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CONTINUOUS INFLOW OF SEAWATER AND OUTFLOW OF BRACKISH WATER IN THE SUBSTRATUM OF THE KARSTIC ISLAND OF CEPHALONIA, GREECE

CLAUDE DROGUE

Laboratoire d'Hydrogéologie, Université des Sciences et Techniques du Languedoc, Place E. Bataillon, 34060 Montpellier CEDEX (France)

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ABSTRACT

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There is massive, continuous inflow of seawater at a place on the coast of the karstic island of Cephalonia in the Mediterranean. This current reappears at the coast on the other side of the island. This is extremely astonishing when it is considered that for water sea level represents minimum potential in the earth's gravitational field. The nature of the energy which causes the phenomenon has been the subject of numerous as yet unconfirmed hypotheses on the part of numerous authors. This study proposes a new explanation connected with the existence of a marine current which creates a hydraulic gradient between the two sides of the island but with inflow being maintained by density flow. This is made possible by a deep karstic conduit created during the Cenozoic period and which runs in the same direction as the marine current.

INTRODUCTION

The Mediterranean island of Cephalonia off the western coast of Greece is the site of one of the most astonishing hydrological phenomena in the world. A seawater current flows continuously into the karstic substratum of the island (area 750 km^2) through sinkholes which have formed in fractures in the rock (Triassic, Jurassic, Cretaceous and Cenozoic limestone and dolomite) on the southwest coast near the town of Argostoli. Current flow can reach as much as 0.3 m^3 s^{-1} and is sufficiently powerful to drive millwheels (sea mills). Maurin and Zötl (1967) used a tracer to show that the seawater reappears on the opposite coast of the island at brackish springs (near the town of Sami). The underground route is 15 km long (Fig. 1).

For over a century various hypotheses have been put forward to explain the phenomenon without support with experimental data. The most recent hypothesis assumed that there is a natural ejector in the substratum of the island which works on the principle of the water pump and that this is probably operated by infiltration of water (Glanz, 1965). Although this hypothesis is

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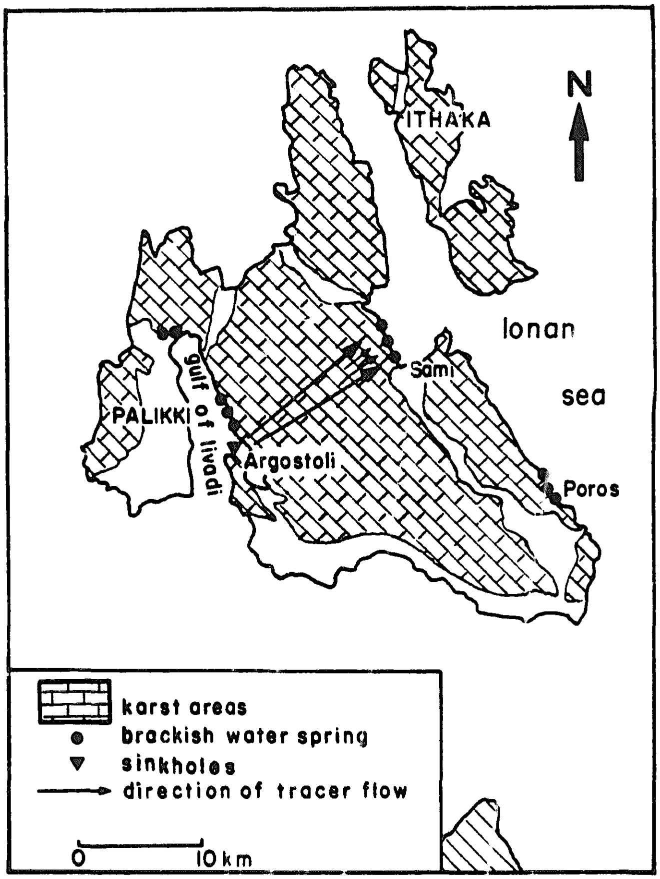

Fig. 1. The island of Cephalonia in the Ionian Sea. Location of the seawater inflow zone (sinkholes) and the Sami springs where resurgence of salt water occurs. The arrows show the results of tracing (from Maurin and Zötl, 1967). There are numerous springs in Argostoli bay, opposite the sinkholes which discharge fresher water than at Sami. These springs were not reached by tracer and appear to be independent of the underground current of salt water which flows from Argostoli to Sami. This is possibly accounted for by a marly level interbedded between the sinkholes and the karstic massif which feeds these springs.

frequently quoted (Zötl, 1974; Bögli, 1978; Bonacci, 1987) it is nevertheless not very probable from a hydrodynamic point of view (Cooper et al., 1964; Stringfield and LeGrand, 1969). Thus, the true cause of the phenomenon has not been elucidated so far. This is made even more interesting by the fact that similar cases known in other countries (intake of seawater but without underground flow across the whole of an island) have been explained by various mechanisms, the most common of which is connected with ocean tides. At some coastal springs, sea level is temporarily higher than the level of adjacent underground water during exceptionally high tides and salt water may then run into the springs. The seawater is discharged at low tide and the springs flow normally again (Kuscer, 1950; Stringfield and LeGrand, 1971). Strong winds from the sea can also have a similar effect to that of tide by submerging the coast and causing temporary penetration of seawater into the substratum (Drogue and Bidaux, 1986). Another process is illustrated by the case of Spring Bayou in

Florida. Here, the brackish water of the Anclote River flows underground to Lake Tarpon when the level of the lake is lower than that of the river (Stringfield and LeGrand, 1971). Whatever the mechanism involved in such phenomena, intake of seawater is always temporary, whereas at Cephalonia salt water runs inland continuously. It is therefore not possible to seek the cause of the phenomenon in periodic tides or winds, which are not constant in either force or direction. There must necessarily be a continuous source of energy to cause the flow of water below sea level since the latter represents minimum potential for water in the field of terrestrial gravity.

HYDRAULIC GRADIENT AND DENSITY CURRENT

A new study was conducted in May and June 1987 to identify the nature of this energy after the discovery of a hitherto undetected permanent marine current extending around the Ionian archipelago from SSE to NNW (Fig. 2). Sea level along the coast facing the current (and where intake of water occurs) must naturally be higher than on the coast on the other side of the island (where the springs are). This hydraulic gradient between the two coasts of the island appeared to account for the underground current, as was envisaged by Brown et al. (1835). In order to check this hypothesis, levelling was carried out with an electronic tacheometer from two points on the island's survey grid. The readings showed that sea level on the sinkhole side was effectively generally higher than on the opposite side (Fig. 3). However, this was not always the case and the difference which is not constant in time, sometimes disappeared for several hours. The observations made showed that the difference in altitude thus varied between 0.30 ± 0.02 m and 0.02 ± 0.02 m. This hydraulic gradient must be involved in the inflow phenomenon. However, it is not the only cause,

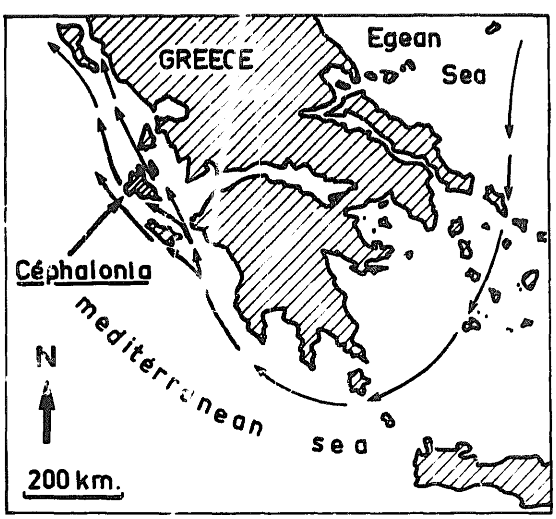

Fig. 2. Routes of the continuous SSE-NNW marine current which touches Cephalonia. This current follows the Aegean current which runs round the southern coast of Greece and joins the Adriatic circuit currents to the NNW. (After the chart "Courants de surface en Méditerranée", Service Hydrographique de la Marine, Paris, 1956.)

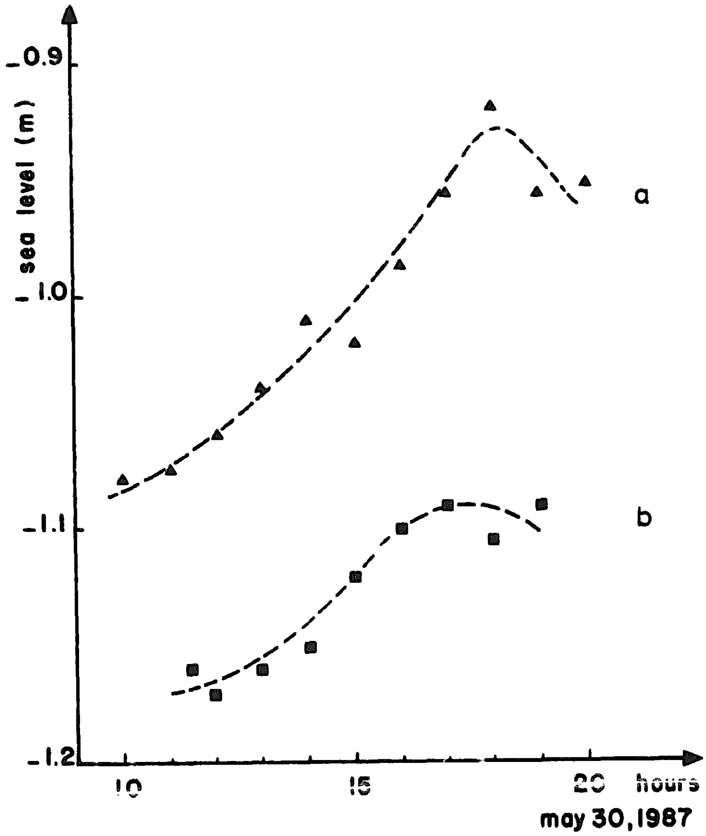

Fig. 3. Comparison of changes in sea level on the south coast of Cephalonia at Argostoli where inflow of sea water occurs (a) and on the NE coast near the Sami springs (b). Levels are given in relation to the zero altitude of the geodetic network of the island. Sealevel and tide amplitude are highest at Argostoli.

since inflow occurs when the gradient is zero. In addition, observations made in the karstic aquifer on each side of the island showed that there was an apparent piezometric slope running in the opposite direction to that of the flow of underground water. In effect, during the study, the water level in a karst cavity near the inflow sites was − 1.70 m ± 0.02 m in relation to the survey base line of the island (i.e. − 0.7 m below mean sea level, as already reported), whereas on the opposite coast near the springs another water level was recorded at − 0.73 ± 0.02 m, i.e. higher than the upstream level. According to the authors mentioned above (Maurin and Zötl, 1967; Brown et al., 1835; Glanz, 1965) the water level in the sinkholes varies from 0.7 ot 1.3 m below sea level, in particular because of precipitation.

This appears to be completely paradoxical, unless it is considered that the underground water varies in density, with the latter decreasing towards downstream.

The possible role of different densities of water in underground flow had already been suggested at Cephalonia and in other coastal karsts (Crosby and Crosby, 1896; Fuller, 1906; Kohout, 1960; Burdon, 1967). The water flowing into the sinkholes has a higher density than the brackish water at the Sami springs. Since the route of underground flow is schematically similar to the flow that would occur in an U-tube containing water with two different densities; the tendency towards hydrostatic equilibrium would cause a downward movement in the part of the tube containing the water with the lowest density.

This must occur in Cephalonia, with flow towards the Sami springs. Indeed, the density of seawater was observed to be 1.2580 kg dm^3 at 25°C, whereas the density of the brackish water at the Sami springs was only 1.0002 kg dm^3 at 15°C (temperature of seawater and underground water respectively).

With these values, calculation of the hydraulic heads upstream and downstream of the aquifer must be carried out taking into account the dept (below sea level) reached by the underground flow. Data on the maximum depths below sea level of circulation of underground water at Cephalonia are not available. However, paleogeography provides very interesting information on the problems. In carbonaceous rock, karstic reserves (spaces formed by the dissolving of carbonates by the aggressive action of water) can develop at great depths below springs, aided by marine regression in coastal zones. During the Cenozoic era the Mediterranean was completely enclosed and had a hot climate. During the Messinian age (7–9 million years BP) sea level probably fell considerably to several hundred metres below today's level (Hsu et al., 1978; Steckler and Watts, 1980). After an overall rise, a fresh regression to −110 m occurred during Würm glaciation 35,000 years BP (Monaco et al., 1972). Thus most of the aquiferous reserves formed in the depths of the carbonaceous mass during these marine regressive episodes are now below sea level. This explains why there are underwater springs at −80 m near the coast of mainland Greece (Mistardis, 1967) and at −150 m in Lebanon (Moulard et al., 1967).

Let us assume a minimum depth of karstification, i.e. of movement of water, of 100 m below today's sea level in the Mediterranean. The piezometric level near the Sami springs with brackish water would therefore be 2.56 m greater than the piezometric level at seawater inflow sites. Since the deviation observed in only 1 m, the difference (1.56 m) makes it possible to justify underground flow. Thus the phenomenon triggered by the rise in sea level on the Argostoli side of the island may be maintained by the density effect, explaining why inflow is continuous even when there is no difference between the two sea levels. This density effect is thus probably not the cause of intake but may contribute to making it continuous.

However, this inflow phenomenon has not been observed in other karstic islands in the Mediterranean or in other parts of the world and is thus a special feature of Cephalonia. It should be considered that the brackish water from Sami springs is the result of a mixture in the substratum of fresh water from infiltration of rainwater (800 to 900 mm per year) falling on the island and salt water flowing in at Argostoli.

For underground flow not to be reversed at Argostoli, with the sinkholes becoming springs, it is necessary that in the heart of the island the hydraulic head of infiltration should be smaller than the head at Argostoli. For this, since

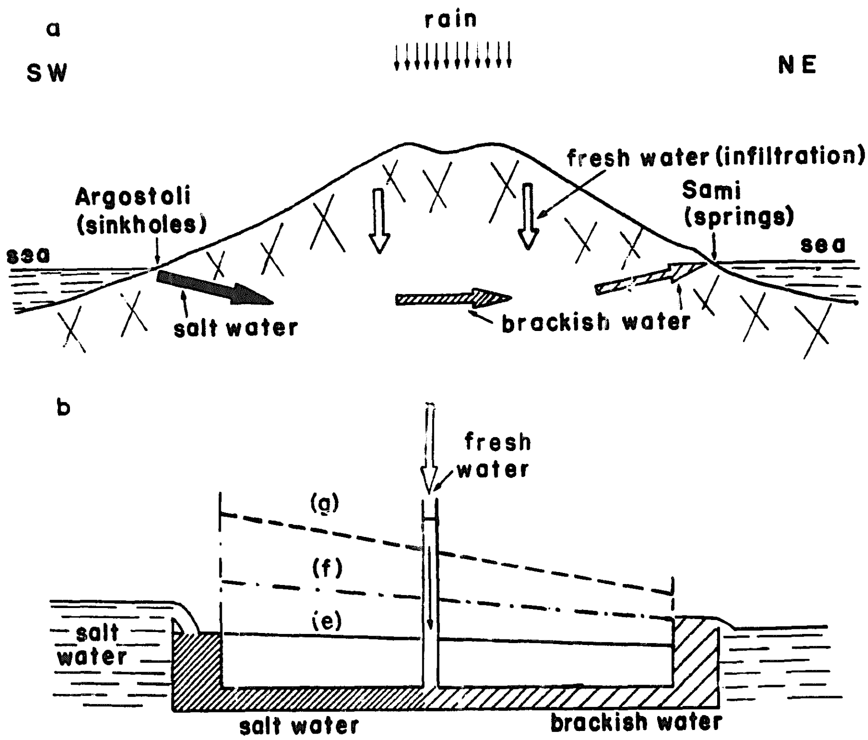

Fig. 4. (a) Diagram of underground flow in the karst in Cephalonia between sinkholes where there is inflow of sea-water and the brackish springs (vertical exaggeration 3:1). Inflowing salt water is mixed with fresh water (infiltrated rainwater) in the deep karst. (b) Simplified representation, not to scale, illustrating the underground flow system. Piezometric lines are traced above the conduit for constant fluid densities along the flow route: sea water (*e*), brackish water (*f*) and fresh water (*g*). It will be noticed that fresh water recharge by infiltration into the karst must not result in a piezometric surface higher than that at Argostoli (calculated for the density of fresh water); if it were higher, inflow of salt water would stop, and the Argostoli sinkholes would even function as springs.

infiltration water has a density of 0.9990 kg cm^{-3} at 15°C (measured on seepage in a cave at a depth of 50 m), the level of underground fresh water should not be more than 3 m above sea level at Argostoli (assuming once again an aquifer which is at least 100 m thick) (Fig. 4).

This assumes that losses of head are very small in underground flow and that there are very permeable karstic conduits connecting the two sides of the island. These conduits were formed in the following way according to Glanz (1965); during marine regression, the marly bottom of the Bay of Livadi, the site of the town of Argostoli and which has a maximum depth of 28 m today, was exposed. Rainwater scoured streams in the impermeable surface which sank into the limestone beyond the marl and formed sinkholes. This flow reappeared on the opposite coast, thus developing large karstic conduits through which seawater flows today.

CONCLUSION

Three factors thus occur simultaneously in this exceptional case and probably contribute to the phenomenon of inflow of sea water and outflow of brackish water. Firstly, the energy of the Aegean–Adriatic marine current probably causes the phenomenon. Density flow must then accentuate and maintain the movement. Finally, the process is made possible by the existence of karstic conduits which were probably formed after the Tertiary period and which lie in a similar direction to that of the marine current.

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