

F. A. KOHOUT (a), M. C. KOLIPINSKI (b) and A. L. HIGER (c)

REMOTE SENSING OF SUBMARINE SPRINGS: FLORIDAN PLATEAU AND JAMAICA, WEST INDIES (1)

1973

Proc. 2nd Intern. Symp. on Ground Water and Hydrogeology of Fractured Rocks
Palermo, Sicily (April: 1973)

ABSTRACT

A change in the turbidity plume formed by a submarine spring located 2-1/2 miles (4 km) offshore from Crescent Beach on the northeast coast of Florida suggests that flow from the spring may be decreasing in intensity with time. This decrease may correlate with increased pumpage in the artesian Floridan aquifer which underlies the mainland.

In a cooperative project with the United Nations Development Programme and the Jamaica Geological Survey Department, the National Aeronautics and Space Administration took more than 17,000 frames of color and infrared color photography of Jamaica and its coastal waters in April 1971. Submarine springs on the north-central coast of Jamaica discharge primarily clear water from karstic limestone and were not discernible in the aerial photos. In contrast, submarine springs on the south coast discharge from sand and gravel aquifers and turbidity plumes are clearly visible in photographs.

At Discovery Bay, on the north-central coast, three factors — small ground-water discharge at the end of the dry season, small temperature differential between the ground water and the bay water at this particular season, and rapid mixing of the spring discharge (observed by SCUBA diving) — coincided so that thermal anomalies on the IR imagery were inconclusive.

A significant anomaly was discovered in infrared imagery of the north-east coast of the island after the field investigation was completed. The anomaly is presumed to be evidence of submarine ground-water discharge. Findings of this type combined with ground truth investigations and repetitive observations from satellite or aircraft platforms can provide a relatively inexpensive foundation for continuous surveillance and monitoring of earth and water resources.

INTRODUCTION

In 1966, at the Central Treaty Organization's symposium on Hydrology and Water Resources Development at Ankara, Turkey, the senior author stated (Kohout, 1966a):

« Few things seem to be more deserving of attention in a thirsty world than fresh water rising up from the bottom of the sea. Yet less than 15 scientific studies have been uncovered to date and these marvels of the sea are justifiably classified as neglected phenomena of coastal hydrology ».

Since that time numerous studies have been made, many papers written, and we are now participating in this symposium on the hydrology of fractured rocks wherein a major role is given to the *Utilization of Submarine Springs*. It seems overwhelmingly apparent that submarine springs no longer can be considered

neglected phenomena of coastal hydrology. We look forward with great enthusiasm toward the final compendium of the symposium.

Early writings demonstrate clearly that submarine springs are not a recently discovered phenomenon. Pausanias (8 : VII), second century A.D., provides the following statement:

« Not only here in Argolis (Greece), but also by Cheimerium in Threspotis, is there unmistakably fresh water rising up in the sea... In front of Diaearchia also, in the land of the Etruscans (western Italy), there is water boiling in the sea and an artificial island has been made through it, so

(a) U.S. Geological Survey, Woods Hole, Mass. 02543.

(b) U.S. National Park Service, San Francisco, California 94120.

(c) U.S. Geological Survey, Miami, Florida 33130.

(1) Publication authorized by the Director, U.S. Geological Survey.

that this water is not "untilled" but serves for hot baths ».

Most submarine springs do indeed result from fresh-water drive and occur at the last exit point before the fresh water is lost to the sea. A second driving force, geothermal heat, is obvious for submarine springs in areas of active volcanism, but, also, slow thermal convective upwellings occur in non-volcanic areas (Kohout, 1965 1967; Henry and Kohout, 1972; Kohout and Munson, in preparation). It is important to note that the differences in temperature and turbidity between the discharging ground water and sea water serve as tracers for remotely sensing the existence of such discharges.

RECOGNITION AND HYDROLOGIC FACTORS OF OCCURRENCE, FLORIDAN PLATEAU

The outcropping of a homogeneous aquifer in the sea bottom produces evenly-distributed discharge which tends to be quickly dispersed in the large volume of overlying sea water. The occurrence of a recognizable submarine spring implies the existence of a large permeability contrast in the aquifer or in the low-permeability bed that overlies and confines the aquifer water under artesian pressure. Thus, submarine springs are reported most frequently from regions of cavernous

limestone or lava flows, both of which are notoriously heterogeneous rock types.

Confined Aquifers

Karstic submarine springs generally appear at the surface of the sea as a boil of water or, in a choppy sea, as a slick or smooth area in the otherwise rough water. Figure 1 is an oblique aerial photo of a submarine spring located 2.5 miles (4 km) offshore from the town of Crescent Beach on the northeast coast of Florida (Fig. 2). The ocean floor adjacent

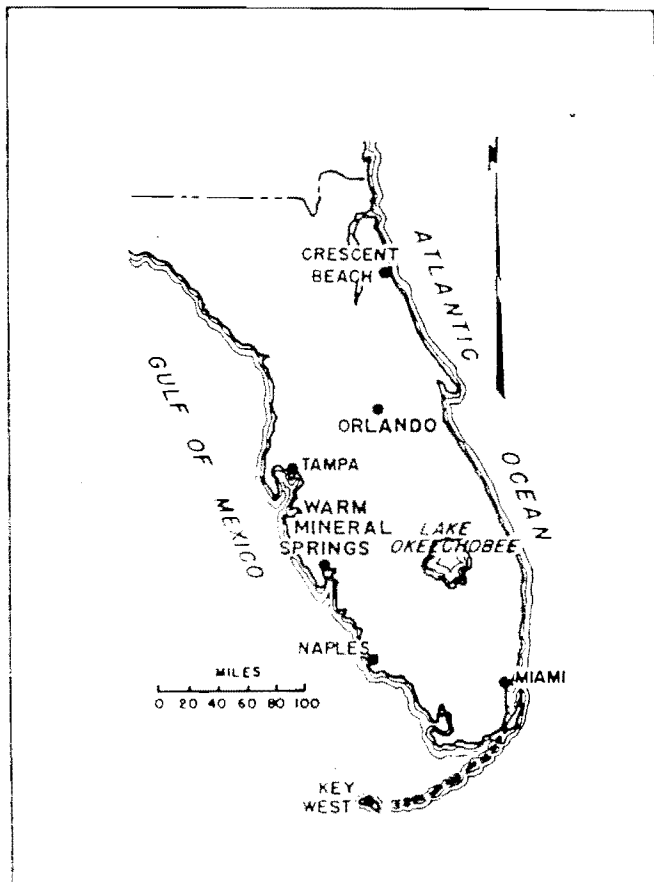


Fig. 1 - Oblique aerial photograph of the submarine spring located 2½ miles (4 Km) offshore from Crescent Beach, Florida. Arrow points to the spring boil located to the left of the 48-foot trawler. A U-shaped line of white caps opens to the left as the spring water is carried northwestward by the drift current. Photo by F. A. Kohout, taken March 1965.

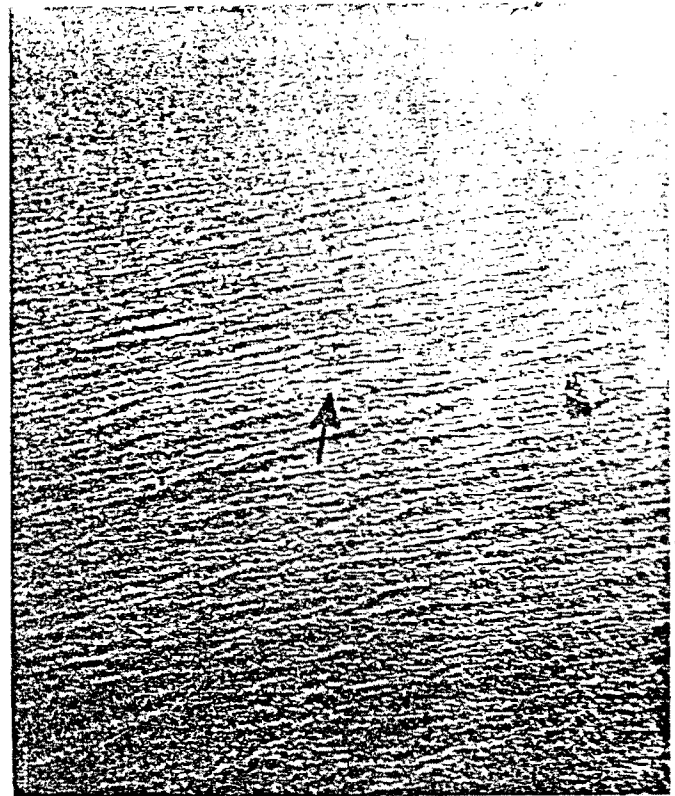


Fig. 2 - Index map of Florida

to the spring is about 55 feet (17 m) below sea level and the water issues from a sink-like crater about 50 feet (15 m) in diameter at a depth of about 126 feet (38 m) below sea level. Using dye as a tracer during SCUBA diving investigations, the discharge was estimated at 1,500 cfs (cubic feet per second, 42 m³/sec) by H. K. Brooks (1961). Comparison of the chloride concentrations at the bottom and top of the water column suggested that only 1/40 of the total upwelling at the surface was spring water. The remaining 39/40 of the upwelling water was sea water that had been sucked in and mixed convectively during the ascent of the spring water to the surface. This indicates that if the discharge is weak or if it takes place at great depth (deeper than about 200 meters), the dispersion and mixing with sea water may obliterate surface evidence of the submarine spring. Remote sensing would have limited application under those circumstances.

Figure 3 is a vertical aerial photo of the Crescent Beach submarine spring taken in October 1959, about 5 1/2 years prior to the photo of Figure 1. In 1959, the spring produced highly turbid water and the well-developed

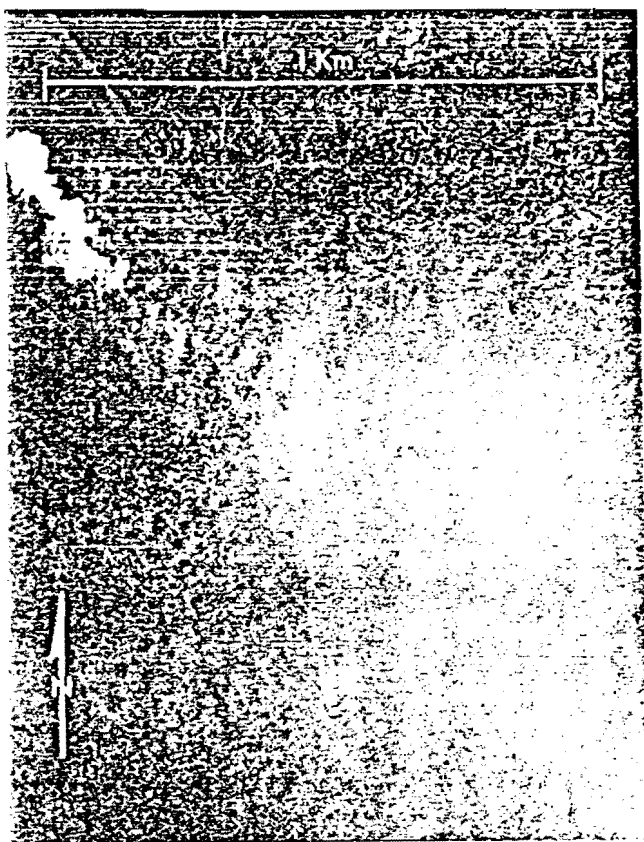


Fig. 3 - Vertical aerial photograph of the Crescent Beach submarine spring taken in October 1959. Photo courtesy of George R. Tarver.

turbidity plume was oriented in a southeasterly direction. The photograph taken in March 1965 does not show a strong turbidity plume. Also, the U-shaped line of white caps (Fig. 1) opens to the left as the spring water is carried in a northwesterly direction by the drift current—approximately opposite to the direction shown in the 1959 photo (Fig. 3). Although the data are very sparse, the two photographs suggest the possibility that discharge from the spring may be decreasing with time. This decrease may correlate with increased pumpage in the Floridan aquifer (artesian) underlying the mainland. On the other hand, ephemeral changes in discharge may be occurring from seasonal changes in ground-water levels or from tide and wind action and changes of this nature can be recognized only by frequent repetitive observation. The EROS (Earth Resources Observation Systems) program of remote sensing by sun-synchronous satellites holds promise for identifying the nature of the changes which now can only be suspected because of the sparse data presently available.

Non-Artesian Aquifers

The occurrence of submarine springs in non-artesian aquifers is quite common and anyone who has visited the seashore may well have observed the phe-

nomenon without realizing it. There is good reason for this—submarine discharge from non-artesian aquifers is so obscure and imperceptible in most cases that one must resort to chemical analysis to be certain that his eyes have not deceived him. Such discharge generally occurs as slow, dispersed seepage on the exposed intertidal flat at low tide and also for considerable distances offshore beneath the sea. This is shown by the flow lines of Figure 4 which are based on flownet analyses

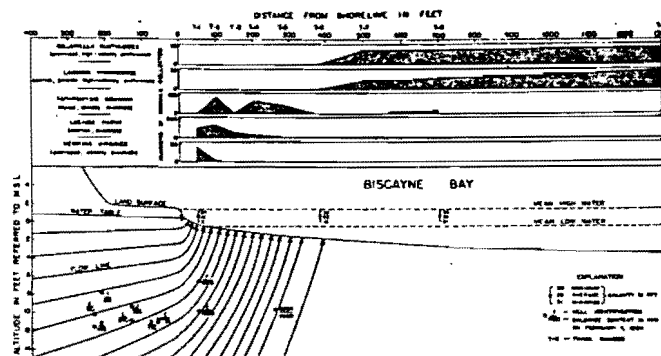


Fig. 4 - Cross-section showing ground-water flow pattern underlying Biscayne Bay at Miami, Florida, related to distribution of selected animals (adopted from Kohout and Kolipinski, 1967).

in the Biscayne aquifer at Miami, Florida (Kohout, 1960, 1967). Figure 4 also shows that the abundances of brackish-water species decreases seaward whereas the abundance of typical sea-water species increases with distance from shore-line. This biological zonation is a consequence of the upward percolation of relatively fresh ground water through the sea floor near shore (Kohout and Kolipinski, 1967). The most noticeable zonation, however, is reflected in the attached plants and sessile animals and can be recognized by the earliest of all remote-sensing techniques — simple aerial photography. For example, the transition between *Diplanthera* and *Thalassia* sea grass is plainly visible in Figure 5. The dark zone at a distance of less than 200 ft (60 m) from shore is almost a solid mat of *Diplanthera wrightii* grass along with a significant amount of a green alga, *Betaphora oerstedii*. The light zone, extending seaward from the transition line (indicated by the arrow) consists primarily of the marine turtle grass, *Thalassia testudinum*.

Thus biological zonation on aerial photographs or multispectral scanner imagery, when properly correlated with ground-truth identification, can serve as a very sensitive tool for remote sensing of submarine springs and of underlying hydrologic phenomena.

SUBMARINE SPRINGS OF JAMAICA

In a cooperative project with the United Nations Development Programme and the Jamaica Geological Survey Department, the National Aeronautics and Space Administration took more than 17,000 frames of color and infrared-color photography and thermal infrared imagery of Jamaica and its coastal waters in April, 1971. The writers of this report made ground-truth investigations for correlation with the remote-sensing-data collected during overflights of the island by a C-130 aircraft at altitudes of 3,000 to 25,000 feet (915-7605).

The main ground investigation was concentrated at Discovery Bay on the north-central coast where numerous submarine springs were known to occur. Also, a one-day reconnaissance investigation was made of

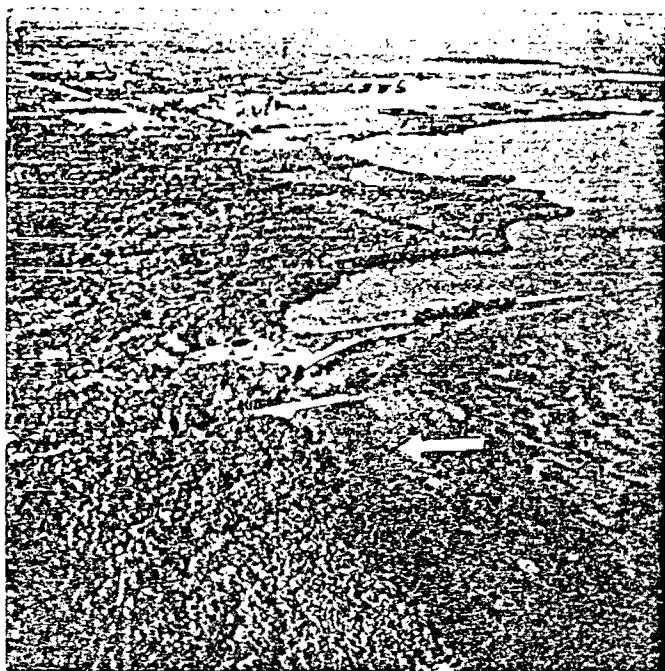


Fig. 5 - Aerial photograph showing the transition between *Diphanthera* (dark) and *Thalassia* sea grass (light). Photo by Richard A. Wade.

reported submarine-springs in the Alligator Pond area on the south coast of Jamaica, about 50 miles (80 km) west of Kingston. The objective was to gather data on temperature, salinity, and discharge of submarine springs for extrapolation to much larger areas of the remote-sensing coverage.

Geological and Geomorphic Features

In general, igneous and metamorphic rocks of Cretaceous age form the central core of the island of Jamaica. This mountainous backbone is flanked on the north and south by limestone deposits of Eocene and Miocene age that are several thousand feet thick in some areas. Percolating ground water has dissolved the rock to form one of the classic karst limestone occurrences of the world by collapse of underlying cavern systems.

Figure 6a shows black and white prints of color-infrared aerial photos of Discovery Bay. The oblique aerial photo looks northeastward over the Discovery Bay Marine Laboratory (buildings in cleared area in foreground).

The coralline barrier reef, which is awash at low tidal stages, has been breached by a channel to permit the entrance of bauxite ore ships. A small sinkhole about 70 feet (21 m) deep forms the circular Blue Hole in the center of the reef. Sinkholes below sea level are commonly called Blue Holes because of their color relative to the surrounding shallow sand or limestone sea floor. The water around the periphery of the Blue Hole is 12 to 15 ft (4-5 m) deep and many

submarine springs occur between the Blue Hole and the shoreline. Discovery Bay itself is the remnant of a much larger sinkhole. The maximum depth of Discovery Bay is about 170 feet (52 m) below sea level.

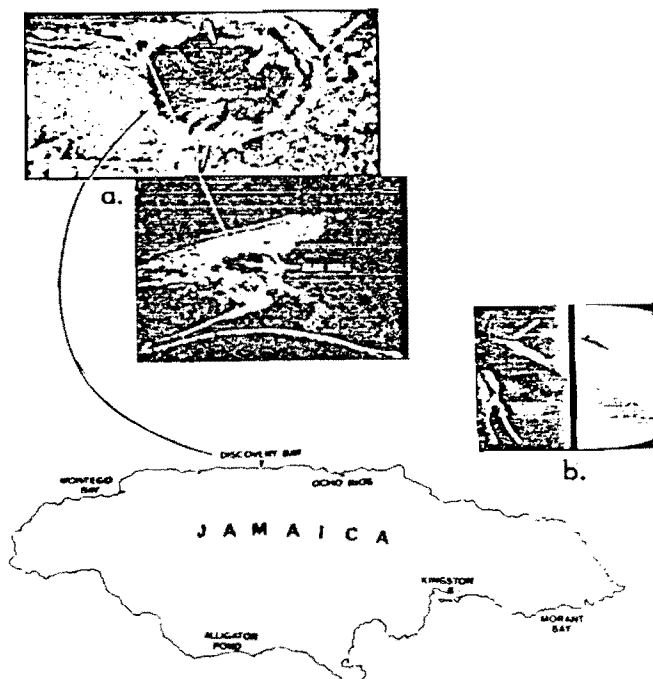


Fig. 6 - Black and white prints of:
a. Color-infrared photos of Discovery Bay
b. Infrared imagery (8-14 micrometers) of a thermal anomaly east of Ocho Rios, Jamaica.

Polyethylene Tent Experiment at Discovery Bay--

Of particular interest to this paper are the techniques employed to obtain data on the ground-water discharge. It should be appreciated that extremely rapid mixing (visually recognized underwater by a variable index of refraction or « heat-wave » zone) occurs after the spring water exits from the sediment. The primary hope of getting an accurate indication of quantity, temperature, or salinity for the discharging water lies in isolation of the spring water from the sea water that is sucked laterally along the bottom into the upwelling water column (Fig. 7a).

To accomplish the isolation, a tent was constructed from 6 mil (0.006 inch, 0.15 mm) polyethylene film (Fig. 7b). One edge of the originally square sheet was wrapped around a garden hose and taped and stapled securely. The garden hose was then screwed into itself to form a closed loop. The remaining part of the sheet was cut in a triangular shape to form a truncated cone (Fig. 8a).

On the first attempt to capture a spring, a 3-inch (7.5 cm) diameter pipe was cinched to the apex of the tent. This caused a buildup of back pressure on the spring so that the spring stopped flowing and discharge broke out all around the outside of the tent. This experience forced the realization that the entire bottom of Discovery Bay was highly permeable and that visible discharge tended to be concentrated where a slightly higher permeability existed only until disturbed

In fact, transient on-off flows of the spring occurred from the mere stirring of the slightly silted bottom by the divers's fins.

As the permeability of the bay bottom would not

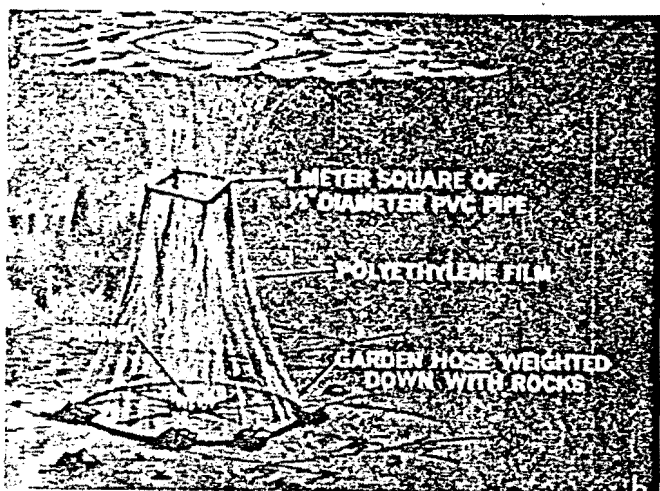
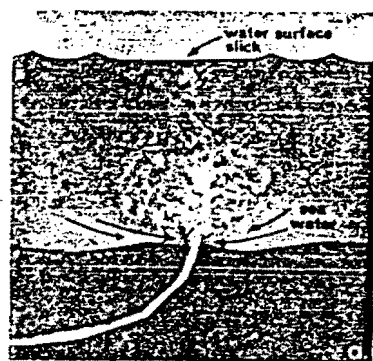


Fig. 7 - a. Diagram of a hypothetical submarine spring showing principle involved in rapid intermixing with sea water.

b. Diagram of polyethylene tent for isolating spring from influx of sea water. Sketch by Walter Popaden, USGS.

permit the buildup of any back pressure, the polyethylene tent was modified with 1/2 inch (1.3 cm) diameter plastic pipe to provide a one-meter square opening at the top (Fig. 8b). The plastic pipe is airtight and bouyant and tends to hold the tent in an erect position when submerged. The garden hose at the bottom of the tent was filled with water to reduce buoyancy and was anchored down with rocks over the spring (Fig. 8c). The haze in the water results from lime silt stirred into the water by the diver.

Figure 8d is an underwater photo showing Norman Copeland, superintendent of the Discovery Bay Marine Laboratory, carrying temperature and salinity probes down into the tent. The sides of the tent tend to be bowed inward due to the higher hydrostatic pressure of the more dense sea water outside the tent. Measurement of velocity of the water passing through the square discharge section can be estimated from movement of fluorescein-dye released from a plastic squeeze bottle. The discharge is then calculated from the formula $Q = Av$, where Q = discharge, A = area,

and v = velocity. The velocity in this particular test was about 1/2 foot per second (15 cm/s). The discharge then would be about 4.5 cubic feet per second (1/6 m³/s). This water is by no means completely



Fig. 8 - Photographs showing:

- Polyethylene tent during construction.
- Preparing the tent for emplacement over a submarine spring.
- Anchoring the bottom of the tent with rocks.
- Diver carrying salinometer and temperature probe into tent for measurement. Photos by F. A. Kohout.

fresh but is heavily contaminated by salt water that penetrates the permeable bay bottom around the tent.

The cell of the Beckman Salinometer (1) was placed on the bottom inside and outside the tent for comparative measurement of temperature and salinity as follows:

	Temperature °C	Salinity g/l
Inside tent	29.0	32.8
Ambient sea water outside tent	28.4	34.0

Although folklore commonly holds that springs are cool, they may have any temperature even within a given body of water such as Discovery Bay. Shallow springs may be warmer than deep springs or vice versa. The remote sensing overflights occurred at the end of the dry season and at the time of year when ground-water temperatures were about the same as the bay water. Large temperature differentials did not exist but the ground water was slightly warmer than the ambient sea water. The relatively high salinity of the spring water (32.8 g/l) indicates that considerable mixing occurs beneath the bay bottom even before the ground water discharges through the sea floor.

Any interpretation of the remote sensing results must bear this fact in mind: water temperatures of the various source water bodies are not constant and there is no invariable functional relationship between temperature anomalies detected by a thermal (IR) scanner and the discharge of a submarine spring. On the other hand, the occurrence of an anomaly directs attention to areas needing further investigation. In this regard, a significant thermal anomaly was discovered in IR imagery of the north-east coast after the field investigation was completed. Figure 6b is a black and white print of the imagery after color enhancement at two different intensities by a computer in the two halves of the photo. The long upper triangle is caused by discharge from a surface stream. However, the small wedge indicated by the curved arrow does not correlate with a surface stream. This anomaly is presumed to be evidence of submarine ground-water di-

from a broad band near the shoreline to a point to form a triangular shaped wedge.

Alligator Pond Area

A reconnaissance investigation was made in the Alligator Pond area about 50 miles (80 km) west of Kingston, Jamaica. Turbidity of the water was excessive but visual inspection from the boat localized one area for investigation by SCUBA diving. The spring orifices were about 3 or 4 inches (7.5-10 cm) in diameter and were probed to a hard bottom about 2 feet (0.6 m) below the bay bottom. Near the spring holes, the bottom sediments consisted of gravel where the fines had been washed out by ground-water discharge.

After exiting from the hole, the relatively fresh spring water and sea water are rapidly mixed together by the boiling motion of the water above the spring orifice (Fig. 7a). Mud and seaweed are entrained in this circular roiling motion and visibility is reduced to about 4 inches (10 cm) near an orifice, of which there are many.

The discharge area appeared to be located opposite a groove and notch in the bluff rising up from the seashore (Fig. 9a). While on the site, the groove was identified by careful inspection of the aerial photo of Figure 9c. Later, stereoscopic photo interpretation showed that the groove correlated with a linear feature trending north-south, roughly perpendicular to the shoreline (identified by the leader from Fig. 9a to 9b). In the offshore area (Fig. 9c) a number of acute-angled triangular shaped plumes (expanding to the west) can be recognized. The heads of these plumes roughly line up with several linear features on land and this suggests that the submarine springs are localized by geological occurrences, possibly faults or joints in the underlying rock.

After considerable difficulty because of poor visibility and the buoyant effect of the upwelling water, underwater samples were collected at the spring discharge point by squeezing a plastic bottle flat, then opening the cap and expanding the bottle in the spring hole. Chemical analysis of the spring water is compared with that of sea water in the following table:

In mg/l	SiO ₂	Ca	Mg	Na	K	HCO ₃	CO ₃	SO ₄	Cl	NO ₃	CaCO ₃	pH
Spring water	6.0	404	563	4500	174	360	0	1130	8400	18	3400	7.8
Sea water	.0	426	1320	11000	400	128	0	2600	19760	.0	6640	8.0

scharge and would be a candidate for further study.

Concerning the triangular shape of the anomalies, the infrared imagery shows only a surface thermal pattern. Though fresh water spreads out over the more dense sea water as a fan-shaped, relatively thin film, the temperature difference between the two fluids is continuously reduced by mixing and radiation of heat. Greatest seaward extent of thermal contrast (the point of the wedge) occurs along the thread of greatest seaward velocity of the fresh water. Thus, as sensed in the infrared imagery, the thermal pattern converges

Because seaward-flowing ground water entrains sea water by a cyclic-flow mechanism within the substrate of a coastal aquifer (Kohout 1960, 1967), it is not determinable whether the sample (half as salty as sea water) was contaminated or whether it truly represents ground water discharging through the sea floor. The nitrate (18 mg/l and silica (6.0 mg/l) of

(1) The use of grand names in this report is for identification only and does not imply endorsement by the U.S.

the spring water are unusually high and in no way compare with sea-water concentrations. The sea-water control sample shows normal sea-water concentrations (as compared with Sverdup et al, 1942, p. 220) with a magnesium-to-calcium ratio of about 3; 1. The corresponding 1 : 1 Mg to Ca ratio of the spring-water sample demonstrates the characteristic

S U M M A R Y

The sea very effectively masks submarine discharge and direct observations are difficult and expensive. The development of remote sensing instruments in recent years provides a possible solution to the difficulties. Frequently, a turbidity plume is thrown up as fresh water mixed with sea water boils up from the sea floor. Aerial photographs of a submarine spring located 2-1/2 miles (4 km) offshore from Crescent Beach on the northeast coast of Florida suggest that flow from the spring may be decreasing in intensity with time. This decrease may correlate with increased pumpage in the artesian Floridan aquifer underlying the mainland. On the other hand seasonal changes in ground-water level, tide, or wind action may produce ephemeral changes in discharge that can only be recognized by repetitive observation. The EROS (Earth Resources Observation Systems) program of remote sensing by sun-synchronous satellites may identify the nature of the changes, which now can only be suspected because of the sparse data presently available.

The submarine springs of the north coast of Jamaica discharge primarily clear water from karstic limestone. In contrast, the submarine springs of the south coast appear to discharge from sand and gravel aquifers. Turbidity plumes that appear to correlate with linear geologic features are clearly visible in the aerial photography of the Alligator Pond area.

The existence of a submarine spring suggests that an aquifer may be underdeveloped and that wells might be drilled into permeable zones on the mainland to capture the water before it reaches the sea. In this regard, remote sensing of submarine springs can fulfill at least two useful functions: (1) the discovery of submarine discharge may help to identify geologic or geomorphic structures on the mainland where there would be high probability of drilling successful wells and (2) periodic observation of the thermal or turbidity anomalies associated with a submarine spring can serve as an outpost system for monitoring hydrologic changes brought about by future exploitation of the aquifer.

Acknowledgements. The investigations in Jamaica were sponsored by the United Nations Food and Agriculture Organization in cooperation with the Jamaica Geological Survey and the National Aeronautics and Space Administration. The writers wish to thank the following individuals for their contributions to this paper: Normal Copeland, David Wozab, John Williams, Thorant Hardware, Merritt Bender, Morris Deustsch, Walter Popaden, Ann Csonka, Robert E. Hill, Daniel G. Anderson, Virginia P. Carter, G. Warren Leve, and George R. Tarver. Peter Reason and Vicki Gaut of the University of West Indies aided in SCUBA investigation of the Alligator Pond submarine springs.

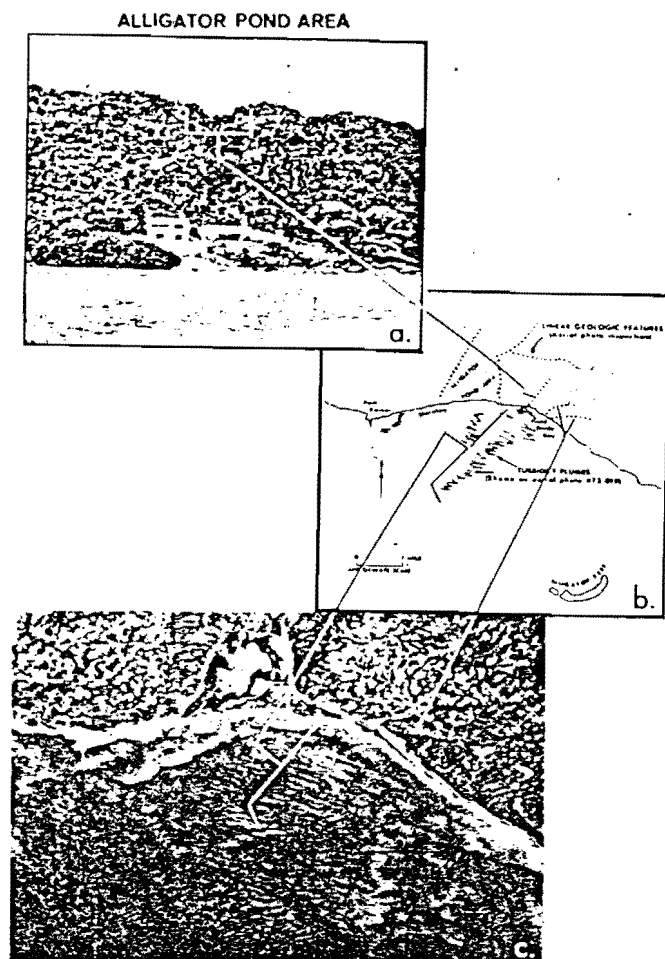


Fig. 9 - Correlation of submarine springs with geologic features in Alligator Pond area:

- Photograph of groove in hill behind house which appeared to correlate with offshore submarine springs.
- Linear geologic features from aerial-photo interpretation.
- Aerial photo showing turbidity plumes which appear to line up with groove behind house.

decrease of this ratio commonly found in coastal ground-water. In spite of the above differences, an admixture of sea water in the spring water cannot be ruled out.

Temperature data obtained with the Beckman salinometer were inconclusive because of the rapid mixing. However, by the feel of the hand, the temperature of the spring water at the orifice was estimated at 1/2 to 1 °C cooler than the ambient temperature of the surrounding sea water. From these observations, a diffused, cool anomaly would be expected on daylight IR imagery.

REFERENCES

- BROOKS, H. K., 1961, The submarine spring off Crescent Beach, Florida: *Quarterly J. Florida Academy Sciences*, v. 24, no. 2, p. 122-134.
- HENRY, H. R., and KOHOUT, F. A., 1972, Circulation patterns of saline groundwater affected by geothermal heating as related to waste disposal: *Am. Assoc. Petroleum Geologists Memoir* 18, p. 202-221.
- KOHOUT, F. A., 1960, Flow pattern of fresh and salt water in the Biscayne aquifer of the Miami area, Florida: *Int. Assoc. of Scientific Hydrology*, Pub. no. 52, p. 440-448.
- KOHOUT, F. A., 1965, A hypothesis concerning cyclic flow of salt water related to geothermal heating in the Floridan aquifer: *Trans. New York Acad. Sciences*, v. 28, no. 2, p. 249-271.
- KOHOUT, F. A., 1966a, Submarine springs: A neglected phenomenon of coastal hydrology: *Symposium on Hydrology and Water Resources Development*, Ankara, Turkey, Feb. 5-12, 1966, Office of U.S. Economic Coordinator for CENTO Affairs, Central Treaty Organization, Ankara, Turkey, p. 391-413.
- KOHOUT, F. A., 1966b, Submarine springs: *Encyclopedia of Earth Sciences Series*, v. 1, Oceanography, p. 878-883, Reinhold Publ. Corp., N.Y.
- KOHOUT, F. A., 1967, Ground-water flow and the geothermal regime of the Floridian Plateau: *Symposium of the Geological History of the Gulf of Mexico Caribbean Antillean Basin*, *Trans. Gulf Coast Assoc. Geological Societies*, v. 17, p. 339-354.
- KOHOUT, F. A., and KLEIN, HOWARD, 1967, Effect of pulse recharge on the zone of diffusion in the Biscayne aquifer: *Symposium of Haifa, Artificial Recharge and Management of Aquifers*, *Int. Union of Geodesy and Geophysics*, Publ. no. 72, p. 252-270.
- KOHOUT, F. A., and KOLIPINSKI, M. C., 1967, Biological zonation related to groundwater discharge along the shore of Biscayne Bay, Miami, Florida: *Estuaries*, *Am. Assoc. Advancement of Science*, Publ. no. 83, p. 488-499.
- KOHOUT, F. A., and MUNSON, R. C., in preparation, Geothermal spring off Florida west coast: *Am. Assoc. Advancement Science*.
- PAUSANIUS «Description of Greece», 1918, translation by W.H.S. Jones: *Harvard Univ. Press*, Cambridge, Mass., 4 vols.
- SVERDRUP, H. V., JOHNSON, M. W., Fleming, R. H., 1942, *The Oceans*, *Prentice-Hall, Inc.*, N.J., 1087 pp.
-