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SALT WATER ENCROACHMENT IN THE LOW ALTITUDE KARST WATER HORIZONS OF THE ISLAND OF KEPHALLINIA (IONIAN ISLANDS)

V. MAURIN and J. ZOETL

Vereinigung für hydrogeologische Forschungen
Graz, Austria

1. Introduction

From the beginnings of karst research Austrian scientists have played a decisive part in this field of study, as the classic karst lay within the boundaries of the former Austro-Hungarian Monarchy.

Among the central problems of karst research is karst-hydrology, whose progress is inseparably connected with the names of A. GRUND, F. KATZER, J. CVIJIC, H. BOCK, N. KREBS, A.E. MARTEL, and O. LEHMANN. Already in its early years investigations were extended beyond the Dinaric karst to include Alpine and Mediterranean regions.

Systematic karst-hydrological investigations carried out by the authors in Alpine regions for more than a decade have brought results that led to the revision of formerly current theories on principles of the water-bearing of karstic mountain systems. In order to enlarge experience, investigations have been extended to the Mediterranean region, chiefly to study those modifications of the genetic process of karst that are either conditioned by the climate or caused by the eustatic fluctuations of the sea-level.

The island of Kephallinia offered itself for a suitable object of research. Its main massive is a largely compact karst body of about 350 km^2, which allows, in the prevailing climate, for the formation of an extensive fresh water reservoir.

Besides general karst-hydrological problems the island of Kephallinia has its particular phenomenon, which has been termed "The Sea-Mills of Argostoli" in the international technical literature of more than a century. It is the phenomenon - long known to the islanders - of the inflow of salt water into the rock-fissures of the northern part of the peninsula named after the town of Argostolion.

The authors made a hydrogeological survey of the entire island in the summer months of 1959 and 1961. On the strength of the results obtained and by means of a large-scale colouring experiment lasting from February to April 1963 the enigma of the salt water disappearing near Argostolion was solved. The considerable expenses of this experiment were borne by the Austrian Research Council, to which we wish to express our thanks also here. For the support of our work we are also obliged to Dipl.-Ing. Dr. K. ZACHOS, General Director, Institute for Geology and Subsurface Research in Athens, Dipl.-Ing. S. MATHEOS (Athens), and Professor Dipl.-Ing. Dr. A. POLLAK (Institute for Mineralogy and Technical Geology, Technische Hochschule, Graz).

2. The area of investigation

The island of Kephallinia is the largest of the Ionian Islands (about 750 km^2). It lies between 38°4' and 38°29' north latitude and 20°20' and 20°49' east longitude.

Accordingly, the island has the typical Mediterranean climate, dry and warm summers and damp and mild winters (July average 26,3° C., January average 11,0° C.). The rain falling mostly in the winter half-year rises in the coastal region of Argostolion to an annual average of 860 mm (Fig. 1).

Formerly there were, besides oak-woods, large fir-woods (Abies Cephalonica), covering the main mountain massive down to about 600 m above sea-level. Today only the summit of the Aenos has a dense fir-wood, while the lower karst areas are occupied by the Frigana. Gardens, some of them lush, exist only in the irrigated Tertiary areas and Alluvial deposits; economic emphasis is on the olive crops. Besides, there is scant cultivation of corn; wine-growing is still common. Goats are reared everywhere.

The main part of the island is rather compact apart from small peninsulas as that of Argostolion. It is only the two large peninsulas Erisos and Palikki that give Kephallinia its striking outline (Fig. 2).

The core of the main body of the island is a mountain chain stretching from the Ag. Dynati (1,131 m) in the north-west to the Aenos (1,628 m) in the south-east. It consists of limestones and dolomites ranging from the Cretaceous to the Palaeogen. In the south and south-east Tertiary sediments extend in front of these older carbonate rocks. Large parts of the eastern coast, i.e. the Kokkini Rachi (1,082 m), consists of Triassic and Jurassic limestones and dolomites.

The peninsula of Erisos and the west and north of Palikki also consist of the Cretaceous-Palaeogen limestone series, while the east and south of Palikki correspond to the younger Tertiary sediments of the main Massive.

Tectonically speaking, the eastern part of the island, the coastal mountain system of Kokkini Rachi, is (according to RENZ 1940, 1955) within the Adriatic-Ionian zone, while the main massive belongs to the Paxos zone, which must be considered as the eastern extension of the Apulian Table.

The wide distribution of the carbonate rocks makes for the karst landscape character of the island. Especially liable to be turned into karst are the well-banked Upper Cretaceous limestones; the development of the subterranean karst cavities is mainly influenced by the banking-joints.

As for the surface karst development, Rillenkarren and especially Kluftkarren are widely distributed all over the island. Solution dolines were seldom found. Sunk dolines and shafts are among the most striking karst phenomena in the island, especially in the hinterland of the Gulf of Sami. Some of them bear brackish water. The most impressive sunk doline is that of Melissani (50 m long, 35 m wide), which contains, at a depth of about 20 m, a brackish water lake of 160 x 40 m. A number of brackish water springs surface on the immediately adjacent coast between Sami and Ag. Evphemia (Fig. 2, 3). A larger polje is to the west at the foot of the Aenos about 390 m above sea-level. It has originated from an old valley system, which discharged south-eastward.

The most peculiar karst phenomenon of the island is, however, the salt water encroachment in the northern part of the peninsula of Argostolion. In this section of the neck of land the groundwater level is permanently below sea-level, which causes a permanent inflow of salt water into the fissures of the carbonate rock. The then British tax-collector, STEVENSON, was the first, in 1835, to make use of this phenomenon for the running of a cornmill by widening out some of the water entrances and closing up adjacent sink holes. Later a second mill was established several hundred metres farther south. In the 1930's the mills fell into disuse; they were totally destroyed by the catastrophic earthquake of 1953. At present they are being restored to attract tourists.

Scientists of various countries have endeavoured to explain this phenomenon for nearly a century. Besides theoretical reasonings, experiments were carried out in order to ascertain, by means of oil, pieces of wood, colour etc., the places in which the salt water that disappears in the sea katavothres surfaces again. The last of these experiments was carried out in 1957 by the American, Dr. PANE, who used 40 kg of fluorescein and small coloured sticks of wood. All these experiments failed.

3. The results of the hydrogeological survey

During investigation in the summer months of 1959 and 1961, 243 springs, borings and wells were mapped out. As far as possible, their yield was measured or estimated, their water temperature taken, carbonate hardness, total hardness, pH-value and electrolytic conductivity determined. The results of these physical and chemical investigations were utilized in the form of synoptical cartograms and diagrams and made it possible to demarcate the coherent hydrogeological areas and especially the brackish water regions. We can, however, not go into details here.

Apart from a few local groundwater fields in Neogen or Pleistocene sediments, the main massive of the island is largely waterless. Overfall springs only form where the water-damming Tertiary deposits extend in front of the foot of the limestone mountains, as on the southern and south-eastern slope of the Aenos and in the south of the Kokkini Rachi ("Big Akoli"). The karst water surfacing points accumulate where the limestones reach the coast in the Gulfs of Sami-Ag. Evphemia and of Livadi. It is therefore in this latter area, in the laguna named "Kutavos", near Argostolion, that we find the largest fresh water springs of the island (one spring yields above 100 l/s), which also form the basis of the town's water supply. To the north the spring waters become brackish, but their yield decreases considerably. There are smaller brackish water areas at the north end of the Gulf of Livadi.

The largest spring surfacings of the island altogether are in the Gulf of Sami. Phridi, Palaeomylos, and Karavomylos are well-known spring names here. Even during periods of draught some of them yield more than 100 l/s. At the Karavomylos the average summer yield was more than 300 l/s in August 1963; until the great earthquake of 1953 this spring was used to run a mill. All springs on the coast between Sami and Ag. Evphemia are about at sea-level and are brackish; their salt water content shows certain local gradations (Fig. 3). A larger number of submarine brackish water springs could also be observed here.

The island's third brackish water area worth recording is at the bluff near Poros.

The peninsulas of Palikki and Erisos are hydrologically independent areas.

4. The colouring experiment of 1963

The hydrogeological survey of the island of Kephallinia resulted in a synopsis of the water occurrences, but left the phenomenon of the sea katavothres of Argostolion unexplained. On the other hand we hoped that our precise knowledge of the hydrographic conditions would provide the basis of an experimental solution.

On principle submarine springs and the brackish water springs on the coasts of Kephallinia had to be envisaged as the re-surfacing points of the salt water entering into the peninsula of Argostolion. If the re-surfacing was to be found in the accessible brackish water springs, our attention was, in view of the quantity of the disappearing salt water, to be focused first of all on the large spring area in the Gulf of Sami. Since, however, brackish water springs are normally the result of local circulation and mixture, our first task was a close investigation of this area. Thus, in the summer of 1961, the Salzburg divers, W. TISCH and A. REISINGER, were employed to check conditions on the coast between Sami and Ag. Evphemia. But they could nowhere ascertain any submarine entrance of salt water. It appeared, on the contrary, that in the whole Gulf there are numerous brackish water discharges also under the surface of the sea.

Permanent observation of the most important springs of this area was another preparatory step. This meets with great difficulties in so remote a region. All the more we have to thank N. NIKOLAKOS, the agriculturist, who controlled for more than a year the total hardness and yield of Phridi, one of the most important springs in the Gulf of Sami. Added to our own measurements taken during our experiment in the spring of 1963, this provided very valuable insight into the interplay of precipitation, yield and chemistry (Fig. 6, 7).

Another question was which method to choose for the explanation of this phenomenon. As we had to make do with a minimum of staff and apparatus, the use of radioactive material and the activation analysis method as well as the use of lithiumchloride had to be counted out. The use of dyed lycopodium spores would have made observation very simple, as this method involves the control of each spring by means of a plankton net. It was, however, to be feared that the lycopodium spores would be filtered off, as large quantities of dulse are continually being washed into the sea katavothres. Besides, the observation of the springs by means of plankton nets would, in places, have been jeopardized by the beating of the waves. Therefore we finally decided on the use of fluorescein (uranin).

The attempt at least roughly to calculate the necessary quantity of colour was extremely difficult, for neither could the yield of the brackish water springs (especially the submarine ones) nor the presumptive time of passage be determined. Financial reasons, too, limited the quantity of the available colour. Finally, we chose for standard the largest known brackish water area, i.e. the yield of all springs of the Gulf of Sami-Ag. Evphemia. At the time of our investigations, of the 35 springs mapped out in the coastal area, 25 yielded less than 20 l/s, only three more than 100 l/s. For the winter months we had been given estimations of 3 m^3/s and had been informed of 5 stronger submarine springs. All our own observations as well as the carefully checked information tended to justify the supposition that the late winter yield in this largest brackish water area of Kephallinia does not exceed 10 m^3/s. A rough calculation of the interplay of precipitation, run-off, infiltration, and salt water addition, yielded no higher values. Thus we had to reckon with colouring a total discharge of 8.6 mill. m^3 of water during ten days, or 17.2 mill. m^3 of water during 20 days, respectively. Therefore a quantity of 160 kg of uranin (our financial limit) seemed to us to guarantee the ascertainment of a minimum concentration of 10^{-8}. With the apparatus at our disposal (UV-lamp) the uranin could be ascertained without doubt to a dilution of 10^{-10}. Exact quantitative gradation of dilution degrees between 10^{-9} and 10^{-10} by means of comparative solutions is indeed impossible.

On Tuesday, 26 February 1963, from 14.30 to 17.30 hrs., two native workers, controlled by the Greek geologists, A. DOUNAS and A. MORIKIS, injected 160 kg Uranin AP conc. into one of the sea katavathres. The colouring material had been shipped by Messrs. E. MERCK of Darmstadt, Germany, direct to Kephallinia (via Athens) and was taken from its original emballage only on the spot. The injection was carried out by persons that had nothing to do with the observation of the springs. The uranin was injected by means of a 200 l-barrel, the bottom of which had been replaced by a dense wire net.

The katavothre thus fed is at the northern point of the peninsula of Argostolion. Here stood the mill erected by STEVENSON in 1835. The salt water is conducted there by a stone-walled conduit, 46 m long and, on an average, 2 m wide; it sinks off into the artificially extended fissures and tubes of the Cretaceous limestone. Its present condition, with the mill-wheel installed for the tourists, can best be seen from Fig. 4.

The quantity of the inflowing water depends on the fluctuations of the sea-level (which amount to 40 cm here) and can, according to our observations, range from a few litres to several hundred l/s. Whenever considerable inflow exceeds the sucking capacity of the rock fissures, the water level in the sinkholes rises, but never quite to sea level. To maintain the running of the mill-wheel, sluice-boards have therefore been installed for the regulation of the inflow. According to our own measurements taken in the spring of 1963 the greatest level difference was, on complete shutting off, 73 cm. WIEBEL (1874) gives the maximum difference as 137 cm (4,4 ft.). When the conduit is closed, it can also be observed that small quantities of fresh water are flowing into the katavothres from rock fissures.

Besides this main katavothre there are on the east coast of the peninsula numerous smaller sinkholes scattered over a stretch of about 1 km. We could therefore, in 1959, observe in this area 10 additional active entrance points, the largest of which received then 10 l/s. These coastal ponors are, however, subject to permanent change, as we noticed on later controls. Thus, also the large mill conduits (more than 200 m long) of the so-called "New Mill" are entirely without water today. Here D. MIGLIARESSI had in 1859 established a similar mill about 400 m south-east of the "Old Mill".

The west side of the peninsula consists mainly of a bluff of 3 to 5 m in height, at which, along the gradually eastward-sloping calcareous banks, deep surf holes have formed. It may be assumed that here, too, are numerous entrance points which can, however, not be observed under present conditions.

Observations of wells and borings have shown that the phenomenon of a groundwater level permanently below sea-level can be traced from the northernmost point of the peninsula to the town of Argostolion. Since contradicting figures have been given for the level difference and no exact observations of its seasonal movement are known, we installed at the southern mill, 32 m from the coast, a groundwater gauge that was adapted to a sea-level gauge installed simultaneously. This device, installed by us at considerable expense, was intended for the observation of the level differences between sea and groundwater during at least one year. These long-term measurements would certainly have yielded interesting information. The headmaster of the Argostolion grammar school offered to look after the gauges, but unfortunately delivered no measurements after our departure, so that only our own gauge measurements taken during the experiment are available (Fig. 5). They show that the sea-level fluctuated during that period by 34 cm, which is mainly due to the wind pressure. The tides make themselves hardly felt in this area and are completely superseded by the swells caused by the wind. The reduced groundwater level joins in the changes of the sea-level, but not without a certain retardation. This phase shifting also causes, as far as one can see, the changes in the level difference, whose minimum was, during the period of observation, 69 cm, and which rose to a maximum of 96 cm. It has not yet been found out if there are any seasonal changes in the level difference. Measurements taken in August 1959 showed a level difference of 1,2 m.

The re-emergence of the colour was controlled at the springs in the north and east of the Gulf of Livadi, the springs on the coast between Ag. Evphemia and Sami and the spring area of Poros, i.e. at all the surfacings of brackish water worth mentioning, except the submarine ones. Samples were taken once a day. The samples were subject to UV-light and tested for traces of uranin in the laboratory installed at Argostolion. A total of about 580 samples was tested.

The first traces of colour appeared on 12 March 1963, at a spring about 3 km north of Vlachata, i.e. about half-way between Ag. Evphemia and Sami. On 13 and 14 March, the uranin also appeared at the brackish water surfacing south of this spring, especially in the large springs "Phridi" and "Karavomylos" and in the brackish water lake of Melissani. The most unequivocal evidence was obtained at a group of springs immediately north of "Phridi", where the passing of the colour was as follows:

Tab. 1: The uranin concentrations determined in the spring group north of "Phridi"

March 14 1963	traces
15	10^{-10}
16	2.10^{-9}
17	10^{-9}
18	10^{-9}
19	10^{-10}
20	10^{-10}
21	traces

Considering the popularity of the phenomenon of the Sea Mills of Argostolion throughout Greece it was small wonder that the islanders soon knew of the positive result of the colouring experiment; during the first days, dozens of interested onlookers watched the samples being subjected to the UV-rays.

The only other spot to show a concentration of 10^{-9} was the brackish water lake of Melissani; in all the rest of the 8 colour-positive groups of springs concentrations were less. The colour-positive groups of springs are scattered over a coastal strip about 3 km long.

The first appearance of the colouring material in the spring group near "Phridi" occurred 16 days after the injection, the passing of the main part of colour 18 days after it.

The brackish water springs in the entire area of the Gulf of Livadi as well as those near Poros remained colour-negative. Observation ceased on 3 April 1963.

When the peak was reached, the colouring material was carried along the 15 km-stretch from the sea katavothres on the peninsula of Argostolion to the large brackish water springs on the east coast of the island at an average rate of flow of 34 m/h (Fig. 2). Compared with the flow-rates of the karst waters in Alpine mountain systems or in the south-eastern European karst areas, this rate seems low; such comparisons, however, are only partly admissible in view of the completely different hydraulic and hydrogeological conditions prevailing in those areas. In order to appraise the result of the experiment, viz. the flow-rate as well as the moderate concentrations of the colouring experiment, the extraordinary meteorological conditions prevailing at the time of the experiment and during the previous months must, above all, be taken into consideration.

The precipitation during October, November and December 1962 (1,026 at Argostolion) greatly exceeded the normal annual total and was certainly much higher still in the upper regions of the Aenos massive. The first months of 1963, too, had extraordinary high precipitation (January, February and March together 493 mm; cf. Fig. 6). Spring yields of an amount unknown till then were the consequence of those catastrophic rainfalls, which had been unparalleled in previous decades. The spring "Phridi", which was kept under permanent observation for a longer period, showed an ordinary winter yield of 150-200 l/s; at the time of the experiment the yield was about 1,5 m^3/s. "Karavomylos", the largest spring of the area rises, given a summer yield of about 300 l/s, to 1-2 m^3/s in normal winters; at the time of the experiment there was a yield of about 10 m^3/s. Some of the submarine springs, hardly visible as a rule, showed in the shape of effervescences on the sea-level.

In this connexion the results of the observation of the chemical composition of the waters is of great interest. Thanks to N. NIKOLAKOS we have at least a complete series of hardness measurements taken from July 1961 to November 1962 (Fig. 7), supplemented by analyses made on 25 February and 25 July 1962, which were placed at our disposal by the Greek Ministry of Agriculture (Table 2), and our own measurements of 1963.

Table 2: Analyses of brackish waters in the Gulf of Sami.

Table 2

Analysis from 25 February 1962

name	pH	total	temporary	permanent	Cl'	SO_4''	HCO_3''	CO_3''	Na^+	Ca^{++}	Mg^{++}	sum total
		hardness in Germ. degrees			in mg/l							
Melissani	7,4	103,6	9,0	94,6	4792,5	816,0	195,2	0	2718,6	154	354,5	9030,8
Phridi	7,4	104,7	9,0	95,7	4899,0	840,0	195,2	0	2789,9	158	356,9	9239,0
Karavomylos	7,8	75,6	9,5	66,1	3159,5	604,8	207,4	0	1794,0	98	267,4	6131,1

Analysis from 25 July 1962

Melissani	7,6	100,8	8,4	92,4	4792,5	768,0	183,0	0	2714,0	132	355,7	8945,2
Phridi	7,6	101,9	8,4	93,5	4863,5	787,2	183,0	0	2760,0	132	360,6	9086,3
Karavomylos	7,7	71,7	9,0	62,7	3372,5	595,2	195,2	0	1955,0	106	245,6	6469,5

Fig. 7 shows only negligible changes in the chemistry of the brackish water springs and thus in their respective proportions of fresh and salt water during the hydrographical year 1961-1962, which was almost an ordinary year regarding water-bearing (Fig. 6); part of those changes surely result from inexact measuring. On comparing further the measurements of WIEBEL 1874 - indeed very old, but exactly taken - one is justified in concluding that there occur no great changes in the proportion of fresh and salt water in the large brackish water springs in the Gulf of Sami-Ag. Evphemia in normal weather. This normal proportion is 3,5 : 1 in the spring group of "Phridi", and 6 : 1 at the "Karavomylos".

The catastrophic rainfall in the winter of 1962-1963 caused a considerable disturbance of this proportion (fig. 7); it was 6 : 1 at the time of the experiment in "Phridi", and 8,5 : 1 at the "Karavomylos". From this follows that there are certain limits to the inflow of salt water, which agrees with the observations made at the sea katavothres.

Regarding the ascertained concentrations of colouring material, it must first be stated that we had to deal with about ten times the amount of the originally estimated quantity of water. On the other hand it must be taken into account that high-waters greatly increase the rate of flow. This means that we greatly over-estimated the rate of flow, owing to our lack of comparative figures. In times of normal precipitation it is probably only a fraction of what we ascertained at the time of extreme high-water.

Ascertainment of the quantity of colour washed out during the time of the experiment in the colour-positive spring groups under observation was impossible, owing to the moderate concentrations and the fact that their yield cannot be exactly assessed. Control of the submarine springs was not possible either.

It is further worth mentioning that the temperature of the brackish-water springs seems to be extremely constant. Of the "Phridi" spring, the following measurements were taken:

Table 3: Water temperatures of "Phridi" spring

15 August 1959	15,1° C
2 September 1959	15,1° C
30 July 1961	15,1° C
24 August 1961	15,1° C
24 February 1963	15,0° C
26 March 1963	15,0° C

It is also remarkable that the water temperature of the largest brackish water spring, "Karavomylos", recorded by WIEBEL 1874 (p. 55) on 4 April 1860, was 14,9° C, which is exactly the value ascertained by us on 15 August 1959. As most of the water surfacing in the brackish water springs is fresh water, whose increased proportion in the spring of 1963 caused no considerable change of temperature, it is to be assumed that the temperature of the large brackish water springs is conditioned not by inflowing salt water but by the large karst water body.

5. The karst-hydrological explanation of the phenomenon of the sea katavothres of Argostolion

The result, surprising at first sight, that the salt water disappearing near Argostolion flows through the entire main massive of the island and surfaces again on the eastern coast, which is 15 km bee-line distant, is to be explained by the geological structure and the karst-morphological development of the island during the Pleistocene.

The main massive of the island consists nearly exclusively of Cretaceous limestones liable to turn into karst, while the south and west (Gulf of Livadi, Palikki) consist of water-damming Tertiary sediments.

During the glacial periods the level of the world's seas was reduced by the enormous masses of ice. In the Würm, which ended about 12,000 years ago, this reduction amounted to about 100 m in the Mediterranean.

A glance at the present-day 100 m isobath (Fig. 2) shows that Kephallinia and Zakinthos formed a continuous complex during the Würm, while Ithaka was even then separated from Kephallinia by the sea. In the centre of the Gulf between Ag. Evphemia and Sami the present 100 m isobath closely approaches the present-day coast. The Gulf of Livadi, however, today with a maximum sea depth of 28 m, was land in the Würm and formed a flat and compact trough, on whose watertight basis brooks could gather, which found a subterranean outlet through the karsted main massive to the lower level of the coast in the Gulf of Sami. This was then the natural drainage through the karsted mountainous body to the coast, whose level was about 70 m lower. Such conditions are by no means extraordinary, but are to be found even today in many karst areas of the world; Yugoslavia's numerous poljes are among the finest specimens. There the drainage along the fissures of rock often covers more than 50 km of subterranean waterways.

After the end of the Pleistocene and the following rise of the sea-level the low-altitude waterways of Kephallinia were filled with salt water. The rainfalls that sink into the main massive today still drain off mainly to the east, owing to the general eastward-sloping of the Cretaceous limestone banks. These great quantities of fresh water make, together with the old waterways, for those hydraulic factors that will be discussed in the course of the physical explanation below.

The deliberations presented here are supplemented in a rather interesting way by the investigation of stalactites from the sunk doline of Melissani near Vlachata. In this there is a brackish-water lake, whose level is only a little above sea-level. In 1961 we managed to have stalactites hanging from the walls of subterranean caves brought up from a depth of 3 m and 26 m respectively below sea-level. The age of these stalactites was determined by the Zweites Physikalisches Institut of Heidelberg University by means of C-14 treatment. The age of the stalactite that was taken from a depth of 3 m was determined as 16,400 ± 300 years, while the stalactite from a depth of 26 m was found to be 20,400 ± 500 years old. This is another piece of evidence, obtained by means of absolute age ascertainment, for the eustatic reduction of the sea-level of the Mediterranean during the last glacial epoch, evidence, which in geological research can only be obtained under extremely fortunate circumstances. For carrying out the age determination we are very much obliged to Dr. K.O. MÜNNICH.

We are aware of the fact that in this area positive as well as negative shiftings of the shore up to the most recent geological epochs may well have tectonic causes. The numerous earthquakes are evidence of this instability. In view of the amount of the eustatic level fluctuations these tectonic movements are, however, likely not to have changed the principle of the development outlined above. We know many extremely karsted horizons, today below sea-level, in the carbonatic mountain systems of many Mediterranean coastal areas. They could be ascertained, among other investigations, by numerous borings, carried out by the Institute of Geology and Subsurface Research in Athens in the Gulf of Corrinth and on the south coast of the Peloponnesos in depths of 10-20, 25-30 and about 80 m.

6. The physical explanation of the phenomenon

Of the submarine karst ways, ascertained by the colouring experiment, the genesis from the eustatic sea-level reductions during the glacial periods could be reconstructed beyond doubt; but the hydraulic aspect of the workings of the sea katavothres needed physical explanation. This problem was taken up and solved by Dipl.-Ing. H. BERGMANN and Dipl.-Ing. Th. GLANZ (Technische Hochschule, Graz) theoretically as well as by the construction of a model. As these calculations and constructions cannot be demonstrated here, we refer to a special paper by Th. GLANZ to be published in the "Steirische Beiträge zur Hydrogeologie", year 1965.

As the above-mentioned analyses show, the fresh water-salt water proportion of the large springs in the Gulf of Sami normally varies from 6 : 1 to 3,5 : 1. The main part of the water masses surfacing here comes therefore from the towering mountain massive extending between the Aenos (1,628 m) and the Ag. Dynati (1,131 m). The storage of winter rainfalls in this extensive mountain system also explains the high yield values of the coastal springs in summer and the relatively low water temperatures with their nearly constant figures throughout the year.

In a karsted mountain system the number of waterways decreases from the surface to the lower regions; the same is true of the sum total of the cross-sections of the karst tubes through which they flow. That means, however, that the rate of flow of the draining-off waters increases with depth. Therefore potential energy is progressively transformed into cinetic. If these karst tubes reach below sea-level, pressure heads may occur in narrow places, heads that are, however, below sea-level. If in such a place there is a connexion (of a larger cross-section) with the open sea, salt water flows in. If the point of its entrance is below the sea surface, it will normally be inaccessible to observation. As the sinkholes of the Sea Mills of Argostolion are, however, about 20 m distant from the shore, the level in these sinkholes indicates, when the conduits are closed, the piezometric head of the karst tube through which the salt water flows. This level also coincides with the general groundwater level at the east coast of the Argostolion peninsula. The pressure head occurring here results from the still lower pressure head at the entrance point of the fresh water tubes into the salt-water-bearing base tube and from its friction losses. Thus this phenomenon can be called a natural ejector working on the principle of the water jet pump (Fig. 8).

This also offers a natural explanation of the occurrence of brackish-water springs in the Gulf of Sami, below, at, and above sea-level. For in an ejector there is a decrease of pressure at the entrance point of the pressure water into the bigger tube, but an increase of pressure behind it. Thus, the mixed water is lifted. This principle has been used for decades for the lifting of water.

Of former authors, who dealt with the problem of the Sea Mills, FOUQUE 1867, LEHMANN 1932, MARKETOS 1963 and WIEBEL 1874 endeavoured after a physical explanation of the phenomenon. While the three first-mentioned argued in favour of a re-emergence of water on the west coast, WIEBEL was the only scientist to envisage the possibility of a connexion with the large brackish-water springs in the Gulf of Sami.