UPRICO/WRRI/PR/71/29/1

SUBMARINE SPRING EXPLORATIONS: NORTHWEST COAST OF PUERTO RICO

Project A-029-PR

by

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"The work upon which this publication is based was supported in part by funds provided by the United States Department of the Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379."

November, 1971

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ABSTRACT

In an attempt to delineate areas of submarine ground water discharge along the northwestern coastal area of Puerto Rico, a series of aerial photographic missions and near coastal conductivity traverses were carried out. It was also an objective of the photographic missions to establish that the use of small format (35 mm) photography, utilizing Ektachrome Infrared and Ektachrome X film, is a fruitful approach to water resources investigations for small agencies.

Three spring areas were found using a trailing specific conductivity probe from the Institute's 34 foot research vessel, the R/V Gaviota. Two isolated areas at 18° 28' 12" N' and 67° 10' 12" W. and 18° 30' 00" N. and 67° 09' 08" W. were found to issue from the pure massive Aymamón Limestone, while the third area yielded a large areal complex of vigorous shoreline and submarine springs at Borinquen Beach at Ramey Air Force Base. The specific conductance of the discharging ground water was 900 μmhos/cm with a constant temperature of 77°F. The ambient sea temperature was 83°F. Additional possible spring areas were indicated at El Tunel, Punta Peñón, and at Hatillo but were not positively identified as submarine ground water discharge. The specific conductivity system was found to be quite sensitive and more than satisfactory.

The results of the aerial photos of the spring areas did not positively indicate their presence; however, large blurry areas could be seen in the vicinity indicating that the differences of indices of refraction between sea water and inflowing ground water may be detected. The films also demonstrated their effectiveness in water resources areas of interest as, pinpointing pollution sources and defining their areal extent, the potential of quantitative determination of sediment transport and influence

of ocean debouching rivers, location of seepage areas and the action of waves along the beaches and the sharp determination of near coastal ocean bottom topography and geologic structures due to the fine detail and excellent water penetration ability of small format, Ektachrome Infrared and Ektachrome X film.

INTRODUCTION

One of the factors in a water budget of an island hydrologic system, exemplified by the limestone hydrologic province of the northwestern portion of Puerto Rico, is assessing that portion of the ground water flow that is lost to the sea via submarine springs, or springs and seeps that occur at the shore. By compiling water levels in the ground water systems and subsequent interpretation of a hydrologic map of the province in question, estimates can be made regarding the quantity of ground water discharging to the sea. Knowledge of the discharge characteristics of ground water into the sea should render the hydrologic equation for the province more relevant as well as provide clues to the movement of underground waters within the limestone system. There is a paucity of water level data in the northwestern portion of the Puerto Rico, making estimates of ground water discharge to the sea very difficult, as well as providing few clues to the pattern of ground water movement in that area. If information on the nature of submarine or coastal ground water discharge were known along the north and northwestern coasts, then estimates of the nature and the quantity of ground water flow could be enhanced.

Kohout, 1966, reported in a Cento paper that very little investigations into the hydrological phenomena of submarine springs were being conducted. Prior to this paper, the most notable investigations of submarine spring occurrences were conducted off the coast of Lebanon by the R. M. Parsons Co. (Parsons, 1963). Since then the majority of studies have centered on using thermal infrared detectors to locate areas of submarine ground water discharge. Robinove, 1966, indicated, however, that projects were being planned to utilize photography to identify areas of ground water discharge. Several researchers have comprehensively used color and color infrared photography in near coastal and estuarine studies indicating that the utilization of color infrared film to delineate waters of different physical character is fruitful (Anderson, 1969, Schneider and Kolipinski, 1969, and Pestrong, 1969).

Submarine springs were indicated during near shore traverses using a conductivity probe in Hawaii by Peterson and Lao, 1969, with good results. The need of locating areas of submarine ground water discharge along certain coastal portions of Puerto Rico, coupled with the realization that there has been an increasing demand for rapid and relatively low cost means of conducting large scale water resources investigations by small agencies suggested the research. Due to the extensive area to be covered, it was decided to use color infrared and ordinary color film, in conjunction with a conductivity probe, in an attempt to delineate areas of submarine ground water discharge along this important coastal strip.

LITERATURE REVIEW

The advantages of investigating various phenomena represented on the earth surface from the air, has long been recognized. With the advent of photographic technology man was able to photograph the earth's surface and obtain a permanent record of the terrain of interest. In recent years he has been able to select portions of the electromagnetic spectrum to view the earth's surface in order to provide more positive identification of the phenomenon he is interested in; however, use of the aerial camera, other than routine mapping, has increased slowly and "the full capability of this sensor for geoscience purposes is not yet fully known", Kinsman, 1965. Pretty much is true today. A paper by Suits, 1960, discusses the nature of infrared radiation and various ways to photograph it to produce a permanent record. Very little is discussed of the near infrared region of the spectrum, the photographic region from 0.7 μ to 1.5 μ, the emphasis of the discussion is centered on the thermal infrared region, photographable only by utilizing thermal IR scanning techniques, specifically in the middle and far infrared ranges that correspond to the atmospheric windows of 3-5 microns and 8-14 microns respectively. Since the declassification of thermal IR imaging methods in 1965, there has been several papers on airborne thermal imaging surveys in water resources investigations.

Robinove, 1965, points to the use of IR imagery in determining thermal loading of receiving waters, submarine spring identification, and ground water discharge. Holter, 1967, discusses thermal IR imagery in the 8-14 micron range, in respect to active geologic processes, sea ice analysis, and coastal circulation patterns. Matalucci and Abdel-Hady, 1968, Van Lopik, Pressman, and Ludlum, 1968, and Taylor and Stingelin, 1969, presented excellent papers on the use of thermal IR scanners in the fields of environmental engineering, and water resources, indicating that important data on the sources and distribution of thermal pollution, ground water discharges along bodies of water and inland watersheds, the delineation of subsurface stream channels and soil moisture differences, and the delineation of geologic structures such as fault and fracture traces could be obtained. Lepley and Palmer, 1967, and Adams, Lepley, Warren and Chang, 1970, demonstrated the use of AGA Thermovision, a thermal IR scanner in the 2 to 6 micron range, in detecting submarine springs in Hawaii as well as the practical uses of the systems in delineation of soil moisture distributions and urban surveys.

The use of color film and color infrared film in water resources has not enjoyed widespread use. Robinove, 1966, indicated that color photography is valuable in identifying and mapping of submerged features as well as identifying ground water discharge areas along rivers, coasts, large lakes, and inland areas where vegetative indicators should allow identification. Anderson, 1969, demonstrated that coastal current patterns could be clearly differentiated on color IR film since the water images on the film show up as various shades of blue rather than differing shades of greenish-brown as in ordinary color film. Schneider and Kolipinski, 1969, indicated that ground water discharging beneath the sea with sufficient velocity may induce turbid conditions that will show up on IR color film. Pestrong, 1969, demonstrated that color infrared film (Ektachrome Infrared) was superior for the differentiation of tidal marsh vegetative types. The report also indicated that color IR delineated areas of soil moisture differences corresponding to buried tidal channels, although not as well in this regard as using filter combinations to partition the spectrum from 400 to 825 mμ on Infrared Aerographic film. Definitive papers by Kiefer and Scherz, 1970 and 1971, clearly demonstrated that the use of small format (35 mm) photography will be a most useful and economical tool in water resources studies from small aircraft. The detection and monitoring of water pollution, the study of stream flooding, mapping of aquatic plants in lakes, and siltation and algal growth in lakes were effectively studied utilizing small format film.

There has been a paucity of data on the effectiveness of aerial photography in locating areas of ground water discharge into open bodies of water. In the past, the majority of water resources research amenable to remote sensing methods has been carried out by large agencies using thermal IR sensors, since ground water discharge into the oceans, lakes, and streams are accompanied by temperature differences. Until the advent of AGA Thermovision, studies of open water temperature distributions has been quite out of reach of most small agency budgets. Stewart, 1969, reported that a fresh water spring discharging into the Hillsborough River in west-central Gulf coast of Florida was clearly discernable on Ektachrome Infrared Aero film taken during NASA Mission 67 with an RC-8 aerial camera. The photos clearly show the discharge from Sulphur Springs (light blue) discharging into the turbid (dark green) Hillsborough River for about 100 feet. The river depth at the point of discharge was 2-3 feet, as was the river depth at the point of discharge. The spring water was highly mineralized relative to the river water and was probably derived from the predominately artesian Floridian limestone aquifer that underlies the study area. The discharge of the Sulphur springs was approximately 33 mgd (million gallons per day). Hunn and Cherry, 1969, reports that Crystal Beach Spring along central Gulf coast of Florida was clearly depicted in the photography obtained during NASA Mission 81. The reported film results were unfiltered Ektachrome Aero 8442 aerial film. The spring appeared lighter in contrast to the surrounding ocean water although the photo reproduction does allow much color differentiation. The authors reported that all known offshore springs and four sinkholes were identified and that the Ektachrome Aero 8442 was "the most useful sensor tested for this purpose." The authors also mention that the color infrared (assumed to be Ektachrome Infrared Aero 8443) worked equally well in shallow water; however, the color IR imagery was not published so no comparisons could be made. In the light of the fact that information in the photographic infrared would depend on variations, in water coloration, organic content, microscopic plant life and suspended solids in the spring area, it would have been exceedingly interesting and of value to compare the Ektachrome and Ektachrome IR imagery obtained by Hunn and Cherry.

GEOHYDROLOGIC SETTING OF NORTHWESTERN COASTAL PUERTO RICO

Puerto Rico lies within the trade wind belt and is classified as a trade wind littoral climate exhibiting some characteristics of a tropical marine and continental climate (Koeppe and de Long, 1958). The Island thus situated, receives very high rainfall in the mountainous eastern region that is orographically induced, and receives diminishing amount west-ward, averaging to some 60 inches in the north west.

The north and north-western hydrologic province, with which this report is partially concerned, is bordered on the east by the Rio Grande de Arecibo and on the west by Mona Passage. The southern portion of this province can be generally seen from Figure I and essentially corresponds to a line connecting the towns of Aguadilla, San Sebastián, and Lares, then east to Rio Grande de Arecibo. The province resembles a broad limestone plateau that is elevated along its southern portion and, in part, flanks the Cordillera Central. This elevated southern portion receives upwards to 80 inches of rainfall per year.

The central core of Puerto Rico, that comprises the "backbone" of the Island, the Cordillera Central, is composed of volcanic and intrusive rocks of late Cretaceous and early Tertiary ages. This complex core is flanked by clastic sediments and limestones deposited during the Tertiary Period.

The Tertiary geologic section of the northwestern coast from top to bottom of the sequence, starts with Camuy Limestone, followed by the Aymamón and Aguada Limestone, the Cibao Formation, the Lares Limestone, the San Sebastián Formation, and Undivided Marine Limestones. The Aymamón Limestone is quite pure and is responsible for the extremely rugged karst topography that lies generally along the latitude of Aguadilla, extending to the borders of the province. This region is characterized as a mogote karst topography exhibiting steep sided conical or dome shaped hills (Briggs, 1968). The Aymamón rests conformably on the Aguada Limestone, a medium grained marine Limestone and less pure than the Aymamón. The Aguada Limestone is responsible for the striking sinkhole karst topography (Briggs, 1968), where it is exposed in a narrow band from Aguadilla to the Río Grande de Arecibo, south of the Aymamón Limestone.

The limestones of the north coastal area offer considerable opportunities for recharge and discharge of ground water. The upland areas are exceedingly rugged exhibiting a mature karst topography. Recharge of these formation is predominately from the high rainfall in the region and goes directly underground via the many solution cavities and fissures that characterize well developed karst regions. According to McGuiness, 1948, recharge rates must be high to these limestones due to their geographical location and purity, consequently the discharge rates are undoubtedly commensurate. In this regard it is of interest to note that streams flowing north over the chalky Cibao Formation vanish into Aguada Formation cliff faces and probably constitute a high percentage of the recharge to this formation. The largest springs in the north coast province occur in the Aymamón and Aguada Limestones (Bogart, Arnow, and Crookes 1964). Along the north west coast a considerable quantity of water has been observed discharging directly into the sea while in other coastal areas, ground water is believed to exit to the sea as submarine springs localized by lagoonal and fine grained alluvial deposits that act as confining layers (McGuiness, 1948).

The geologic quadrangle maps of Aguadilla, Moca-Isabela, Quebradillas-Camuy, and Arecibo show certain geologic information of hydrologic interest. The Aguadilla quandrangle map, compiled by Monroe, 1969, indicates a northwest plunging anticline that dominates the quadrangle and disturbs the structure contours drawn on the Aguada Limestone. The Aguada Limestone is a relatively pure marine limestone and is some 90 meters thick. A general trace of the anticline can be seen in Figure 1.

East of the flexure the structure contours on the Aguada Limestone roughly parallel the north shore of the Island and dip steadily to the north. The Aymamón Limestone rests conformably on the Aguada surface and the thickness of this pure marine limestone is some 190 meters thick. The upper member of the limestone forms the steep cliffs that are characteristic of the coast from Aguadilla to Quebradillas. The cliffs north of Punta Borinquen (Borinquen Beach) that skirt Ramey Air Force Base situated on the extreme northwestern tip of the Island, are some 50 meters in height. The Aymamón Limestone is fairly uniform and relatively undisturbed structurally along the north coast, and generally follows the aspect of the Aguada surface. The Aymamón Limestone at the base of the cliffs at Borinquen Beach strikes northeast-southwest and dips gradually to the northwest at seven degrees.

The undersea outcrop of the Aguada Limestone is probably shallow at Borinquen Beach since two miles south, near the town of Aguadilla, cliffs of Aguada Limestone meet the sea. The lower member of the Aymamón Limestone dissappears from view at the north end of Borinquen Beach, and the upper member forms the cliffs. As one proceeds east towards Arecibo, the Aguada Limestone lies deeper and deeper until the formation must outcrop several hundred meters deep offshore of Arecibo.

The Aymamón Limestone is a water table aquifer, consequently near the sea, some of the wells pump slightly saline water (Bogart, Arnow, and Crooks, 1964). Since the Aymamón Limestone rests conformably on the Aguada Limestone, and the two limestones are relatively pure and are of marine origin, one could expect that the two aquifer systems are hydraulically connected and probably behave as one unit. There is a paucity of well data due to the extreme rugged topographical nature of the northwestern part of the massive northern limestone block, yielding little light on aquifer characteristics and ground water contours. There are virtually only a mere handful of wells that predominately lie along the coast, and offer little information to characterize the total ground water system. The San Juan office of the United States Geological Survey is in the process of completing a hydrogeological survey of the north coast limestone block; however, the lack of well data in the north west section has resulted in extremely generalized water level contouring in that area (Giusti, 1971, personal Communication).

The water transmitting characteristics of the Aymamón and the Aguada Limestones must be considerable. Bogart, Arnow, and Crooks, 1964, estimated, on the basis of similar limestone terranes in Florida, that the composite transmissibility is in the neighborhood of one million gallons per day per foot.

The Lares Limestone outcrops as a rugged karst topography between the towns of Corozal and Lares, resulting in few wells drilled in the limestone, and consequently little is known of the aquifer system. The Lares is probably artesian and the undersea outcrop lies several hundred meters deep offshore of Arecibo. It was recently learned that some pharmaceutical companies on the north coast are utilizing deep wells for waste disposal. Little is known of the disposal systems and the quantities involved; however, the effluent must be disposed into the Lares.

METHODOLOGY

Aerial Photographic Coastal Survey

A Cessna 182 aircraft equipped with a camera hatch, was used for the low altitute coastal aerial photography conducted in this study. A series of seven missions were flown between the towns of Arecibo and Aguadilla to record a land-sea coastal strip on film. Two kinds of 35 mm film was used throughout this phase of the project to determine the efficacy of using small format photography in water resources investigations and to learn of the detectability of submarine ground water discharge on color infrared film.

The color infrared film used was Kodak Ektachrome Infrared, designated as IE-135-20. As the designation implies, 20 exposure rolls were used. This film is identical to the type 8443 used previously by other researchers. A newer color infrared film manufactured by Kodak and designated as type 2443 was not available in 35 mm format. Recent information received by the author stipulated that IE-135-20 was no longer available and is replaced by HIE-135/20 High Speed IR. Ektachrome X, in 20 exposure rolls was utilized in conjunction with the color infrared film. A total of 46 rolls of IE-135-20, hereafter referred to as EIR, and 36 rolls of Ektachrome X, hereafter referred to as EKX, were used in the photography.

A test run was flown at 1000 feet on 5/13/71 to determine a optimum shutter speed and lens opening over various portions to the coast to be covered. Since the majority of the coastline to be photographed was aligned with the sun's' transit across the sky, lighting variations were minimized. It was determined that a shutter speed of 1/250 sec and a lens opening of f/5.7 would produce satisfactory exposures.

These values were corroborated by Kodak's Aerial Exposure Computor, assigning an Aerial Exposure Index of 10 to the EIR film, and agreed with information supplied by Data Corporation (Krueger, 1971, personal communication).

The photography was completed using a Nikon F and a Pentax Spotmatic SLR camera mounted in tandem on a hand held acrylic plastic (Plexiglass) frame such that simultaneous exposure could be taken. The Pentax was loaded with the EKX film and exposed with a Super Takumar Automatic 55 mm f/2 lens and a Skylight (1A) filter. The Nikon F was loaded with the EIR film and was equipped with an Automatic Nikkor 50 mm f/2 lens and a Wratten 12 filter.

The majority of the missions were flown at an altitude of 1500 feet, yielding a scale of approximately 1:8400 corresponding to a ground image of approximately 660 x 1000 feet. The long dimension is perpendicular to the coastline and the land-sea distribution was maintained at roughly one-third land and two-thirds sea surface.

The EIR film is very sensitive to heat hence the film was removed from the refrigerator 24 hours prior to flight time and allowed to come to room temperature. The film was subsequently stored in a small styrofoam cooler and was only removed for camera loading and the return of unused rolls to the refrigerator. A changing bag was used for total darkness loading of the EIR film into the camera during the missions.

The EIR film rolls were numbered from A-029-1 to A-029-46. Since only 36 rolls of EKX film were shot there are some rolls of EIR with no accompanying EKX rolls but in most cases the EKX and EIR rolls are fairly well matched together in time and area covered. Complete coverage from Arecibo to Aguadilla was achieved during three missions with the film cannisters numbered from A-021-21 to A-029-42, and flown on 6/22/71, 6/24/71, and 7/2/71. The last missions on 7/6/71, objective was to ascertain the efficacy of utilizing the film at higher altitudes in respect to color rendition, haze interference, overall appearance of the frames regarding possible spring observation, as well as obtaining the coastal picture in larger scale. The last run commenced at Punta Higuera, the western most point of Puerto Rico, see Figure I and was flown at 5000 ft. The first two missions covered the coastal stretch in two stages, and were flown on 5/21/71 and 6/8/71.

During each mission close coordination was required between the three people in the plane. The photographer was primarily responsible for ensuring that the coastal strip was adequately presented in the camera view finder by issuing commands to the pilot. The pilot's task was made easier by initiating the missions at Arecibo and flying west such that the coastline would be on the pilot's side of the aircraft. Specular reflection was also reduced in this manner. The photographer was instructed to keep a third of the view finder filled with land surface; however, in many instances this criteria was extremely difficult to manage.

Coordination between pilot and camera man steadily improved during the course of the project. Flying at higher altitudes would obviate the difficulty of maintaining optimum land-sea ratios, however, small presentations on the sea surface could be missed.

Coastal Conductivity Survey

The sea going phase of the project involved using a conductivity probe to sense areas of submarine ground water discharge along the northwest coast of Puerto Rico. The near coastal traverses were conducted between the towns of Aguadilla and Arecibo, a distance of some 60 kilometers, see Figure 1. The traverses were accomplished by trailing a conductivity probe along-side the Water Resources Research Institute's 34 foot research vessel, the R/V Gaviota, using a davit and running the vessel at slow speeds. The probe was weighted with seven pounds of lead and was attached to the meter by a heavy duty 200 foot cable and thread through the davit block.

The conductivity instrument was a Beckman RB3-3341 Solu Bridge equipped with a CEL-VS02-2VH20-KP-X10 conductivity cell. The Solu Bridge model allowed the measurement of the entire conductivity range from 40-400,000 micromhos/cm utilizing three cell constants of 0.200,2.00, and 20.0/cm and a range selector switch. The fourth position of the selector switch, temperature, sensed the range from 0-50°C. Measurements of conductivity and temperature could be completed within a matter of seconds.

The conductivity probe was trailed from the moving vessel such that the sensitive end of the probe was within the first 12 inches of sea water. Since fresh water floats on the sea surface the immersion of the probe up to the one foot depth insured an indication of fresh water discharge nearby. In fact the instrument probed to be very sensitive in this regard. In the area north of Aguadilla, a small quantity of sewage effluent from the Urbanization Marbella, cascades on to a narrow strip of beach. The instrument was quite capable of sensing the diluted effluent some 100 ft. from shore. The instrument would also indicate that the probe was passing through a zone affected by a nearby discharging river. The needle would immediately deflect from its null position upon entering the zone of mixing between river and sea water, corroborated by observing the instruments response when changes in sea water color were encountered.

The instrument indicates conductivity changes by a deflection of a small galvanometer needle from its null position. The instrument was nulled before each traverse commenced and was periodically checked throughout each traverse. The average sea water salinity corresponded to 50,000 micromhos/cm yielding 32% from Figure 2. During the traverses the instrument was watched constantly for any needle deflections indicating less saline water surrounding the probe. A search pattern was initiated if the needle deflected to half its range or more.

Four conductivity traverses were planned utilizing the R/V Gaviota between Aguadilla and Arecibo. The first run commencing at the Air Force Crashboat Facility at Aguadilla on 7/14/71, had to be shortened somewhat due to a severe squall that arose after midday suspending further operations in that area, resulting in incomplete coverage. The return trip on 7/15/71 was fully completed. The ramaining two traverses were conducted on 7/17/61 and 7/18/71 and completed. In addition, several months prior, on 2/25/71, the coastal area from Aguadilla to Ramey Air Force Base was traversed as well as short traverses were conducted in the Punta Higuera region on 1/27/71 to investigate near coastal sea surface disturbance reported by Mr. David Hernandez-Acevedo, a prominent fisherman of that area. The disturbance were actually very large "boils" on the sea surface induced by massive movements of fluid from large holes in the flat limestone sea bottom; however, no deflection of the galvanometer needle was observed and the disturbance were assumed to be caused by the heavy sea swells that are indigenous to that area.

The boat captain was generally instructed to maintain a one hundred to two hundred food distance from the shore line; however in many instances this was quite dangerous due to heavy swells along rocky headlands and high cliffs. In this regard it was deemed provident, as an after thought, that the original specifications calling for twin 130 HP diesels was strictly adhered to.

RESULTS AND DISCUSSION

Conductivity Traverses

The springs found as a result of the near coastal survey are summarized below in Table 1.

TABLE I

Date 1971	Location Area Lat.	Long.	Specific Cond. (micro mho/cm)	Salinity (0/00)	Temp. (°F)	Remarks
2/25	18°-28'-12"	67°-10'-12"	22,000	14	78	Col. B. Smith's House
7/14	18°-30'-00"	67°-09'-08"	32,000	20	80	U.S. Coast Guard Lighthouse (rough sea)
7/15	18°-30'-00"	67°-09'-08"	12,000	7	80	U.S. Coast Guard Lighthouse
7/17	18°-29'-42"	67°-09'-18"	12,500	7	79	Borinquen Beach (South)
7/18	18°-29'-42"	67°-09'-18"	10,000	5	--	Borinquen Beach (North) (rough sea) used Gaviota Dinghy

Several perturbations resulting in needle deflections of over 2 division, occurred at three areas during the runs made on 7/17/71 and 7/18/71. On 7/17/71 a search pattern was set up off the western end of Punta Peñón with no results although the needle was responding within one to two divisions. Rough sea conditions prevented close proximity to shore areas. On the following day, needle deflections to one division were encountered near shore at the inlet at Hatillo; however, no results were obtained upon searching. The Gaviota continued towards Rio Camuy and encountered additional needle fluctuations as the river was approached. The erratic behavior and proximity to shore and river precluded detailed search. The same day off the point at Río Guajataca, commonly known as El Tunel, needle fluctuations were encountered to three divisions. Heavy swells prevented close examination and no positive results were obtained. The Río Guajataca is a controlled river and is generally at low stage and clear flowing, and during the traverses a bar blocked the mouth of the river allowing only minor amounts of flow into the sea. Faith in the system was high since the spring areas observed were indicated by erratic needle behavior often as little as one division fluctuations, as in the Borinquen Beach area. As was indicated in the section on Methodology, minor quantities of sewage effluent entering the sea as surface flow from the beach, some 100 feet away, could be easily detected. During most of the traverses the needle remained immobile indicating a very stable sea water conductivity which was to be expected.

The general spring areas, listed in Table I, were later investigated from shore using smorkeling equipment, except the spring at 18°-28'-12" N latitude and 67°-10'-12" W. longitude. This spring issues from the base of 20 ft. cliffs near the house of Colonel B. Smith and effectively renders the offshore area very blurry. By personally handling the probe, readings from 22,000 to 49,000 micro mhs/cm were recorded. The exact source of the outflow was not located but is believed to issue from one of the many cave-like solution cavities of moderate size figuring the cliff faces. North shore swells that are heavy during the winter months, agitated the water preventing detailed, close-in study; however, the conductivity reading and the "tendrils" of waters of different refractive indices, that were quite evident under water, positively indicated moderate ground water discharge there.

The largest area of shoreline and submarine springs was located as bordering Borinquen Beach (see Figure 1) from its northern point to just south of the cliffs of Aymamón Limestone that jut out to the waters edge. These cliffs can be seen looking north from the beach area. Shore springs were observed to be bubbling up vigorously through the loose sand in the surf zone on either side of the Aymamón Limestone spur. The size and number of "sand boils" changed during periodic visits. The maximum number of boils, usually found in clusters of two to three, were not more than 10, and were commonly about 12 inches in diameter. Hand samples were collected and a constant conductivity reading of 900 micromhos/cm was obtained. The temperature was a constant 77°F, while the ambient sea temperature in the bay was 83°F. Some 10 yards north of the cliff spur, the beach area is covered with cobbles and the shore width steadily decreases with passage way increasingly blocked by huge limestone boulders. Areas of ground water discharge can be easily seen emanating from the cobbles and from under the huge boulders.

The waters off the northern perimeter of Borinquen Beach were explored using skin diving equipment. Areas of submarine ground water discharge could be easily spotted due to the clarity of the sea water. The spring that caused the perturbations on 7/18/71, investigated using the Gaviota dinghy, was located some 20 feet offshore and could be seen emanating vigorously behing a prominent limestone rock of low relief in about 4 feet of water. Sand boils were observed along a line of seven feet in length. The ground water issuing from these boils had a temperature of 77°F.

Continuing further north another area of submarine outflow was observed as a cloud of blurry water viewed from the sea surface. The outflow was vigorous enough to form pockets in the sand, some four inches deep around a limestone outcrop surrounded by sand. The water depth was 15 feet and the spring temperature was 77°F. Another submarine spring occurrence was observed in 12 feet of water along the southern edge of the aircraft engine "graveyard" that lie off the steep cliffs bordering the northern edge of the bay. The water temperature of the ground water was 77°F. This area is approximately marked by huge, partially submerged, boulders and covers a wide areal extent. Shoreward of this graveyard, and to the north, there is an extensive area of blurred sea water infering substantial ground water outflow in this area. There are many fjord-like indentations caused by these boulders that would be exceedingly tedious and somewhat difficult to fully explore, however, it is believed that larger spring areas could be found along this rocky perimeter of the bay.

Aerial Survey

Although the emphasis during the photographic missions was placed on obtaining infrared representations of areas of submarine ground water discharge, it was deemed fruitful to endeavor to photograph any feature that would demonstrate the efficacy of utilizing small format photography in water resources investigations. In this regard, features that would depict river pollution, sediment transport, surface drainage, water penetration, shore line morpholology, plant vigor, and ground water see page, were sought after and photographed.

It was learned that even though one could visually discern that what appeared to be adequate terrain illumination, was inadequate insofar as optimum illumination in the infrared range was concerned.

Figures 3 through 6 were taken in the vicinity of the shore spring of 2/25/71 in Table I. The dwelling in Figure 3 and 5 is that of Colonel B. Smith. The photos of Figures 3 and 4 are from EIR film and Figures 5 and 6 are from EKX film. Note the blurry nature of the calm sea in the EIR photographs, somewhat offshore. Since the refractive indices of fresh and ocean water are such that very positive visual differences can be discerned between the two waters, this blurriness could indicate presence of ground water discharge. Differences in plant vigor, emphasized by a decided magenta color for healthy plants, in Figures 3 and 4. Slight indications of blurriness can be seen in the corresponding EKX photographs. Note that the sea bottom detail offshore of the dwelling in Figure 5 is quite well defined and is correspondingly obscured in Figure 3.

The rocky area at the base of the steep limestone cliffs on the north end of the perimeter of Borinquen Beach is depicted in the EIR photograph of Figure 7. Fine bottom detail is shown in this photo; however, little positive inference can be made from the evidence in the photo as to submarine spring location. Some

Figure 3: EIR photo from A-029-29 showing area of 18 28' 12" N. and 67 10' 12" W. and Colonel B. Smith's dwelling.

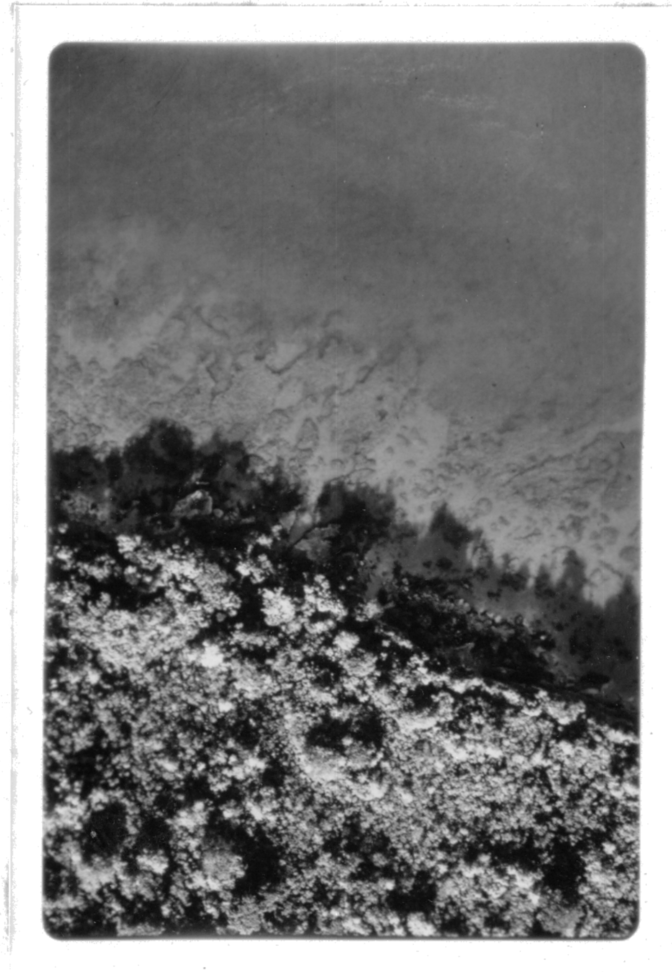


Figure 4: EIR photo from A-029-37 showing area adjacent to Figure 3.

Figure 5: EKX photo from A-029-29 of the area of Figure 3.

Figure 6: EKX photo from A-029-29 of the area of Figure 4.

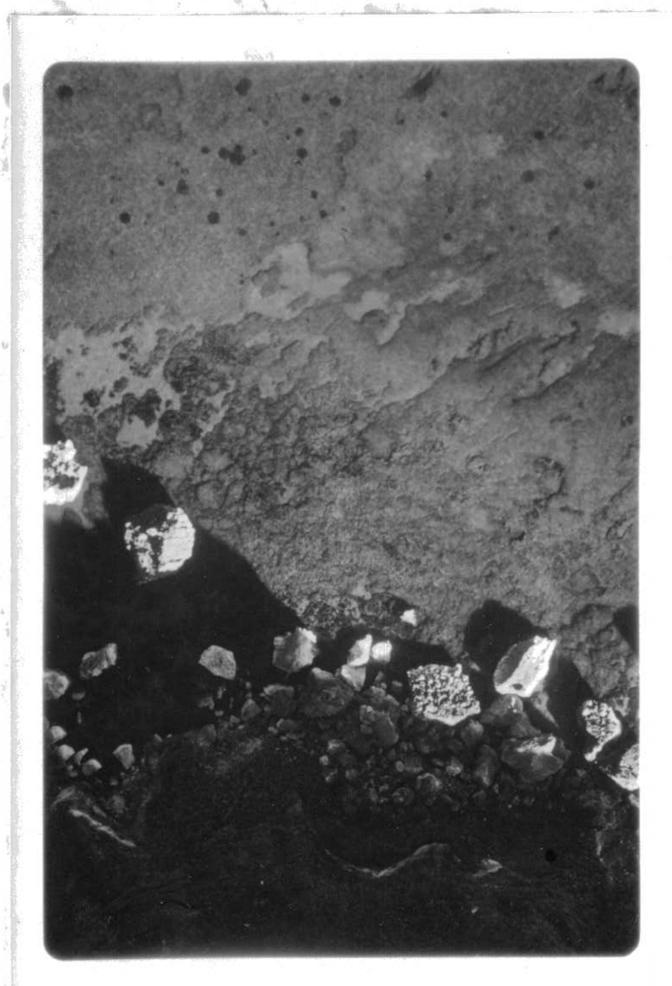


Figure 7: EIR photo from A-029-27 showing area of 18 29' 42" N. and 67 09' 18" W.

Figure 8: EIR photo from A-029-27 showing the cobble beach just south of Surfers Beach of Ramey Air Force Base.

detail across the photo has dropped out, indicating some refractive variation perhaps, but this would be meaningful only with prior knowledge that there was spring outflow in the area. Figure 7 illustrates the effects of insufficient illumination in the shadowy areas. In such cases detail can be gained by overexposing the film during printing.

During the study, various people in the Ramey Air Force Base diving organization were consulted about possible springs off the coastal confines of the installation. The only lead in this regard was a possibility of a ground water outflow occurrence some 50 yards directly offshore of the cobble beach some 500 yards south of Surfers Beach. This area is reached by turning off the paved road to Surfers Beach, on a short dead-end dirt road. The EIR photograph in Figure 8 and the Ektachrome photograph in Figure 9 show part of the cobble beach. Note the blurry area near shore on both photographs. The spring area mentioned was never found and no outflow was observed to coincide with the blurriness on the pictures. Variations in magenta tones in the vegetation cover can be easily noted in Figure 8, indicating a variation in plant vigor there. Figure 10 shows the dirt road and the cobble beach and several hundred feet of ocean. The color rendition is high and water penetration is excellent in this photograph.

Figure 9: EKX photo from A-029-27 showing the southern tip of the cobble beach on Ramey Air Force Base

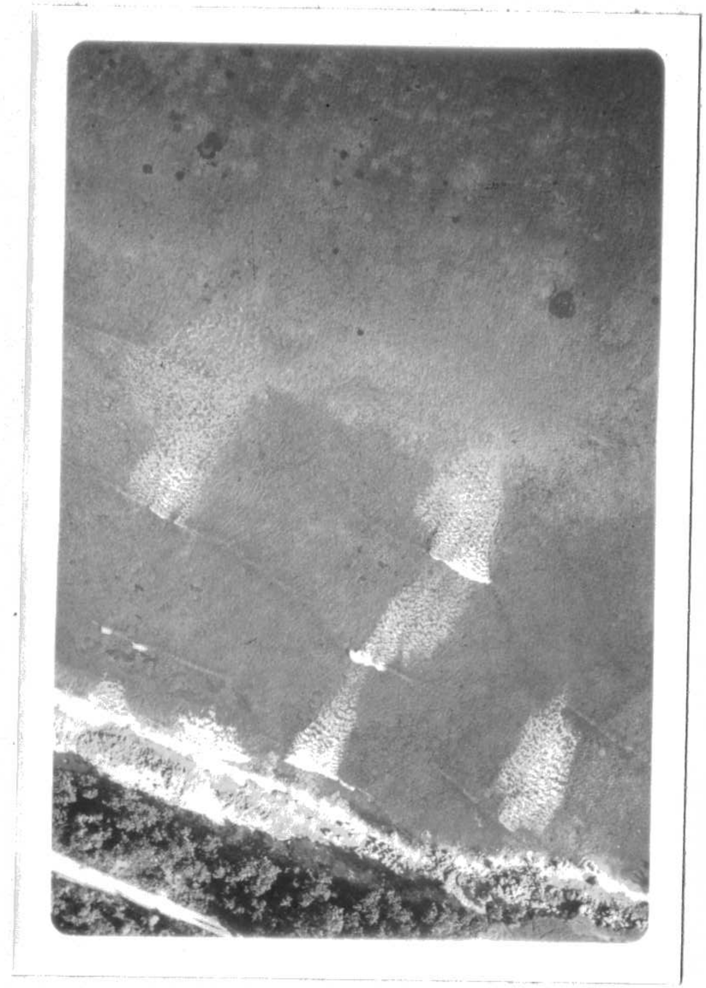


Figure 10: EKX photo from A-029-27 showing the northern portion of the cobble beach on Ramey Air Force Base.

The area over El Tunel was flown to detect the possible submarine spring occurrences there and Figure 11 and 13 depict the point of the mountain spur that is El Tunel on EIR film. Figure 12 is obviously of the same area on EKX film. The clarity of the sea bottom and rock structure can be easily seen on the photographs in Figure 11 and 12. It is difficult to judge the blurriness in Figure 13. The surf zone is fairly well defined; however, the patch in the lower right hand corner and the area at far left center appear to be somewhat unrelated. The blurred zones in Figure 14, just west of El Tunel in which the old railroad bed can be seen in the bottom of the photo, appear to be induced by the surf in that area. The sea-shore transition here is more gradual than the abrupt condition in Figure 13.

No indication of possible submarine ground water outflow can be seen in the inlet at Hatillo depicted on EIR film in Figures 15 and 16. Figure 17 shows an area similar to Figure 15 on EIR film. Wetted sand areas are more clearly defined in the photograph in Figure 15 than in Figure 17, as well as, vegetative growth and vigor assessment. The contrast in the EIR photographs is more pronounced.

Just east of Hatillo the debouchment of the Rio Camuy can be discerned in the photographs in Figures 18 and 19. Figure 19 clearly depicts on EKX film the influence of the silty Rio Camuy water east of the river mouth, and Figure 18 shows the lobate patterns of the river's input to the sea on EIR film. Subsidiary blurriness of the surrounding waters is great due to the strong mixing of the fresh and saline water induced by the heavy swells clearly depicted on the film. Great detail of the areal distribution of silt laden river water can be more readily depicted on EIR photography

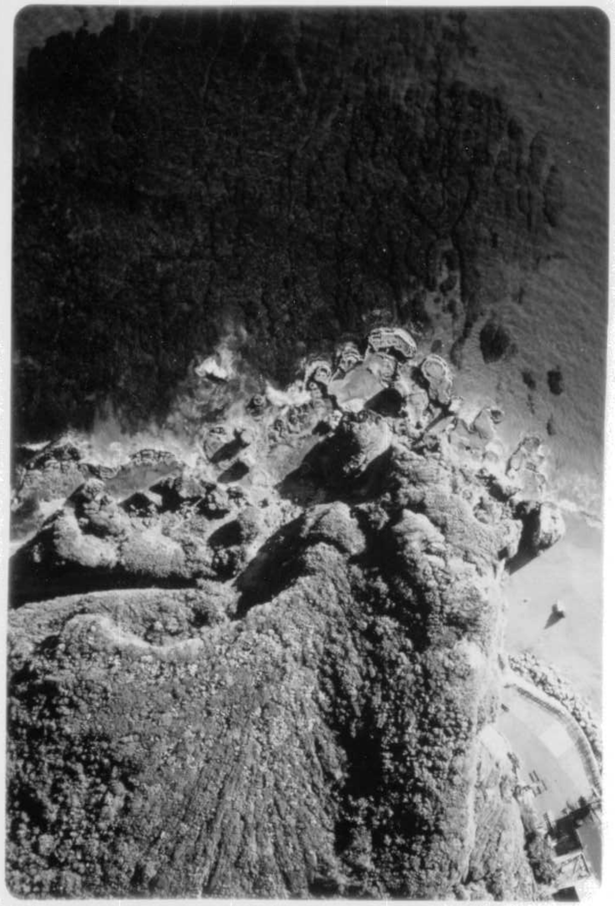


Figure 11: EIR photo from A-029-25 showing the point at El Tunel.

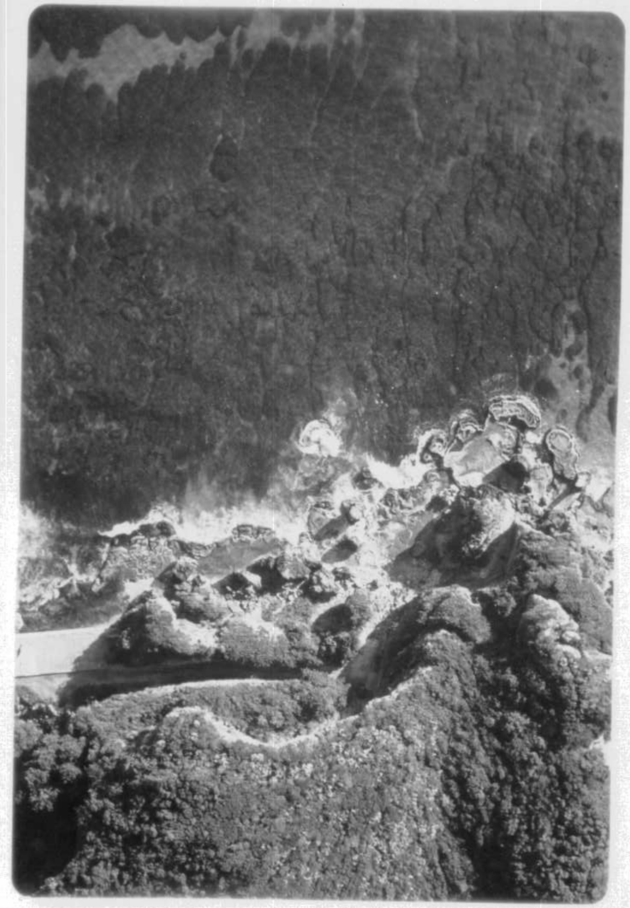


Figure 12: EKX photo from A-029-25 showing the point at El Tunel.

Figure 13: EIR photo from A-029-II showing the point of El Tunel.

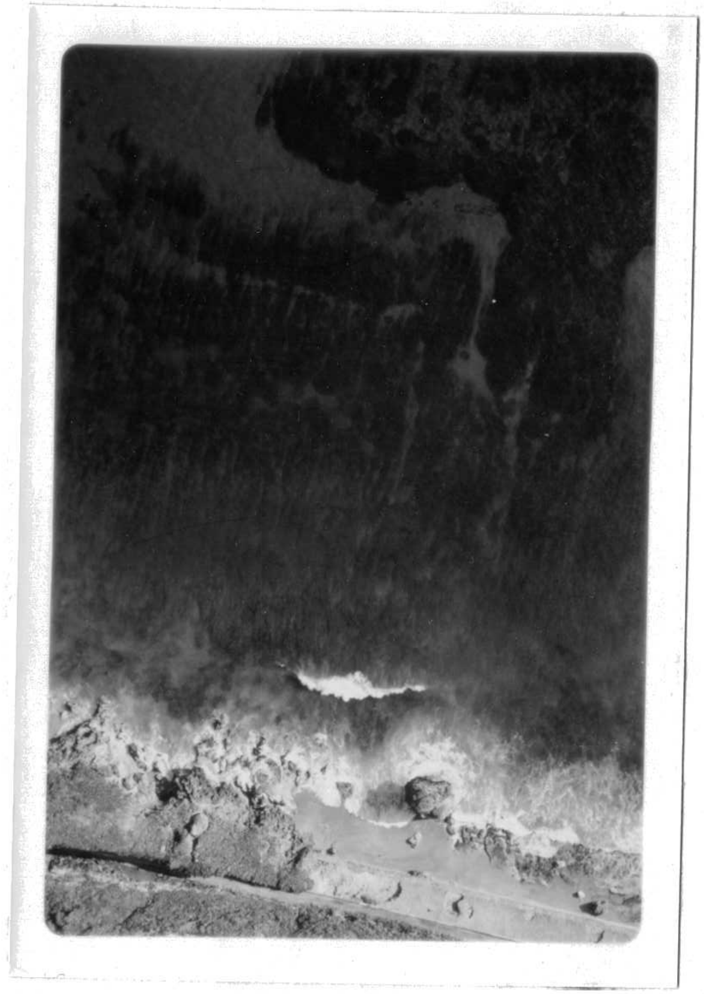


Figure 14: EIR photo from A-029-II showing the old railroad bed south of El Tunel and the blurry areas and the surf action.

Figure 15: EIR photo from A-029-31 showing the entrance to the inlet at Hatillo.

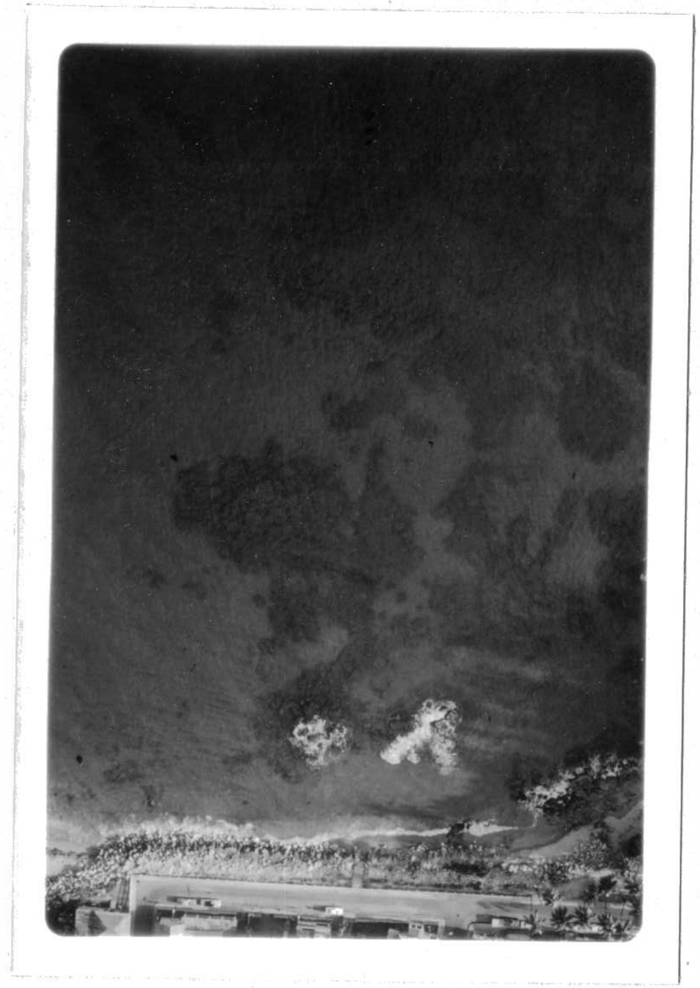


Figure 16: EIR photo from A-029-31 showing the inlet of Hatillo.

in more calmer sea conditions. Figure 20 shows the detail obtainable utilizing EIR film from the Rio Grande river mouth 5,000 ft. west of the town of Aguada. The lobate structure of the silt laden river into the ocean is clearly defined in this EIR photograph, by various shades of blue rather than by various shadings of greens and browns as in conventional photography. The sharp contrast between unmixed ocean water and river water is clearly depicted. The encroaching river water is depicted by the sharp line of crenulations in the upper left of the photograph. Plant vigor assessment can be clearly ascertained in this photo.

The plume of waste effluents of the Ron Rico Rum Distillery in Arecibo is shown in Figures 21 and 22 on EIR and EKX film respectively. The plume extends several thousand yards to the east along the shoreline; however, the denser portions of the plume tends to vectored away from the shore area. The plume strongly absorbs infrared radiation and appears black on the EIR film. The character of the plume can be clearly discerned in both photos. The red input area illustrated in the very top right of the EKX photograph shows up as yellow in the EIR photograph due to the translation of the sensitivity of the EIR film towards the longer wavelengths of the electromagnetic spectrum. The red colored effluent in the photographs is unknown. Additional photos on EIR and EKX film of the plume is depicted in Figures 23 and 24.

Wetted sand areas and seepage zones are clearly depicted on IR photography. Examples of such are shown in Figures 25 and 26 where the lobate character of the waves washing up on the beach and seepage areas, particularly in Figure 25, is easily analyzed.

Figure 17: EKX photo from A-029-31 showing an area similar to Figure 15 and vegetation contrasts to be compared with Figure 15.

Figure 18: EIR photo from A-029-31 showing the debouchment of the Rio Camuy and the fine detail of the silt-laden water even under heavy swell conditions.

Figure 19: EKX photo from A-029-31 showing shore area a little north of the Rio Camuy.

Figure 20: EIR photo from A-029-43 taken at 5000' showing the excellent detail of the lobate structure of the Rio Grande plume and the sharp zone between silt laden river water and the ocean.

Figure 21: EIR photo from A-029-38 showing the plume of waste effluent from the Ron Rico Rum Distillery at Arecibo and the reddish effluent east of the plume entry.

Figure 22: EKX photo from A-029-38 showing the Ron Rico Distillery area.

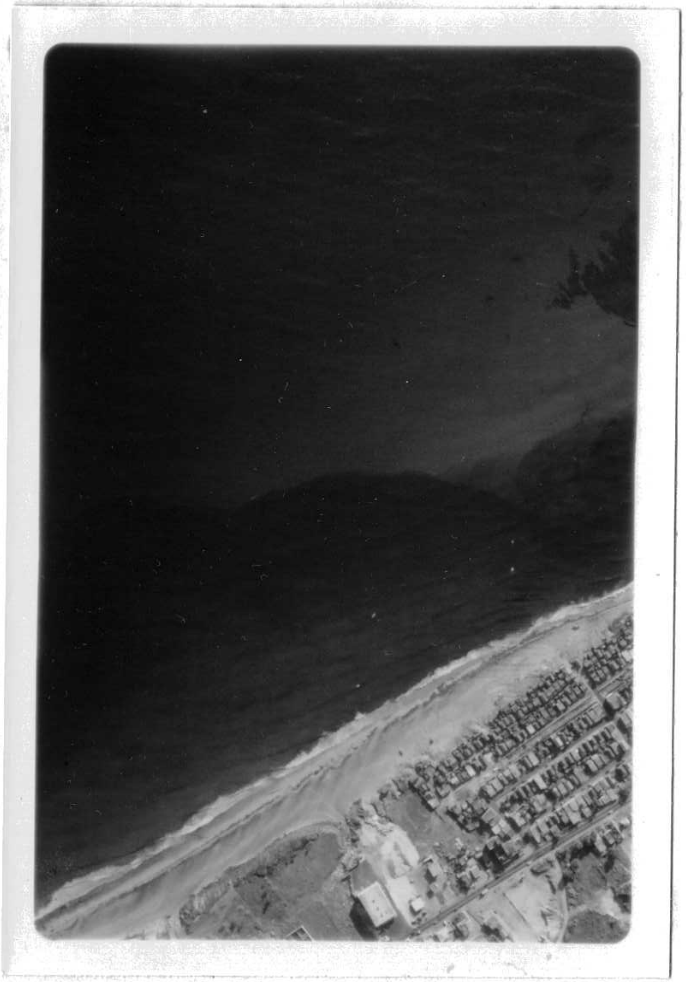


Figure 23: EIR photo from A-029-38 showing the westward portion of the Ron Rico plume. The plume characteristics are such that infrared radiation is absorbed and the lightening of plume shoreward.

gure 24: EKX photo from A-029-38 showing the are of Figure 23.

Figure 25: EIR photo from A-029-8 showing area near San Antonio Beach, the fine bottom detail, excellent color contrast, and the beach seepage areas.

Figure 26: EIR photo from A-029-8 showing the area east of Figure 25, the magenta contrasts induced by plant vigor, and the wetted sand areas caused by wave action and seepage.

Subsurface structural relationships can be observed in photography achieving excellent water penetration. In this regard note the lineations in Figures 27 and 28 that can be traced in both photographs. The long lineation in the lower left, in both photos can be traced a considerable distance out to the sea, while in Figure27, a series of fine parallel lineations can be also seen in the far left center of the photograph. The area depicted in these two photographs is south of the cobble beach off Ramey Air Force Base.

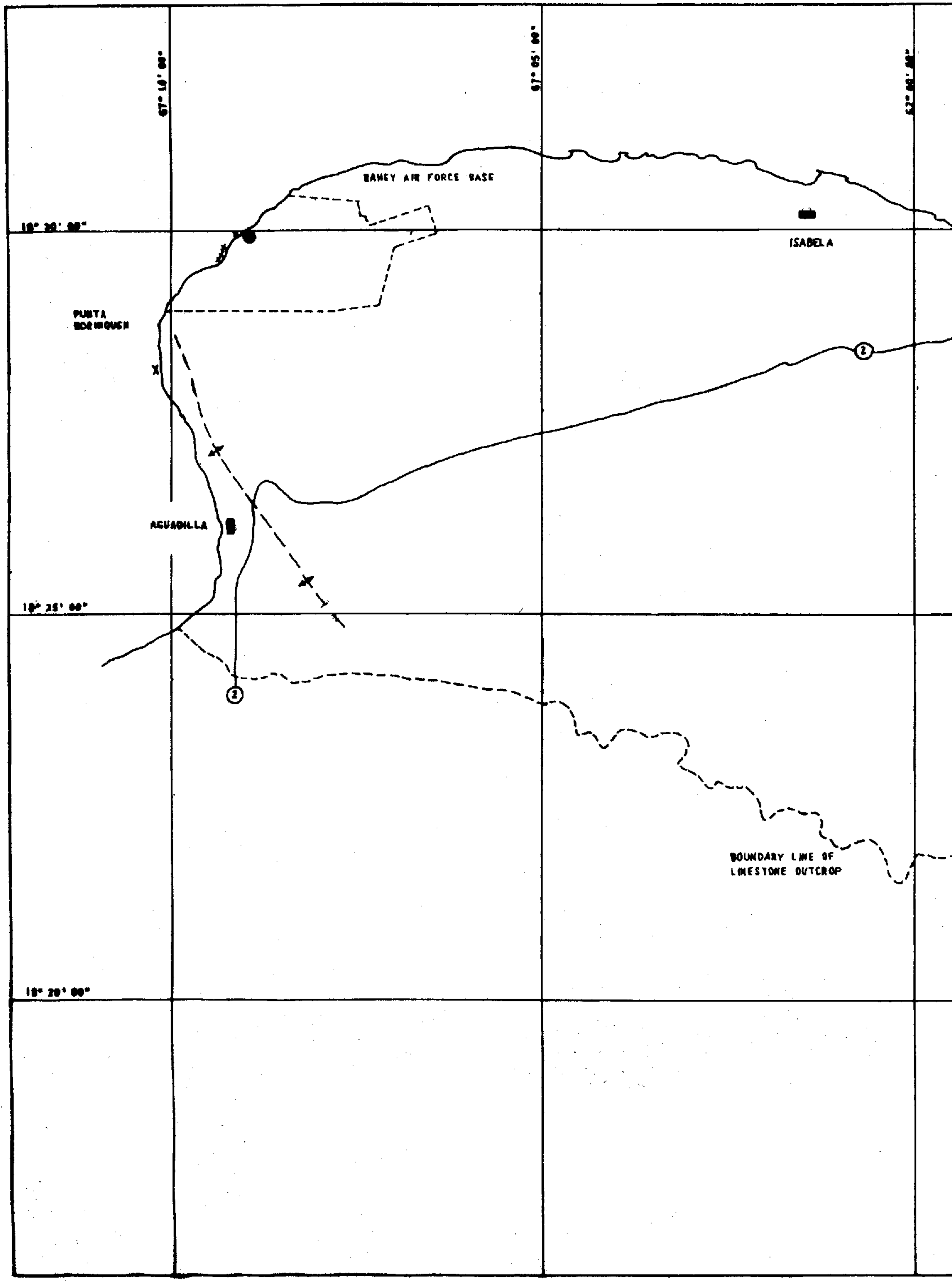
An excellent example of water penetration and the sea floor can be clearly seen in Figures 29 and 30. Figure 29 is on EKX film and shows fine contrast. Figure 30 is a EIR print of a shadowy water area, the print is consequently overexposed but of value indicating that it is better to underexpose the original than to overexpose. This bears out advice by a Data Corporation representative (Krueger, 1971) personal communication.

Figure 27: EIR photo from A-029-27 showing area south of Surfers Beach showing traceable lineations in the lower left to some distance out to sea and the parallel series of lineations in the right center of the photo.

Figure 28: EKX photo from A-029-27 showing the same area as Figure 27 showing an additional lineation to the right of the major lineation in the lower left of the photo.

Figure 29: EKX photo from A-029-27 showing fine bottom detail and excellent water penetration of the area near the cobble beach on Ramey Air Force Base.

Figure 30: EIR photo from A-029-36 illustrating an over exposure of the print to render bottom detail of an underexposed slide due to excessive shadows.


67° 10' 00"
67° 05' 00"
67° 00' 00"
RAMEY AIR FORCE BASE
18° 30' 00"
ISABELA
PUNTA
BORINQUEN
2
AGUADILLA
18° 25' 00"
2
BOUNDARY LINE OF
LIMESTONE OUTCROP
18° 20' 00"

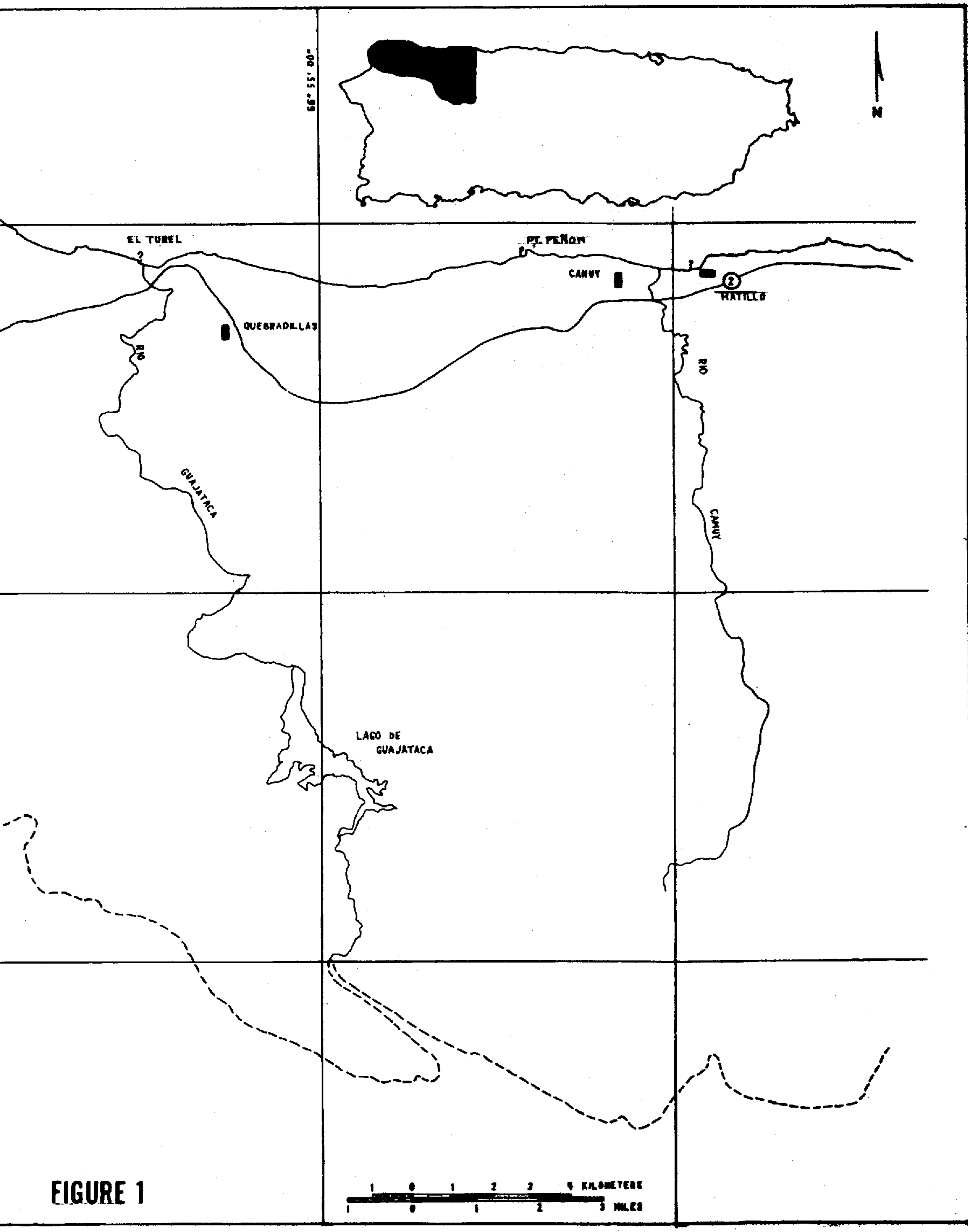

66°55'00"
N
EL TUNEL
PT. PEÑON
CAMUY
HATILLO
QUEBRADILLAS
RIO
GUAJATACA
RIO
CAMUY
LAGO DE
GUAJATACA
1 0 1 2 3 4 KILOMETERS
1 0 1 2 3 MILES

FIGURE 1

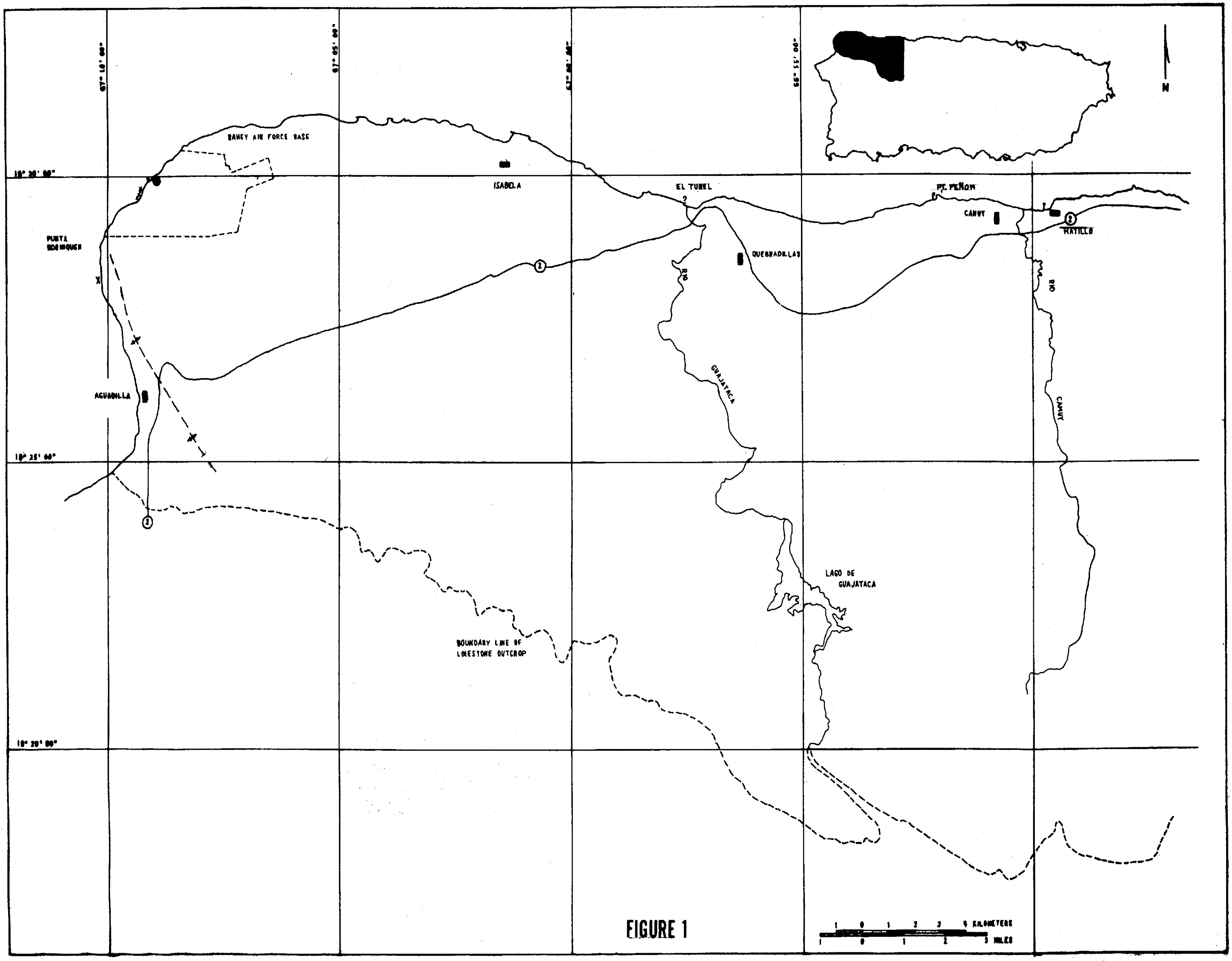

N
67° 10' 00"
67° 05' 00"
67° 00' 00"
66° 55' 00"
18° 30' 00"
18° 25' 00"
18° 20' 00"
RAMEY AIR FORCE BASE
ISABELA
EL TUNEL
PT. PEÑON
CAMUY
HATILLO
PUNTA BORINQUEN
QUEBRADILLAS
AGUADILLA
RIO
GUAJATACA
CAMUY
LAGO DE GUAJATACA
BOUNDARY LINE OF LIMESTONE OUTCROP
KILOMETERS
MILES

FIGURE 1

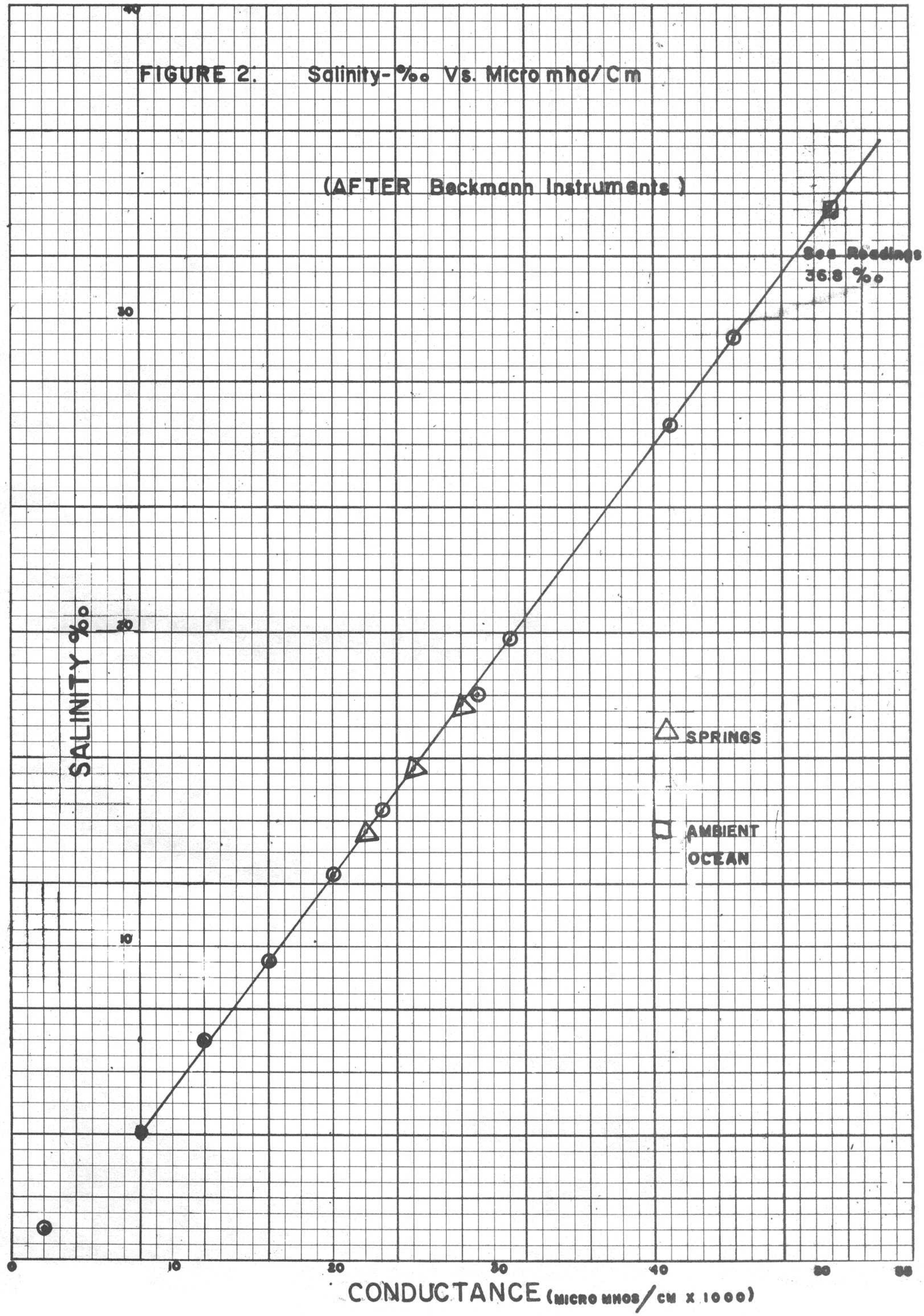


FIGURE 2. Salinity-‰ Vs. Micro mho/Cm
(AFTER Beckmann Instruments)
Sea Readings 36.8 ‰
SPRINGS
AMBIENT OCEAN
SALINITY ‰
CONDUCTANCE (MICRO MHOS/CM X 1000)
0
10
20
30
40
50
55
10
20
30
40

CONCLUSIONS AND RECOMMENDATIONS

The results of the conductivity traverses have clearly demonstrated the presence of a considerable outflow of water from the Aymamón-Aguada limestones of the northwest coast. Several springs were found to be issuing along the shore in the Ramey area and south. The bulk of the flow is indicated at the Borinquen Beach area in which three distinct spring areas were observed in 5 to 15 feet of water. Personal exploration indicated that additional large springs could be found off the cliffs in the Boquerón Beach inlet area. A constant six degree difference was observed between the ground water outflow and the ambient sea temperature. Ground water temperatures were constant at 77°F while the sea temperature was constant at 83°F. during the bulk of the study. Ground water specific conductance was observed to be 900 micro mhs/cm indicating that good quality ground water is available. The spring areas are located on Figure I.

It appears that ground water flow in the northwestern area is influenced by the anticlinal flexure depicted generally in Figure I. The dip of the limestone bedding at the Borinquen Beach area is in a north westerly direction and the ground water flow is probably funneled along the northern flanks of the flexure. The large springs that flow in the Ojo de Agua Park area in the town of Aguadilla may originate on the southern flanks of the flexure and flow towards the town in a general down-dip direction.

Large quantities of ground water must enter the sea along the northern coast from the pure Aymamón and Aguada limestones but no large areas of submarine spring outflow were revealed using either the conductivity probe or the comparative EIR and EKX photographs; however, the traverses indicated possible areas of submarine ground water discharge at El Tunel, Punta Peñón, and Hatillo areas.

The aerial photography did not positively indicate areas of submarine ground water discharge, although few photographs around the northwest coast, near known spring occurrences, did seem to indicate that the differences in the indices of refraction between fresh and salt water could be discerned. Certainly the outflow of these spring areas are enough to conceivably appear on the film in shallow water areas. It is the author's opinion that the lack of more positive evidence of submarine spring locations does not preclude their presence.

The aerial photographic survey results indicate the efficacy of the use of small format photography in water resources research area. River outflow and sediment transport can be effectively analyzed utilizing infrared photography, the density differences in the outflow and mixing area could be contoured fruitfully, submerged geological features can be easily traced utilizing both film types although it appears that more information could be discerned on EIR film, assessment of vegetation distribution and vigor can be quickly and fruitfully handled as indicated by the photographic assemblage herein, and coastal seepage areas can be quickly determined and mapped. This is also undoubtedly true of inland areas.

The value of color infrared photography to depict areas of submarine ground water discharge could be definitively tested by photographing the known spring areas under various lighting conditions. The same is, of course, true of the EKX film type, where different color renditions of spring areas may produce interesting results. Optimum aircraft altitudes should also be investigated. High quality printing from custom laboratories might also be fruitful, although with a good camera system, Kodak processing currently available for EIR 35 mm format, could probably produce adquate prints.

A camera hatch in the plane is a necessity. In addition an automatic camera system, such as the Robot Cameras, would greatly facilitate the photographing and enhance future projects.

The spring locations described herein should also be investigated by a diving team and mapped. The discharge of these areas should also be measured and a search for additional spring areas should be instituted to provide data that would enhance the ground water flow characteristics of this region.

The northwestern portion of the Island is relatively shielded from the highly energetic north coastal area. It is quite possible that color IR photographs can only be fruitful in more quiet environments. Ground water outflow discharge studies along the important north coast region may require the use of a thermal IR scanner system. The contrast in sea and ground water temperatures render a study of this nature quite feasible. The author has recently looked into AGA Thermovision for such a study. This Thermovision system has been used successfully in Hawaii and is available at very nominal monthly rates and require little instruction for the operation of the system. The system can be mounted in a small aircraft and successfully operated. The thermal mapping of the north west coastal area may well prove to be of immense value in determining the ground water flow characteristics in this area of sparce well data.

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