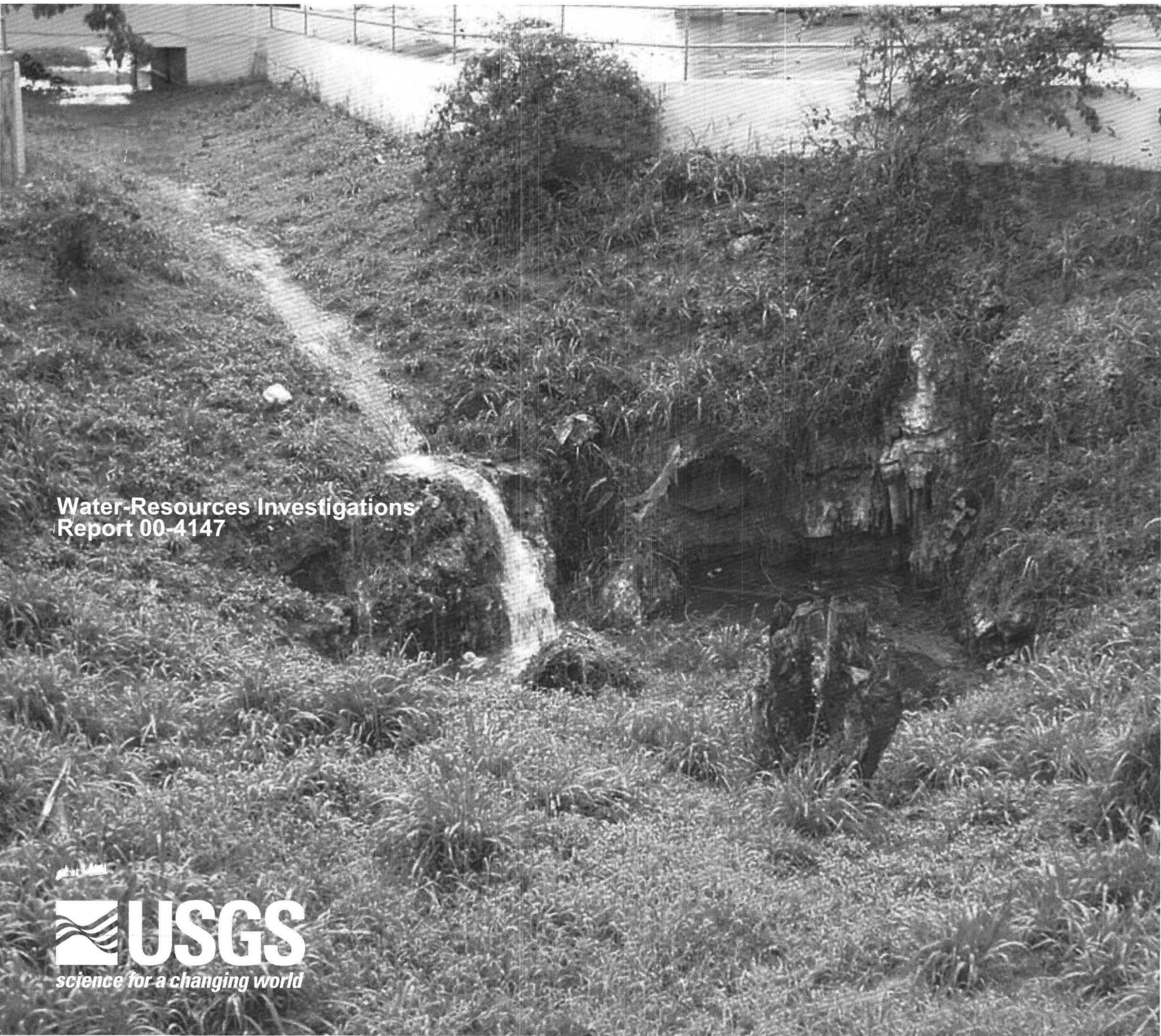
U.S. Department of the Interior
U.S. Geological Survey

Detection of Conduit-Controlled Ground-Water Flow in Northwestern Puerto Rico Using Aerial Photograph Interpretation and Geophysical Methods

Prepared in cooperation with the
PUERTO RICO AQUEDUCT AND SEWER AUTHORITY



Water-Resources Investigations
Report 00-4147

USGS
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Cover

On August 10, 2000, a rain storm caused flow in the ephemeral stream that drains into the sinkhole that is located on Highway 474, just south of Highway 2 in Isabela, Puerto Rico.

Photograph by Ronald T. Richards

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San Juan, Puerto Rico: 2000

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CONTENTS

FIGURES

CONVERSION FACTORS, SCIENTIFIC UNITS, and ACRONYMS

Multiply	By	To obtain
centimeter (cm)	0.03281	foot
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
millimeter (mm)	0.03937	inch
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot

Abbreviated scientific units used in this report:

mv	millivolt
mgal	milligal
µS/cm	microsiemen per centimeter

Acronyms used in report:

DOQQ	Digital Ortho Quarter Quads
NP	Natural potential
PRASA	Puerto Rico Aqueduct and Sewer Authority
RAFB	Ramey Air Force Base
UPR	University of Puerto Rico
USGS	U.S. Geological Survey

Detection of Conduit-Controlled Ground-Water Flow in Northwestern Puerto Rico Using Aerial Photograph Interpretation and Geophysical Methods

***By* Jesús Rodríguez-Martínez and Ronald T. Richards**

Abstract

The development potential of ground-water resources in the karst limestone of northwestern Puerto Rico, in an area extending from the Río Camuy to Aguadilla, is uncertain as a result of limited knowledge of the location of areas where a high density of cavities (interconnected fractures, conduits, and other dissolution features) might suggest the occurrence of high water yields. The presence in northwestern Puerto Rico of numerous coastal submarine springs, cavernous porosity in some of the wells, and rivers with entrenched and underground paths, indicate that it is probable that water-bearing, subterranean interconnected cavities occur in the area between the Río Camuy and Aguadilla. The number of exploratory wells needed to determine the location of these conduits or zones of enhanced secondary porosity could be substantially reduced if more information were available about the location of these subterranean features, greatly reducing the drilling costs associated with a trial-and-error exploratory process.

A 3-year study was conducted by the U.S. Geological Survey, in cooperation with the Puerto Rico Aqueduct and Sewer Authority, to detect the presence of cavities that might suggest the occurrence of conduit-controlled ground-water flow. Aerial photographs, geologic and topographic maps, and field reconnaissance were used to identify such linear terrain features as ridges, entrenched canyons, and fracture traces. Natural potential and gravity geophysical methods were also used. The following sites were selected for the aerial photograph interpretation and geophysical testing: Caimital Bajo uplands and former Ramey Air Force Base in Aguadilla; Quebrada de los Cedros between Aguadilla and Isabela; the University of Puerto Rico Agricultural Experiment Station, Otilio dairy farm, and Pozo Brujo in Isabela; the Monte Encantado area in Moca and Isabela; and the Río Camuy cave system in Hatillo and Camuy.

In general, the degree of success varied with site and the geophysical method used. At some sites such as Pozo Brujo, the University of Puerto Rico Agricultural Experiment Station, and Monte Encantado area, natural potential anomalies strongly suggest the existence of conduits with flowing water. At most sites, however, the results obtained did not clearly reveal the presence of subsurface cavities that might be associated with the occurrence of conduit-controlled ground-water flow. Sites such as the University of Puerto Rico Agricultural Experiment Station, Pozo Brujo, and Quebrada de los Cedros warrant a more detailed analysis, including a test well drilling phase to confirm the presence of suspected high-yield water-bearing zones.

INTRODUCTION

The development potential of ground-water resources in northwestern Puerto Rico, from the Río Camuy to Aguadilla, is uncertain due to limited knowledge of aquifer properties, ground-water occurrence, and ground-water quality. A major limitation to the assessment of the ground-water resources in this area is the limited number of existing wells.

Freshwater springs are common along the northwest coast of Puerto Rico, because of the prevalence of conduit flow in the aquifer. Little is known about the areal extent and exact locations of the conduits feeding these springs, because few deep wells have been drilled in this region, and because of the apparent low transmissivity of the aquifer between the suspected locations of these major flow components, particularly in the area underlain by the Camuy and Aymamón Limestones. Only two deep exploratory wells of more than 300 meters (m) have been drilled west of Arecibo (Rodríguez-Martínez and Hartley, 1994).

The term conduit-flow refers to subsurface solutional features that are large enough to store and transmit water. The acquisition of the data needed to define these subterranean features in northwestern Puerto Rico would require the drilling and casing of test wells to depths generally exceeding 100 m through an unsaturated zone of cavernous limestone. The number of deep wells that need to be drilled in this scenario could be reduced substantially if more information were available regarding the location of these conduits, thus reducing the drilling costs associated with a trial-and-error process.

Purpose and Scope

This report summarizes the results of a 3-year investigation conducted by the U.S. Geological Survey (USGS) in cooperation with the Puerto Rico Aqueduct and Sewer Authority (PRASA) from October 1, 1994, to September 30, 1997, to define the occurrence of high-yield water-bearing zones associated with subterranean conduits at selected sites in the karst aquifer, which extends from the Río Camuy to Aguadilla in northwestern Puerto Rico, using aerial photograph interpretation and geophysical methods. Results of this study will assist the PRASA to optimize the development of the karst aquifer in the study area while minimizing drilling costs.

Previous Investigations

Hydrologic investigations conducted along the northwest coast of Puerto Rico include studies to map coastal submarine springs using infrared aerial photography (Percious, 1971); develop a regional water balance (Giusti and Bennett, 1976); detect submarine springs using an aerial multiple-frequency radiometer (Blume and others, 1981); develop a digital ground-water flow model of the Río Camuy to Aguadilla area (Tucci and Martínez, 1995); and define the hydrogeologic framework of this geologic province (Rodríguez-Martínez, 1995). The combined results of these studies suggest that water-bearing subterranean conduits are present between the Río Camuy and the Aguadilla area in northwestern Puerto Rico.

The importance of conduits to the occurrence and movement of ground water in the North Coast Limestone karst aquifer system has not been addressed in previous studies. The studies on the hydrogeology of the North Coast Limestone aquifer, mentioned above, have postulated the prevalence of diffuse flow to explain the movement and occurrence of ground water. Percious (1971) identified a lineament in the area of the former Ramey Air Force Base that could be a surface expression of a fracture system responsible for the offshore springs near Aguadilla. Meyerhoff and others (1983) discussed the existence of some lineaments in the north coast middle-Tertiary sequence as indicative of deep-seated structures; however, the dense vegetation cover throughout the year prevented an intensive use of stereo-aerial photographs for the identification of linear terrain features, particularly lineament analysis. Rodríguez-Martínez (1997) characterized several springs in the North Coast Limestone aquifer system as conduit-type springs. These springs commonly are connected to the subsurface by an integrated conduit network. Rodríguez-Martínez and Hartley (1994) reported the presence of caverns in test wells NC-6 and NC-11, drilled in Hatillo and Isabela, respectively, as part of a study of the hydrogeology of the North Coast Limestone aquifer system. A PRASA public-supply well, Monte Encantado, is developed in an underground stream in a cavern. The well is located on Highway 112 in Isabela. Tucci and Martínez (1995) called this well El Rey 2.

Approach

A series of geological and geophysical methods were selected for use in this investigation after conducting an extensive literature review of similar studies in other karst terranes (Lange and Quinlan, 1988; Ogilvy and others, 1969; Stokowski, 1987; Carpenter and others, 1995; Bogolovsky and Ogilvy, 1973; Stewart and Wood, 1990). The selection was made considering the depth to the water table, which generally exceeds 100 m below land surface, and the unique karst topography of the study area. The selected geological methods included the determination and analysis of the (a) alignment of surficial and near-surface dissolution features such as sinkholes and caves; (b) occurrence of springs and their spatial relation with nearby sinkholes, caves, and other dissolution features; (c) presence of straight segments of streams and their spatial relation with nearby dissolution features; (d) presence of linear terrain features, which may reflect subsurface fractures, conduits, or both, as identified in aerial photos at a scale of approximately 1:20,000; (e) the presence of caverns or voids documented in well construction logs, in both abandoned and producing wells, as they relate to nearby dissolution features; and (f) any combination of these methods.

Following the literature review and consultation with several geophysicists, the use of geophysical techniques was limited to natural potential (NP) and gravity. The depth to water table, generally greater than 100 m below land surface, was a major reason in deciding against the use of such geophysical techniques as passive acoustic method, direct current resistivity, and ground-penetrating radar, among others. Time and cost constraints also limited the application of other geophysical techniques.

The project was conducted in two phases. Phase one consisted of selecting a series of sites in northwestern Puerto Rico that, according to field reconnaissance and the analysis of topographic maps, geologic maps, and stereo-aerial photographs or their more recent equivalent, Digital Ortho Quarter Quads (DOQQ), met the hydrogeological criteria mentioned above for the presence of conduits or caverns in the subsurface. Phase two consisted of using the two previously mentioned geophysical techniques to determine whether conduits and caverns were present at those sites selected in phase one.

Eight sites in northwestern Puerto Rico were selected for this investigation (fig. 1). The numbered boxes in figure 1 designate the figure number of the aerial photograph or map corresponding to that site location. The selected sites include: the Caimital Bajo uplands to the east of Aguadilla (fig. 3); former Ramey Air Force Base (RAFB) in Aguadilla (fig. 4), Quebrada de los Cedros between Aguadilla and Isabela (fig. 6); Pozo Brujo in Isabela (fig. 8), University of Puerto Rico (UPR) Agricultural Experiment Station (figs. 10, 11), and Otilio dairy farm (Otilio) site in Isabela (figs. 10, 16); Monte Encantado area in Moca and Isabela (figs. 20, 22, 23, 24); and Río Camuy cave system in Hatillo (fig. 27).

Acknowledgments

The authors are grateful to Edwin Acevedo of the Agricultural Experiment Station of the University of Puerto Rico at Mayagüez, the management of the Río Camuy Cave Park in Hatillo, the owners of the former RAFB lands, and the various landowners for allowing the collection of geological and geophysical data on their properties.

REGIONAL SETTING

The study area is within the North Coast Limestone belt and extends from the Río Camuy to Aguadilla in northwestern Puerto Rico. Karst topography, the result of dissolution of the middle-Tertiary limestone sequence, is present in most of the study area. Three substantial surface-drainage features in the study area are the Río Camuy, Río Guajataca, and Quebrada de los Cedros.

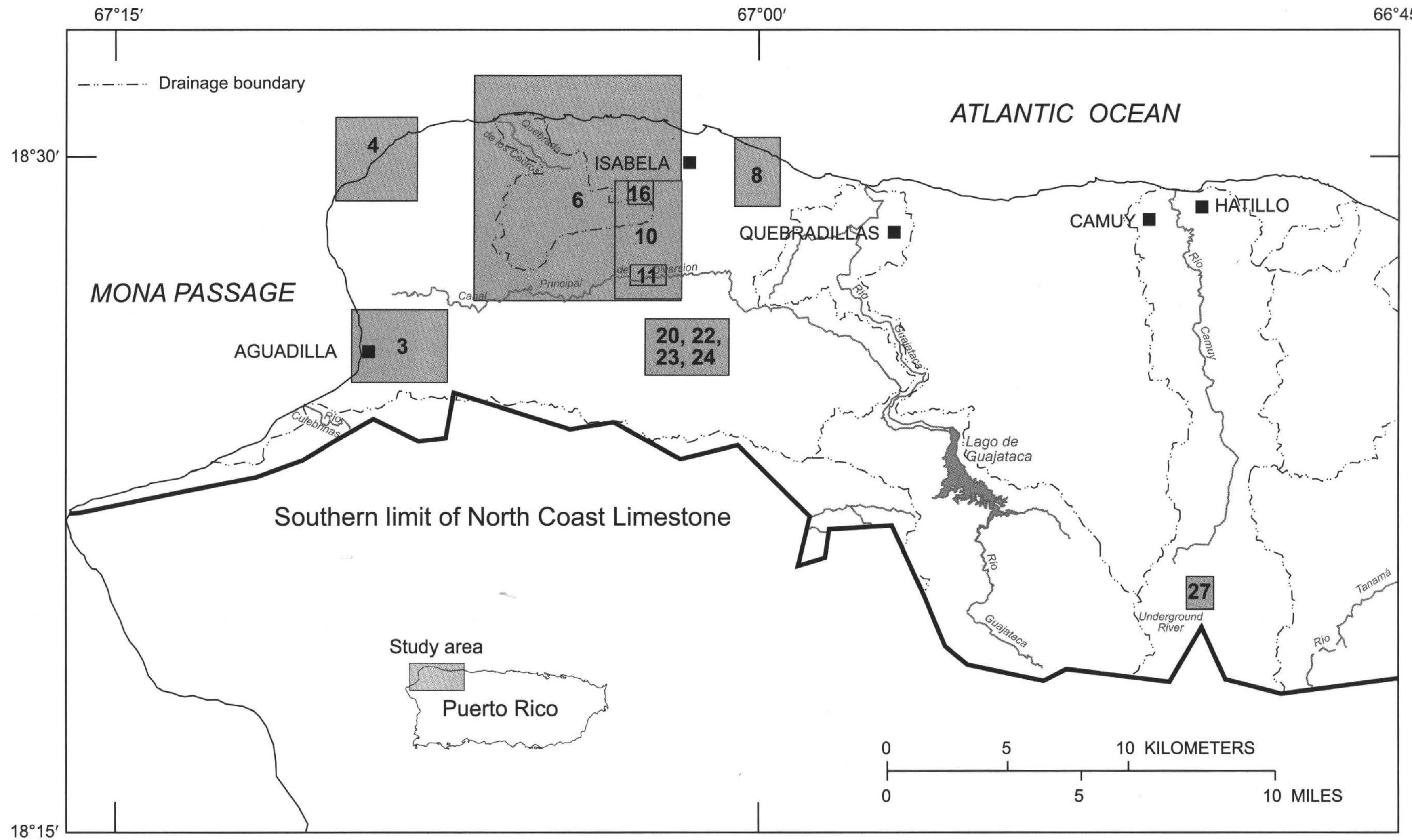


Figure 1. Extent of the general study area in northwestern Puerto Rico and individual sites where linear terrain features analyses and geophysical tests were conducted. The numbered boxes refer to the figure with aerial photographs or maps of the corresponding site. Sites included: Caimital Bajo, Aguadilla (fig. 3); former Ramey Air Force Base (RAFB) in Aguadilla (fig. 4); Quebrada de los Cedros between Aguadilla and Isabela (fig. 6); Pozo Brujo in Isabela (fig. 8); University of Puerto Rico (UPR) Agricultural Experiment Station (figs. 10, 11); Otilio dairy farm (Otilio) site in Isabela (figs. 10, 16); Monte Encantado area in Moca and Isabela (figs. 20, 22, 23, 24); and Río Camuy cave system in Hatillo (fig. 27).

Climate

The climate of the study area, as in the rest of northern Puerto Rico, is humid tropical (Giusti, 1978). The average annual rainfall is 1,800 millimeter (mm) ranging from 1,550 mm on the coast to 2,300 mm along the limestone contact with the volcanic rocks of the central region (Calvesbert, 1970). This difference in rainfall can be attributed to differences in topographic relief between the coastal and inland areas. Seasonal variation in precipitation within the study area follows a general island-wide trend: a relatively dry season that begins in December and usually ends in March or April; a spring rainfall period in April and May; a semi-dry period in June and July; and a relatively wet season from August through November.

Landforms and Drainage in the Study Area

The study area is characterized by a well-developed karst topography having substantial underground drainage. Three types or styles of karst topography prevail in the study area: the so-called cone or cockpit karst, the rampart or wall karst, and the mogote karst (Monroe, 1976). Doline and zanjones karst also are present, but are limited in areal extent (Monroe, 1976).

Cone or cockpit karst, which consists of pronounced, deep solution depressions that are irregularly to cockpit shaped, is present mostly in the outcrop areas of the Lares Limestone near the Río Camuy. Rampart karst, which consists of steep walls of limestone indurated on the surface by reprecipitation, is well preserved along the Río Guajataca. Mogote karst, which is characterized by subconical steep-sided hills that rise out of a flat plain, is present in some of the interior lowlands of the study area where the Aymamón and Aguada Limestones are covered by surficial deposits. Doline karst, which consists of circular to oval depressions, is present in the outcrop area near the Río Camuy. Zanjones karst, which consists of vertical-walled trenches believed to result from the enlargement of joints by solution, is present in an area east of the Río Camuy in Lares.

The drainage in the study area is largely underground with only three surface-drainage features of note: the Río Camuy, the Río Guajataca, and the Quebrada de los Cedros (fig. 1). Both the Río Camuy and the Río Guajataca have their headwaters in the central volcanic terrain and flow northward across the limestone belt. The drainages of both the Río Camuy and the Río Guajataca within the limestone terrain are undefined. The courses of these rivers are characterized by underground passages and deep narrow canyons that attest to their origins as underground drainage systems. The Quebrada de los Cedros is an ephemeral stream flowing only during extreme rainfall events with its headwaters in the karst belt. Some reaches of Quebrada de los Cedros are narrow, deep, and straight indicating it probably originated as an underground drainage system.

An underground drainage system, which is characterized by caves with flowing water, is located in the Monte Encantado area of Moca and Isabela. The extent and hydrogeology of this underground drainage system is unknown. At present, a cave stream of this system is being used by the PRASA as a public water-supply source for nearby communities.

Geology

The study area is underlain by a thick sequence of platform carbonates and minor terrigenous clastics, ranging in age from Oligocene to Miocene, that is part of the regional sequence of middle-Tertiary rocks of the North Coast Limestone belt (fig. 2). These rock units compose a homoclinal sequence that mostly strikes east and dips northward (Monroe, 1980; Meyerhoff and others, 1983) at an average of 3 to 4 degrees. The dip ranges from 2 degrees near the coast to 6 or 7 degrees at the southern edge of the outcrop. However, in the Aguadilla and Moca area, the strike is near north and the dip is as much as 10 degrees toward the west because of a north-northwest plunging anticline.

Various stratigraphic nomenclatures have been used to differentiate among the various formations of the middle-Tertiary sequence exposed along the north coast of Puerto Rico (Meyerhoff and others, 1983). The stratigraphic nomenclature of Monroe (1980) is used in this report, because it has been used in earlier USGS reports and is based on stratigraphic observations made along the entire north coast.

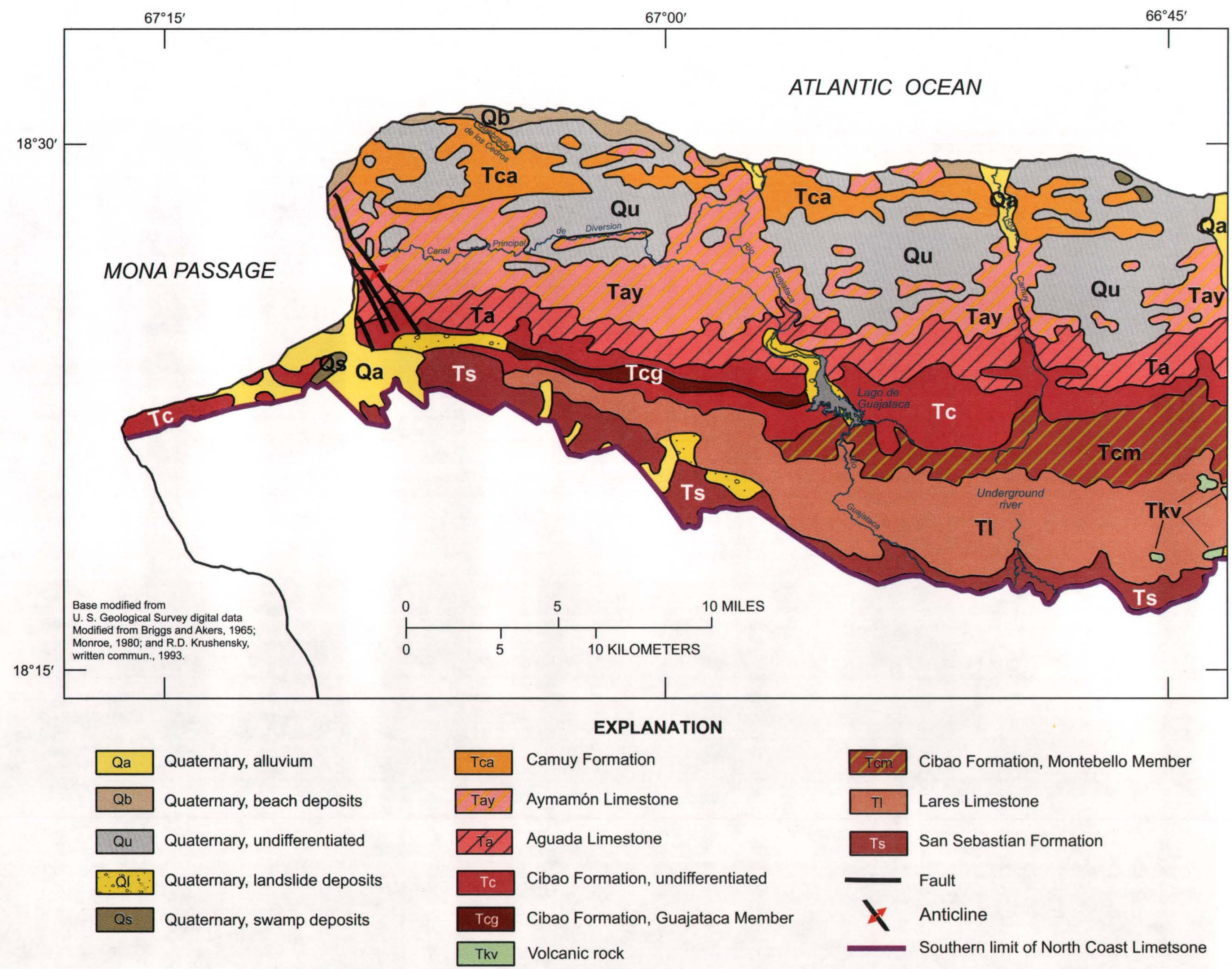


Figure 2. Generalized surface geology of northwestern Puerto Rico (modified from Miller and others, 1997).

The geologic units exposed in the study area are, from oldest to youngest, the San Sebastián Formation, Lares Limestone, Cibao Formation, Aguada Limestone, Aymamón Limestone, and Camuy Formation. The San Sebastián Formation consists of coastal and fluvial clastics, marginal marine clay, and inner platform limestone. The Lares Limestone consists of mid-platform and minor inner- and outer-platform carbonates. The Cibao Formation, separated into several members along the middle-Tertiary sequence of the north coast (Scharlach, 1990; Hartley, 1989), is represented in the study area by (a) an informal upper member that consists of claystone, marl, and terrigenous limestone, (b) the Guajataca Member that consists mostly of sand and gravel, and (c) the Montebello Limestone that consists predominantly of reefal and mid-platform carbonates. The Aguada Limestone consists mostly of inner-platform carbonates. The Aymamón Limestone is comprised predominantly of mid-platform carbonates. The Camuy Formation consists mainly of inner-platform carbonates and marginal marine terrigenous material. Data on the subsurface lithology in the study area is limited to two deep wells drilled in the municipios of Hatillo and Isabela (Rodríguez-Martínez and Hartley, 1994). Paleontologic and lithologic analyses of these two wells revealed that near the coast and west of Hatillo, the Lares Limestone is increasingly replaced by the Cibao Formation in the deeper and downdip portions of the middle-Tertiary sequence.

An anticlinal flexure, already mentioned, disrupts the homoclinal sequence in the Aguadilla and northern Moca area (Monroe, 1969). West of the axis of the anticline, the strike of the strata is near north and the dip is as much as 10 degrees west. This dip towards the west is interrupted by a series of small faults that have uplifted the strata as much as 30 m (Monroe, 1969). The regularity of dip also is interrupted near Isabela by a gentle reversal that seems to be a continuation of an anticline north of Quebradillas (Monroe, 1967). A small dome, which seems to reflect the antecedent topography of deeply buried volcanic basement rocks, similarly disrupts the dip of the strata in an area extending north of the confluence of the Río Guajataca and one at its tributaries in Quebradillas and Isabela.

Northwestern Puerto Rico seems to be undergoing a higher uplift rate than the rest of the middle-Tertiary carbonate sequence of the north coast (Giusti, 1978; Taggart and Joyce, 1989). The sea cliffs so conspicuous in the Quebradillas-Aguadilla area are considered to have formed by tectonic uplift. Giusti (1978) explained the preferential occurrence of springs in the western banks of streams as a consequence of the eastward tilting of the carbonate platform that supposedly occurred in the Pleistocene. Giusti (1978) estimated an uplift rate of about 0.055 millimeter per year (mm/yr) based on denudation rates calculated for the North Coast Limestone belt. Using radiometric dates obtained from corals in growth position retrieved from marine-terrace deposits, Taggart and Joyce (1989) estimated a minimum rate of uplift ranging between 0.03 mm/yr and 0.05 mm/yr during the late Pleistocene.

Hydrogeology

The hydrogeology of northwestern Puerto Rico was studied by Giusti (1978). Other studies focusing on the hydrogeology of the study area include an investigation on the hydrogeology of the northern karst belt from 1983 to 1988 emphasizing the lower aquifer (Rodríguez-Martínez, 1995), and the construction of a digital ground-water flow model of the Aguadilla to Río Camuy area (Tucci and Martínez, 1995).

Ground water occurs under both confined and unconfined conditions in the study area (Rodríguez-Martínez, 1995). A major ground-water divide, the effect of anticlinal structures in the study area, diverges ground-water flow northward and westward to the sea, and southward to the Río Culebrinas. In addition, draining of the upper aquifer by the Río Camuy, the Río Guajataca, and probably by the underground drainage system in the Monte Encantado area, causes substantial local variation in ground-water flow to the north and west. In general, ground-water flow in the study area is northward toward the coast. The upper aquifer, extending throughout the North Coast Limestone belt and contained within the Aymamón and Aguada Limestones, is the most important ground-water source in the study area. The lower aquifer in the study area consists of alternating water-bearing zones of low yield and confining units contained within the Cibao Formation. The lower aquifer, predominantly confined, is discontinuous and much less productive in the study area than in the rest of the North Coast Limestone belt (Rodríguez-Martínez, 1995).

Conduits seem to influence the ground-water flow pattern in the study area. However, information is lacking regarding the importance of ground-water movement as conduit flow and the distribution of the most important conduits. The importance of conduit flow in the study area is exemplified by inland springs such as Ojo de Agua in Aguadilla and Ojo Claro in Camuy (Rodríguez-Martínez, 1997), the Río Camuy cave system, the underground drainage system of the Monte Encantado area, and the Pozo Brujo cave-collapse sink. The occurrence of near shore submarine springs at Aguadilla, Isabela, and Quebradillas, also attests to the probable importance of conduit flow in the study area (Percious, 1971; Blume and others, 1981). Some production wells in the study area are known to be completed in cavernous zones, and cavities of considerable size were found while drilling test wells NC-6, NC-7, and NC-11 (Rodríguez-Martínez, 1995). The occurrence of conduits in the study area seems to be, at least in part, structurally controlled, as indicated by the existence of straight cave segments in the conduit network of springs such as the Ojo de Aguadilla Spring in Aguadilla (M. Morales, Sociedad Espeleológica de Puerto Rico, Inc., oral commun., 1996), and straight reaches in the Quebrada de los Cedros and the Pozo Brujo drainage network, as revealed during the field reconnaissance of the study area.

METHODS OF DATA COLLECTION AND ANALYSIS

Geological and geophysical methods were used to detect the presence of cavities that might suggest the occurrence of conduit-controlled ground-water flow. Aerial photograph interpretation in conjunction with geologic and topographic maps were used to detect the presence of linear terrain features that might be indicative of subsurface fractures zones, which in turn might coincide with zones of preferential flow and high water yields.

The natural-potential geophysical method measures natural direct-current potentials on the earth's surface. Voltage readings that are significantly higher or lower than a background value might be indicative of subsurface cavities or conduits that in turn might suggest the presence of high water yields. The gravity geophysical method, which indirectly measures contrasts in densities, has been used in detecting the presence of cavities in the subsurface of karst terranes (Stewart and Wood, 1990).

Aerial Photograph Interpretation

Interpretation of aerial photographs, complemented with the use of geologic and topographic maps, were used to detect the presence of linear terrain features that might suggest the presence of conduit-type flow in the subsurface. The term linear terrain features, as used in this report, refers to straight stream reaches, ridges, fracture traces as expressed by contrasts in vegetation types and separation lines between soils of different color tones, alignment of sinkholes (including the long axes of the sinkholes) and mogotes (in the case of Puerto Rico). Field reconnaissance is needed to verify the existence of linear terrain features and to determine that they do not represent anthropogenic artifacts.

Linear terrain features have been used previously to infer the presence of conduits and fractures in the subsurface which in turn might indicate the occurrence of zones of high water yields, or preferential and discrete flow paths, or both. For example, Lattman and Parizek (1964) related the presence of linear terrain features with the occurrence of ground water in carbonate rocks. Likewise, Rinker (1974) applied the analysis of linear terrain features to delineate a probable surface trace of the underground course of the Río Camuy. Finally, Ruhl (1994) related the orientation of linear terrain features with the anisotropic transmissivity and seepage to streams in the karst developed in the Prairie du Chien Group of southeastern Minnesota.

In this study, the greatest emphasis was placed on linear terrain features such as straight river reaches and ridges, and alignment of sinkholes (including orientation of the long axes of sinkholes), because these features can be readily identified and studied in the field. This also provided the opportunity for geophysical tests and further geological analysis across and along these features. Fracture traces were identified during this study, but because these features were not readily identified in the field, they were given secondary emphasis.

Natural Potential Method

The natural-potential geophysical method measures the direct current potentials or voltages on the earth's surface. Differences of potential on the millivolt level can be caused by a wide range of subsurface features and processes, both natural and anthropogenic, including heat flow, chemical reactions, industrial activities and the flow of fluids including, but not limited to ground water. At the Third Conference on Environmental Problems in Karst Terranes in Nashville, Tennessee, in 1991, two papers were presented describing the natural potential method as it related to caves. The first paper described the physical basis for the method (Kilty and Lange, 1991), and the second gave examples of using the method over actual caves (Lange and Kilty, 1991). Of particular interest to the study of voids in karst is the electrokinetic or streaming effect (Kilty and Lange, 1991). The selective movement of ions to and from the walls of the cave create a subsurface distribution of voltages that can affect the distribution of voltages on the surface.

In this study, one electrode was fixed at a base location and the other was placed at regular increments along a transect line. A high-impedance digital voltmeter, either a Fluke model 25 or model 8020B, was used to measure the voltage difference between the electrodes. The wire between the electrodes changed color every 100 m, and was used to measure horizontal distances. Pacing was used to measure distances between color changes. At the millivolt level, the friction of driving a stake into the ground, as well as other effects such as electrochemical, can polarize the electrode and create spurious voltages. In this study, non-polarizing electrodes were used. The electrodes consisted of a 7.5-centimeter (cm) plastic cylinder with a semipermeable ceramic base. Inside the cylinder, a copper electrode was immersed in a saturated solution of copper sulfate (Lange and Kilty, 1991). The presence of roots, gravel, and humus can change voltage readings. To obtain a more representative voltage reading, a pick was used to make a 10-cm-deep hole at each station to remove the surficial soil layer, which is heated by the sun and is rich in organic material. At each site, two readings were taken within 15 cm and 15 seconds of each other. If the readings differed by more than a threshold voltage, usually 4 millivolts (mv), then more readings were taken at the station. The final result was the average of the readings at the station. Additional stations were established between the regular increments if large changes in voltage were observed.

Measurements of potential collected at the stations along a transect line were corrected for changes in the average of voltage readings collected in four shallow holes located within 1 m of the base electrode. Voltage readings were collected at these four holes before and after each transect line was completed. Changes in the averages of the potential readings at these four holes resulted from ambient drift caused by changing electric potentials in the ground; this drift was corrected during data processing.

There is no simple shape that describes the natural potential anomaly over a cave or conduit. Fluid flow above and within a cave, the ratio of the air-filled to water-filled parts of the void, the chemistry of both the water in the cave and the water in the unsaturated zone can all affect the shape of the anomaly. What is commonly observed over caves is an "M-shaped" or "sombrero-shaped" anomaly. Flow in a passage that is completely filled with water may result in spikes. Changes in chemistry can produce polarity reversals causing an "M-shaped" anomaly to become a "W-shaped" feature. The theory behind some of these changes in shape can be found in Kilty and Lange (1991), and examples of natural potential anomalies over caves are given in Lange and Kilty (1991).

On a practical level, it is important to distinguish between the natural potential signature of hydrogeologically important processes like conduit-controlled ground water and anthropogenic objects like rusting metal.

Natural potential surveys were conducted at the following sites: the former RAFB and Quebrada de los Cedros, the UPR Agricultural Experiment Station, the Otilio dairy farm, the Pozo Brujo, the Monte Encantado area, and the Río Camuy cave system (fig. 1). The Monte Encantado area in Moca and Isabela and the Río Camuy cave system, where caverns and subterranean streams are known to exist, were used to test the response of the natural potential method.

Gravity Method

The gravity geophysical method is used to measure differences in mass distribution in the subsurface, which may record cavities in the subsurface. In this study, the collection of gravity data was limited to the UPR and Otilio sites owing to the relatively flat terrain, prior knowledge of the general subsurface geology, and availability of access roads. Gravity measurements were made at 10-m intervals to detect lateral variations in density along several profiles at the UPR and Otilio sites in the municipio of Isabela (fig. 1). A Worden Master gravimeter, capable of resolving approximately 0.1-milligal (mgal) anomalies, was used to collect gravity data. Tide and drift rate corrections to the gravity data ranged from 0.03 to 0.29 milligal per hour (mgal/hr), and were made following the procedure in Dobrin and Savit (1988). Gravity readings were obtained at base stations at intervals not exceeding 1 hour to correct for transient changes in gravity. Ground-surface elevations were surveyed to within 0.06 m.

Ground-surface elevation changes were small and gradual along the profiles run at the UPR site. As a result, the terrain corrections were less than the accuracy of the gravimeter readings and consequently were not applied to the gravity data collected at this site. The topographic relief created by the sinkholes and depressions at the Otilio site ranged from 6 to 8 m, which made terrain corrections necessary. A latitudinal correction also was applied to gravity data from both sites and used to reduce the data to simple Bouguer gravity values using station-elevation data. A reduction density of 1.9 grams per cubic centimeter (g/cm^3), the assumed density of surficial material at the UPR and Otilio sites, was used. Varying the reduction density at the UPR site within reasonable limits (1.8 to 2.5 g/cm^3) did not substantially change the detected shape and amplitude of the gravity readings along the survey transects due to the relatively low relief. A computer program based on the method of polygons was used to produce two-dimensional forward models that could explain the observed microgravity anomalies (Dobrin and Savit, 1988). The method of polygons calculates gravity anomalies from the differences in mass distribution described by two-dimensional polygons. These polygons extend infinitely in both directions perpendicular to the line of profile within a uniform limestone background. Assumed density contrasts used in the models were based on the range of densities reported for sedimentary materials (Dobrin and Savit, 1988). Densities of 2.2, 1.7, and 0.0 g/cm^3 were assigned to the Aymamón Limestone, soil, and void spaces, respectively. The modeled blocks used were 150-m deep and extended 100 m beyond each end of the profile. All models assumed that gravity anomalies were due to mass variations created by air-filled cylindrical voids within the Aymamón Limestone (above the water table, which at the test site was about 84 m below land surface), or thickness variations in uniformly low-density unconsolidated material above the Aymamón Limestone.

RESULTS OF THE AERIAL PHOTOGRAPH INTERPRETATION AND THE GEOPHYSICAL FIELD TESTS

Aerial photograph interpretation was used to identify linear terrain features. Geophysical surveys were conducted at eight sites in the study area. The results were used as indicators of the presence or absence of conduits, which may represent zones with potential high water yields.

Caimital Bajo Uplands in Aguadilla

Two distinctive sets of aligned ridges are identified from the interpretation of aerial photographs in the Caimital Bajo uplands area of Aguadilla (fig. 3). It appears that one of the sets of aligned ridges with an orientation ranging from N. 03° E. to N. 13° W. is abruptly interrupted by a second set of aligned ridges with an orientation ranging from N. 60° E. to N. 80° E. The length and straightness of these features indicates fault control. The evidence for significant structural control is provided by the series of faults to the southeast and east of Aguadilla that trend north-northwest, similar to the trend of the first set of ridges (Monroe, 1969a). Structural control also is indicated by statements of cave explorers referring to the existence of straight cave segments in this area (R. Carrasquillo-Nieves, USGS, oral commun., 1996). A series of aligned sinkholes with an orientation similar to the first set of ridges occurs in the southern part of Caimital Bajo uplands (Monroe, 1969a). The two sets of aligned ridges and the sinkholes in the Caimital Bajo uplands area could be surface expressions of the apparently well-integrated conduit network feeding the Ojo de Agua Spring at Aguadilla (Rodríguez-Martínez, 1997). The changes in the stable isotopic composition of deuterium and oxygen-18 observed at this spring (Rodríguez-Martínez, 1997), and the known occurrence of sudden floods of turbid water observed during field reconnaissance of the area may indicate the presence of a well-connected conduit network coupled to the land surface.

Former Ramey Air Force Base in Aguadilla

The likely presence of conduits in the area of the former RAFB is suggested by the occurrence of nearshore freshwater springs, some of which have been identified by Percious (1971). The former RAFB site, in contrast to the Caimital Bajo uplands, is flat with no surface drainage. The topography of the site consists of a plateau with a shear cliff directly to the water or to a fragmented coastal plain. As a result, the aerial photograph interpretation at this site was limited to the identification of fracture traces. The orientations of the fracture traces identified in the RAFB area vary from N. 30° E. to N. 87° W. However, the predominant orientations range from N. 30° W. to N. 87° W. (fig. 4). Percious (1971) identified a lineament (a fracture trace with a length exceeding 1 km) at the former RAFB that he considered to be the surface expression of a fracture system responsible for the offshore springs and coastal seepage. A series of sinkholes, exhibiting some general alignment in the direction of these offshore springs, are present at the former RAFB site. These sinkholes might be a surface expression of this lineament. Blume and others (1981) used remote sensing data to detect the presence of freshwater floating on top of the seawater offshore the RAFB site. The large circle in figure 4 shows the aircraft navigation error radius of about 900 m.

Four natural potential survey lines were run at the former RAFB in Aguadilla (fig. 4). To minimize problems with anthropogenic artifacts, lines A-A´ and B-B´, and C-C´ were run as close to the cliff line as possible. Line D-D´ was run on a coastal plain about 5 m above sea level. Various distinctive potential anomalies were measured (fig. 5). These anomalies are interpreted to be of both anthropogenic and hydrogeologic origin. There was a negative (natural) potential anomaly of about 100 mv that extended about 40 m, which appears to be a human artifact. This value was measured next to a concrete pad that suggests the presence of underground utilities. At 920 m, there was a positive 15 mv, natural potential peak that extended for about 40 m and coincided with a 5-cm-diameter PVC pipe that shot water 2 m into the air.

Line B-B´ at the former RAFB has four anomalies that are interpreted to be of hydrogeologic origin. At 440, 630, and 1,120 m, there were positive peaks ranging from 50 to 60 mv and about 40-m long. These three peaks correlated with the submarine springs visited by Percious (1971). The first two were above a region where divers found a line of 10 to 12 freshwater seeps at the base of the cliff (Percious, 1971). The last peak also was above a submarine spring located by Percious (1971). Although there were no known caves in the area, an "M-shaped" natural potential anomaly of positive 50 mv that extended 250 m, centered at 920 m, was interpreted to be an air-filled void.

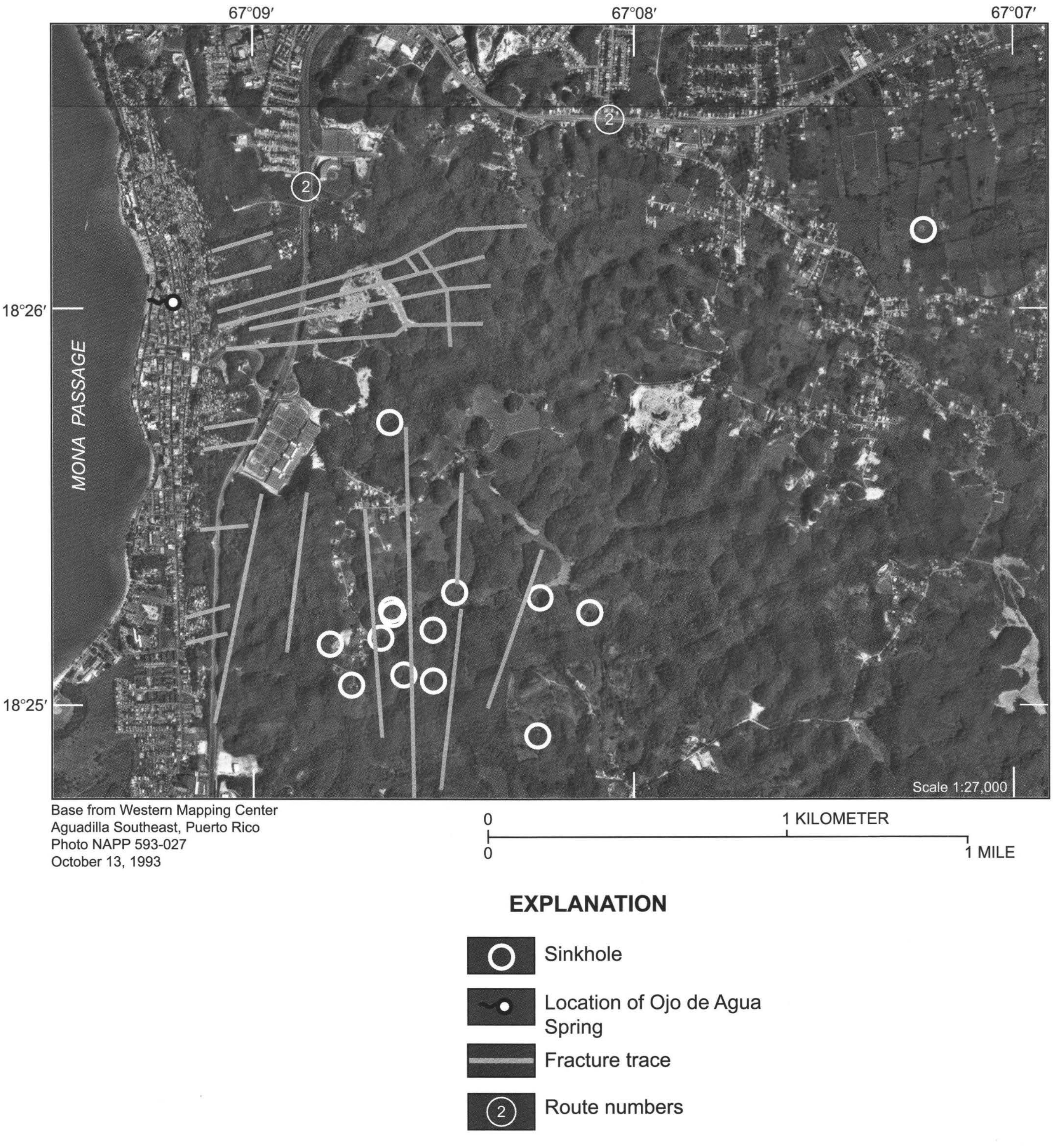


Figure 3. Rectified aerial photograph and interpreted structural features in the Aguadilla urban area and the Caimital Bajo uplands east of Aguadilla, Puerto Rico.

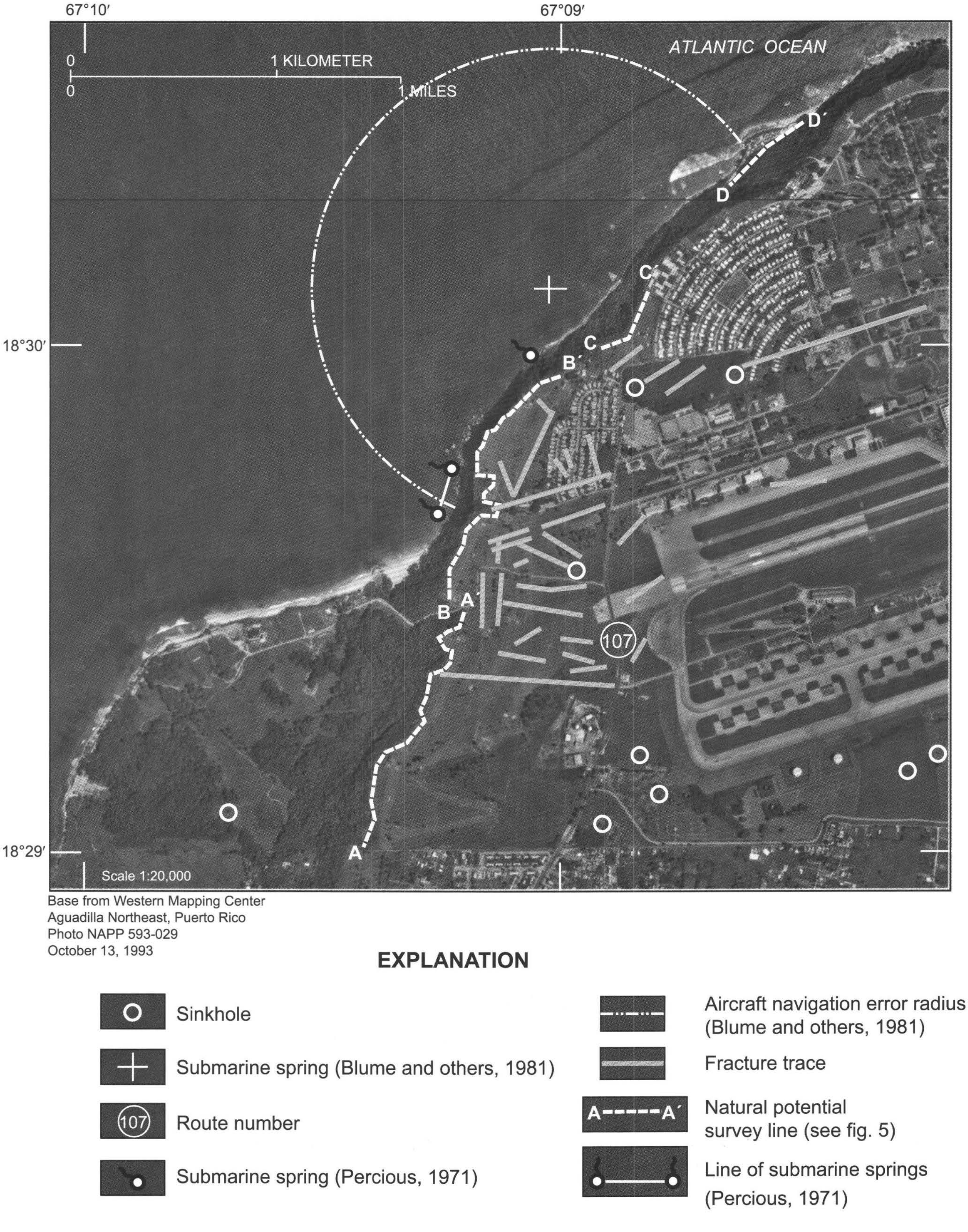
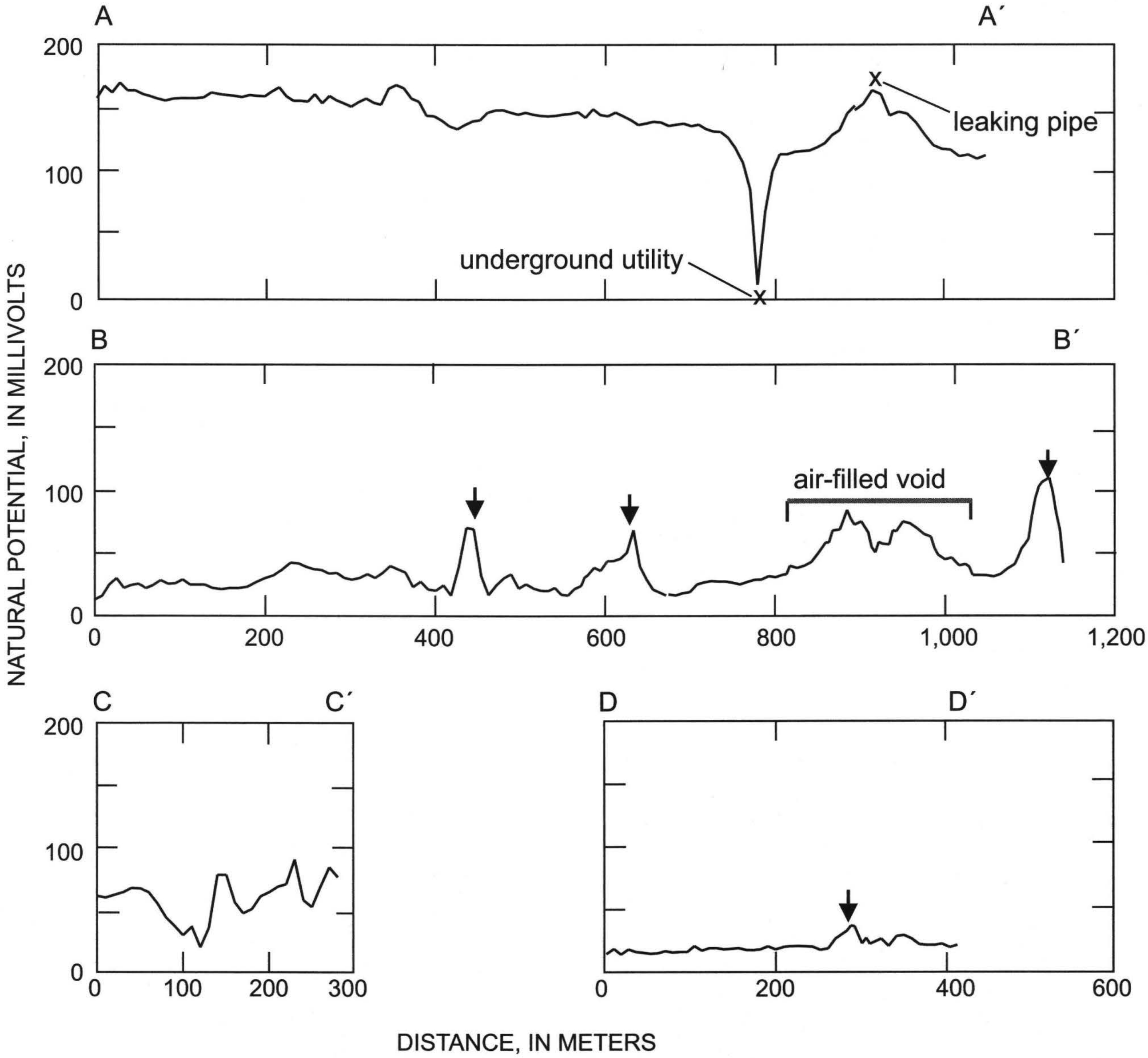


Figure 4. Rectified aerial photograph of the former Ramey Air Force Base in Aguadilla, Puerto Rico.



EXPLANATION

↓ Natural potential anomaly interpreted as a conduit

Figure 5. Natural potential profiles at the former Ramey Air Force Base in Aguadilla, Puerto Rico. The locations of the survey lines are shown in figure 4.

Quebrada de los Cedros between Aguadilla and Isabela

Quebrada de los Cedros is an ephemeral stream that serves as the boundary between Aguadilla and Isabela (fig. 6). The drainage area of this ephemeral stream is well developed and lies north of Highway 2 entirely within the Aymamón and Aguada Limestones. The origin and evolution of Quebrada de los Cedros has not been studied, but the main trunk, entrenched in a narrow canyon about 30-m deep, might have originated as a collapsed underground passage, as in the cases of the canyons of the Río Camuy and Río Guajataca (Giusti, 1978). Quebrada de los Cedros presumably evolved from a perennial stream, fed by the regional aquifer system, to an ephemeral stream as the water table became deeper as a result of the uplift of northwestern Puerto Rico.

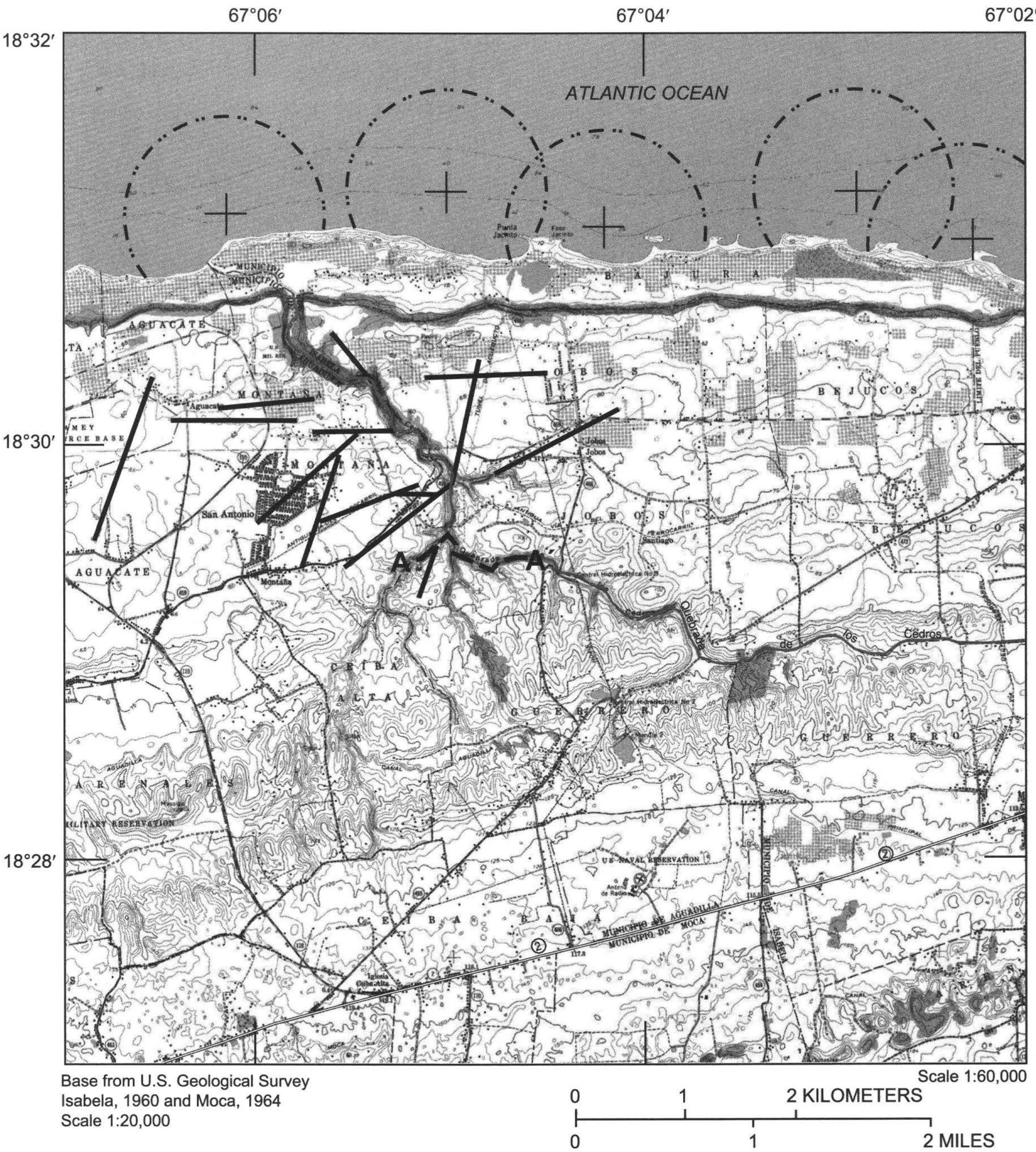
The presence of a narrow and straight stream reach and a series of aligned sinkholes might indicate substantial local control of ground-water flow by joints or fractures (fig. 6). The spatial distribution of sinkholes relative to the main trunk of the Quebrada de Los Cedros indicates the probable occurrence in the past of tributary conduits to a main underground passage.

Quebrada de los Cedros offered the opportunity to apply an exploration method already used with great success in carbonate terrains to locate ground-water sources with development potential. The exploratory method consists of identifying dry stream reaches in carbonate terrains where subsurface drainage is expected to compete successfully with surface drainage (Brahana and Holliday, 1988). This would tend to enhance dissolution along bedding planes, fractures, and joints occurring beneath the streambed creating local ground-water sources with development potential. A good indicator of the presence of these subterranean conduits is the occurrence of wet stream reaches upstream of the dry reaches (Brahana and Holliday, 1988). In Quebrada de los Cedros, the upstream reaches include some pools of standing water, but no flow was observed. In Quebrada de los Cedros, the occurrence of high ground-water yields beneath the main channel is further indicated by the occurrence of depressions in the channel bed that might facilitate the entrance of surface flow into the subsurface. Some of these depressions were observed to have cracks in the rocks with pieces of wood and other debris wedged into them. One natural potential line, A-A′, was run along the Quebrada de los Cedros (fig. 6). Closed depressions in the dry channel are shown as upward arrows in figure 7. Test drilling might be considered to verify whether or not these natural potential anomalies correspond to local subterranean conduits for ground water. Similarly, additional segments of the Quebrada de los Cedros need to be studied to better assess the development potential along various reaches of the drainage area.

Pozo Brujo in Isabela

The Pozo Brujo is a cave-collapse feature characterized by a pond of water (also known as a karst window) and located at the base of a cliff along the narrow coastal plain of Isabela (figs. 1, 8). The existence of several ponds of brackish water along the shore attest to the probable occurrence of freshwater discharge from conduits in the carbonate platform the carbonate platform does not mix with seawater. There are various sinkholes in the area south of the cliff that may be surface expressions of tributary conduits to the main conduit that feeds Pozo Brujo. Part of this conduit network may have risen into the unsaturated zone as the carbonate platform uplifted over geologic time and the water table migrated downward. The abandoned nature of the conduit network of the Pozo Brujo might also be the result of water-table fluctuations in response to sea-level changes.

In the area south of Pozo Brujo, aerial photographs were examined and natural potential data were collected (figs. 8, 9). In general, the fracture traces are mostly oriented in N. 15° E. to N. 40° E. (fig. 8). Using remote sensing, Blume and others (1981) found freshwater floating on the surface of the ocean about 800 m east of Pozo Brujo.



EXPLANATION

	Submarine spring (Blume and others, 1981)
	Aircraft navigation error radius (Blume and others, 1981)
A———A′	Natural potential survey line (see fig. 7)
	Aligned sinkholes

Figure 6. Location of Quebrada de los Cedros between Aguadilla and Isabela, Puerto Rico. Quebrada de los Cedros is the narrow, pronounced stream valley in the west central portion of the map.

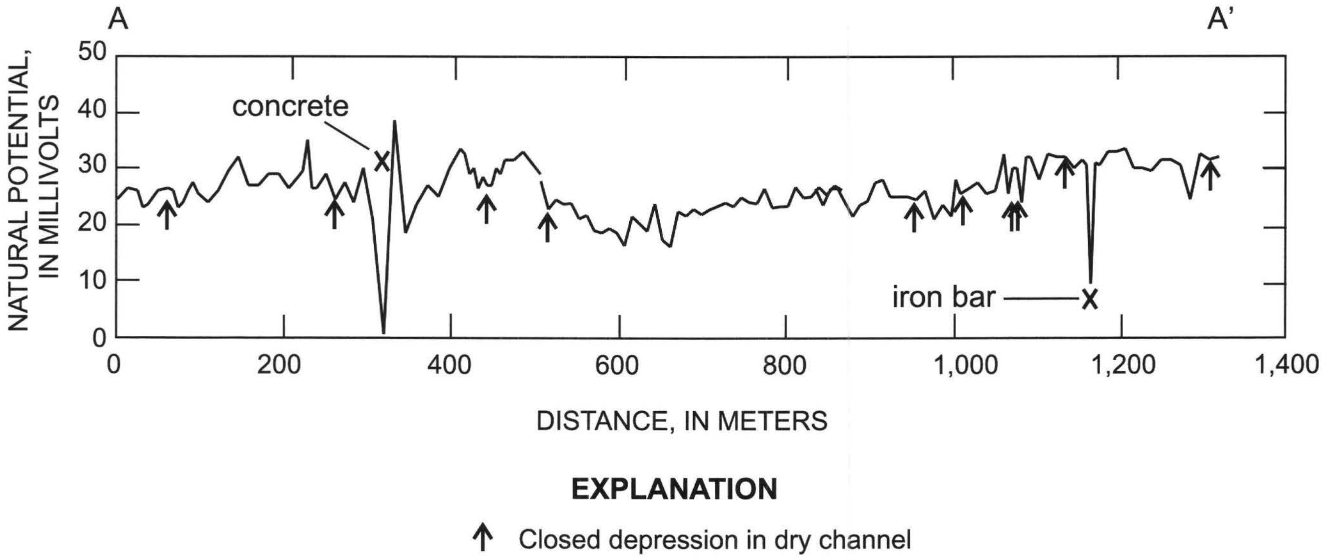


Figure 7. Natural potential profile along Quebrada de los Cedros, Puerto Rico. The location of the survey line is shown in figure 6.

Two natural potential lines were run along a road and in a field south of Pozo Brujo (fig. 8). The first natural potential line (line A-A´) was run along the south side of a paved road approximately 300 m south of Pozo Brujo. The resulting natural potential profile showed three prominent positive anomalies (fig. 9). The easternmost anomaly is an "M-shaped" anomaly. Line B-B´, which is parallel and about 125 m south of line A-A´, extends eastward for a distance of 320 m. The natural potential profile obtained for line B-B´ contained several positive anomalies (fig. 9). Three distinctive peaks at the western end of the line may be due to water flowing in conduits. As indicated by the arrows and dashed lines, several of these anomalies seemed to correlate with natural potential highs found along line A-A´, and are likely expressions of ground-water-flow paths in the subsurface. A domestic well with a "high and sustained yield," as reported by the owner, was found to be located about 25 m west from the edge of the major natural potential anomaly in the eastern end of line A-A´ south of Pozo Brujo (fig. 9). In order to correlate a particular conduit to Pozo Brujo, additional natural potential surveys would need to be conducted along parallel lines between line A-A´ and the sea cliff.

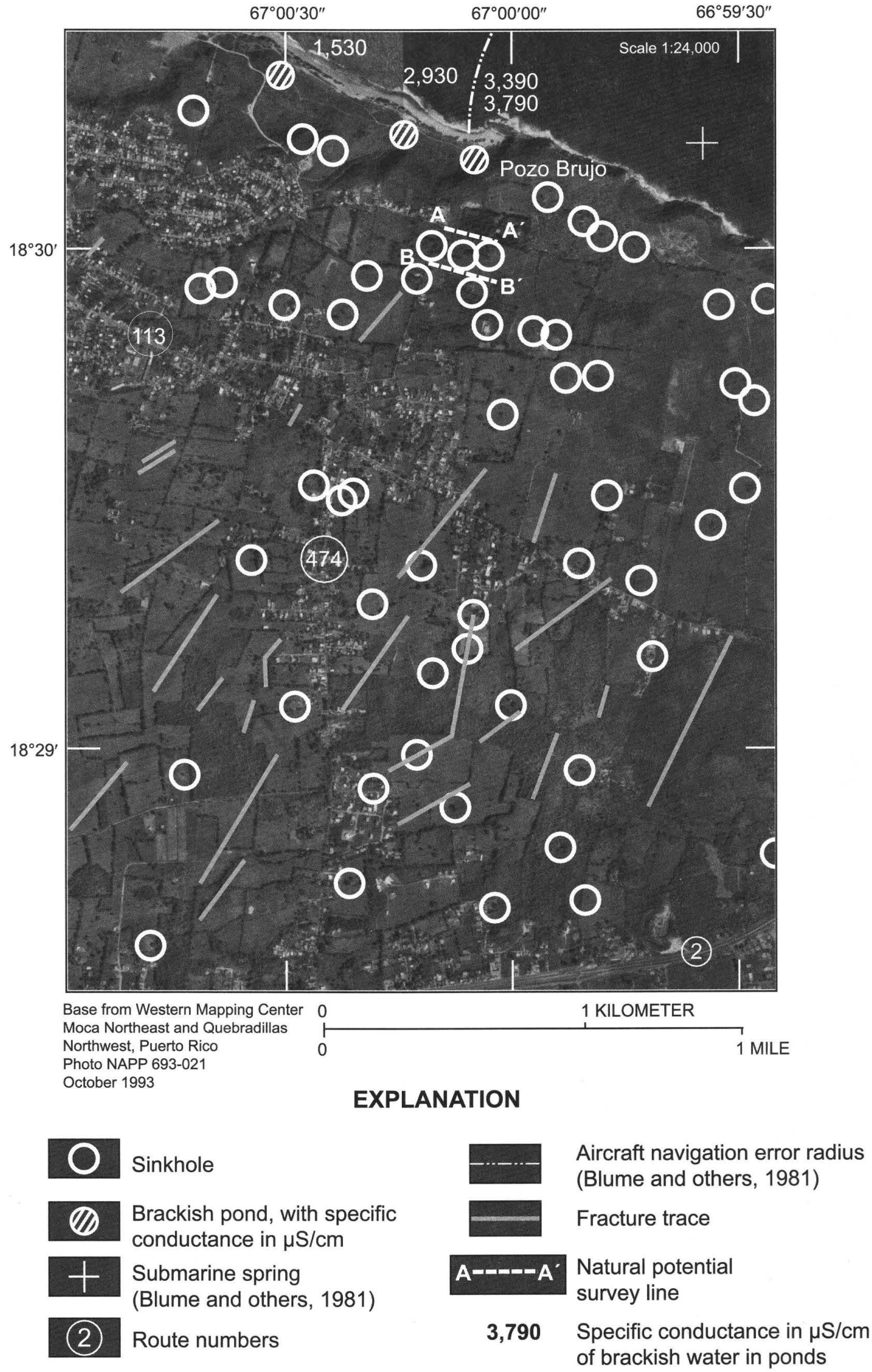


Figure 8. Rectified aerial photograph of the area south of Pozo Brujo in Isabela, Puerto Rico.

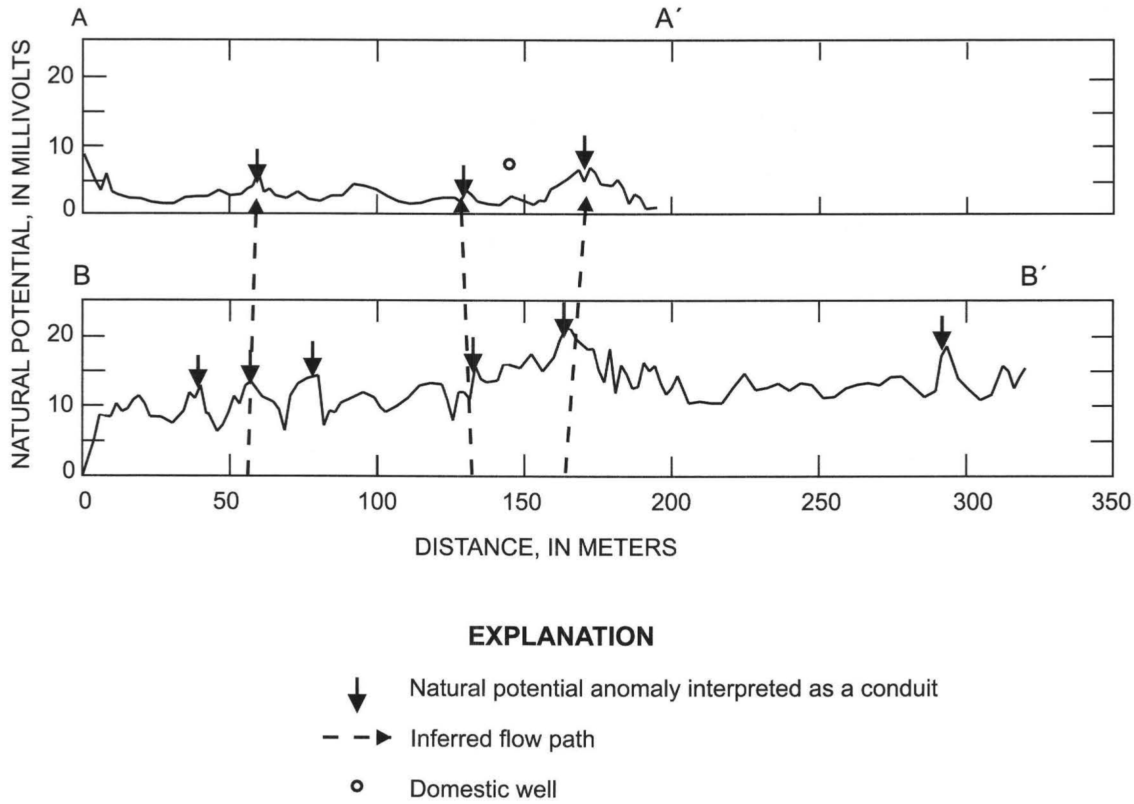


Figure 9. Natural potential profiles south of the Pozo Brujo site in Isabela, Puerto Rico. The locations of the survey lines are shown in figure 8.

The University of Puerto Rico Agricultural Experiment Station and Otilio Dairy Farm in Isabela

The University of Puerto Rico (UPR) Agricultural Experiment Station site is located on the north side of Highway 2 in Barrio Guerrero in Isabela (figs. 1, 10). The UPR Agricultural Experiment Station site is relatively flat with several closed surface depressions and sinkholes. A test well (NC-7) drilled by the USGS in 1986 at this site revealed caverns of substantial size at depths below 33 m within both the unsaturated and saturated zones. The drainage at this site is underground, as is the case in karst plains.

The search for conduits at the UPR site consisted of using both natural potential and gravity geophysical methods. The natural potential coverage at the UPR site is shown in figure 11, and the natural potential profiles are shown in figure 12. A substantial drop in natural potential greater than 20 mv at the western end of the profile A-A′ is attributed to cathodic protection on a pipeline serving the nearby plant nursery (fig. 12). Other artificial effects appear as positive anomalies over concrete culverts and probably are caused by metal within the culverts. The remaining natural potential anomalies shown as arrows pointing downward in figure 12 might be due to the presence of subsurface conduits. Several minor natural potential anomalies, not indicated by arrows in figure 12, might be the effect of naturally cemented (reprecipitated) limestone gravel road surface, which also appear as small positive anomalies. Toward the eastern end of line A-A′, the natural potential values rise sharply with an extrapolated maximum value exceeding 500 mv within the vicinity of a telephone facility. This rise in natural potential is an artificial effect probably related to grounded industrial equipment at the site.

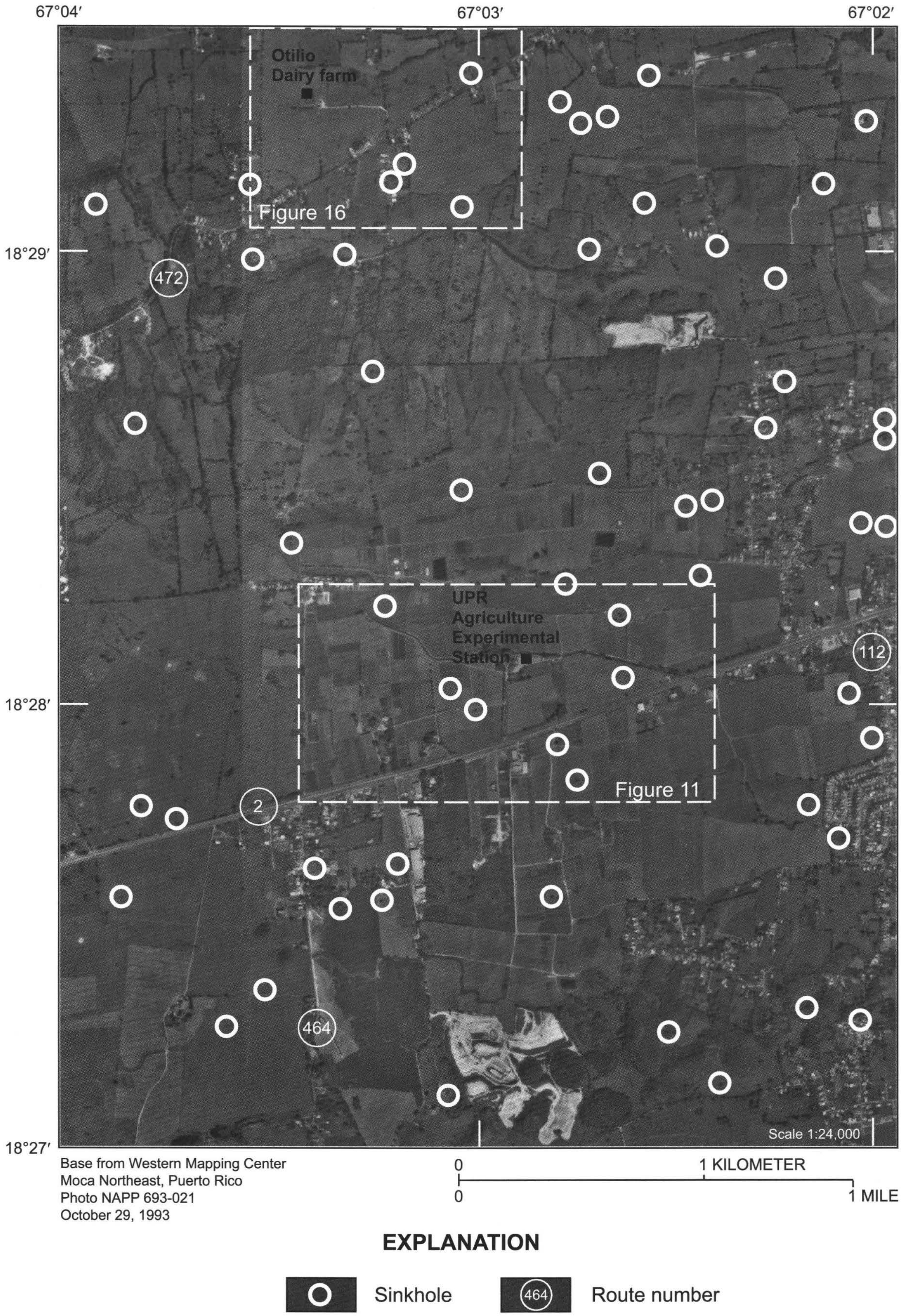


Figure 10. Rectified aerial photograph of the University of Puerto Rico and Otilio sites in Isabela, Puerto Rico. The boxed areas are enlarged in figures 11 and 16.

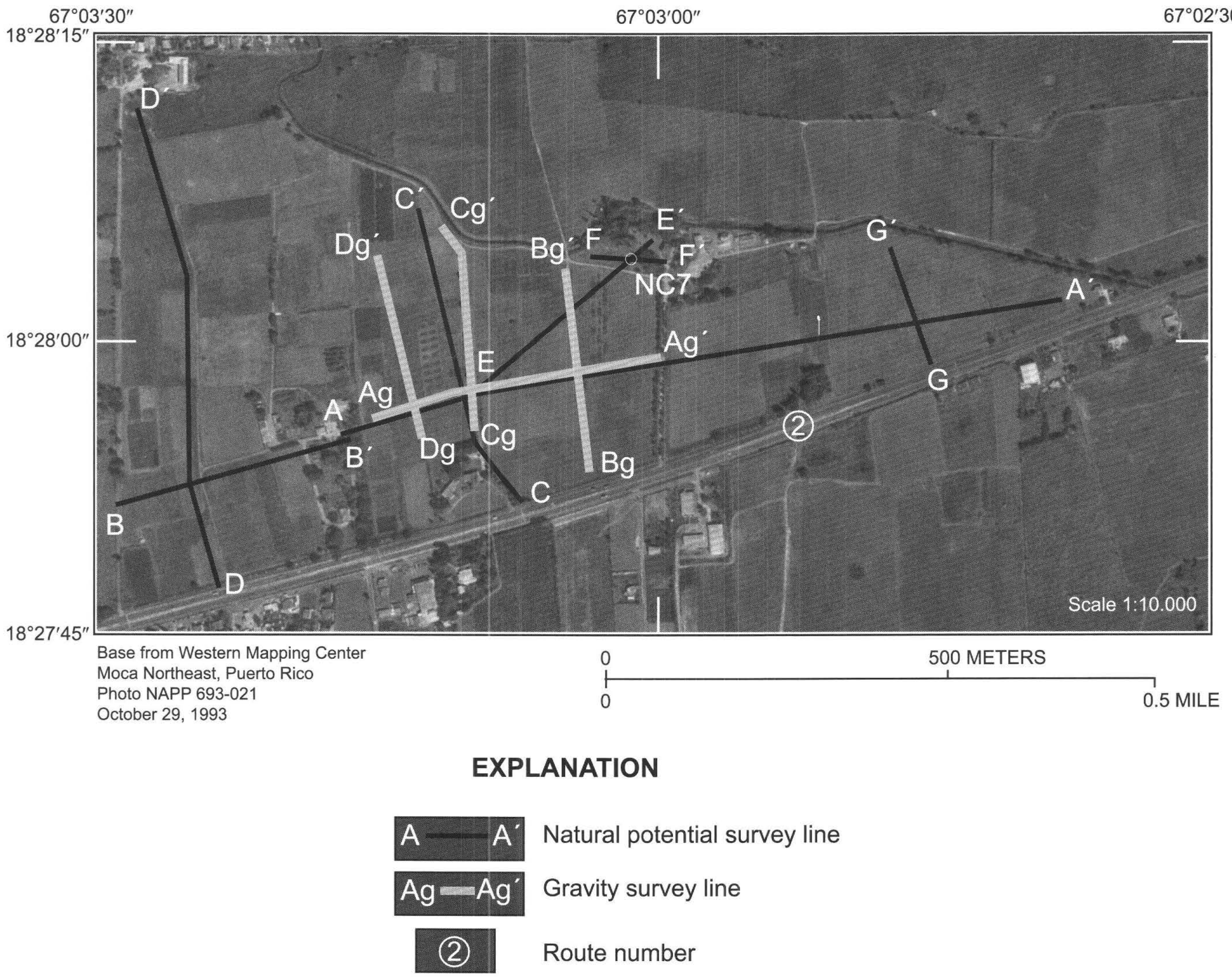


Figure 11. Rectified aerial photograph of the University of Puerto Rico site in Isabela, Puerto Rico.

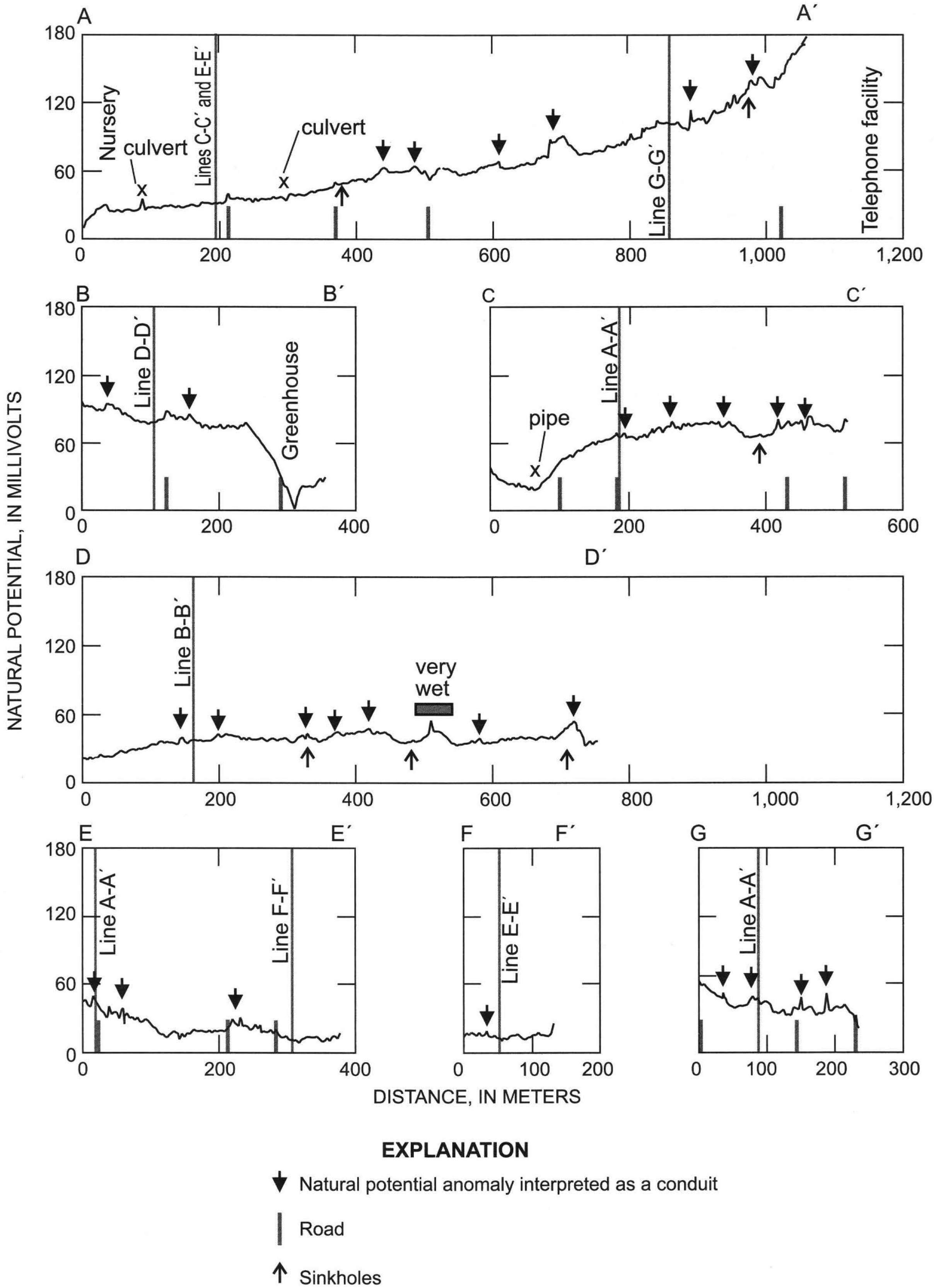


Figure 12. Natural potential profiles at the University of Puerto Rico site, Isabela, Puerto Rico. The locations of the survey are shown in figure 11.

The negative natural potential anomaly at the northeast end of line B-B´ (fig. 11) is the same anomaly at the beginning of line A-A´, and is produced by a cathodic protection effect associated with a pipeline (fig. 12). In the profile of line B-B´ the usual minor peaks might be associated with roads.

Five natural potential positive peaks occurred along line C-C´ (the one about 450 m is "M-shaped"), and suggest underlying conduit flow (fig. 12). A negative natural potential anomaly in the southern part of line C-C´ might be the effect of a nearby metallic pipe casing that is part of the irrigation system.

Line D-D´ exhibits the usual positive anomalies probably due to subsurface conduits and naturally cemented (reprecipitated) limestone gravel road surface. A pronounced positive anomaly at about 500 to 515 m in line D-D´ probably is caused by wet ground caused by ongoing irrigation (fig. 12). In line D-D´, two sinkholes approximately located at 340 and 700 m might be responsible for the most substantial positive anomalies along this line. The anomaly near 340 m is "M-shaped", which suggests flow in a subsurface conduit.

Line F-F´ intersects line E-E´ in a broad depression directly south of a water-supply canal (fig. 11). A well drilled in this vicinity, test well NC-7, penetrated several cavernous zones from 17 to 45 m below land surface. The wide natural potential low divided between line E-E´ and line F-F´ is typical of the profile produced by a cavern (fig. 12).

The solid arrows in line G-G´ designate other natural potential highs probably resulting from flow in karst conduits. The sharp drop in potential at the eastern end of line G-G´ may be the result of a strong moisture gradient beneath the boundary between a paved and a dirt road.

At the UPR Agricultural Experiment Station site there are several anthropogenic features affecting the natural potential data. The most important of these antropogenic features is grounded industrial equipment at a telephone facility (fig. 12). Consequently, the natural potential data collected at the UPR site was replotted using the residual left after subtracting a 21-point running average from the raw natural potential value (fig. 13). This method served as a filter to significantly reduce the long-wavelength trends caused by the antropogenic features, which obscured the short-wavelength features associated with actual conduit flow. However, two disadvantages were found in using the 21-running average method. First, the method cut off 10 data points at each end of the natural potential line. Second, the method changed the shape of the flanks of anomalies. An example of this can be seen in figure 13 on line B-B´ at 240 m and on line C-C´ at 105 m. The peaks that flank both negative anomalies are artificially raised. The running average was lowered by the trough, which caused the shoulder of the anomaly to be elevated.

Relative gravity Bouguer anomalies were detected along north-south and west-east trending lines at the UPR Agricultural Experiment Station site. Small-scale gravity anomalies of 0.10 to 1.0 mgal were measured that may indicate the presence of shallow and relatively large density contrasts (fig. 14). The largest negative anomalies typically are associated with sinkholes or more subtle circular depressions of the ground surface, as demonstrated in line Ag-Ag´ (fig. 14). The large negative anomaly on line Cg-Cg´ is not associated with a topographic depression, and in fact, corresponds with an elevation maximum (fig. 14).

An example of combining the results obtained from the natural potential and gravity geophysical techniques is shown in figure 15, using data from the A-A´ and Ag-Ag´ in the UPR Agricultural Experiment Station site. An "M-shaped" anomaly in the natural potential profile of line A-A´ coincides with a negative anomaly at 450 m in the gravity profile of line Ag-Ag´ (fig. 15). The occurrence of a natural potential anomaly at 390 m with a gravity anomaly strongly indicates the presence of conduit flow at the UPR Agricultural Experiment Station site.

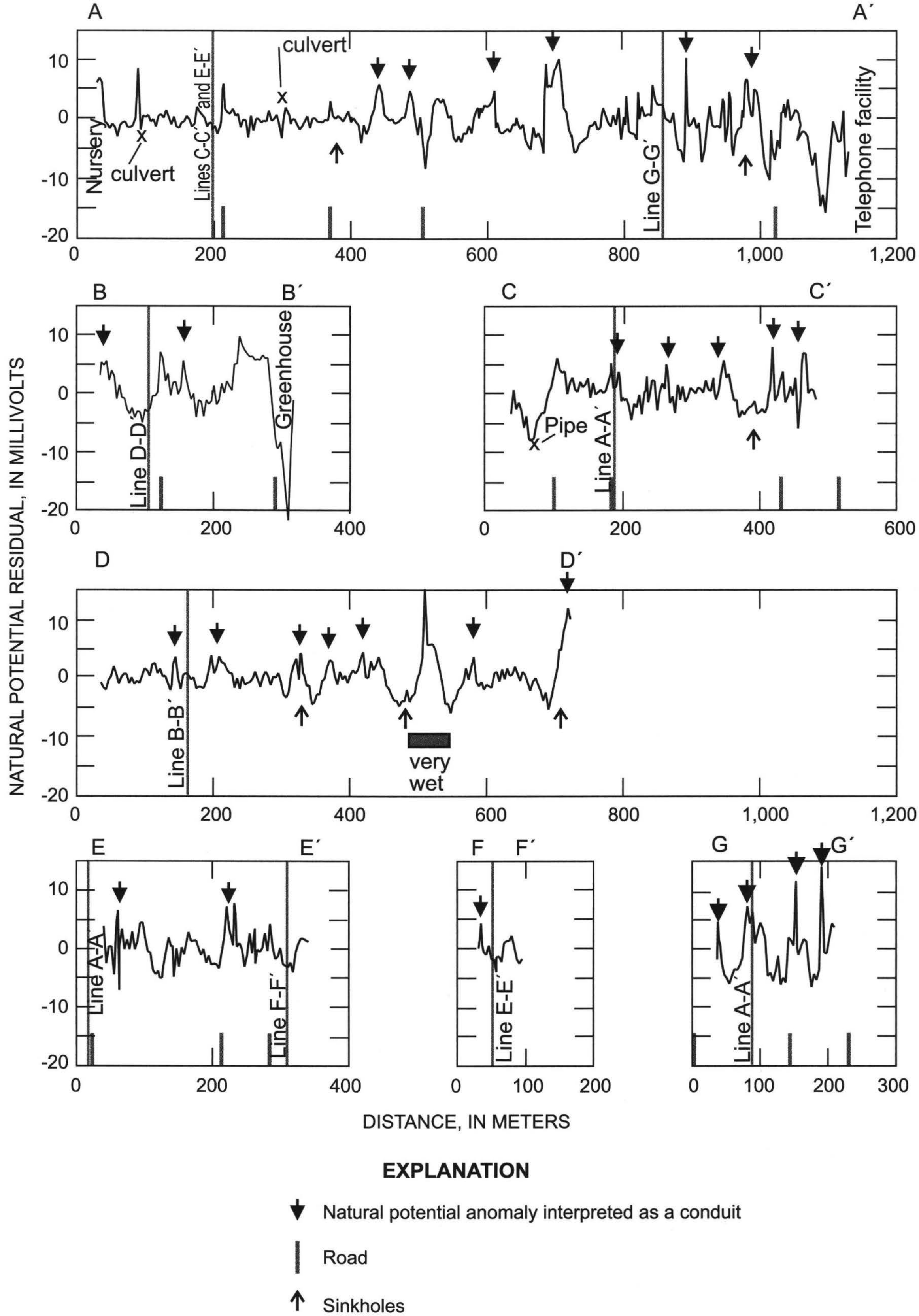


Figure 13. Natural potential residual at the University of Puerto Rico site, Isabela, Puerto Rico. The locations of the survey are shown in figure 11.

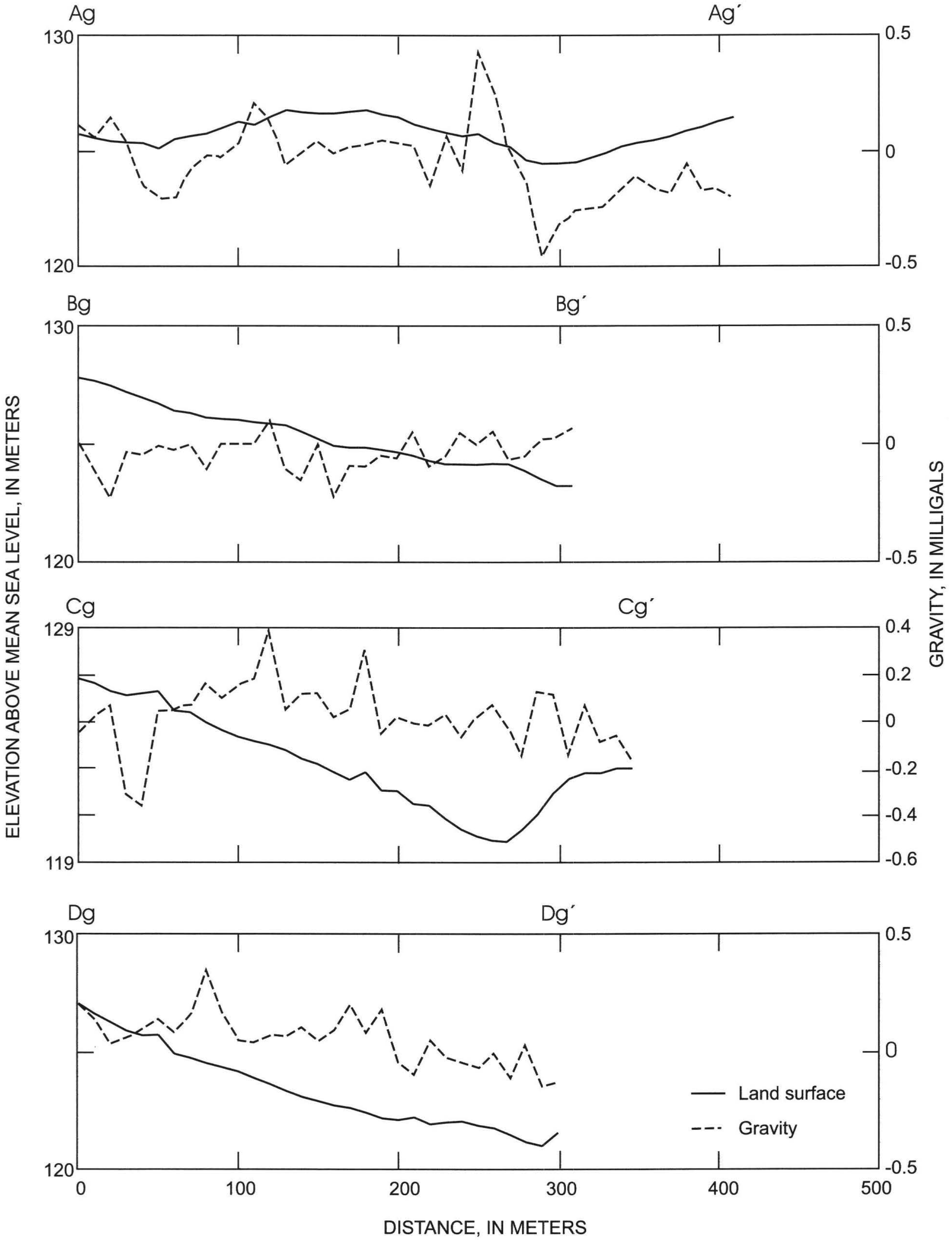


Figure 14. Gravity profiles at the University of Puerto Rico site, Isabela, Puerto Rico. The locations of the survey lines are shown in figure 11.

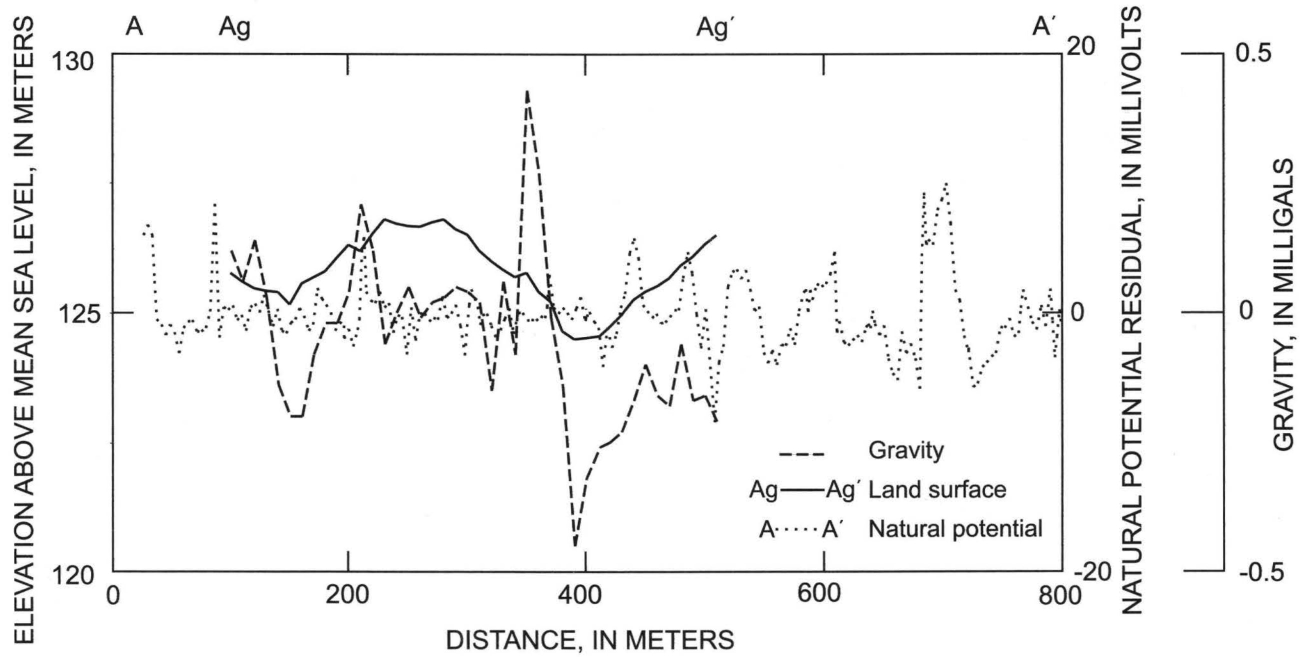


Figure 15. Combined gravity and natural potential profiles at the University of Puerto Rico site, Isabela, Puerto Rico.

The Otilio site is located along Highway 472 in Barrio Bejucos in Isabela (figs. 1, 16). The Otilio dairy farm is located 1.6 km north of the UPR site. The presence of cavities in a test well, NC-11, drilled by the USGS and several surrounding sinkholes suggests the occurrence of conduits at this site (Rodríguez-Martínez and Hartley, 1994).

The natural potential and gravity geophysical techniques were used to detect the occurrence of cavities and conduit flow at the Otilio site (fig. 16). Three natural potential survey lines were run at the site (fig. 16). The sinkhole encompassing the northeastern part of line A-A′ is characterized by low natural potential, as indicated by the upward pointing black arrows in figure 17. The low potential suggests that water may be actively infiltrating downward. The road produced the expected positive natural potential expression. The other natural potential anomalies, indicated by black arrows pointing downward, are indicative of karst conduits (fig. 17). The resulting natural potential profile along line B-B′ exhibits a series of erratic readings that cannot be reasonably attributed to subsurface flow.

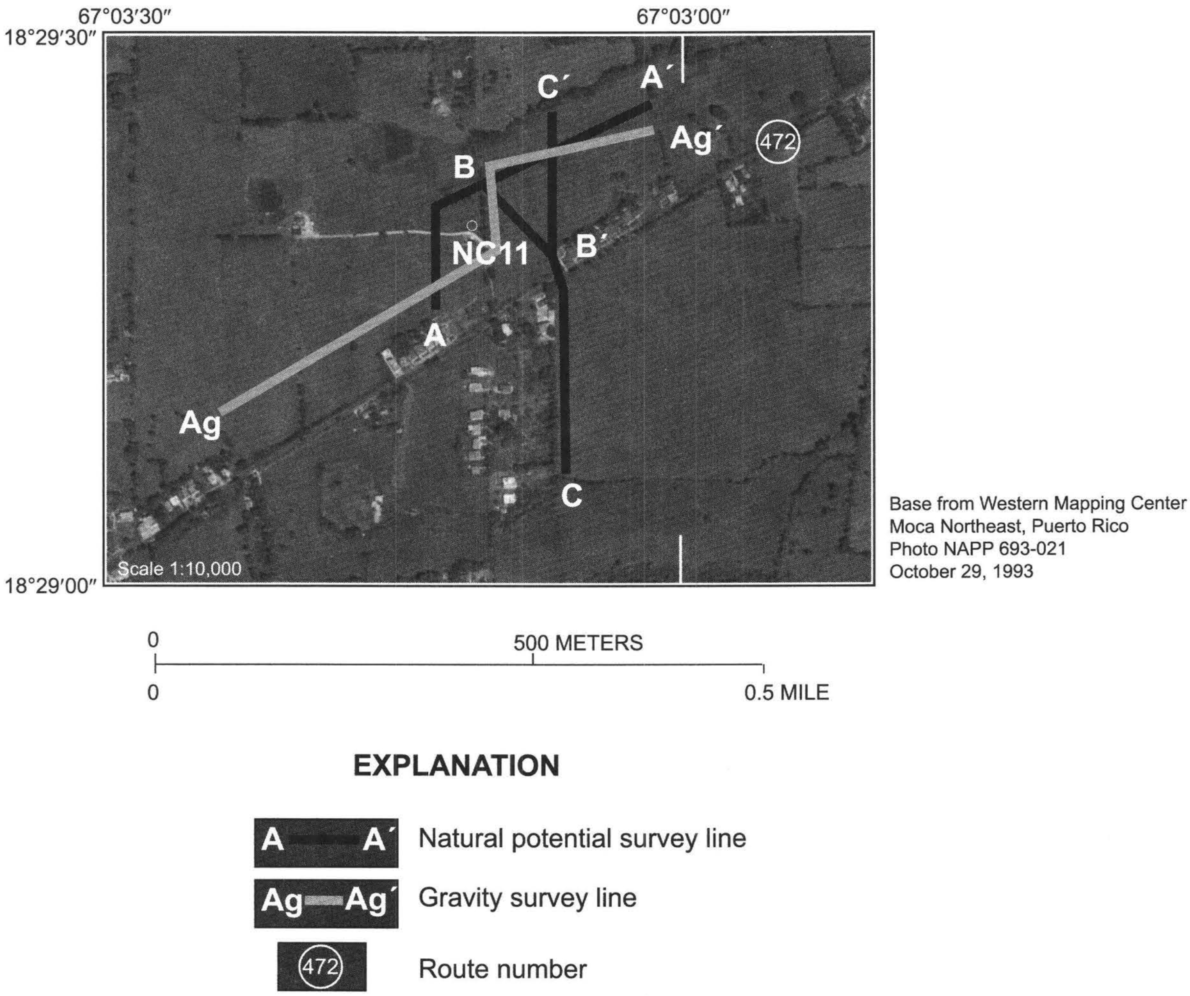


Figure 16. Rectified aerial photograph of the Otilio site in Isabela, Puerto Rico.

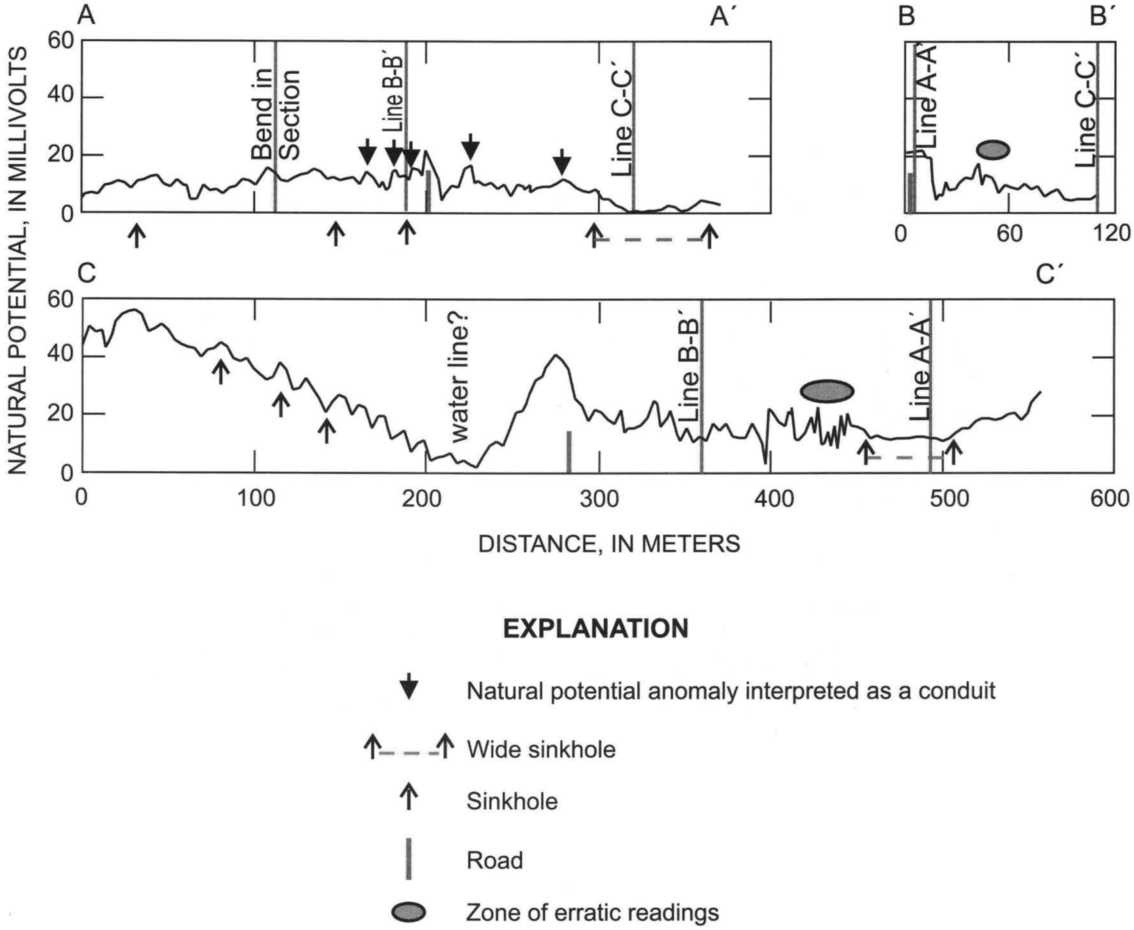


Figure 17. Natural potential profiles at the Otilio site in Isabela, Puerto Rico. The locations of the survey lines are shown in figure 16.

A gravity survey line (Ag-Ag´) was run at the Otilio site (fig. 18). As at the UPR Agricultural Experiment Station site, small-scale gravity anomalies of 0.10 to 1.0 mgal may indicate the presence of shallow and relatively large density contrasts (fig. 18). The largest negative anomalies typically are associated with sinkholes or more subtle circular depressions of the ground surface, as illustrated in the line Ag-Ag´ at a distance of 190 m (fig. 18).

Incorporating only variations in soil thickness, the two-dimensional forward modeling technique could not produce calculated anomalies that match the observed data at the Otilio site. Consequently, larger variations in density were required by the two-dimensional modeling technique to reproduce the calculated gravity anomalies. Limestone exposures were observed in at least one of the topographic depressions associated with a negative anomaly, and thus, a shallow subsurface void rather than thickened soil was considered the preferred interpretation. The topographic profile of the gravity line Ag-Ag´ at the Otilio site shows a symmetrical depression 4-5 m below the surrounding elevations (fig. 18). A gravity minimum was predicted by the model over the southwest edge of this depression (fig. 19). Within the simplifying assumptions, a reasonable match between modeled and observed Bouguer gravity anomaly was obtained by assuming a cylindrically shaped void with a 15-m radius located 6 m below land surface (fig. 19). One interpretation is that a thin veneer of soil overlies the limestone within the depression, which in turn is flanked by wedges of soil that thicken to 25 m away

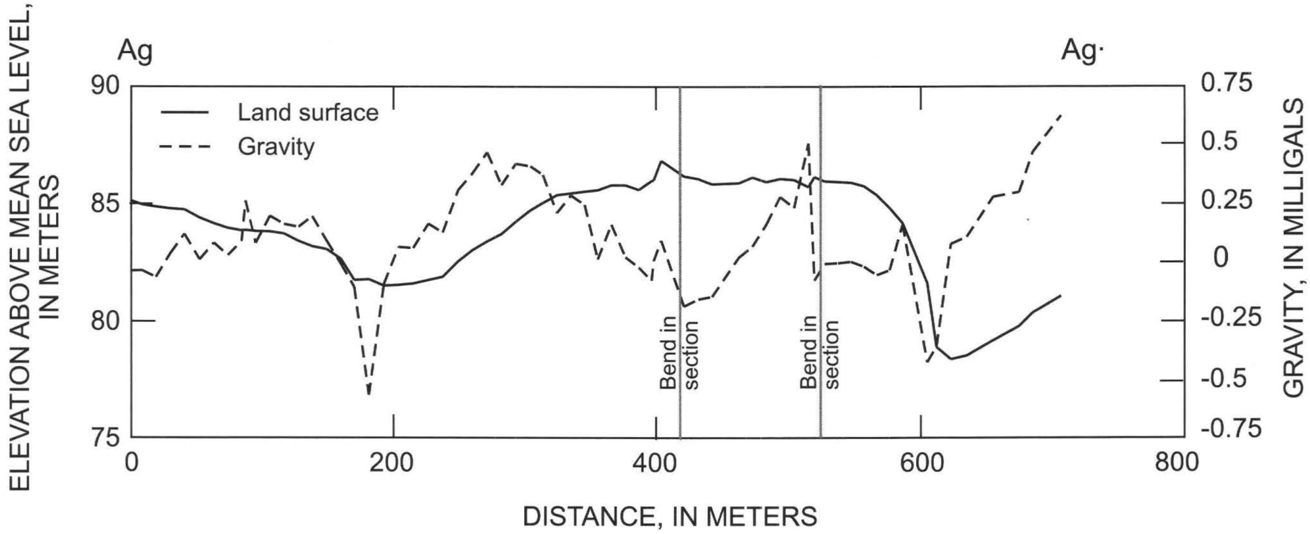


Figure 18. Gravity profile at the Otilio site in Isabela, Puerto Rico. The locations of the survey lines are shown in figure 16.

from the topographic low. A similar gravity anomaly from the Tertiary carbonates of Florida was interpreted differently by assuming that the void is flanked by regions of higher density (Stewart and Wood, 1990). The higher density could result from the reprecipitation of the calcite removed when the void formed beneath the sinkhole. Despite the well established non-uniqueness of gravity modeling, the simplistic models indicate that a substantial, shallow mass deficiency is present below some surface depressions.

Monte Encantado area in Moca and Isabela

The Monte Encantado area is located in Isabela and Moca (figs. 1, 20). The area is characterized by a well-developed cockpit karst topography with steep densely forested limestone hills and star-shaped depressions. A cave stream in this area, probably part of a larger river-cave system, is used as a public-water supply source by the PRASA. Because of the dense forest cover, identification of fracture traces was not possible, therefore, the linear terrain analysis was limited to the identification of aligned ridges and sinkholes. Natural potential surveys were conducted along the periphery and in the immediate vicinity of this area to identify potential subsurface conduits that might be part of the underground drainage system of Monte Encantado.

The presence of aligned ridges and sinkholes, as well as the existence of cave streams suggest the presence of a joint or fracture system in the Monte Encantado area. The predominate range in the orientations of the long axes of the sinkholes is from N. 10° E. to N. 35° E. The Monte Encantado area seems to be affected by a slight structural flexure as indicated by the northward change in the dip of the middle-Tertiary sequence from 8 to 4 degrees (Monroe, 1969b) (fig. 21).

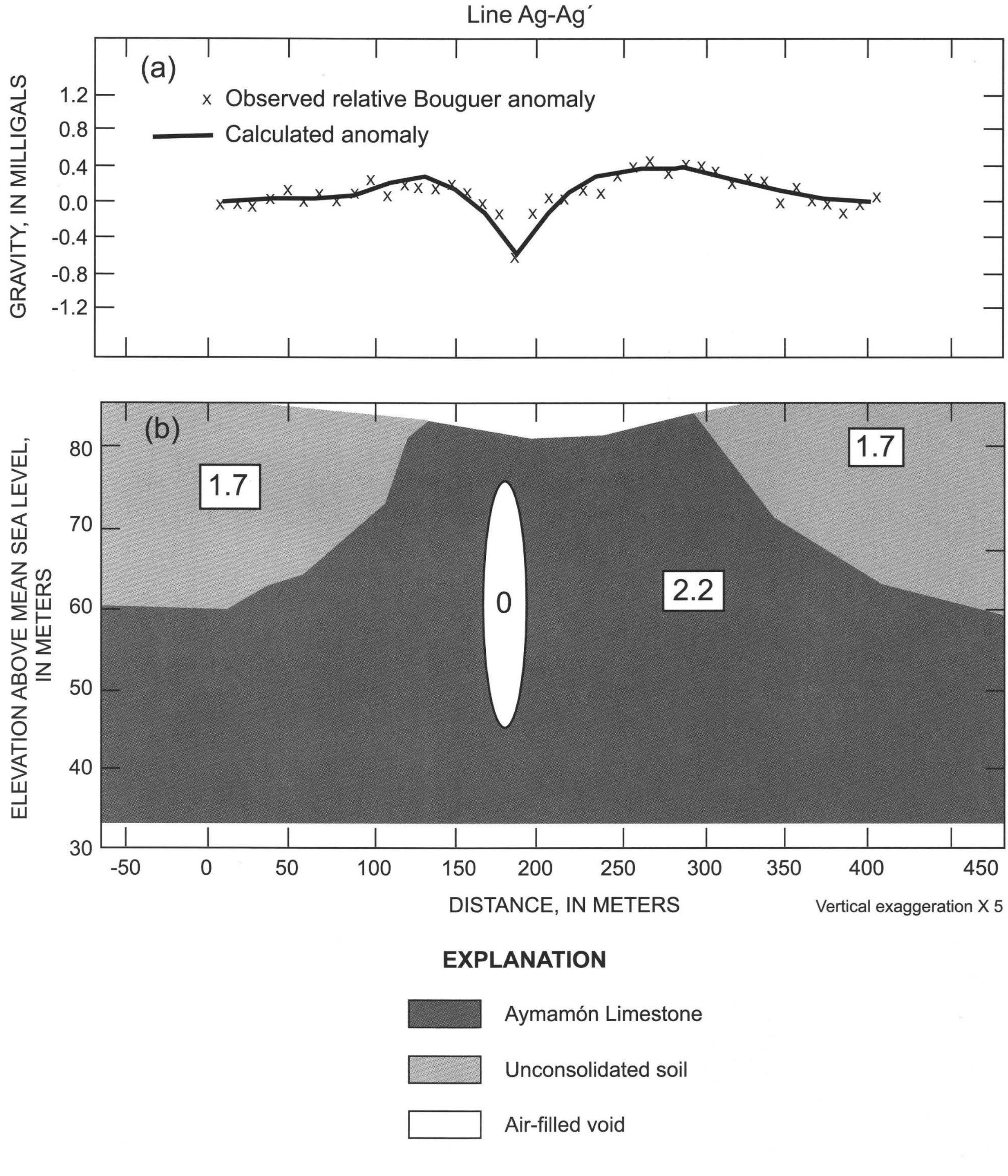


Figure 19. Density-distribution model for the first 450 meters of gravity survey line Ag-Ag' at the Otilio site in Isabela, Puerto Rico. Numbers indicate density in g/cm^3.

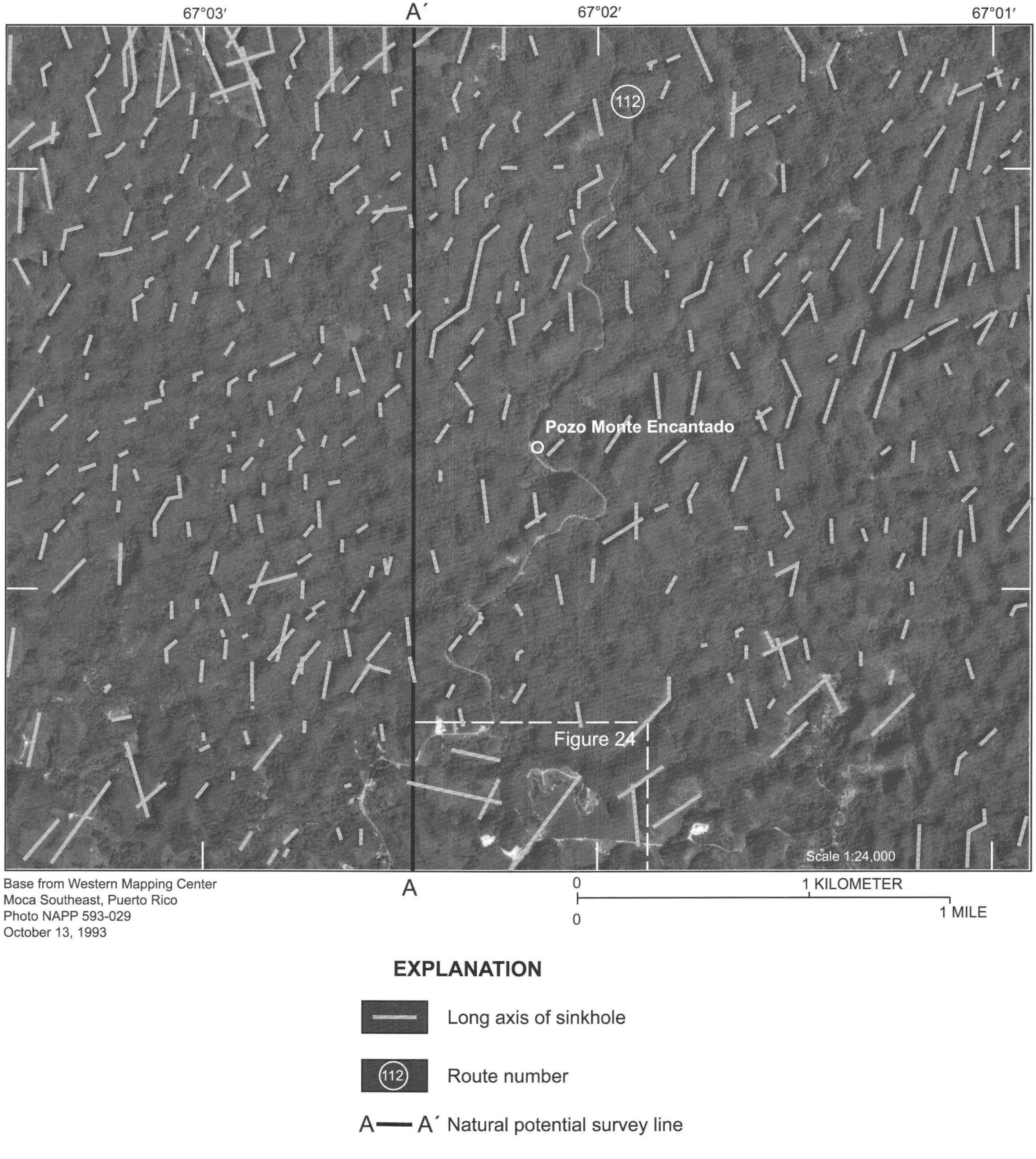


Figure 20. Rectified aerial photograph of the Monte Encantado area of Moca and Isabela, Puerto Rico, showing the line of the geologic section A-A′ shown in figure 21. Also shown are the long axes of sinkholes in the Monte Encantado area. The boxed area is enlarged in figure 24.

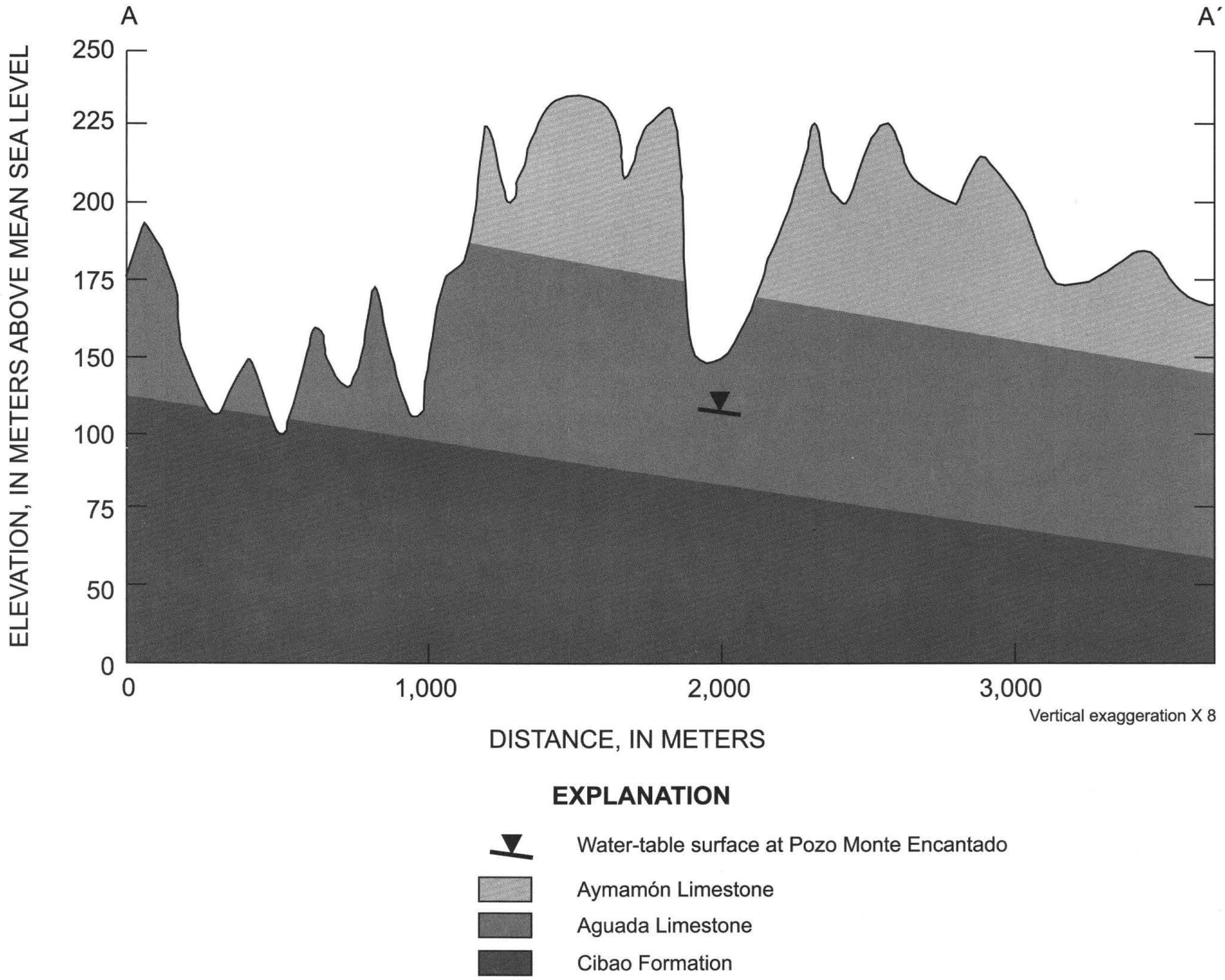
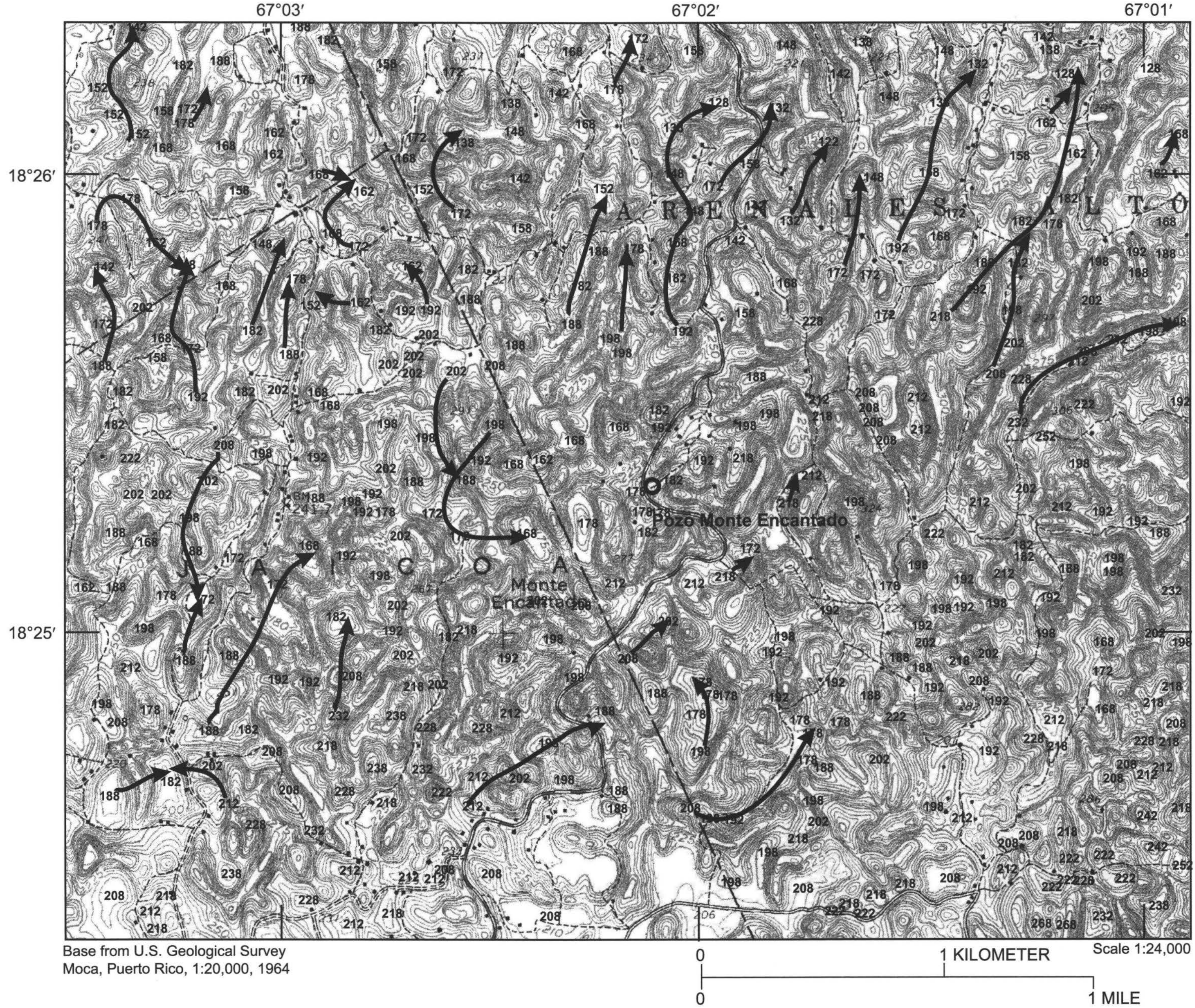


Figure 21. Geologic section A-A´ in the Monte Encantado area in Moca and Isabela, Puerto Rico. The line of section is in figure 20. The geology is from Monroe (1969b).

The Monte Encantado area is near the southernmost extension of the carbonate platform in an area having no substantial surface-water drainage. The presence of a joint-fracture system implies that ground-water flow might be along highly preferential paths. In section A-A´, shown in figure 21, an inflection in the dip of the middle-Tertiary sequence coincides with the deepest sinkhole in the Monte Encantado area, as determined from a topographic map. This sinkhole seems to act as one of various probable convergence points for ground-water flow paths. Two ways of examining the probable paths of ground-water movement are shown in figures 22 and 23. In figure 22, probable paths of ground-water flow were estimated by assuming that water in a sinkhole will move preferentially to the nearest sinkhole of lower elevation (Giusti, 1978). This methodology also suggests a substantial convergence of ground-water flow towards sinkholes with lower bottom elevations, and a predominant movement towards the northeast. In figure 23, the elevations of the bottoms of the sinkholes in the Monte Encantado area were contoured. The resulting topographic gradients in such contoured surface were used to identify probable preferential paths of ground-water flow. According to figure 23, a predominant direction of ground-water flow appears to be along a zone to the northeast.

Natural potential surveys were conducted along two lines in the vicinity of the Monte Encantado area (fig. 24). Four natural potential lines were run at Monte Encantado site 1 (fig. 24). Line B-B´ passes approximately 2.5 m north of a 10-m-diameter sinkhole, into which a northward draining spring-fed stream disappears. The underground route of the subterranean conduit from the sinkhole was expected to pass beneath lines A-A´ and B-B´. A steel-cased water well and saturated ground-water conditions in the area of the transect may have produced substantial natural potential anomalies, and thus masking any subterranean conduits. The well or saturated ground may have caused the substantial positive natural potential anomaly at a distance of about 30 m on line B-B´ (fig. 25). The anomalies observed in lines A-A´ and B-B' at about 15 to 20 m, however may be attributed to the conduit (fig. 25). The "sombrero-shaped" anomaly at about 15 m, which coincides with the stream, was also used to test the natural potential response (fig. 25). The irregular positive natural potential anomaly at 75 m on line D-D´ and the double-peaked anomaly at 75 m on line C-C´ are interpreted to represent the shallow underground feeder conduits to the spring. The remaining anomalies identified by downward-pointing arrows may be subterranean conduits with water.

Two natural potential lines were run at Monte Encantado site 2 (fig. 24). Line E-E´ crossed several stretches of saturated ground and two surface streams, of which, only the western stream at about 75 m produced a natural potential anomaly (fig. 26). Two prominent highs occurred in saturated ground along line E-E´ at distances of 178 and 192 m. Line F-F´ passed within about 2 m of a non-active steel-cased water well located at a distance of about 120 m, and induced a positive natural potential anomaly of 10 mv. Line F-F´ crossed an eastern stream, intersected by line E-E´, which resulted in a positive anomaly (fig. 26). The broad positive anomaly in line F-F´ between 60 and 75 m, was associated with saturated ground, but may also have been a conduit that fed the surface stream in line E-E´ at about 72 m (fig. 26). The peaks in the eastern part of line F-F´ occur in an area of seeps and small springs, and may be connected to the pair of peaks that coincide with saturated ground on line E-E´, as possible "leaky conduits" (fig. 26). The presence of saturated ground also could be explained as ground-water discharge. Consequently, the associated natural potential anomalies may result from the upward movement of ground water or evapotranspiration occurring at shallow depths.



EXPLANATION

192 Elevation, in meters above mean sea level of the bottoms of sinkholes

Apparent ground-water flow path

Figure 22. Probable flow paths in the Monte Encantado area of Moca and Isabela, Puerto Rico.

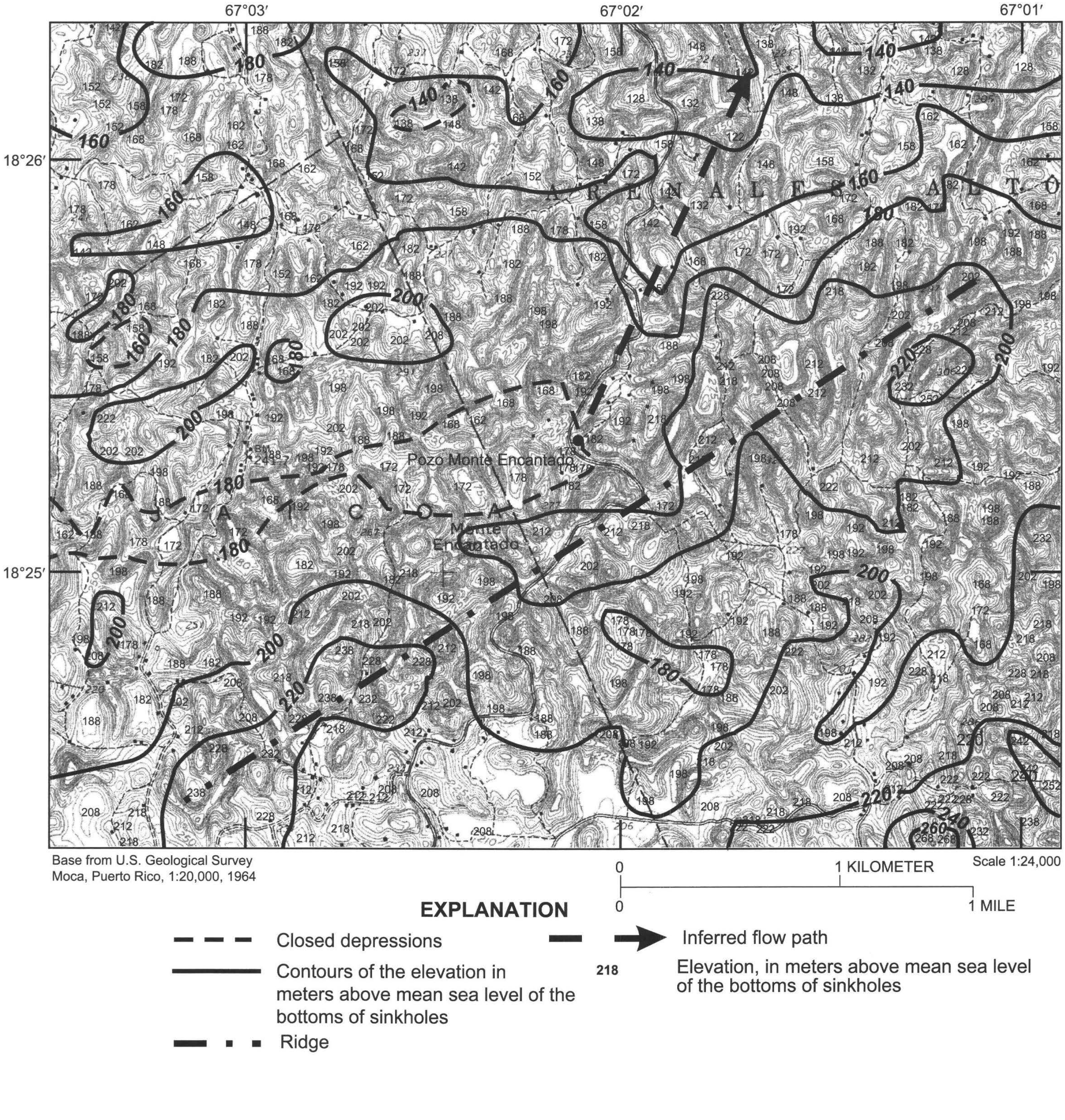


Figure 23. Contoured elevations of the bottoms of sinkholes and probable ground-water flow paths in the Monte Encantado area of Moca and Isabela, Puerto Rico.

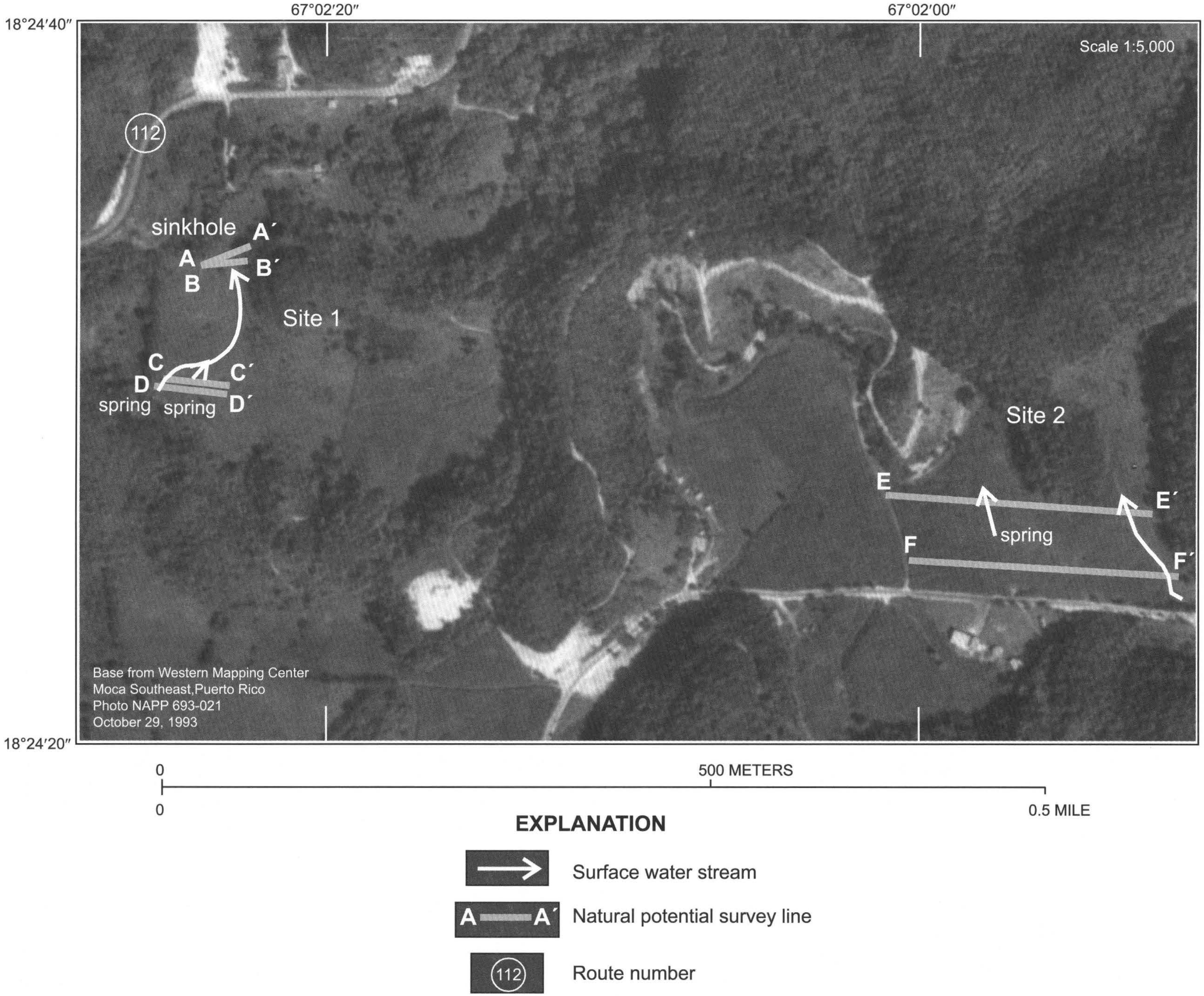


Figure 24. Rectified aerial photograph of the Monte Encantado area in Moca and Isabela, Puerto Rico. Showing the locations of natural potential survey lines in the Monte Encantado area, Puerto Rico.

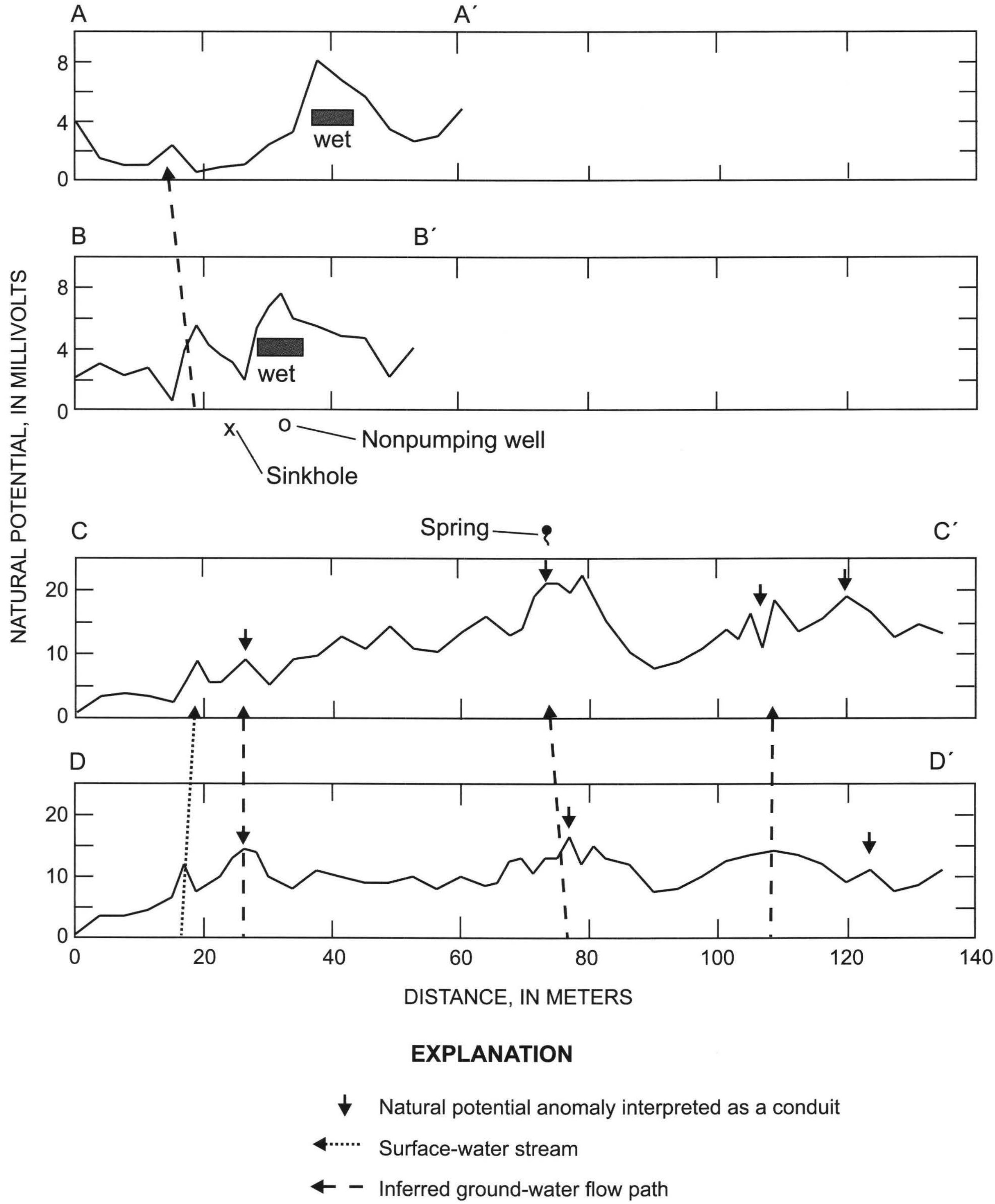


Figure 25. Natural potential profiles at Monte Encantado site 1, Puerto Rico. The locations of the survey lines are shown in figure 24.

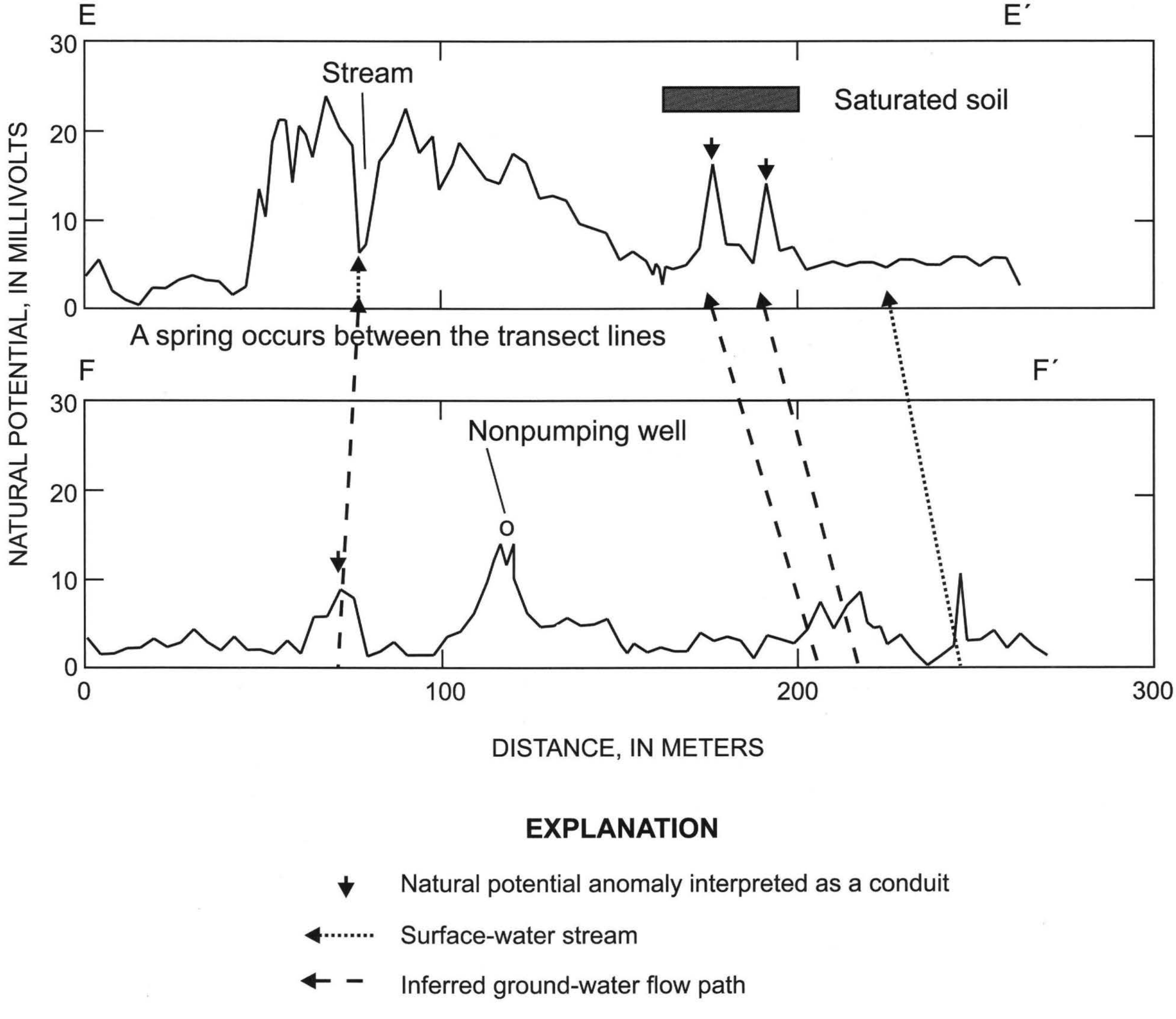


Figure 26. Natural potential profiles at Monte Encantado site 2, Puerto Rico. The locations of the survey lines are shown in figure 24.

Río Camuy Cave System in Hatillo

The Río Camuy cave system is a complex of underground and open steam reaches, underground tributaries, associated sinkholes, karst windows, and other karst dissolution features. As of 1997, the Río Camuy cave system had not yet been fully explored (C. Conde-Costa, Sociedad Espeleológica de Puerto Rico, Inc., oral commun., 1997). This river-cave system is used as a public water-supply source by the PRASA.

Linear terrain features analysis using aerial photographs was performed by Rinker (1974) to infer the most probable locations of the main and tributary underground passages of the Río Camuy. Rinker's (1974) findings were in general agreement with maps prepared later by local cave exploration groups. In this study, natural potential data were collected in that part of the Río Camuy cave system in Hatillo and Camuy (fig. 27). The natural potential lines A-A´ and B-B´ were run along opposite sides of Highway 129 (fig. 27) in an area where large sinkholes overly the underground path of the Río Camuy; however, the river's exact location beneath Highway 129 is not known. In a sinkhole to the north of line A-A´, a vertical shaft, which is considered a karst window, gives access to the Río Camuy. Line A-A´ was run along the embankment on the north side of Highway 129. A metal guard rail extending along the edge of the highway did not seem to have any substantial effect on data collection. The profile obtained with line A-A´ is uniformly undulatory with only a prominent 15-mv positive natural potential peak less than 13-m wide (fig. 28). It is reasonable to infer that this natural potential anomaly may be due to a subterranean portion of Río Camuy.

Line B-B´ was run along the south side of Highway 129, in order to corroborate an anomaly observed in line A-A´. Unfortunately, the embankment on the south side contained not only a guard rail (of minimal effect as in line A-A´), but also a steel water-pipe line. An "M-shaped" anomaly near the origin of line B-B´ that occurred over a culvert can be discarded as indicative of subsurface conduits and/or caverns. Another positive but weaker anomaly of about 6 mv was detected at about 134 m, and likely was caused by the Río Camuy.

Two other natural potential lines, C-C´ and D-D´ (fig. 27), were run in an area known to overlie the subterranean river, which is about 120 m below land surface (Gurnee and Gurnee, 1987) (fig. 27). The area where lines C-C´ and D-D´ were run is complicated by the intervening air-filled galleries of Cueva Clara, which is an entrance cave to the Río Camuy cave system. However, the location of the river is revealed at the surface by the location of a public water-supply well that pumps water from the subterranean river (R. Carrasquillo-Nieves, USGS, oral commun., 1996). The natural potential profile obtained with line C-C´ reflects the presence of nearby buildings and an abandoned road. The broad positive anomalies may be produced by the underlying chambers of the cave system (fig. 28). A distinctive natural potential peak is observed at about 44 m and is accompanied by lows on both sides ("W-shaped") and a positive anomaly 10 m to the west. This natural potential anomaly may be due to the subterranean Río Camuy.

Line D-D´ produced a natural potential profile in which man-made features seem to predominate. These features include a well, a paved road, and a water pipe. The locations of these features coincide with positive anomalies (fig. 28). The cause of the high positive readings around the origin of line D-D´ is not known; however, proximity to the road and buildings suggests an artificial source. This anomaly, as well as that near the well also could reflect the presence of underlying caverns. Alternatively, the natural potential lows could relate to subsurface features such as cave chambers. In order to resolve these ambiguities, a more detailed map of the underground system is needed. The location of the subterranean river was interpreted to coincide with the sharp positive anomaly about 13 m along line D-D´ (fig. 28). The adjacent natural potential lows, a "W-shaped" anomaly, may also be part of the river's natural potential signature.

Figure 27. Rectified aerial photograph of the ground surface above the Río Camuy cave system in Hatillo and Camuy, Puerto Rico.

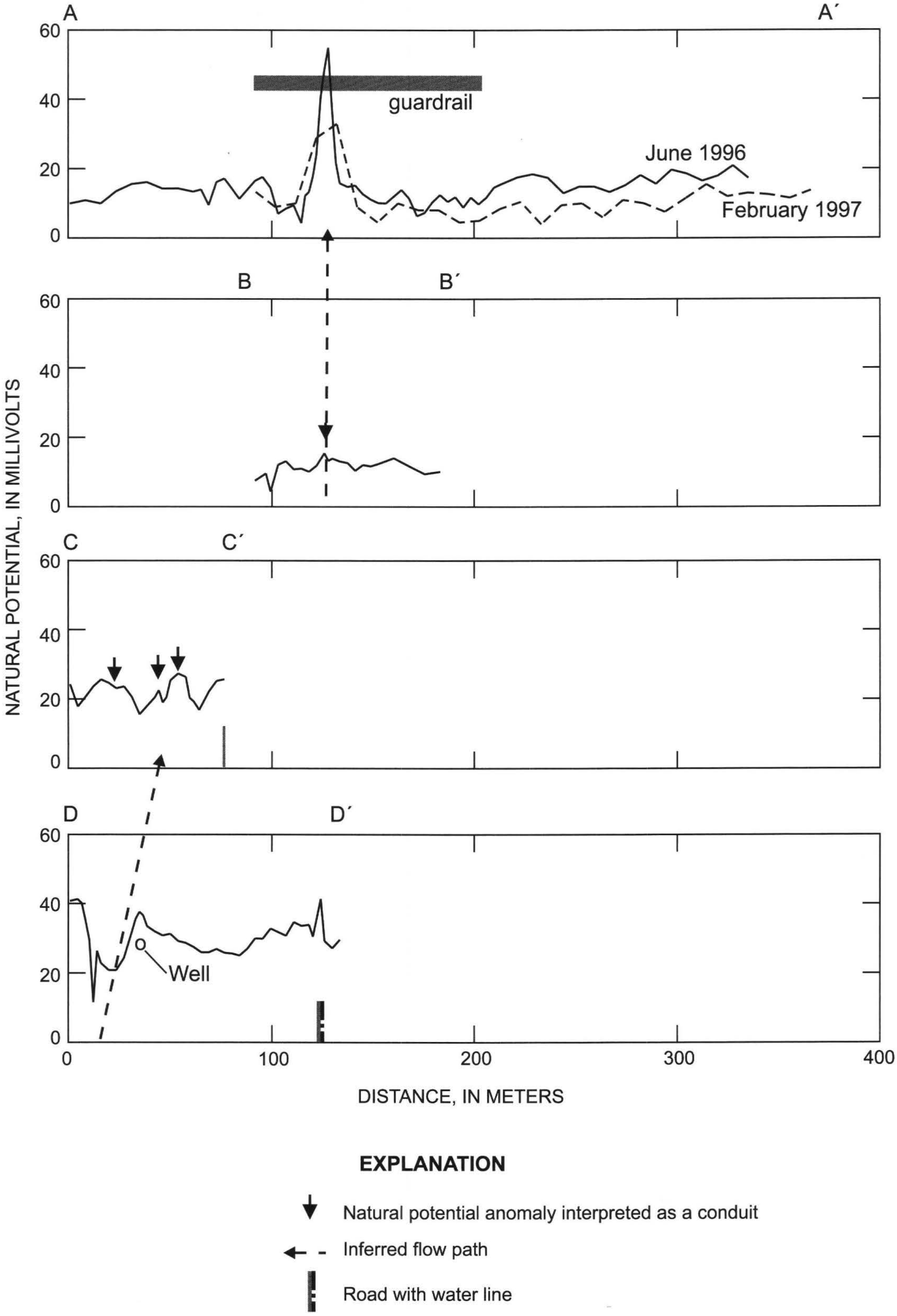


Figure 28. Natural potential profiles above the Río Camuy cave system in Hatillo and Camuy, Puerto Rico. The locations of the survey lines are shown in figure 27.

SUMMARY AND CONCLUSIONS

A 3-year study conducted by the USGS in cooperation with the PRASA consisted of using aerial photograph interpretation to analyze the presence of linear terrain features and the natural potential and gravity geophysical methods at selected sites to detect the presence of conduit-controlled ground-water flow, which commonly is associated with subsurface karst cavities. The following sites were selected for linear terrain features analysis and geophysical testing: (1) the Caimital Bajo upland area in Aguadilla, (2) the former Ramey Air Force Base (RAFB) in Aguadilla, (3) the Quebrada de los Cedros between Aguadilla and Isabela, (4) the University of Puerto Rico Agricultural Experiment Station in Isabela, (5) the Otilio dairy farm in Isabela (6) the Pozo Brujo in Isabela, (7) the Monte Encantado area in Moca and Isabela, and (8) the Río Camuy cave system in Hatillo.

Aerial photographs, geologic and topographic maps, and field reconnaissance were used to identify linear features such as ridges, entrenched canyons, fracture traces, and aligned sinkholes. The range in orientation was determined for the predominant directional trend of these linear terrain features. Natural potential and gravity geophysical methods were used, because both techniques have proven to be successful in detecting the presence of individual subsurface conduits and cavities (Dobin and Savit, 1988; Stewart and Wood, 1990; Kilty and Lange, 1991; Lange and Kilty, 1991; Lange and Quinalan, 1988; Ogilvy and others, 1969; Bogoslovky and Ogilvy, 1973; Stokowski, 1987).

Directional trends in the orientation of linear terrain features were identified which indicate that enhanced dissolution along joints, fractures, and faults influences ground-water flow in the study area. At sites such as Quebrada de los Cedros and Pozo Brujo, the linear terrain features, particularly sinkholes, are aligned and oriented in a spatial arrangement similar to that between a tributary conduit network and a trunk conduit in present-day river-cave systems. The lack of surface drainage features at the UPR Agricultural Experiment Station and the Otilio dairy farm in Isabela, together with the presence of numerous sinkholes, indicate fairly efficient underground drainage by karst conduits. Underground drainage is further suggested by the alignment of sinkholes and the identification of fracture traces, as well as the occurrence of cavities observed in test wells drilled at these two areas. Analysis of the orientation of ridges and the long axes of sinkholes suggests strong joint and fracture control of ground-water flow in the Monte Encantado and the Caimital Bajo upland areas. The presence of large, straight segments in the conduit network of Ojo de Agua Spring in Aguadilla, also suggests strong fault control. At other sites in the study area, the surface expression of karst conduits was less evident. Such is the case at the former RAFB, where the existence of karst conduits is strongly suggested by the occurrence of near-shore springs.

At the surveyed sites, recognizing the signature of subterranean flow paths in the form of karst conduits from the natural potential surface anomalies was based on examples in similar hydrogeologic settings in other areas, where the association of natural potential expressions with underlying conduits has been established. Substantial natural potential anomalies were observed at most of the selected sites, which suggests the presence of karst conduits. Furthermore, some anomalies were of the type commonly associated with karst conduits that contain flowing water. The best examples of natural potential anomalies associated with conduits containing flowing water were detected at the former RAFB in Aguadilla, at Pozo Brujo in Isabela, and in the area of Monte Encantado in Moca and Isabela. Distinctive natural potential anomalies suggesting the occurrence of flowing water, but less expressive than at the sites previously mentioned, were detected at the UPR Agricultural Experiment Station and the Otilio dairy farm in Isabela (figs. 11 to 19).

The natural potential anomalies at the former RAFB in Aguadilla are significant in that they may be surface expressions of the master conduits that feed the springs known to exist offshore. At Pozo Brujo, strong natural potential anomalies detected on the carbonate platform likely express feeder conduits of the spring at the foot of the sea cliff. The natural potential anomalies in the Monte Encantado area were detected over what might be the conduit feeding a spring and the underpath of flowing water into a sinkhole. The gravity method for detecting underground conduits was used both at the UPR Agricultural Experiment Station and the Otilio dairy farm sites. Small-scale gravity anomalies of 0.10 to 1.0 mgal indicate the presence of shallow and relatively large density contrasts at both sites. These anomalies were interpreted to be variations in the thickness of low density soil cover and voids (caverns) within the limestone. A two-dimensional forward model of the gravity data collected at one of the survey lines, assuming cylindrical air-filled voids and variations in soil thickness, represented one possible mass distribution capable of producing the observed gravity anomaly.

The degree of success of the geophysical methods in detecting the presence of conduits with flowing water was variable among the various sites studied. At sites such as Pozo Brujo, Monte Encantado area, former RAFB, the UPR Agricultural Experiment Station, and the Otilio dairy farm, the geophysical methods were used successfully to detect cavities with what were presumed to contain flowing water. At these sites, and particularly at the UPR Agricultural Experiment Station and Otilio dairy farm sites, the interpretation of collected data from the two geophysical methods agreed highly with the observed geological features and the available knowledge.

The usefulness of both the terrain analysis and geophysical methods varied, but particularly among the geophysical methods. At the UPR Agricultural Experiment Station site, linear terrain analyses using aerial photographs combined with field geological reconnaissance suggested the presence of conduit-controlled ground-water flow. The gravity method was limited to two sites in the Isabela area, because of the need for relatively flat terrain to minimize the corrections due to topography and variations in soil cover thickness. The most useful geophysical method employed in this study was natural potential. The equipment required for this technique was highly portable and could be used in nearly any type of terrain, thus making the method a relatively low-cost tool to use for detecting subsurface cavities with flowing water; however, the natural potential method was highly affected by the presence of cultural artifacts.

In general, the combination of selected geophysical and geological methods proved successful in detecting the presence of karstic conduits in the subsurface that may be associated with conduit-controlled ground-water flow. To confirm the presence of water-bearing conduits at sites such as the UPR Agricultural Experiment Station, Pozo Brujo, and Quebrada de los Cedros, a more detailed analysis including test drilling is needed.

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