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The Morphogenesis of Submarine Springs in the Bay of Kaštela, Croatia

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Key words: Submarine spring (vrulja), Morphogenesis, Hanging barrier, Coastal karst spring, Adriatic Sea, Croatia.

Abstract

Offshore, in the Bay of Kaštela, karst groundwater, which initially flowed under a hanging karst barrier, flows out from two submarine springs. The water flows from fissures enlarged by corrosion and erosion at sites that were previously coastal karst springs. They were submerged due to sea level rise at least 7,000 years ago and, since that time, they function as submarine springs, at about 32-35 m below sea level.

1. INTRODUCTION

In the Bay of Kaštela, which extends between Split and Trogir, two submarine springs (or *vruljas* - as such water phenomena are called in the Croatian Adriatic coast) occur (Fig. 1). The submarine spring Arbanija is about 800 m and the Slatina about 3200 m from the mainland. The data on their depth differ. After ALFIREVIĆ (1960), the both submarine springs discharge from the bottoms of doline-like depressions: Arbanija at 35 m and Slatina 32 m below sea level. BREZNIK (1973) mentioned that the Arbanija is at 32 m and the Slatina at 39 m depth. Both authors concur that the Kaštela Bay bottom around the submarine springs is mainly flat and about 15 m below sea level. The depth differences of the submarine springs (-32, -35, and -39 m) are unimportant in the interpretation of submarine spring morphogenesis, therefore, Alfirević's measured data (Breznik did not measure them; pers. comm.) will be used in continuation.

The submarine springs are intermittent and, in the winter, they are of a large size, and thus probably have large discharge rates. ALFIREVIĆ (1966) observed the activity of these submarine springs once a month during the hydrological year 1963-64 and states that they became active between 20 November and 18 December 1963 and ceased to discharge between 16 April and 18 May 1964. During a wet period, the author recorded a sea water sink into the submarine spring Arbanija and required this to be confirmed by tracing (ALFIREVIĆ, 1969). The endeavour was not successful due to poor visibility and a low sink rate. Furthermore, with regard to the submarine spring activity, he concludes that "two time periods can be sharply distinguished: the winter period including the late autumn and early spring and the summer period with the late spring and early autumn". ALFIREVIĆ (1966) also states that the surface water is warmer than the bottom water during winter activity (the coldest water was that from the Arbanija, measured in February, at 10.6°C), which is the converse situation to that of the surrounding sea water. In the summer, during the submarine spring "rest" (i.e. inactivity), the temperature of the submarine spring water equals that of the surrounding sea (in the Arbanija, the maximum in September was 24.4°C). These two periods can also be differentiated in terms of salinity. During the winter, the sea has a normal salinity distribution (the surface water is less saline and the emerged groundwater more saline) while the submarine spring water has the opposite situation. Low salinity values cause the appearance of frost in the central part of the Kaštela Bay when special meteorological conditions occur. In general, sea water is more saline during the summer than in the winter.

In September 1971, Alfirević succeeded in confirming the water sink in the Arbanija submarine spring (MIJATOVIĆ, pers. comm. 1972). 20 kg of sodium fluorescein was used on that occasion and it gradually disappeared into the submarine spring. It was proof that this submarine spring is also a ponor (swallow hole), i.e. that it is an estavelle.

2. GEOLOGICAL AND PALAEOGEOGRAPHIC EVENTS

A large volume of fresh water flows out from the mentioned submarine springs which, no doubt, is karst groundwater derived from the hinterland (Fig. 1). Since the whole coast and a part of the offshore Bay of Kaštela is composed of impermeable Eocene flysch deposits, overlain by a permeable Cretaceous-Palaeogene carbonate complex, the flysch deposits provide a hydrogeological barrier for mainland karst groundwater. Therefore, the groundwater, on its way to the submarine

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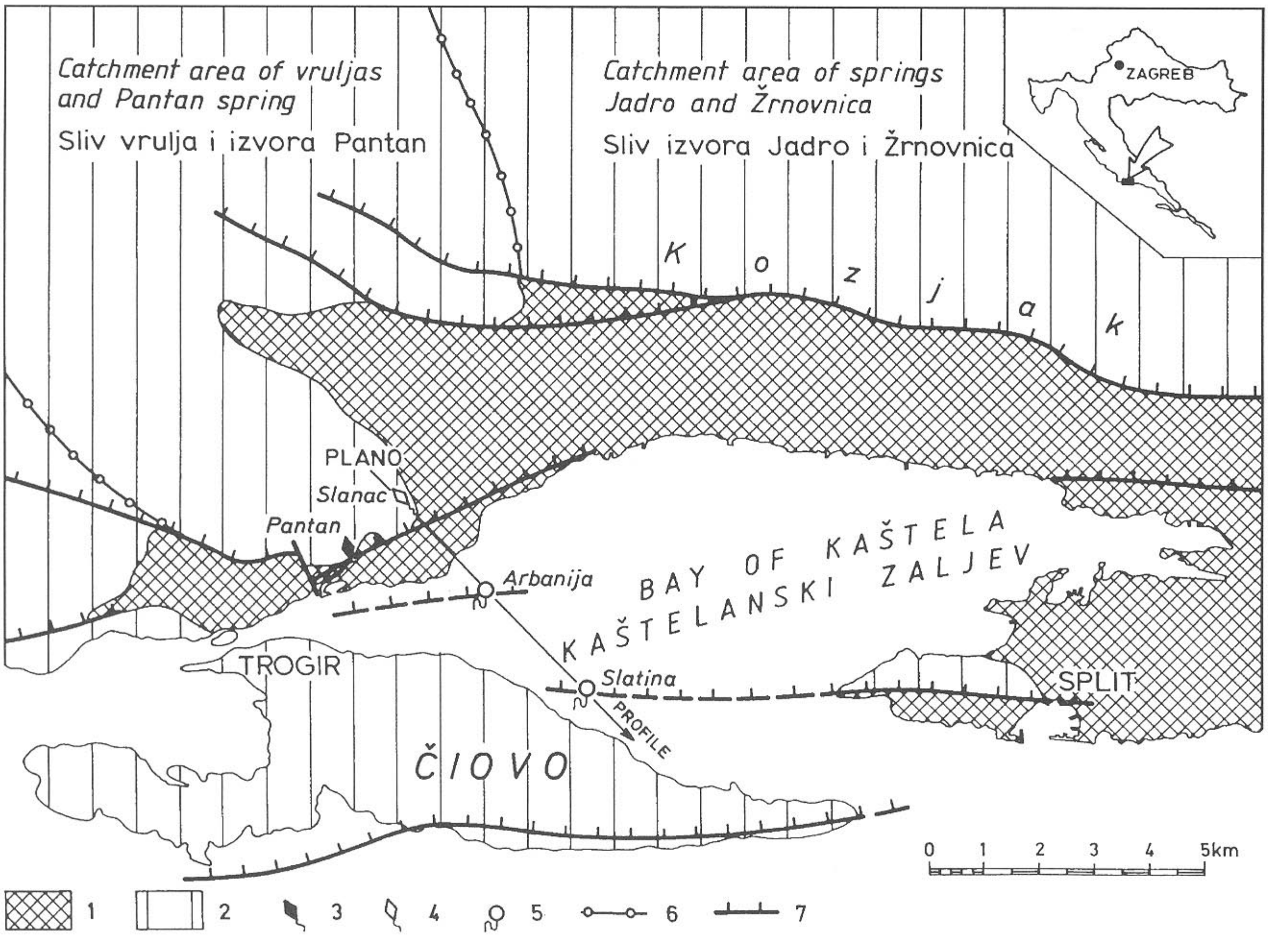

Fig. 1 Hydrogeological map of the Bay of Kaštela, Southern Croatia. Legend: 1) impermeable rocks (Eocene flysch); 2) permeable Cretaceous-Palaeogene carbonate rocks; 3) brackish spring, permanent; 4) brackish spring, intermittent; 5) submarine spring; 6) watershed; 7) major reverse fault.

springs, must pass beneath those impermeable rocks (Figs. 1 and 2). The barrier in one part does not extend deeply enough underground and forms a "hanging" barrier. From this point laterally, the flysch deposits have function of a true (entire) barrier. Under these conditions, a large volume of karst groundwater, partly retarded by flysch deposits in the western part of the Bay of Kaštela, is drained towards the hanging hydrogeological barrier. Taking into account the present groundwater discharge from the drainage basin Pantan-Slanac-submarine springs, on average from 1- >30 m^3/s of brackish water flowed out from these submarine springs (FRITZ et al., 1993). Were earlier precipitation more abundant, even greater rates of submarine spring discharges may be assumed.

If the origin of these submarine springs is considered, we have to return to not too far past, to the period between the last glacial stage and the present conditions in the areas where karst groundwater had hydrogeologically open pass towards its erosional base - towards the sea. As a rule, with some exceptions caused by local hydrogeological conditions, the sea level is the erosional basis for karst groundwater and, below it, there is no recent karstification that would penetrate toward greater depths. Under such conditions, the karst springs of Würm glacial age were mainly coastal brackish springs as are the present springs. Meanwhile, the altitude of the erosional base has changed due to the influence of sea level fluctuations (eustatic changes) and/or because of tectonic movement of the land surface. It refers primordially to the question of whether the present erosional basis is also the karstification basis or it is situated in an already karstified medium. Since we have no more accurate data about neotectonic movements in this region, we shall accept the known and wide acknowledged data presented by ŠEGOTA (1962, 1968) and ŠEGOTA & FILIPČIĆ (1991) on sea level fluctuation from the Würm till the recent time, which states that all the old coastal springs would have been submerged, becoming submarine springs due to a global sea level rise between the Würm and approximately 1,000 years ago. This resulted in a gradual migration of the submarine springs in the direction of the present coastline.

As a result of the hydrogeological conditions in karst terrains, the sea level change (coastal movement, or rather the movement of the erosional base) is always accompanied by the appearance of new coastal springs. From a primordial spring, several hydraulically connected submarine springs could have been formed, as well as the coastal spring occurring at the present coast.

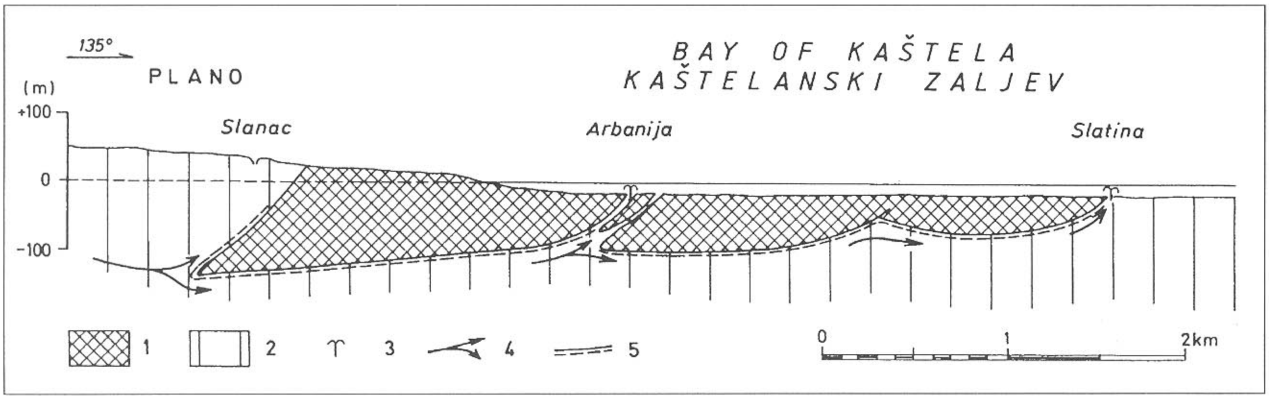

Fig. 2 Schematic hydrogeological cross section. Legend: 1) impermeable rocks (Eocene flysch); 2) permeable Cretaceous-Palaeogene rocks; 3) submarine spring; 4) assumed groundwater flow direction during rainy season; 5) assumed position of the boundary between flysch and limestones.

Therefore, the most distant submarine springs gradually become inactive or are intermittently active, during the maximal rates of mainland water flow. This is the reason why most present submarine springs are situated relatively near the present coastline, and also why a small number of them are permanently active and why the largest portion of karst groundwater flowing from the mainland hinterland during dry seasons does not emerge from submarine springs but along the coastline, from brackish coastal springs.

The submarine springs in the Bay of Kaštela differ considerably from the described scheme of the appearance of Croatian submarine springs because their position has not changed during the Holocene. Such a fact, in the genesis of karst phenomena, is not surprising in this area as the result of the described hydrogeological conditions including especially the groundwater flow towards the considered submarine springs (Fig. 2). The submarine spring Arbanija occurs as close to the mainland as is at all possible. It appears in the boundary zone between permeable carbonate and impermeable flysch deposits, even within marginal Eocene flysch deposits (ALFIREVIĆ, 1966). The submarine spring Slatina is about 3500 m from the mainland. It is, according to the available data, the most distant Adriatic submarine spring to which groundwater flows from the mainland. The true situation is probably more complex, particularly in the zone between the Arbanija and Slatina submarine springs, but we do not have more detailed data on the hydrogeology of this part of the study area.

The reconstruction of sea level fluctuations, as mentioned above, indicates that the beginning of the recent sea level rise occurred after the last glacial stage, some 25,000 years ago, and it has risen approximately 96 m (ŠEGOTA, 1968). The spot altitudes where water emerges from the submarine springs are -35 or -32 m (Arbanija) and -32 or -39 m (Slatina) after ALFIREVIĆ (1966) nad BREZNIK (1973). This indicates that both submarine springs were formed after the last glacial stage, i.e. during the first part of the last 25,000 years, or 10,000 - 11,000 years ago according to ŠEGOTA (1968). Since then, this area has been submerged and these submarine springs have definitely been formed from older springs.

The springs, which preceded the present submarine springs, ceased to function over two time periods in the Bay of Kaštela. The first period is related to the Riss glacial stage, i.e. to the penultimate fall of the global sea level, between 200,000 and 110,000 years before the present time, when the sea level fell to the deepest position, to -110 m below the present level. If the present submarine springs were formed during the penultimate glacial, i.e. between about 200,000 and 110,000 years ago, when they were already submarine springs this could have occurred between 11,000 and 75,000 years ago. That is to say, then the sea level was higher than their surface sites, and the highest elevation (+17 m) was reached about 96,700 years ago. In this case, the Bay of Kaštela depression and the area where the present submarine spring occur would have twice been an erosional basis for the karstification of the present drainage basin of the neighbouring springs Pantan and Slanac and the submarine springs Arbanija and Slatina (Fig. 1).

The second period is related to the Würm glacial stage, i.e. to the last sea-level fall below the spring site, or below the site of the present submarine springs (about 75,000 years ago). Since then, the most intensive erosion-corrosion processes, or optimal climatic conditions for the development of springs within the palaeodepression of the Bay of Kaštela occurred after the lowest sea level position (96.4 m below the present sea level occurred some 25,000 years ago) untill the submergence of the springs, 10,000 to 11,000 years ago, i.e. during the latest Pleistocene. The transformation of springs into submarine springs coincide approximately with the beginning of the Early Holocene, when the climatic conditions became relatively calm. With the gradual sea-level rise (i.e. the erosional base for the neighbouring karst groundwater) the groundwater table within the carbonate hinterland also gradually rose. This resulted with ever longer siphonal groundwater flow paths to the submarine springs. As a result of further sea-level rise, karst groundwater began to flow out on the land itself, at the upstream side of the hanging barrier, first from the Pantan spring and later from the Slanac spring (Fig. 1).

The submarine spring activity decreases with the recent sea-level rise and karst groundwater begins to flow out at increasing rates from higher altitudes, e.g. from the Pantan spring. The submarine springs are nowadays active only during the rainy season and the Pantan spring has become a significant permanent karst brackish spring. During dry seasons, as mentioned above, the submarine spring Arbanija even draws in sea water, so this water phenomenon is in fact a submarine estavelle (brackish water flows out during the winter while sea water sinks into it during the summer). This term, a submarine estavelle, has not yet been used in the literature; it has been known only as the submarine spring Arbanija.

The questions of whether the submarine springs in the Bay of Kaštela have been active during one or two periods of time, and whether the groundwater conduits towards these submarine springs were karstified during one or two cycles, have not been resolved. The appearance of submarine springs in the Bay of Kaštela at only two sites, and the appearance of younger springs at the contact between impermeable and permeable rocks at the "upstream" part of the barrier also at only two sites (the Pantan spring at the altitude of 2.7 m above sea level and the intermittent spring Slanac even about 30 m above sea level), together with a relatively low sea-level elevation (+17 m) suggests that the water conduits towards the submarine springs were developed during the second part of time period which began about 75,000 years ago. The most intensive karstification period occurred between about 25,000 and 10,000 years ago, at the end of the Pleistocene. During this time, only the karst springs at the present submarine spring sites were active. According to the concept that the submarine springs are active only from the last sea-level fall, they then became active by the beginning of the Holocene and are of Holocene age. Such a conclusion is in accord with the idea that the karstification cycle from the end of the Pleistocene and its continuation within the Holocene is related to the development of groundwater flow conduits towards the present karst springs and that the present relief was formed during this period (BAHUN & FRITZ, 1987; FRITZ, 1991, 1992).

3. THE MORPHOGENESIS OF SUBMARINE SPRINGS AND THEIR DEVELOPMENT

The morphology and geology of the area where the submarine springs appear has been studied by ALFIREVIĆ (1966, 1969). He writes that the morphologic aspect of submarine springs coincide with the fossil ponikvas (dolines, sinkholes) formed during the continental phases of the littoral Dinaric Karst and that the submerged submarine springs, according to their lithological and micropaleontological composition, occur within Eocene marly limestones which, according to their geological structure, coincide with the flysch syncline of the Bay of Kaštela. Furthermore, the author writes that the divers recorded "the rocky edge of a conical depression" i.e. the existence of the funnel of a compact lithological composition (1969, p. 189).

Further exploration has not been performed, thus, according to the mentioned data, the "ponikvas", from where the submarine springs emerge, should occur within flysch deposits. It would be exceptional for the submarine springs to appear out of calcareous-dolomitic rocks. Our opinion is that there are interlayers of calcareous rocks, close to the considered submarine springs, through which groundwater flows from the hinterland, beneath the impermeable rocks, to the springs or submarine springs, i.e. that the submarine springs occur within the contact zone of impermeable calcareous and impermeable flysch deposits. The impermeable rocks comprise the whole area between the submarine spring Arbanija (at the village of Divulje) and the springs Slanac and Pantan (Figs. 1 and 2). It is not important whether the final conduits to the submarine springs occur in limestones of the Cretaceous-Palaeogene complex or calcareous breccias which are a constituent of flysch. In the both cases, the flow of water towards the springs (submarine springs) is siphonal and it passes through calcareous rocks. The submarine spring water flows out, as also from most karst coastal springs in the Adriatic littoral, mostly along a reverse or thrust contact of permeable and impermeable rocks, probably from a calcareous interlayer within, in general, impermeable flysch deposits.

Within our concept of the origin of submarine springs in the Adriatic sea, as described above, the submarine springs are submerged earlier karst coastal springs. From that point of view, the depths of submarine springs: -32 m and -35 m (after ALFIREVIĆ, 1966) and even -39 m and -32 m (after BREZNIK, 1973) have to be analyzed taking into account the present depths of the bottom of the Bay of Kaštela, 15 m below sea level, because the former springs were definitely submerged only when the Bay of Kaštela bottom was submerged. Therefore, the dilemma of the depth of these submarine springs should be resolved by the assumption that the former springs were at the level of palaeorelief, i.e. at the contemporaneous level of the Bay of Kaštela bottom, naturally without the sediments deposited later. Therefore, it should be said that a submarine spring is a spot at the sea bottom from where permanently or intermittently fresh or brackish water flows out, as it happens in brackish coastal springs in the mainland. Thus, it is not important how deep a water bearing fracture penetrates below the land surface or sea bottom or what size it is.

In order to display a comparison, let us see what happens in a major coastal brackish spring, e.g. the Pantan spring, especially regarding its "morphological aspect". Water emerges from the bottom of a lake 30 x 60 m in size that is 2.7 m above sea level and about 12-13 m below the lake water surface. This water emerges from the base of a depression, 9-10 m below sea level, from a 40 m long fracture (FRITZ et al., 1993). The spring is situated in a thrust contact between permeable limestones of the Palaeogene-Cretaceous complex and impermeable flysch, while the lake and fracture are within flysch deposits. The Pantan spring morphology is interesting. The spring site has a funnel form, resembling a ponikva (doline, sinkhole) and water emerges from the bottom of this "funnel", from a widened fracture. Consequently, almost the same relief form, observed at the submarine springs in the Bay of Kaštela, also occurs at ascending springs or at springs with siphonal conduits, as observed in the Pantan spring. Similar morphological forms also occur at the Jadro and Ombla springs which are the most well known Croatian karst springs. The morphology of the bottom of the submarine springs in the Bay of Kaštela resembles more a widened fracture, as at most ascending karst springs, than a ponikva. This can be concluded from the photos of the submarine spring Slatina (ALFIREVIĆ, 1966, 1969) and from the echogram of the submarine spring Arbanija (ALFIREVIĆ, 1969). In addition, it is necessary to emphasize that the genesis of ponikvas, as karst relief forms, is difficult to explain when they occur within flysch deposits.

Therefore, the present submarine springs, do not derive from ponikvas. They are fractures widened by water and initiated by tectonics in the zones of thrust and reverse movements and through which water flew toward coastal springs during earlier time phases.

By considering the morphogenesis of these submarine springs, it may be concluded that the submarine springs (coastal springs) of the Bay of Kaštela were the erosional base for the pertinent groundwater during the Pleistocene epoch. In the Holocene, the erosional base gradually rose to a higher altitude, where the Pantan and Slanac springs appeared as outlets for the earlier formed "privileged" groundwater conduits serving the submarine springs. This is why in the immediate hinterland of the Pantan and Slanac springs it is assumed that the occurrence of a highest porosity of calcareous rocks, the rocks of "privileged" groundwater flows is at a lower altitude than the present sea level. Furthermore, until relatively recently the largest portion of groundwater derived from the entire drainage basin probably flowed through siphonal conduits toward the submarine springs in the Bay of Kaštela. This flow enabled the development of recent karstification in the hinterland of the submarine springs reaching unknown depths beneath and behind the mentioned hanging hydrogeological barrier.

When the submarine springs are inactive, sea water migrates landward through the whole calcareous permeable medium occurring below the hanging hydrogeological barrier, primarily through the siphonal conduits. This sea water intrusion varies during the year because of different hydraulic conditions and the same happens with the flow of fresh (brackish) water toward the submarine springs, both causing complex relations between saline and fresh water. Intermittent flows of brackish water from the Slanac spring occurring 30 m above sea level (being the global altitude record for a coastal brackish spring - FRITZ, 1992, 1994), is the consequence of the rapid inflow of large quantities of water from the calcareous hinterland under the described hydrogeological conditions. The higher water salinity in the Slanac spring than the Pantan spring at the same time together with the described submarine spring genesis indicate that the route of sea water penetration into the land is from the submarine springs, to the Slanac spring, then further into the land, mainly separately from the underground flows toward the Pantan spring. The geographic shift and rise in altitude of the erosional base from the submarine springs toward the Pantan and Slanac springs, together with the gradual increase in discharge rate at the Pantan spring are the results of the last sea level rise. The submarine springs that had earlier been permanent gradually became intermittent and periods of their inactivity became ever longer thus the submarine springs gradually died off. Then, the permeable strata situated in the hinterland of the hanging hydrogeological barrier became largely filled with sea water and this is one of the reasons why the brackish Slanac spring occurs at such a high altitude above sea level. It is difficult to predict whether the submarine springs in the Bay of Kaštela will die off entirely by the end of the present interglacial stage when the sea level should rise by an additional 1.17 m (ŠEGOTA, 1968), but, there is no doubt that the periods of submarine spring inactivity will become longer and the coastal Pantan spring will discharge more water. The sea level rise will probably be greater than 1.17 m due to the still unknown magnitude of the atmospheric temperature rise caused by human activity.

4. CONCLUSION

The submarine springs of the Bay of Kaštela are unusually far from the mainland and the groundwater on which their activity is dependent. They are a consequence of many reverse and allochthonous relations within the Cretaceous-Palaeogene carbonate complex and Eocene flysch deposits. Thus, the coastal area and a large part of the bottom of the Bay of Kaštela are built of impermeable flysch deposits. This is the reason why part of the groundwater percolates above a flysch barrier (the Pantan and Slanac springs) and the other part flows beneath this barrier to the submarine Arbanija and Slatina springs in the bay.

The published data on the submarine spring morphology support the idea that the submarine springs were formed when the bottom of the present Bay of Kaštela was above sea level. The submarine spring morphology can be explained as a result of the erosion and corrosion of tectonic fractures along which ascending water flowed toward original karst springs within the Bay of Kaštela palaeodepression. During the last sea level rise, these springs were submerged by the sea and so became submarine springs.

The question of the age of the submarine spring remains open. The supposed age of 10,000 to 11,000 years is based on published data that the submarine springs are between 32 to 35 m below present sea level and that they were active only after the last glacial stage. If the morphogenetic concept described in this paper is accepted, i.e. that the present submarine springs are submerged ascending karst springs, then the submarine springs are younger, because water flowed out from the former springs at the level of the present bottom of the Bay of Kaštela, i.e. about 15 m below the present sea level. The sea level reached that elevation some 7,000 years ago (ŠEGOTA, 1968; ŠEGOTA & FILIPČIĆ, 1991), meaning that the former springs have existed as submarine springs during the last 7,000 years. This is, probably, the real age of submarine spring activity in the bay of Kaštela. The difference in these proposed ages of the submarine springs, obviously, is not large - whether we accept that the submarine springs are situated a little more than 30 m (10,000 to 11,000 years) or about 15 m below the present sea level (7,000 years) because the sea level rise decelerates with time. After ŠEGOTA (1968), during the present interglacial stage, the sea level will continue to rise during the next 1,900 years and it will only be approximately 1.17 m higher than present. During this period, the submarine springs will become more inactive, while ever more water will flow out from the Pantan spring during the rainy seasons, and therefore, the submarine springs will most probably "die off".

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