. The waters from Banjška planota and Trnovski gozd are flowing in it. This region is built by Mesozoic limestones and dolomites and by Eocene and Cretaceous flysh. Permeable and impermeable rock belong to Trnovo nappe, over-thrusted to impermeable flysh base, representing on the border of karstified rocks the impermeable dam. The rocks are crushed and faulted in Dinaric and transverse direction as well as in the direction north-south. Crushed zones are more favourable for underground water flows, hence there the majority of permanent and periodical karst springs occurs. From impermeable surface the waters flow in smaller sinking streams (P. HABIČ, 1982).

In the autumn 1980 water tracing test with 20 kg of Uranine was carried out in Čepovan brook (595 m). Mrzlek karst springs are distributed on the distance of 400 m on the both banks of Šoca river in tight canyon between Skalnica (683 m) and Sabotin (610 m). The water takes its springs in fissures of Uppercretaceous limestones on 18 points, two important springs are on the right, and two on the left bank. The water level oscillates for 13 m according to Soča level but also independently on the river between 57 and 70 m. Regarding the temperatures (8 - 10°C), chemical composition (130 - 150 mg/l $CaCO_3$) and isotopic analyses was stated that water of river Soča and karst water in springs does not mix. By construction of hydroelectric plant Solkan the springs and water supply catchment will be flooded up to Hill 77, while the consequences on water regime can not be foreseen. Heavy rain followed longer dry period and superficial and underground waters quickly augmented. The dye appeared in low concentrations in springs along Soča near Mrzlek, partly near Avšček and Idrija too. It means that Čepovan brook flows in three different ways, northwards to Hotešk, westwards to Avšček and southwards to Mrzlek.

Low discharge and great dilution represent the most important characteristic of this water tracing. The runoff into three different directions is dependent upon geotectonic structure and upon the way of transfuse in this karst after extremely heavy rain. The majority of karst water flows southwards. Smaller permanent springs on the northern and western side of Banjška planota have their own background from where a part of water flows into periodical effluents. Detailed hydrological deliminations between springs and effluents have to be proved by further water tracing tests.
The mixture of underground runoff from different parts of Banjška planota and the orientation of greater part of this water towards Mrzlek spring require special measurements on the whole region for the quality protection of this important water source near Gorica.

KARST SPRING BOKA IN SOČA RIVER VALLEY

The route follows the alpine valley of Soča upwards through tectonic basins of Tolmin, Kobarid, and Bovec. From Bovec and Trenta valley the itinerary reaches the pass Vršič and goes on the other side to Sava Dolinka valley. Following this valley, between Karavanke Mts. on the north and Julian Alps on the south, we reach town Jesenice, later Bled and afterwards Ljubljana basin.

Canyon-like Soča river bed passes near Tolmin into wide alpine valley, surrounded by Krn Mts. (2245 m) on northeastern side and Matajur Mts. (1641 m) on southwestern side. Tectonic valley is covered by differently thick quaternary sediments of glacial, fluvio-glacial and fluvial origin. Near Kobarid Soča is deeply cut in rocky bottom and in the slopes of Krn Mts., otherwise it has up to Bovec (450 m) meandrous river bed in quaternary sediments.
The upper part of Soča valley as well as its tributaries Zadnjica, Trenta and Koritnica lies among the highest peaks of Julian Alps, where high mountainous alpine karst predominates. This one is geologically, morphologically and hydrologically different from Dinaric karst. In Alps bare karst developed, with mostly vertical forms of karstification (grooves, kettles) and simple outflow hydrographic system. The underground runoff of abundant precipitations (more than 3.000 mm, up to 6 m of snow) is adapted to overthrust and faulted structure of Julian Alps. Upper Triassic limestones and dolomites are several times thrusted southwards to Jurassic and Cretaceous clastic rocks. Karst waters spring in glacially deepened valleys and reach the surface through the gravel and scree. The springs are differently high in limestone walls of these valleys. The most significant among them is the karst spring of Boka not far from Bovec taking the waters from a part of high plateau of Kanin Mts. (2.585 m). The waters from Kanin Mts. flow also to abundant spring Glijun

near Bovec. In the Trenta valley above Bovec is the main Soča karst spring, obtaining the waters from Jalovec (2.643 m) and Mojstrovka (2.332 m). On the Vršič pass (1.611 m) where we cross the watershed between Adriatic and Black Sea the view to Julian Alps is excellent; we can see Triglav (2.863 m), the highest peak in Yugoslavia, and also all the other mountain chains of the Eastern Alps.

BLED

The field trip ends on Bled, well known touristic town of Slovenia. The town has numerous historical and archaeological curiosities and extraordinary natural position. It lies around beautiful lake (1.33 km^2 of surface, 2.1 km long, 1.3 km wide, 80 m deep) developed after the retreat of the glacier; the glacier extended from the Alps up to the Radovljica basin.

The landscape shows glacial relief forms, morraines and terraces of glacial and fluvioglacial sediments. Epigenetic valleys of Sava and its tributaries are cut into the terraces. These valleys rendered possible the construction of hydroelectric plants, f.e. Moste near Medvode.

The lake of Bled has modest inflow of fresh water and biologically it is dying out also because of touristic exploitation. In last time the pipette method is used in order to revitalize and preserve the lake.

FIGURES

13.1. Novokračine blind valley. 1 - rocky boundary with alluvions; 2 - doline; 3 - cave; 4 - dry valley; 5 - flysh surface; 6 - border limestone surface.

13.2. Schematic review of Ljubljanica Karst River Basin (after R. Gospodarič and P. Habič, 1976). 1 - important gauging stations and sinking streams; 2 - karst polje with sediments; 3 - central hydrogeologic relative barrier; 4 - intake area of permanent karst spring; 5 - periodic high water discharges of karst water; 6 - underground water connections; 7 - surface stream with spring and ponors; 8 - surface watershed; 9 - supposed karst watershed.

13.3. Postojna Karst geologic sections with Postojna Cave System drawn in (from R. Gospodarič, 1976).

13.4. Škocjanske jame and Divača Karst (after P. Habič, 1972). I-V - morphologic terraces; 1 - underground channel; 2 + 3 - canyon with pocket valley; 4 + 5 + 6 - collapse dolines and depressions; 7 + 8 - caves.

13.5. Mrzlek Karst Springs in Soča River bed (from Acta carstologica, 1982).

13.6. Banjšcice Plateau hydrogeologic sketch (from Acta carstologica, 1982). 1 - superficial watershed; 2 - partly superficial watershed; 3 - hydrogeologic watershed; 4 - underground karst watershed under hanging barrier; 5 - karst watershed; 6 - semipermeable, relative barrier; 7 - hanging barrier, unpermeable; 8 - Mrzlek catchment area; 9 - karst spring; 10 - temporary karst spring; 11 - sink in river.

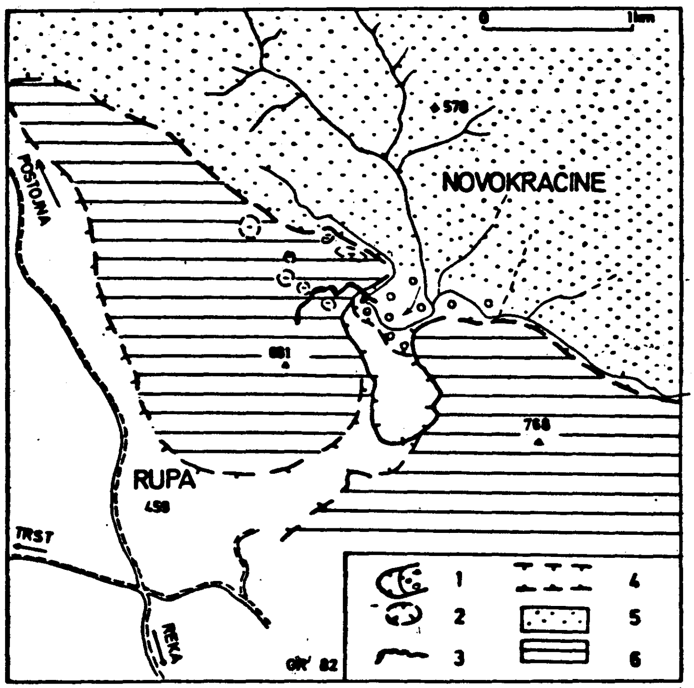


Figure 13.1

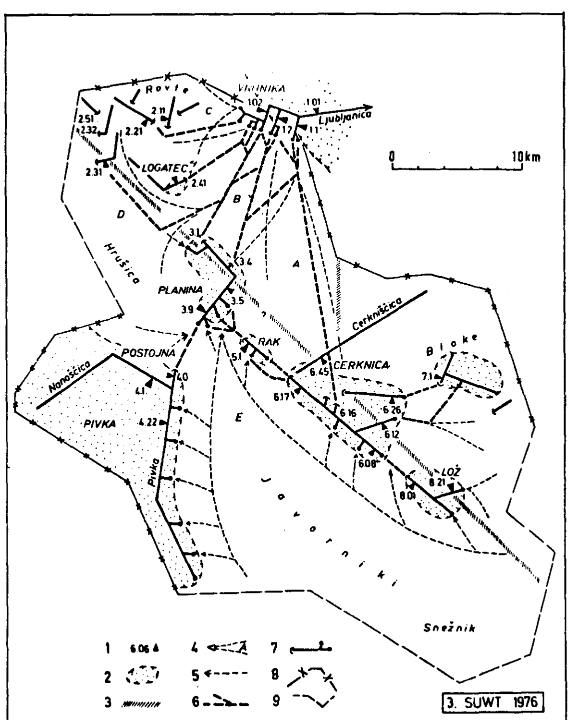


Figure 13.2

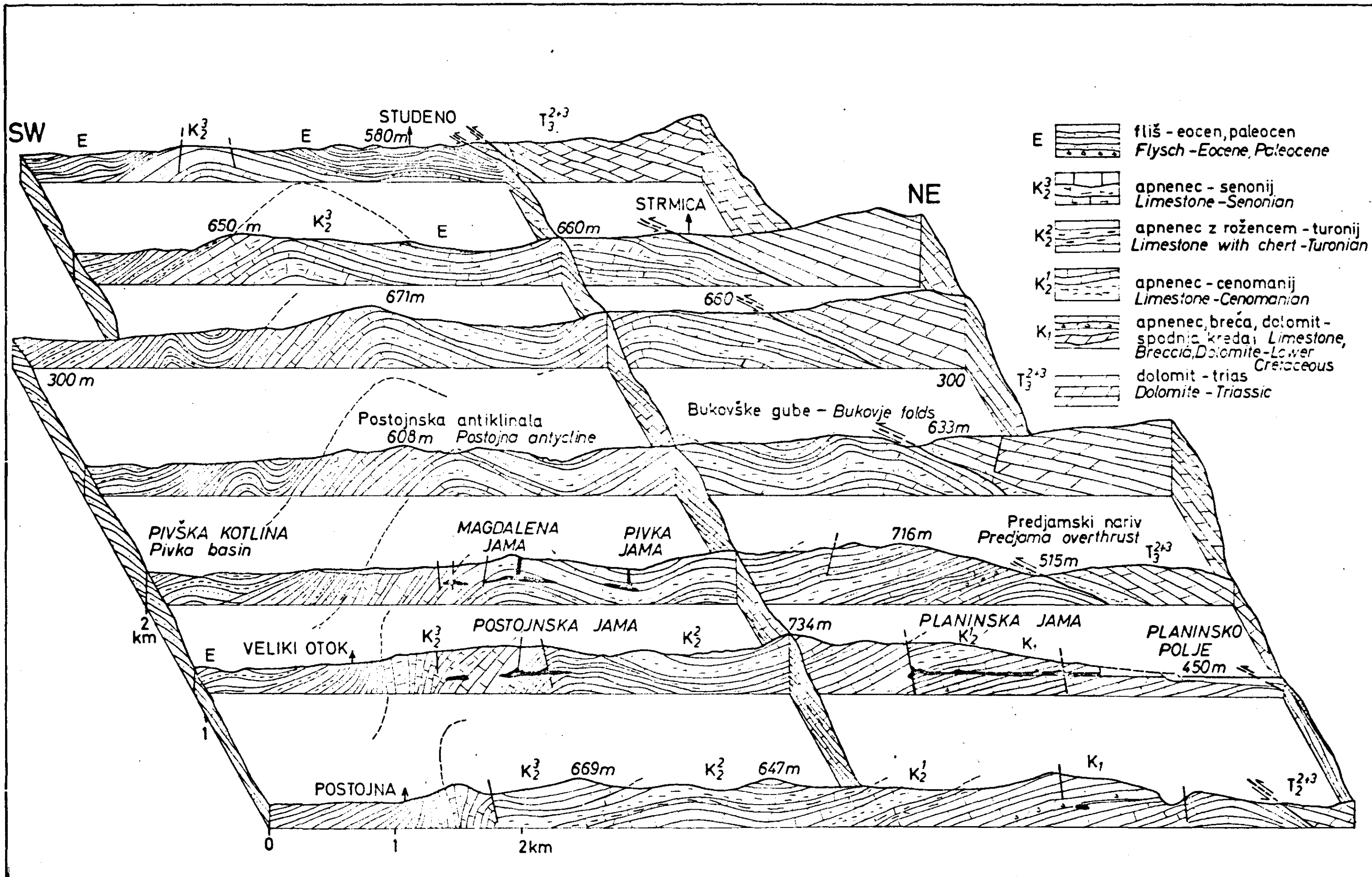

SW
NE
STUDENO
580m
STRMICA
660m
650 m
671m
660
300 m
300
Postojnska antiklinala
608m Postojna antycline
Bukovške gube – Bukovje folds
633m
PIVŠKA KOTLINA
Pivka basin
MAGDALENA JAMA
PIVKA JAMA
716m
Predjamski nariv
Predjama overthrust
515m
VELIKI OTOK
POSTOJNSKA JAMA
734m
PLANINSKA JAMA
PLANINSKO POLJE
450m
POSTOJNA
669m
647m
0
1
2km
2 km
fliš - eocen, paleocen
Flysch - Eocene, Paleocene
apnenec - senonij
Limestone - Senonian
apnenec z rožencem - turonij
Limestone with chert - Turonian
apnenec - cenomanij
Limestone - Cenomanian
apnenec, breča, dolomit - spodnja kreda
Limestone, Breccia, Dolomite - Lower Cretaceous
dolomit - trias
Dolomite - Triassic

Figure 13.3

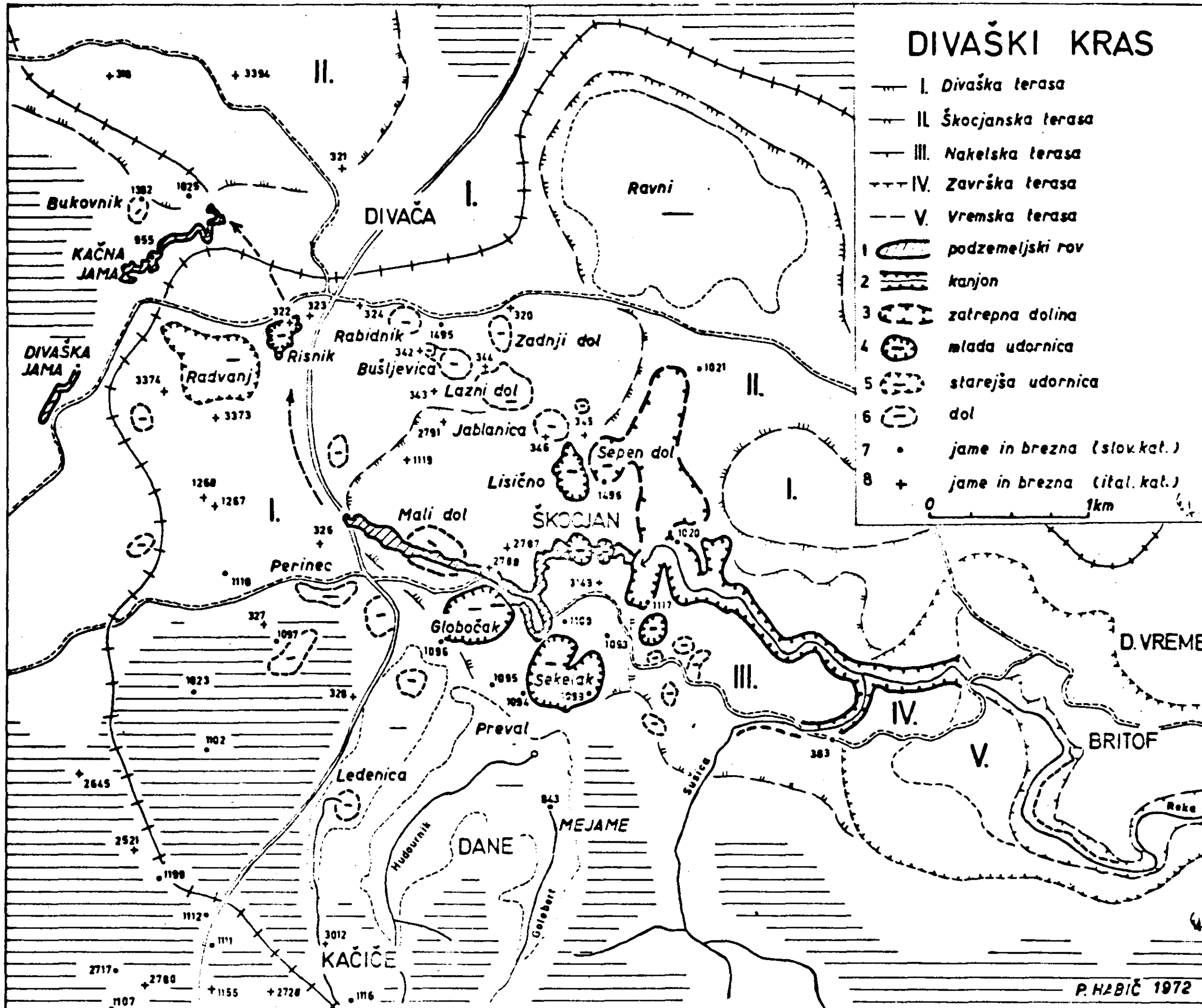

DIVAŠKI KRAS
I. Divaška terasa
II. Škocjanska terasa
III. Nakelska terasa
IV. Završka terasa
V. Vremska terasa
1 podzemeljski rov
2 kanjon
3 zatrepna dolina
4 mlada udornica
5 starejša udornica
6 dol
7 jame in brezna (slov. kat.)
8 jame in brezna (ital. kat.)
0 1km
Bukovnik
KAČNA JAMA
DIVAŠKA JAMA
DIVAČA
Ravni
Radvanj
Risnik
Rabidnik
Bušljevica
Zadnji dol
Lazni dol
Jablanica
Sepen dol
Lisično
ŠKOCJAN
Mali dol
Perinec
Globočak
Sekelak
Preval
Ledenica
DANE
MEJAME
Hudournik
Golobort
Sušica
KAČIČE
D. VREME
BRITOF
Reka
P. HABIČ 1972

Figure 13.4

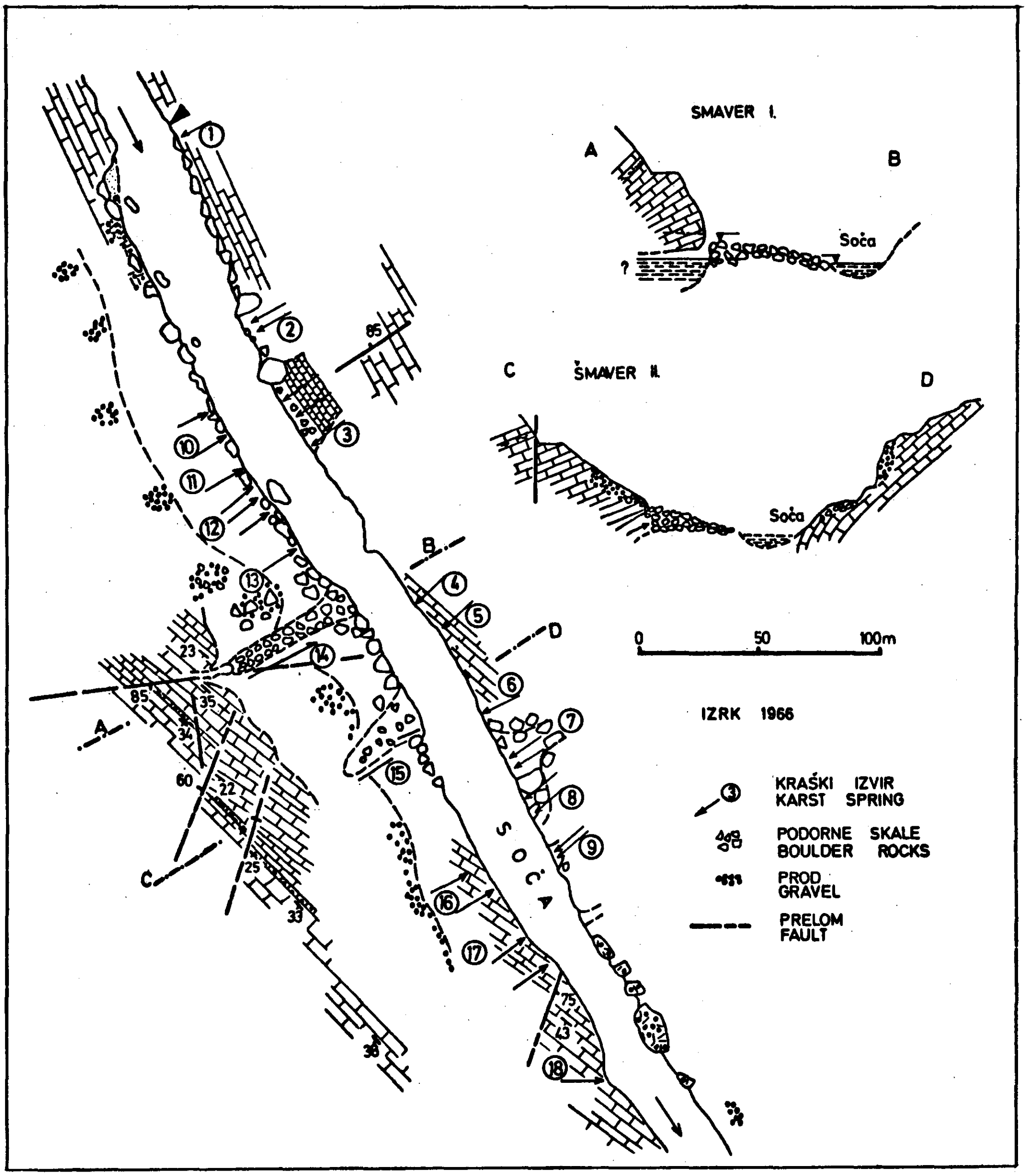

SMAVER I.
A
B
Soča
?
C
ŠMAVER II.
D
Soča
0
50
100m
IZRK 1966
KRAŠKI IZVIR
KARST SPRING
PODORNE SKALE
BOULDER ROCKS
PROD
GRAVEL
PRELOM
FAULT
SOČA

Figure 13.5

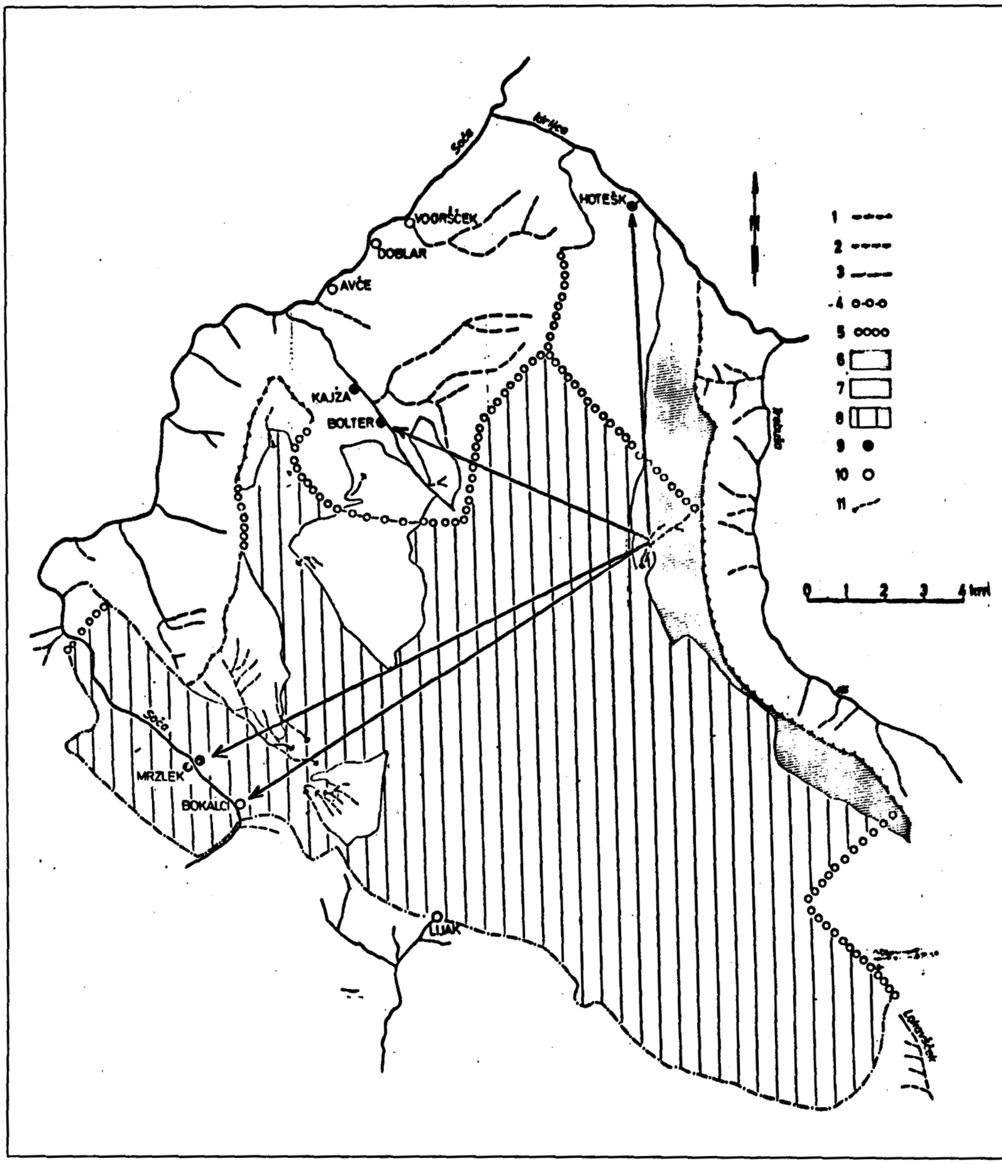
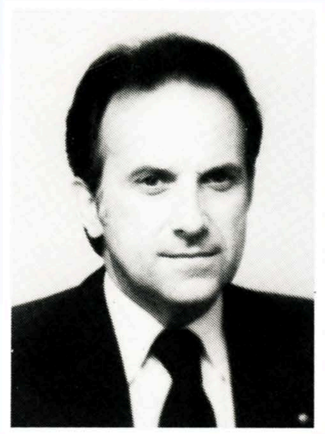

Soča
HOTEŠK
VOGRŠČEK
DOBLAR
AVČE
KAJŽA
BOLTER
MRZLEK
BOKALCI
LIJAK
0 1 2 3 4 km

Figure 13.6



Borivoje F. Mijatović

The Dinaric limestone mountains situated along the Adriatic coast of Yugoslavia are one of the „classical square miles“ for the hydrogeological research of karstic terrains. Since 1970 the International Association of Hydrogeologists (IAH) maintains a scientific commission which concerns itself intensively with the problems of the hydrogeology of karstic terrains (see Volume 1 of the book series „International Contributions to Hydrogeology“).

In May 1983 the National Committee of the IAH in Yugoslavia invited interested persons to take part in a two weeks' excursion. Scientists and engineers in Yugoslavia have presented the ways of thinking, methods and results of their research work to the participants of the excursion in a book comprising 13 chapters.

The IAH takes the view that the Excursion Guide should be made accessible to a larger group of geoscientists in a concise form. Perhaps this book will be an incentive to take a close look at the Dinaric mountains as well as their extraordinary karstic phenomena the problems of which have not yet been solved in all their details.

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