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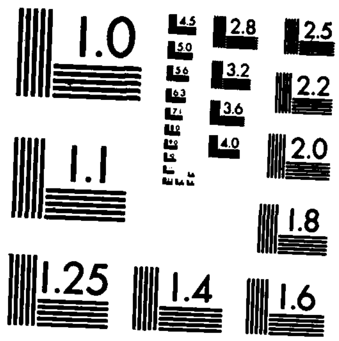

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TECHNICAL REPORT GL-83-1

CAVITY DETECTION AND DELINEATION RESEARCH

Report 4

MICROGRAVIMETRIC SURVEY: MANATEE SPRINGS SITE, FLORIDA

by

Dwain K. Butler, Charlie B. Whitten, and Fred L. Smith

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March 1983
Report 4 of a Series

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under CWIS Work Unit No. 31150

Technical Report GL-83-1

CAVITY DETECTION AND DELINEATION RESEARCH

	Title	Author
Report 1:	Microgravimetric and Magnetic Surveys: Medford Cave Site, Florida	Dwain K. Butler
Report 2:	Seismic Methodology: Medford Cave Site, Florida	Joseph R. Curro, Jr.
Report 3:	Acoustic Resonance and Self-Potential Applications: Medford Cave and Manatee Springs Sites, Florida	Stafford S. Cooper
Report 4:	Microgravimetric Survey: Manatee Springs Site, Florida	Dwain K. Butler, Charlie B. Whitten, Fred L. Smith
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(12)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report GL-83-1 -4	2. GOVT ACCESSION NO. AD-A125	3. RECIPIENT'S CATALOG NUMBER 908
4. TITLE (and Subtitle) CAVITY DETECTION AND DELINEATION RESEARCH; Report 4, MICROGRAVIMETRIC SURVEY, MANATEE SPRINGS SITE, FLORIDA		5. TYPE OF REPORT & PERIOD COVERED Report 4 of a series 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dwain K. Butler Charlie B. Whitten Fred L. Smith		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Geotechnical Laboratory P.O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS Work Unit 31150
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE March 1983 13. NUMBER OF PAGES 59
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cavities (Underground)
Geophysical exploration
Gravimetric surveys
Manatee Springs
Subsurface exploration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results of a microgravimetric survey at Manatee Springs, Levy County, Fla., are presented. The survey area was 100 by 400 ft, with 20-ft gravity station spacing, and with the long dimension of the area approximately perpendicular to the known trend of the main cavity. The main cavity is about 80 to 100 ft below the surface and has a cross section about 16 to 20 ft in height and 30 to 40 ft in width beneath the survey area. Using a density

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20. ABSTRACT (Continued).

contrast of -1.3 g/cm^3, the gravity anomaly is calculated to be -35 μGal with a width at half maximum of 205 ft.

The microgravimetric survey results clearly indicate a broad negative anomaly coincident with the location and trend of the cavity system across the survey area. The anomaly magnitude and width are consistent with those calculated from the known depth and dimensions of the main cavity. In addition, a small, closed negative anomaly feature, superimposed on the broad negative feature due to the main cavity, satisfactorily delineated a small secondary cavity feature which was discovered and mapped by cave divers.

PREFACE

This investigation was performed by personnel of the Earthquake Engineering and Geophysics Division (EEGD) and the Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), for the Office, Chief of Engineers (OCE), U. S. Army, during the period May 1980 to January 1981. The investigation was part of CWIS Work Unit 31150, "Remote Delineation of Cavities and Discontinuities in Rock." Mr. Paul R. Fisher, OCE, was Technical Monitor for this work.

This report was prepared by Mr. Dwain K. Butler, EEGD, and Messrs. Charlie B. Whitten and Fred L. Smith, EGRMD, under the supervision of Dr. Arley G. Franklin, Chief, EEGD, and Dr. Don C. Banks, Chief, EGRMD, and under the general supervision of Dr. William F. Marcuson III, Chief, GL. In addition, Mr. Rodney N. Walters, EEGD, assisted with the fieldwork. This investigation was closely coordinated with ongoing work under Project 4A161102AT22, Work Unit 002/Q6, "Analytical and Data Processing Techniques for Interpretation of Geophysical Properties."

Special appreciation is expressed to Mr. Sheck Exley and Dr. John Zumrick of the National Speleological Society for assistance in obtaining maps of the Manatee Springs Cave System and arranging for cave divers to conduct detailed cave mapping during the fieldwork. Also, the courtesy extended by MAJ Ellison E. Hardee of the Florida Department of Natural Resources in granting permission to use the Manatee Springs Site and the assistance of CPT Cecil Dykes, Park Superintendent, throughout the fieldwork are gratefully acknowledged.

COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE, were Commanders and Directors of the WES during this investigation. Mr. Fred R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report may be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
gallons (U. S. liquid) per minute	3.785412	cubic decimetres per minute
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres

CAVITY DETECTION AND DELINEATION RESEARCH

MICROGRAVIMETRIC SURVEY: MANATEE SPRINGS SITE, FLORIDA

PART I: INTRODUCTION

Background

1. Early in 1979, two field test sites in karst regions were selected for assessment and evaluation of geophysical methodologies for cavity detection and delineation. The first of these sites, Medford Cave, in Marion County, Fla., has a relatively shallow (approximately 10 to 30 ft* (3 to 9 m) to top) air-filled cavity system. Manatee Springs, in Levy County, Fla., the second site, has a deeper (approximately 100 ft (30 m) to top) water-filled cavity system. In addition to the known and mapped cavity systems, the sites have additional geologic complexities in common with other sites in karst regions.

2. The field programs at the two sites were not equivalent in scope. An extensive program was carried out at the Medford site, including 19 geophysical techniques. Report 1 in this series (Butler 1983) discusses the scope of the program at the Medford site in more detail. The program at the Manatee Springs site was more limited in scope due partially to fiscal and time constraints in the research program. Also it was desired to limit the program at the Manatee Springs site to those techniques showing the greatest potential and to techniques for which understanding would be considerably advanced by application at the deeper, water-filled site.

3. This report documents the results of a microgravimetric survey conducted at the Manatee Springs site. Detection and delineation

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3. The customary unit for gravitational acceleration in microgravimetric surveys is the μGal, which is defined in the text. Also grams per cubic centimetre is used as the unit for density.

of the Manatee Springs cavity system represents a more difficult objective for microgravimetric surveying than Medford Cave, since the density contrast is less than for the air-filled Medford Cave system and the depths are considerably greater than for the Medford Cave system. Maximum residual gravity anomalies at the Medford Cave site were about -70 μGal,* while calculations based on the known cave system depth and dimensions indicate that the maximum residual gravity anomaly at Manatee Springs should be about -35 μGal (Butler 1980, 1983). Since the error of relative gravity determinations in a microgravimetric survey lies in the range of ±5 to ±10 μGal (Butler 1980) and there is likely a certain level of lithological gravity noise at the Manatee Springs site (as was present at the Medford Cave site (Butler 1983)), the Manatee Springs site will allow further definition of the range of applicability of microgravimetry for geotechnical objectives.

4. In addition to the microgravimetric survey, the following geophysical techniques were also applied at the Manatee Springs site:

- a. Crosshole acoustic surveys.
- b. Crosshole radar surveys.
- c. Acoustic resonance (surface survey with subsurface sonar source).
- d. Spontaneous-potential (SP) survey (surface).

Conventional borehole geophysical logging suites were also obtained in two boreholes at the site. The results of these geophysical investigations at the Manatee Springs site will be the subjects of other reports in this series.

Purpose

5. Results of geophysical investigations at the Medford Cave site indicate that microgravimetry is one of the best methods for shallow cavity detection and delineation. The purpose of the present work is to determine the capability of microgravimetry to detect the deeper

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* 1 Gal ≡ 0.01 m/sec^2.

Manatee Springs cavity system. A secondary purpose of this work is to investigate procedures for determining the local regional gravity field, and the effect on the residual gravity anomaly map, qualitatively and quantitatively, of using different local regional fields.

Scope

6. Part II of this report will discuss the Manatee Springs site, the site grid system and topographic survey, and the cave system. Part III will discuss the site geology and drilling program. Results of the microgravimetric survey and correlations with known site conditions will be presented in Part IV. Finally, a summary and conclusions will be presented in Part V.

PART II: THE MANATEE SPRINGS SITE AND CAVE SYSTEM

Location and History

7. Manatee Springs is located in the Manatee Springs State Park, which is in Levy County, Fla., about 6 miles west of Chiefland, Fla. The site chosen for the geophysical surveys is near the spring boil,* which is located about 1500 ft from the east bank of the Suwannee River and 23 miles upstream from the Gulf of Mexico. Figure 1 shows the location of the site on a road map and Figure 2 is a portion of the Manatee Springs 7.5-minute Quadrangle Sheet (U. S. Geological Survey 1954).

8. The spring has been known and used by man for centuries, originally for the crystal-clear drinking water and abundant fish and game and more recently as a popular site for picnicking and swimming. William Bartran, a naturalist, visited the spring in 1774 and provided the first known description of the area. The spring was named for the manatee, an endangered aquatic mammal, which is occasionally seen in the area.

Cave System

9. The Manatee Springs cave system extends several miles to the southeast of the spring boil, and through 1980, 10,040 ft had been mapped by the Cave Diving Section of the National Speleological Society. Figure 3 is a map of a portion of the cave system (Exley 1979). Depths to the top of the cave system are in the range of 80 to 100 ft (25 to 30 m) in the vicinity chosen for the geophysical surveys, and the cavity has a cross section 18 ft in height and greater than 40 ft in width at one location in the survey vicinity.

10. Depth and cross section of the cave system are actually quite variable. Also, there are numerous smaller branching cave features along the length of the system. Sinkholes and even smaller

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* Flow from the spring is 81,820 gallons/min.

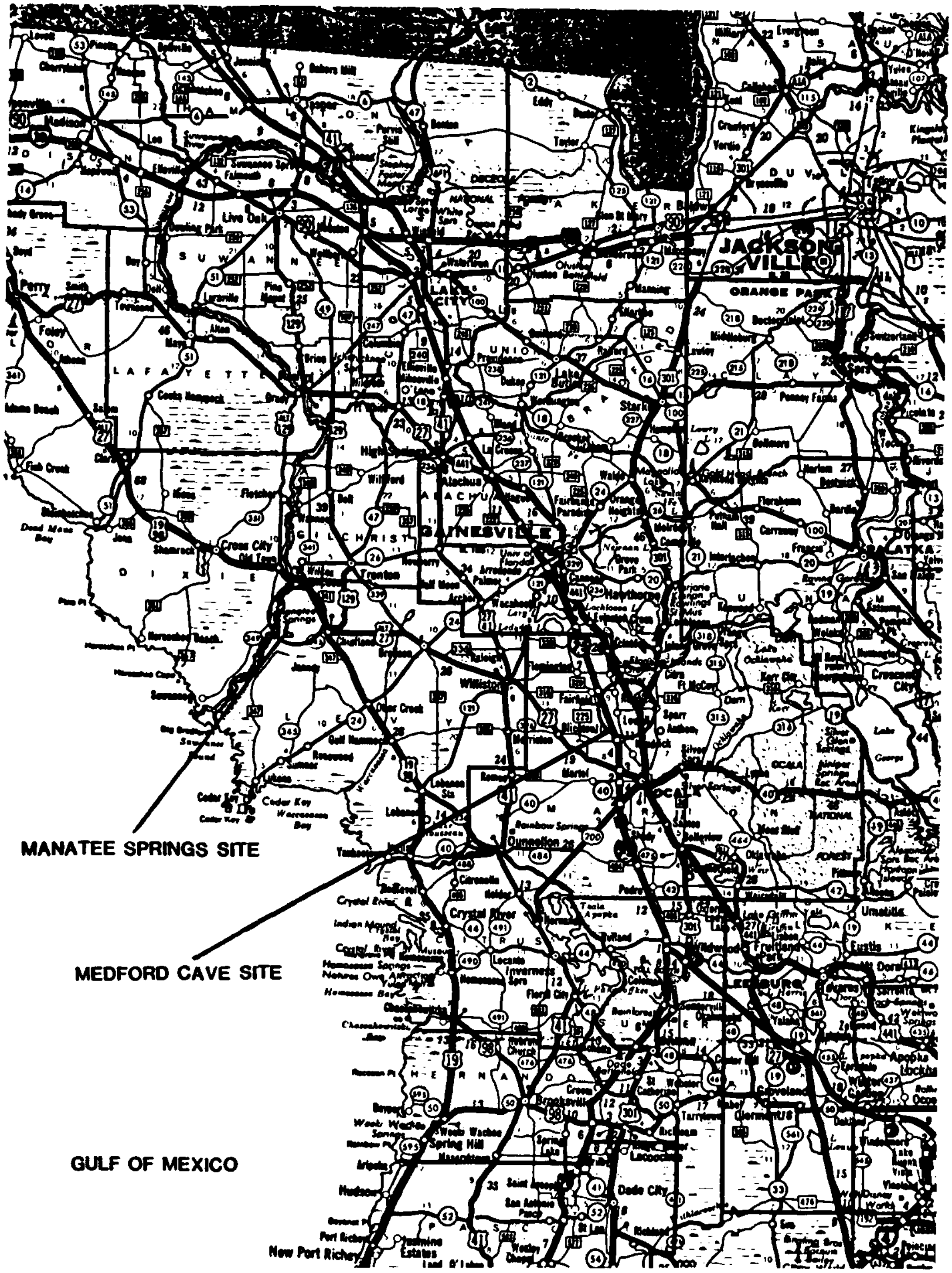


Figure 1. Road map showing location of the Manatee Springs site

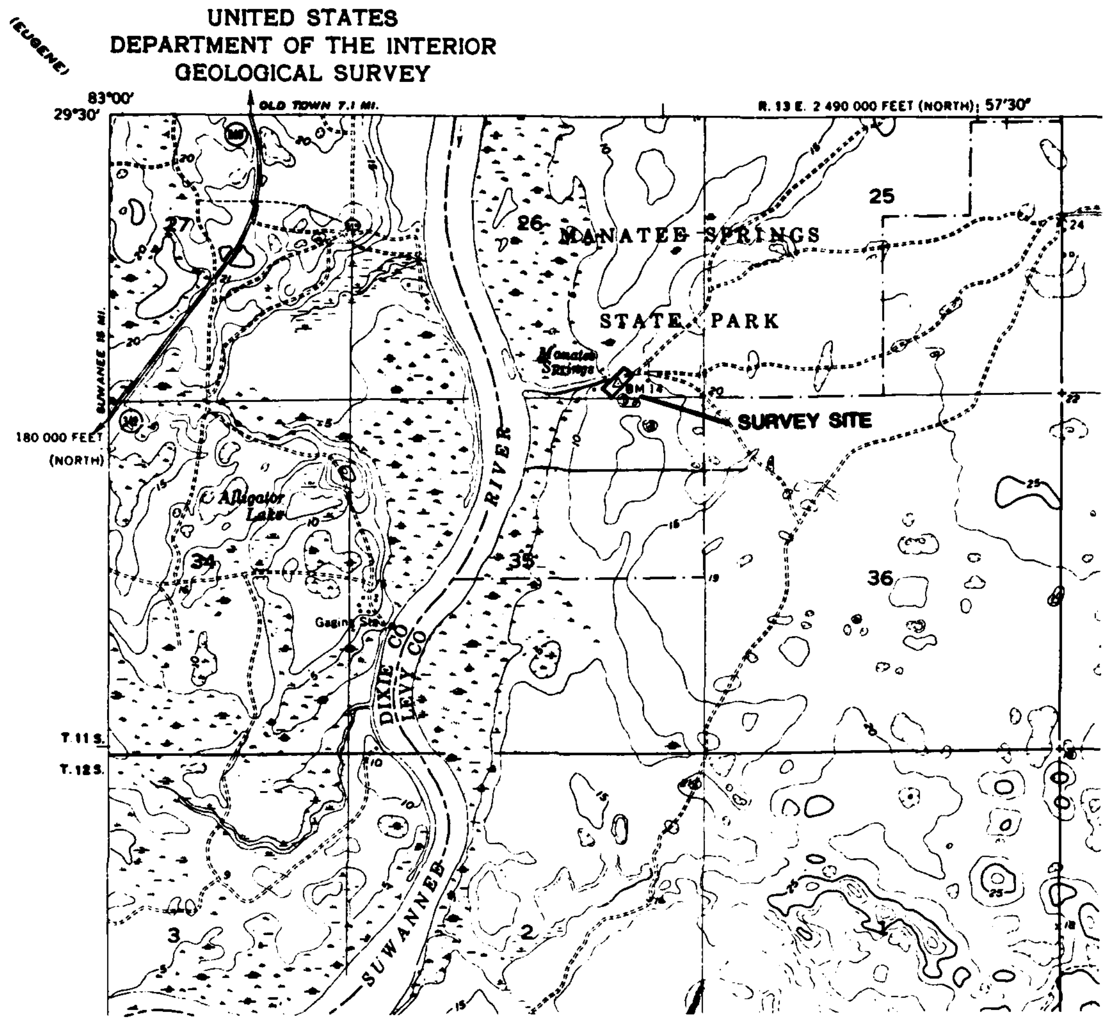


Figure 2. Topographic map of area surrounding the Manatee Springs site

springs occur along the length of the main cave system. Otherwise, there is no surface expression of the presence of the cave system. The cave system will be described in greater detail in Part III of this report.

Site Grid Layout and Topographic Survey

11. The site chosen for the microgravimetric survey is about mid-way between the spring boil and the Catfish Hotel (sink), as shown in Figure 4. The long axis of the rectangular topographic survey area was

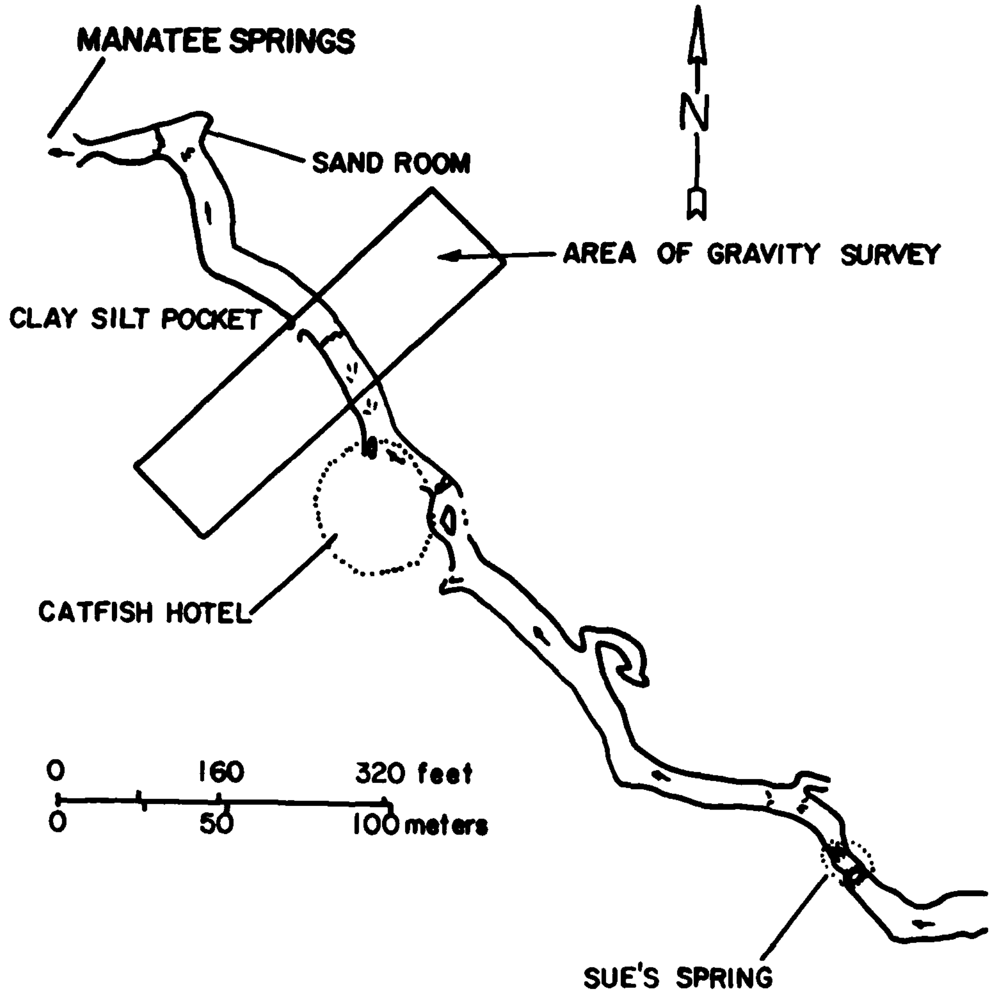


Figure 3. Map of a portion of the Manatee Springs cave system (Exley 1979)

chosen to be perpendicular to the local trend of the cavity system, and was originally 120 by 400 ft.* Discovery of a small branching cavity feature by cave divers led to the extension of the survey area to the southeast to include the small cavity feature (Figure 5) and thus accommodate other geophysical tests planned to investigate detectability of the smaller feature.

* Microgravimetric survey area--100 by 400 ft (Figure 4); topographic survey area--120 by 400 ft (Figure 6); extended grid area (Figure 5) was not topographically surveyed.

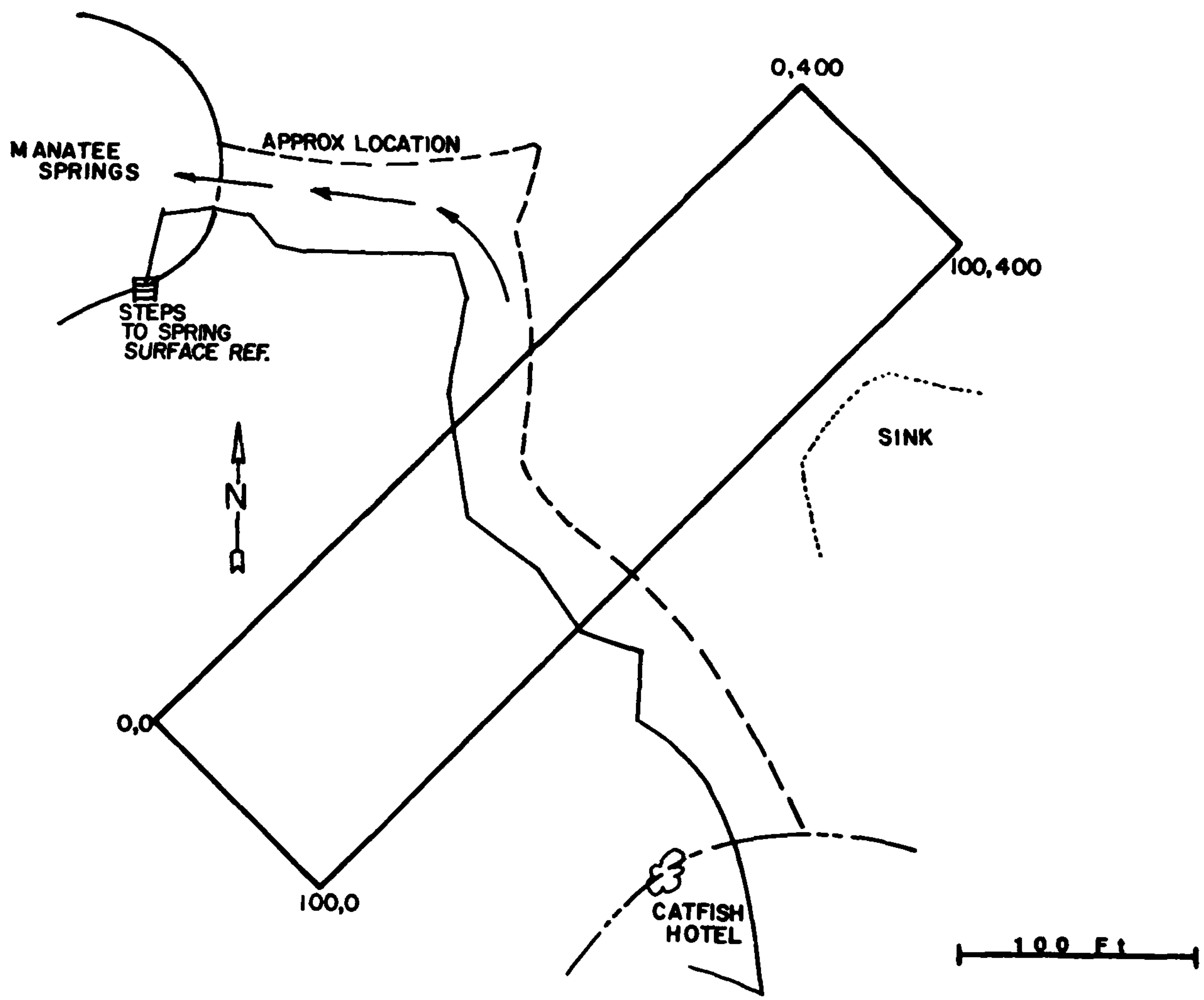


Figure 4. Location of area of the microgravimetric survey at the Manatee Springs site

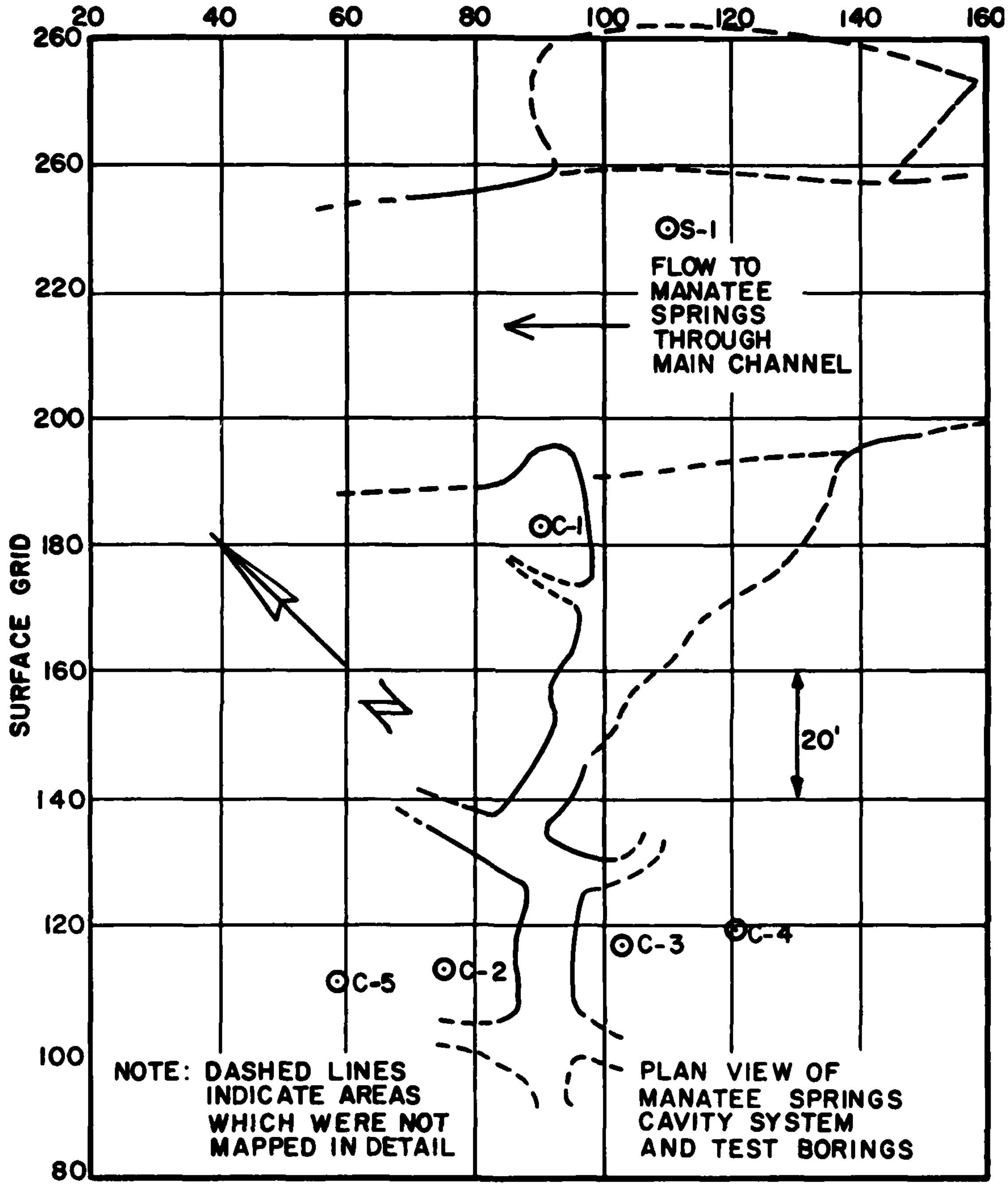


Figure 5. Extended survey area and map of small cavity feature discovered by cave divers

12. A basic site grid dimension of 20 ft was chosen (illustrated in Figure 5). Orientation of the long axis of the survey area was established at N45°E. Grid locations were determined using steel tapes and chaining pins in the usual manner. At each grid location, a 2- by 2- by 6-in. stake was driven flush with the ground surface. At every alternate grid location, an offset reference stake labeled with coordinates was placed. The sense of the survey coordinates is explained in Figures 4 and 5.

13. Elevations of the tops of the 2- by 2-in. stakes were determined to ±0.01 ft. Elevations were referenced to a U. S. Geological Survey benchmark (14.00 ft mean sea level (msl))* located at (47,250) of the survey grid, and the closure error was 0.01 ft. Figure 6 is the topographic map resulting from the elevation survey. Elevation variations over the site are very small, with the maximum elevation difference in the survey grid being approximately 7.0 ft. Except for the semiconcentric contours about the point (120,320) with an elevation of 8.5 ft msl, which reflects the presence of a small sinkhole with center approximately 100 ft beyond the survey area, the topography resembles an inclined plane, decreasing in elevation from 15.6 ft msl at (120,0) to 10.0 ft msl at (0,400). The grid layout, elevation survey, and mapping of the plan location of the cavity system required four man-days (two days for two-man crew).

* United States Geological Survey Benchmark TT28BB5.

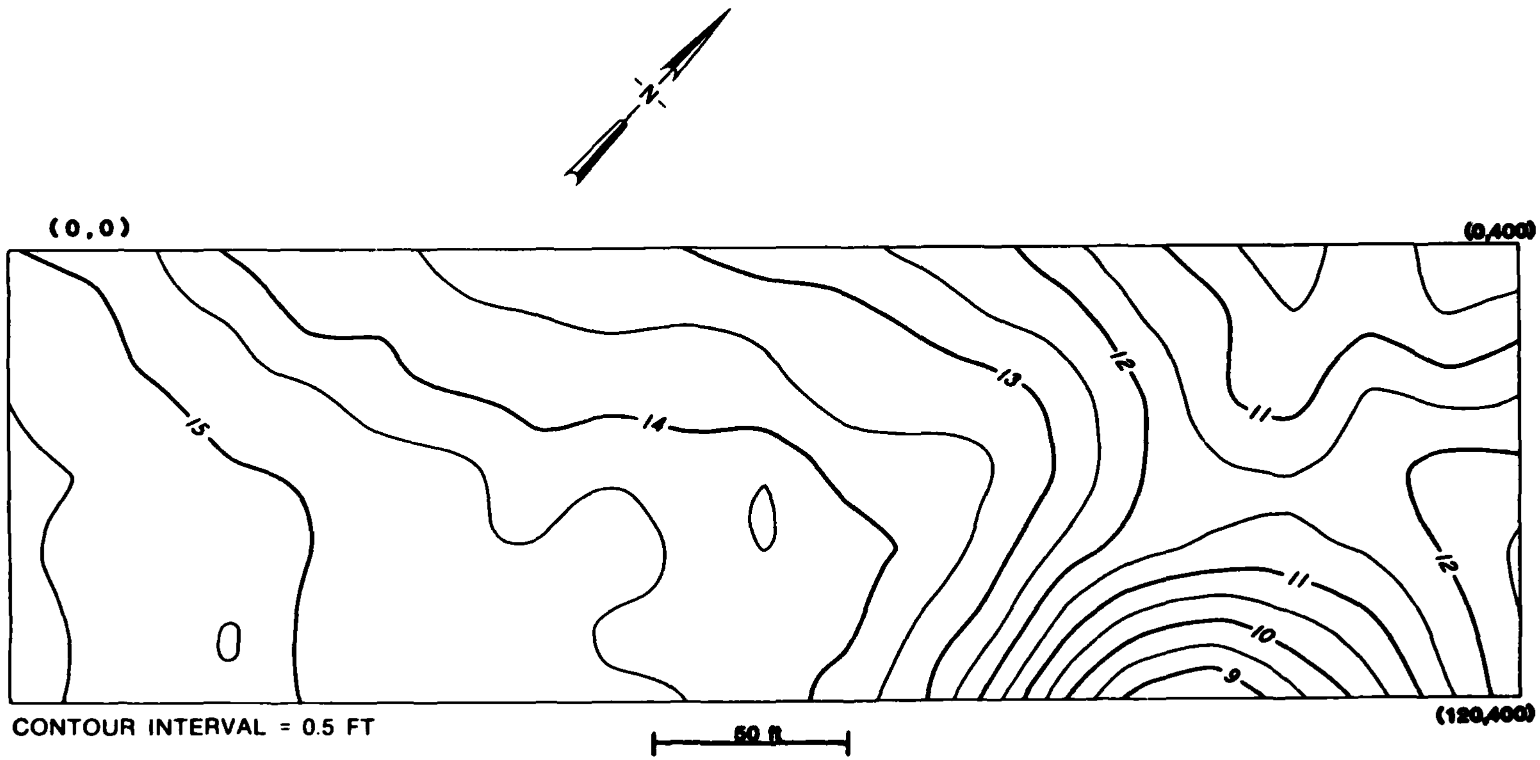


Figure 6. Topographic map of surveyed area of Manatee Springs site

PART III: GEOLOGY OF THE MANATEE SPRINGS SITE

Physiography

14. The site is in Vernon's Terraced Coastal Lowlands Subdivision which is within the Floridian Section of the Coastal Plain Province (Vernon 1951). This section is a very youthful, recently emergent, terraced coastal plain with karst topography. The Terraced Coastal Lowlands is divided into four Pleistocene marine terraces based on elevation above msl--the top elevation of the Coharie is 220 ft msl; the Okefenokee, 150 ft msl; the Wicomico, 100 ft msl; and the Pamlico, 25 ft msl. The Manatee Springs site ranges in elevation from about 10 to 15 ft and is within the Pamlico marine terrace which extends inland from the coast.

15. The Pamlico surface in the Manatee Springs area consists of a broad shelf of Tertiary limestones covered with a thin veneer of Pleistocene sands. Erosion of the Tertiary limestones prior to deposition of the sands created a rugged surface with considerable relief. The ground surface at the site varies less than 2 ft between any of the boreholes, but the top of the limestone varies in depth from 6.6 ft at boring S-1 to 20 ft at boring C-4 (Figure 7). The top of limestone at C-5 varies 9.5 ft vertically in a 2.5-ft horizontal distance (see boring log C-5 in Appendix A).

Field Exploration Program

16. The number of borings was initially limited to a maximum of 10 by the Florida State Park Service. Only six borings were actually drilled in the initial program. Borings C-1 through C-5 are for testing downhole geophysical instruments, and S-1 was an exploratory boring used to locate borings C-2 through C-5 (Figure 7). The boring locations, diameters, and depths were selected to accommodate test equipment requirements and are discussed in the following paragraphs.

17. Prior to the fieldwork, a map of the Manatee Springs cave,

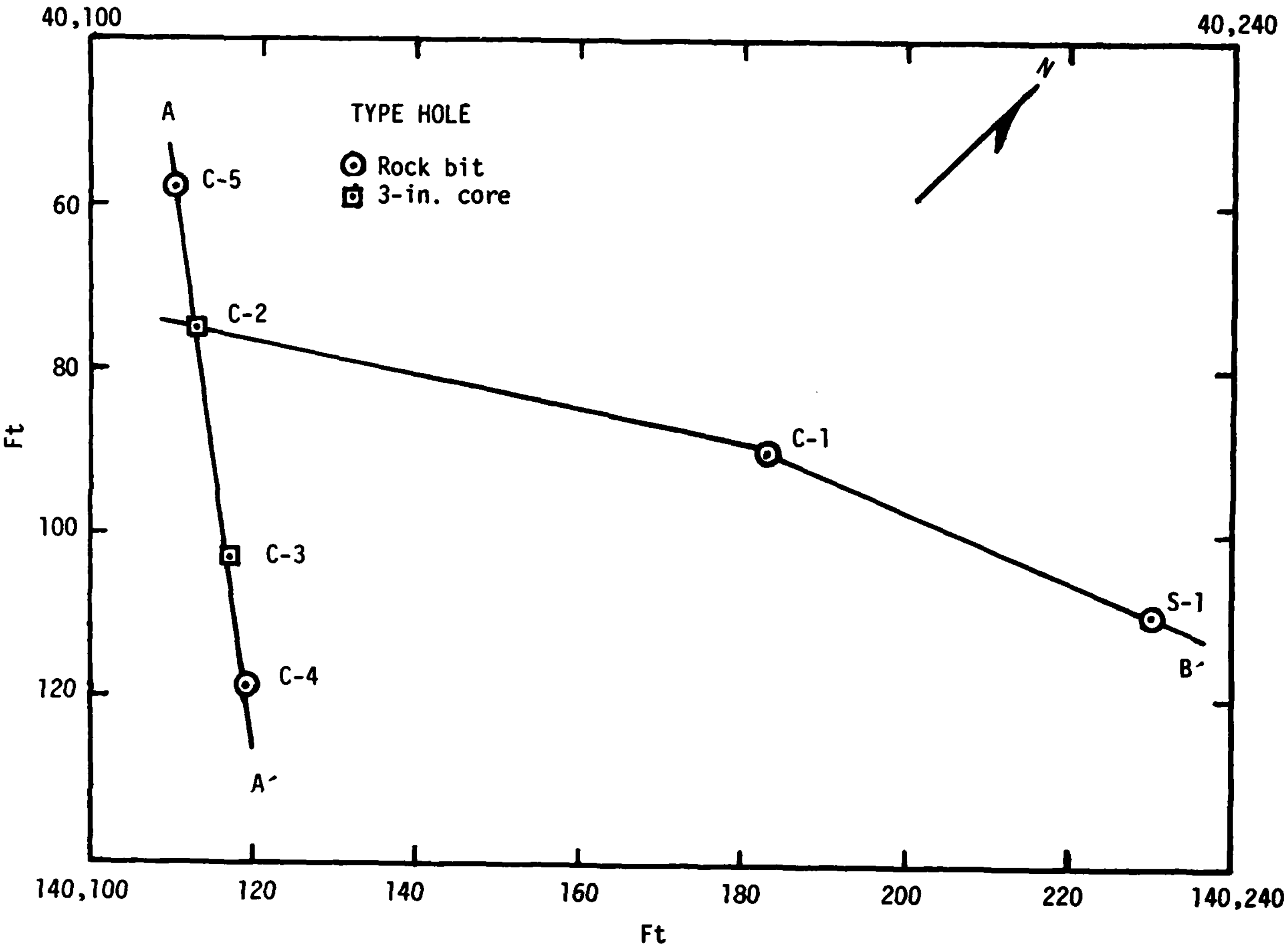


Figure 7. Location of borings and geologic sections

prepared by cave divers, was used to project the cave outline to the surface at the site, and a 20-ft grid was established. The survey was used to position the borings. The cave outline was used for the drilling of two exploratory borings; the first boring was to penetrate the cave, and the second boring was located approximately 50 ft to the east of boring 1. Divers found boring 1 was drilled through a relatively thin angular section of limestone projecting out from the west cave wall. Boring 2 penetrated the cave near its east wall and was used by the divers as a fixed point for distance and direction measurements to locate borings C-2 through C-5. Boring 2 was later designated boring S-1. Boring 1 was later designated boring C-1 and was to be used for testing. Boring logs are presented in Appendix A.

18. The divers discovered a small side cave extending approximately 600 ft to the southwest of boring C-1. The small cave was more suitable for testing purposes than the larger Manatee Springs cave, so borings C-2 through C-5 were located astride the small cave. The small cave is between borings C-2 and C-3.

19. Borings C-2 and C-3 were cored with 3-in. core barrels and then reamed with a 6- and 6-1/2-in. rock bit, respectively. Boring C-1 was drilled with a 4-in. rock bit, and borings C-4, C-5, and S-1 were drilled with a 6-1/2-in. rock bit.

20. The depth requirement for borings C-1 through C-5 was 165 ft, but the borings were drilled to 170 to 180 ft to allow room for cuttings and possible spalling material to settle. Boring S-1 penetrated the roof of the Manatee Springs cave at a depth of 88.0 ft and was not drilled any deeper. The floor of the cave was at a depth of 105.6 ft.

21. Cavity openings, varying from 1.1 ft in boring C-2 to 7.0 ft in boring C-4, were detected in borings C-2, C-3, and C-4. Divers confirmed that the cavities were not locally connected with the small cave. Boring C-4 was grouted with 155 sacks of cement and reamed to 6-1/2 in. to prevent instruments from getting hung up in the openings. Borings C-2, C-3, and C-4 were not affected by the grouting, indicating that the cavities were probably not locally interconnected.

Stratigraphy

22. The geologic units encountered were the Pamlico Formation of Pleistocene age and the Ocala, Williston, Inglis, and Avon Park Formations of Eocene age (Figure 8). The Ocala Formation has been renamed the Crystal River Formation in more recent publications, but the term Ocala Formation will be used in this text to maintain continuity with previous work. Lithologic descriptions of the Eocene limestones are limited to the core samples from borings C-2 and C-3 and cuttings from borings S-1, C-1, C-4, and C-5.

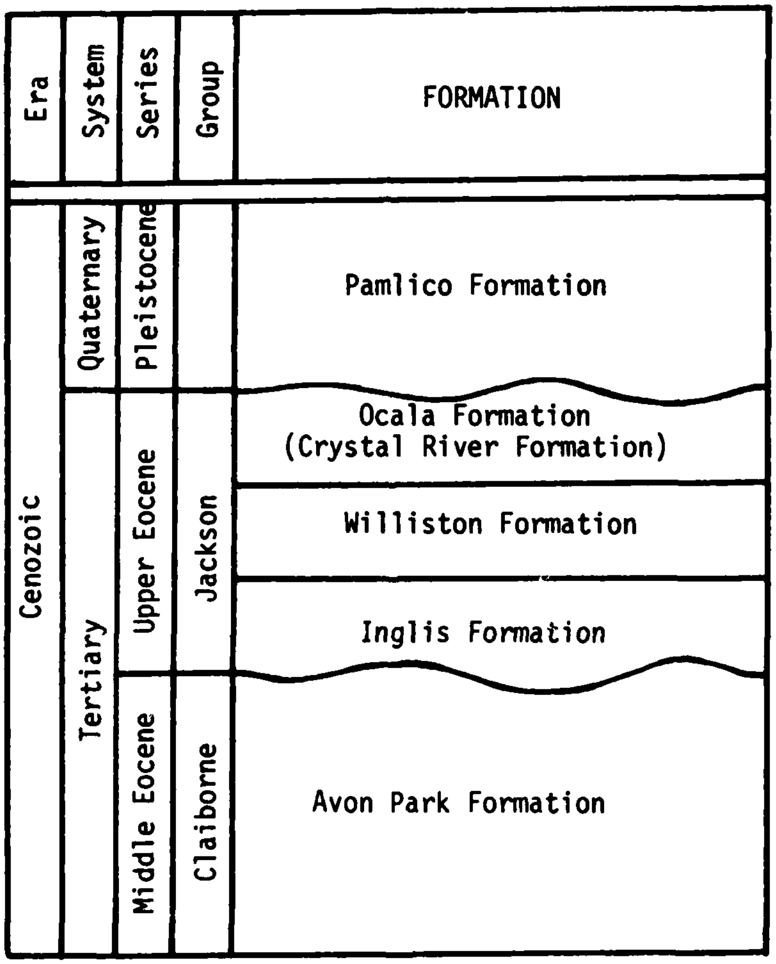


Figure 8. Geologic formations at the Manatee Springs site

Pamlico Formation

23. The Pleistocene Pamlico Formation is a fine, well-sorted, white to yellow sand, varying from 6.6 to 20 ft thick (Figures 9a and 9b). The sands were deposited in a marine environment and later reworked into a Pleistocene marine terrace as sea level regressed. The terrace sands have been locally reworked by the Suwannee River. Vernon (1951) classified the sands at the site as Suwannee River sandbars.

Ocala Formation

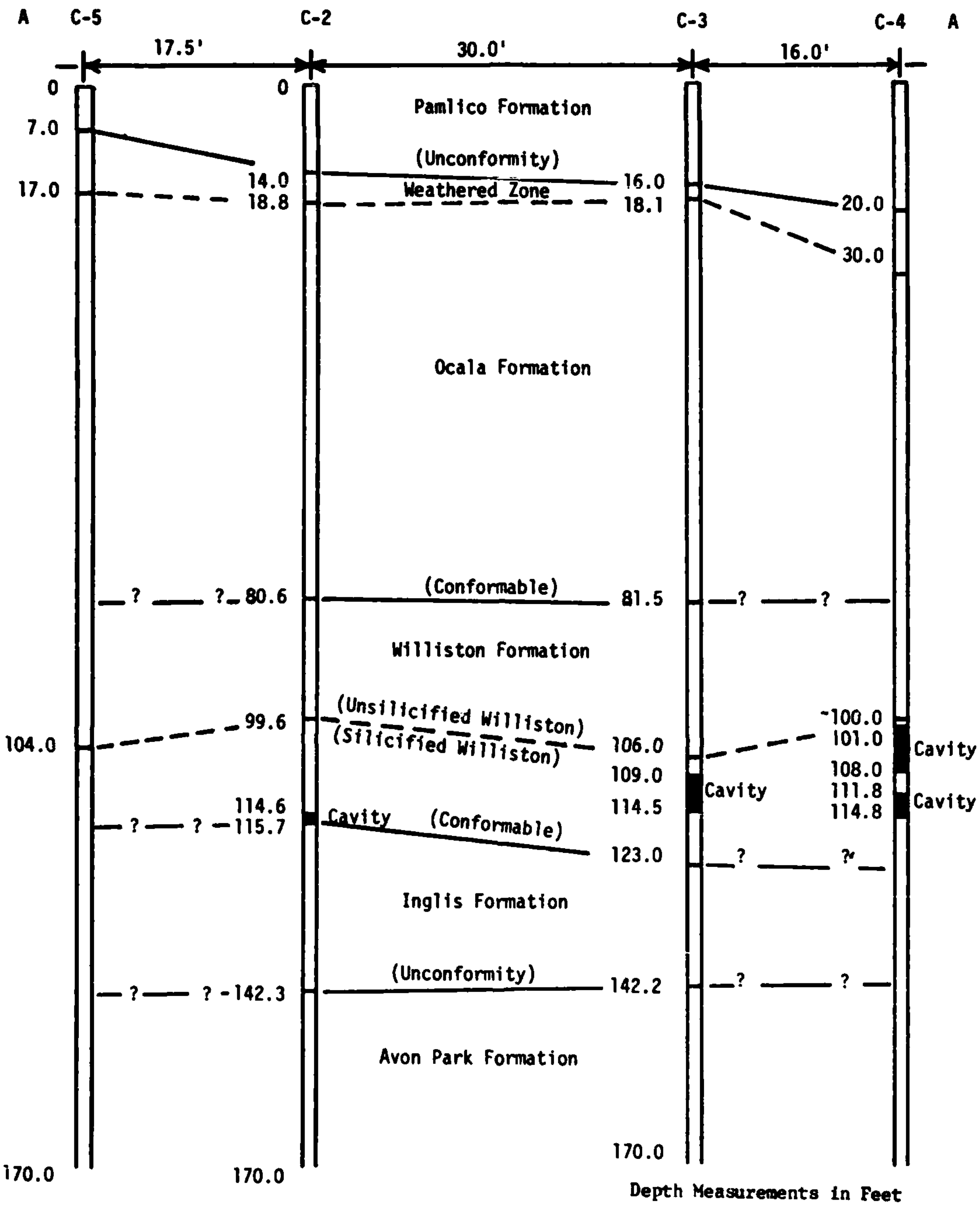
24. The Ocala Formation is the upper limestone in the Jackson Group and is typically a soft to moderately hard, white to pink, massive, friable, fossiliferous limestone (Figures 9a and 9b). The fossils consist mainly of gastropods, pelecypods, and foraminifera, and form a coquina in many places. The Ocala is up to 63.4 ft thick at the site. The upper 2 to 10 ft of the Ocala is a weathered zone consisting of limestone fragments in a sandy clay to clay matrix. The Ocala grades conformably downward into the Williston Formation. Changes in fauna and the granular texture of the Williston were used to identify the Ocala-Williston contact.

Williston Formation

25. The Williston Formation is a grey, moderately hard, friable, fossiliferous limestone and is harder than the Ocala and softer than the underlying Inglis. The abundance of foraminifera gives the Williston a granular appearance. The Williston is up to 41.5 ft thick at the site. The lower 16 to 17 ft is partially silicified with scattered zones of poorly silicified to unsilicified limestone (Figures 9a and 9b). The silicified zone was encountered at a depth of 15.7 ft in boring C-2 and 125 ft in C-3 and can be easily identified in the subsurface by the increased drilling time. The Williston-Inglis contact is conformable and can be recognized by the change from a silicified limestone to a porous dolomitic limestone.

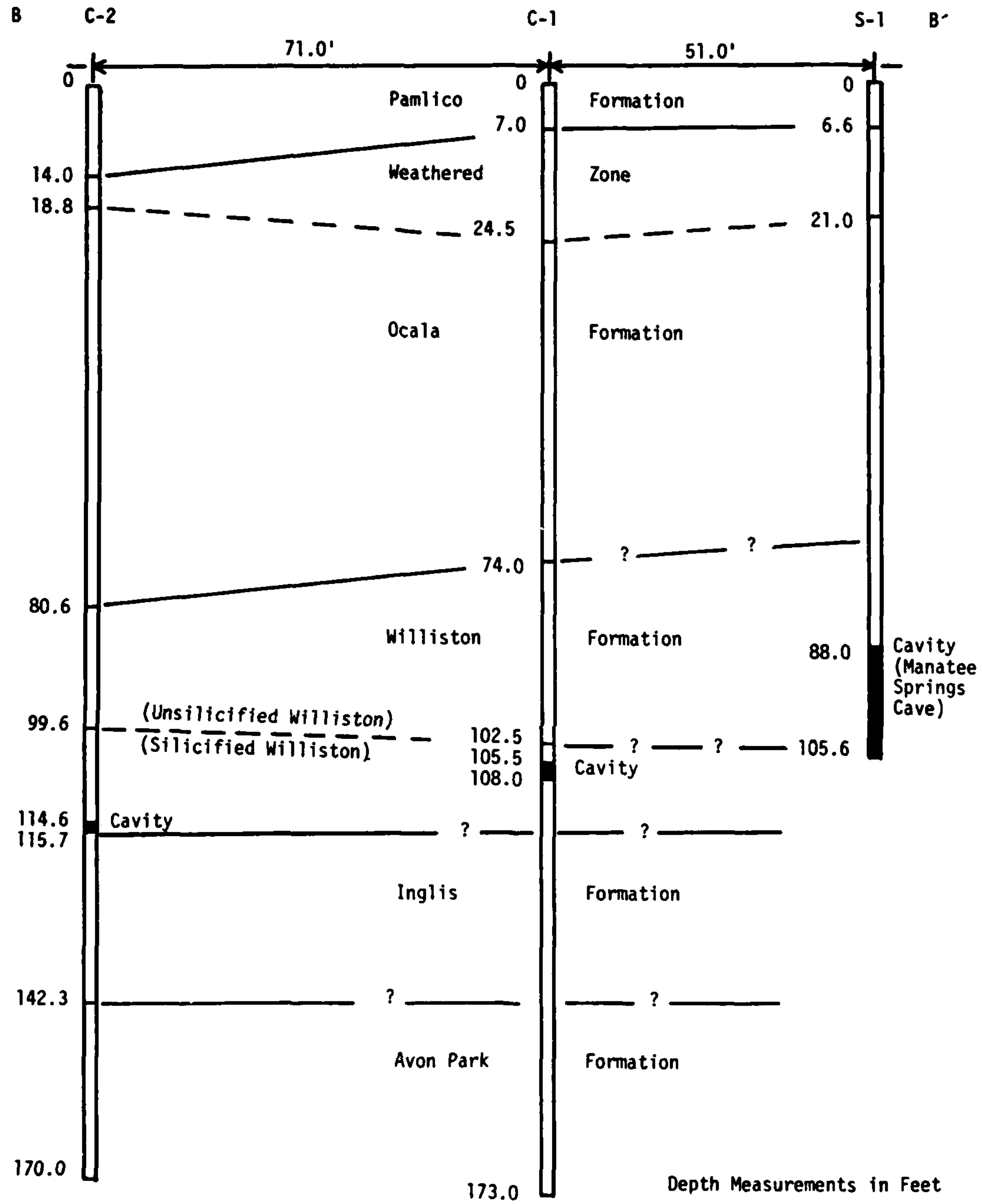
Inglis Formation

26. The Inglis Formation is the base of the Jackson Group and is a hard, brown, porous, partially dolomitic limestone with scattered zones of hard, grey, fossiliferous limestone. The dolomitic limestone



a. Section A-A'

Figure 9. Geologic sections (Continued)



b. Section B-B'

Figure 9. (Concluded)

is porous but poorly permeable and ranges from soft and friable to hard and indurated. Laminated dolomitic clasts eroded from the Avon Park are incorporated in the base of the Inglis. The Inglis-Avon Park contact is unconformable with a soil zone on the eroded surface of the Avon Park. The thickness of the Inglis varies from 26.6 ft at boring C-2 to 19.2 ft at boring C-3.

Avon Park Formation

27. The Avon Park Formation is a brown to grey, porous, partially dolomitized, moderately hard limestone with carbonaceous plant remains scattered throughout. A few large fossil casts and molds of gastropods and pelecypods and a burrow occur at the top of the unit (Figures 9a and 9b). Only 23 ft of the Avon Park was cored at the site; however, Vernon (1951) described it as being several hundred feet thick in this area.

Groundwater and Solution Features

28. The high permeability of the Pamlico sand and the Eocene limestones has produced a very poorly developed surface drainage system which has resulted in almost all of the rainfall being absorbed directly into the groundwater system. The groundwater elevation at the site is controlled by the fluctuation of the Suwannee River which was above flood stage at the beginning of drilling operations on 5 May 1980. The water table at the site was at 7.6 ft on 5 May 1980. As the flooding receded, the water table dropped to 9.5 ft on 15 May 1980 and 11.5 ft on 16 June 1980.

29. The groundwater is highly charged with organic and carbonic acids and plays an important part in the development of the caverns in the area (Vernon 1951). The permeability of the Ocala and Williston limestones allows for rather free movement of groundwater through these units. The poor permeability of the Inglis has restricted groundwater flow, thus concentrating the groundwater in the overlying more permeable lower Williston. This concentration of goundwater in the Williston has resulted in the development of a large complex cavern system and

probably in the irregular silicification of the lower Williston. Cave divers have explored over 10,000 ft of the Manatee Springs cave and report that it probably extends much further. The Manatee Springs cave has a variable height and width, and has numerous smaller branching caves. Data from the divers and boring S-1 show Manatee Springs cave is 17.6 ft high and over 40 ft wide at boring S-1. The small cave is approximately 4 ft high and 8 ft wide between borings C-2 and C-3, but the height and width are very variable along the length of the cave.

30. The depth of the Manatee Springs cave decreases from 105.6 at boring S-1 to approximately 55 ft (relative to the borings) at the Manatee Springs boil, a distance of approximately 250 ft to the north. The measured surface discharge from the spring has varied from 110 ft^3/sec to 238 ft^3/sec (Rosenau et al. 1977). The spring pool is approximately 100 ft wide and 55 ft deep.

31. The only other solution features detected during the drilling operations were in the Ocala. Boring S-1 intersected a vertical solution pipe 1 to 1.5 ft in diameter. The solution pipe collapsed as a drill rig was being moved by the boring, creating a hole approximately 5 ft in diameter at the surface. Boring S-1 and the funnel-shaped collapsed area were filled with a sand-cement mixture to prevent further deterioration or enlargement by rainfall. Some minor weathering along fractures was found in the core samples, but it is only recognizable by the discoloration of the limestone.

32. The collapse of caverns has created several sinks in the Manatee Springs area. Three sinks, varying from approximately 75 to 200 ft in diameter, are located along the course of the main underground cave, and are within 500 ft of the study site. Catfish Cabin, the largest of the sinks, is approximately 75 ft southeast of boring C-4 and is connected to the Manatee Springs cave by an opening up to 10 ft in diameter.

PART IV: MICROGRAVIMETRIC SURVEY

Background

33. As noted in Part I, detection and delineation of the Manatee Springs cave system by microgravimetry represents a more difficult problem than the delineation of the Medford Cave system. The difficulty arises from two aspects of the situation: (a) the maximum value of the gravity anomaly at Manatee Springs should be smaller by a factor of two (-35 μGal compared to -70 μGal); and (b) the greater depth of the Manatee Springs cave system will cause the spatial wavelength or width of the gravity anomaly to be much larger than the gravity anomalies at the Medford site (see Butler 1980, 1983). Low amplitude, long wavelength anomalies are difficult to discern in cases where the dimensions of the survey area are comparable to the wavelength.

34. For site surveys with areas comparable to those at the Medford and Manatee Springs sites, it is possible that long wavelength anomalies will be interpreted as part of the local regional component. This fact can be illustrated by considering a model calculation of the anomaly caused by a structure with dimensions and density contrast appropriate for the Manatee Springs cave system. The depths and dimensions of the main cave near boring S-1 (see Part III) are used to model the cave as a long horizontal cylinder with rectangular cross section and a density contrast of -1.3 g/cm^3 (simulating a water-filled cavity in limestone of density 2.3 g/cm^3). The gravity anomaly is calculated along a 400-ft-long profile line perpendicular to the cylinder axis, with the 200-ft position directly above the axis. The geometry is illustrated and the gravity anomaly profile is shown in Figure 10. Magnitude of the anomaly is -36 μGal; and the wavelength, defined to be the width at half-maximum (Butler 1980), is 205 ft. However, the anomaly still has an amplitude of -7 μGal at the ends of the profile line.

35. Unless there is considerable lithological noise (Butler 1983) or there are other superimposed gravity anomalies, an anomaly such as shown in Figure 10 should be detected by a carefully conducted

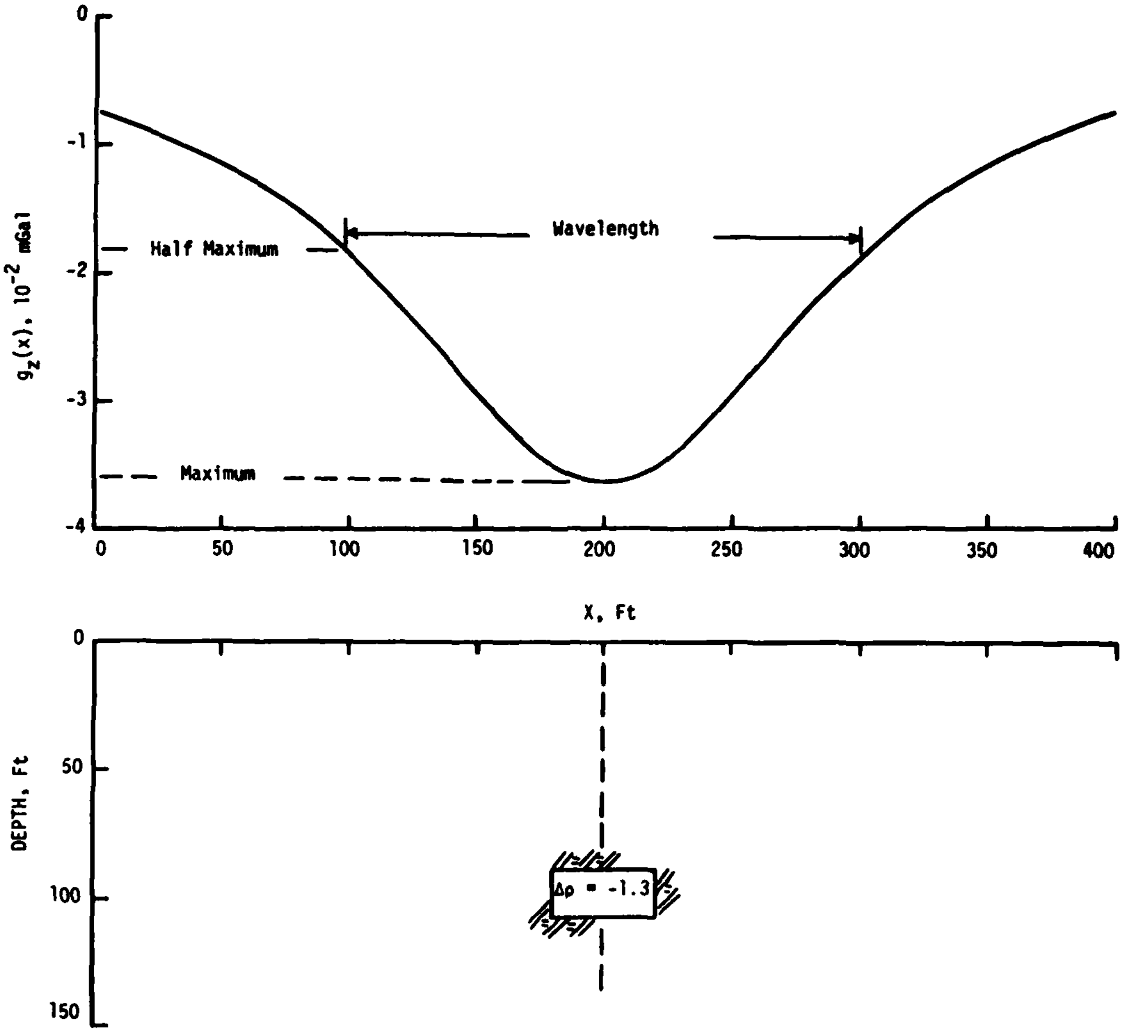


Figure 10. Idealized model of the Manatee Springs Cavity System under the microgravimetric survey area and the calculated gravity

microgravimetric survey. The primary difficulty is that the size and depth of the feature causing the gravity anomaly may be underestimated due to clipping of the gravity profile by the selected regional field or because profile lines are too short to define the complete anomaly.

Survey and Data Processing Procedures

Station layout and survey programs

36. Stations occupied during the microgravimetric survey are

illustrated in Figure 11. The survey consisted of 126 stations on the 20 ft grid with about 30 percent of the stations reoccupied at least once during the survey. Station (0,200) was selected as base station for the survey. All stations occupied between successive reoccupations of the base station are referred to as a program. Programs were designed to occupy stations in a "zigzag" or "leapfrog" fashion in order to distribute random errors and to prevent any cumulative errors from combining to produce fictitious anomalies or elongated anomalies such as can result from a long, continuous program of station occupations. Three typical programs (E, I, and N) are indicated by the dashed lines in Figure 11. Each program was planned to include at least one repeat station occupation and to be short enough that the base station can be reoccupied in less than 1 hr. In fact, the mean program duration was 40 min. The field gravity measurements required a total of 40 man-hr (20 hr each for a two-man crew).

37. The survey was conducted with LaCoste and Romberg Model D-25 gravimeter. This instrument has a range of about 200 mGal and the smallest dial division equals approximately 1 μGal.* All field measurements were obtained using the top-mounted galvanometer (capacitance electronic readout option) rather than the eyepiece to obtain a null indication. With this procedure, the reading sensitivity is 1 to 2 μGal. A concave leveling baseplate was used. At each station, the baseplate was pressed to make contact with the elevation survey point and the bull's-eye level bubble centered. The gravimeter was placed on the baseplate and shifted to obtain approximate level prior to final precision level. Microgravimetric survey procedures are discussed in detail in Butler (1980).

Base station drift

38. Reoccupations of the base station are used to correct the gravity data for time variations caused by gravity meter drift and earth-tide gravity variations, with the correction referred to as the drift correction. A drift curve for the survey is shown in Figure 12.

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* The meter factor for Model D-25 is 1.1980.

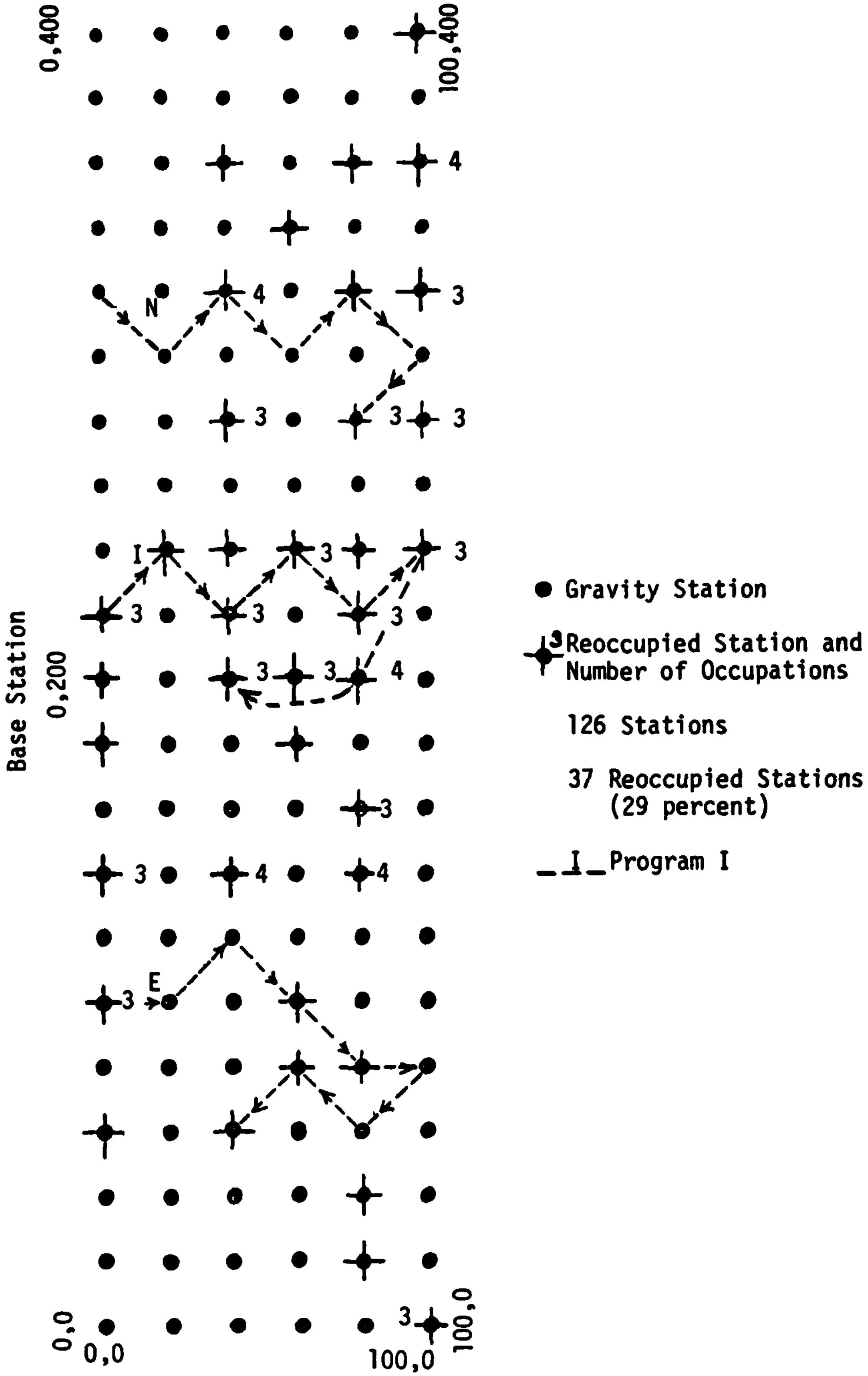

Figure 11. Gravity station plan

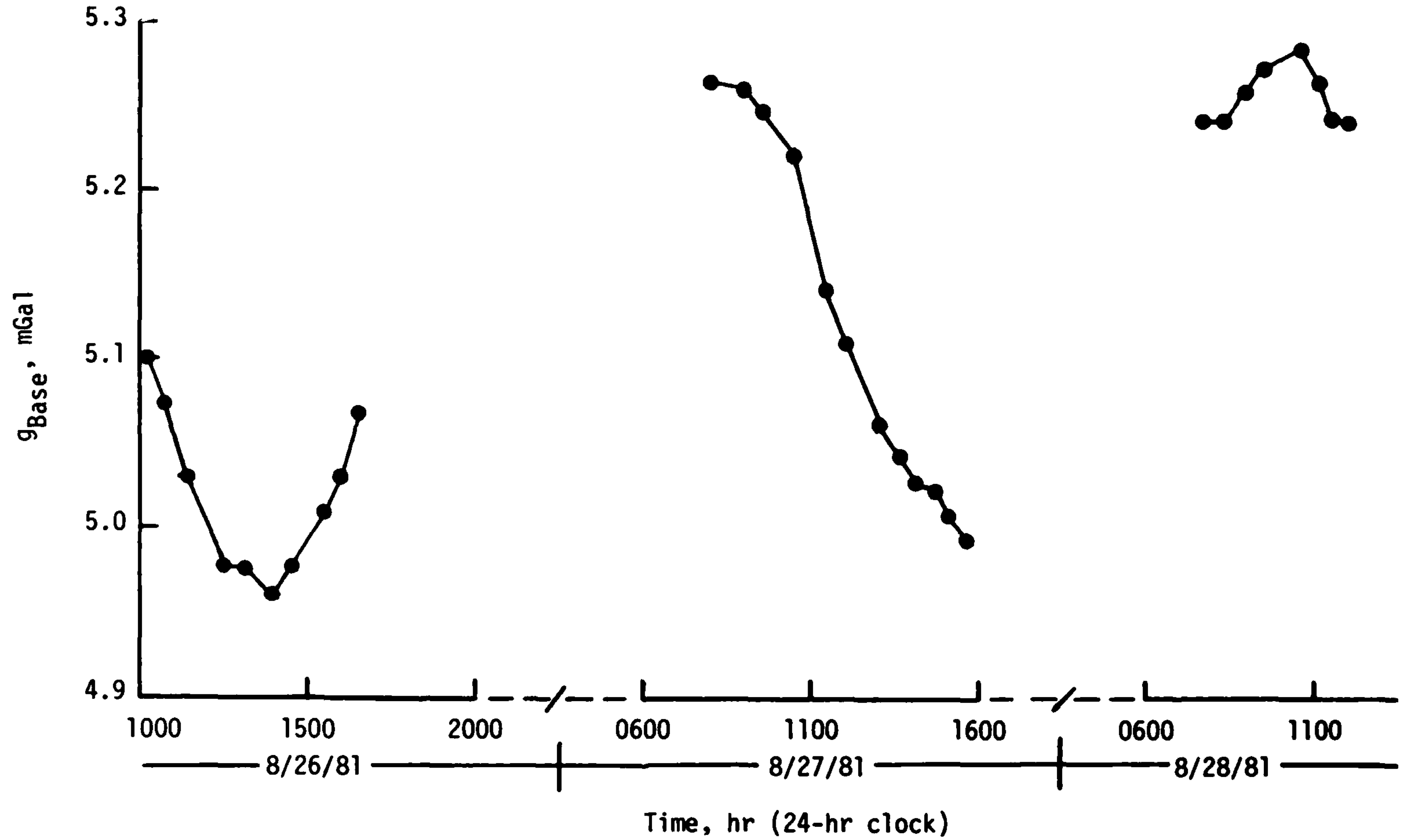

Figure 12. Base station drift record

It is assumed that the drift was the same at all stations in the survey grid and linear interpolation is used to compute the correction for stations in each program.

Data corrections

39. Required corrections to gravity data are thoroughly discussed in Butler (1980) and will only be summarized here. Briefly, the data corrections are necessary because of latitude and elevation differences between the gravity stations and the effects of surrounding topography. The corrections applied to the drift-corrected data for the Manatee Springs microgravimetric survey are summarized below:

a. Latitude correction. The latitude correction to be applied to each station gravity value is given by $\pm 0.81 \times \sin 2\phi \times \Delta L$ μGal/m, where ϕ is the latitude of the site ($\phi \simeq 29.5°$) and ΔL is the north-south distance in metres from a reference station. Using station (0,0) as the reference station, $\Delta L = \Delta Y \times \cos 45°$, where ΔY is the distance along the NE-SW grid lines from a line passing due east through the survey grid from (0,0). The positive sign is used if the station is south of the line, and the negative sign is used if the station is north of the line. The final expression is $\pm 0.49\ \Delta Y$ for ΔY in metres or $\pm 0.15\ \Delta Y$ for ΔY in feet, with the correction given in μGal.

b. Free-air correction. Three corrections (free-air, Bouguer, and terrain) are used to compensate for elevation differences between stations. The free-air correction accounts for the normal free-air vertical gravity gradient and is given by $\pm 308.55 \times \Delta h$ μGal for Δh in metres or $\pm 94.04 \times \Delta h$ μGal for Δh in feet, where Δh is elevation difference of a station relative to a reference elevation. For the Manatee Springs site, msl is used as a reference elevation.

c. Bouguer correction. The Bouguer correction accounts for the fact that gravity values in a survey are affected by differing masses of material beneath the stations due solely to elevation differences. The correction is calculated using $\pm 41.91 \times \rho \times \Delta h$ μGal for h in metres or $\pm 12.77 \times \rho \times \Delta h$ μGal for Δh in feet, where ρ is the density of the near-surface material (1.8 g/cm^3 was used for the Manatee Springs site).

d. Terrain correction. The terrain correction compensates station gravity values for nearby topographic variations which are not included in the Bouguer corrections.

Because of the nature of the problem, the terrain correction is always added (Butler 1980, Telford et al. 1976). Terrain corrections were determined using a terrain template and correction curves as described in Butler (1980). As a consequence of the small topographic variation in the survey area, no station required a correction greater than 5 μGal, and the majority of the stations required corrections $\lesssim 2$ μGal. The spring boil sink and the Catfish Cabin sink were not of concern since they were a sufficient distance from the survey area; effects due to these sinks would be small (due to distance, low density contrast due to being water-filled, and the relatively small elevation differences) and tend to be roughly equal over the survey area. Stations along a line from (100,260) to (100,340) had terrain corrections of $\lesssim 5$ μGal due to the small water-filled sink centered about 100 ft to the southeast of this area. Generally, the effects of terrain corrections as small as for this survey area can be ignored.

Results

Bouguer gravity map

40. Station gravity values which have been correceed for drift, latitude differences, and elevation differences (free-air, Bouguer, and terrain corrections) are called the Bouguer gravity values for the station. Figure 13 is the resulting Bouguer gravity contour map for the Manatee Springs site. Two prominent features or trends are evident from examinations of the Bouguer gravity values along profile lines: (a) along the NW-SE profile lines, the gravity values decrease from SE to NW; and (b) along the SW-NE profile lines, the gravity values decrease from the SW reaching minimum values near the center and then increase to the NE.

41. The Bouguer gravity values reflect density variations in the subsurface caused by geologic structures or other lateral variations with varying scales. An important step in analyzing the results of a gravity survey is to separate out a "regional" component of the gravity field, presumably caused by deeper sources or structures, leaving a "residual" component which consists primarily of anomalies caused by structures of interest. Clearly the scale of the regional will depend

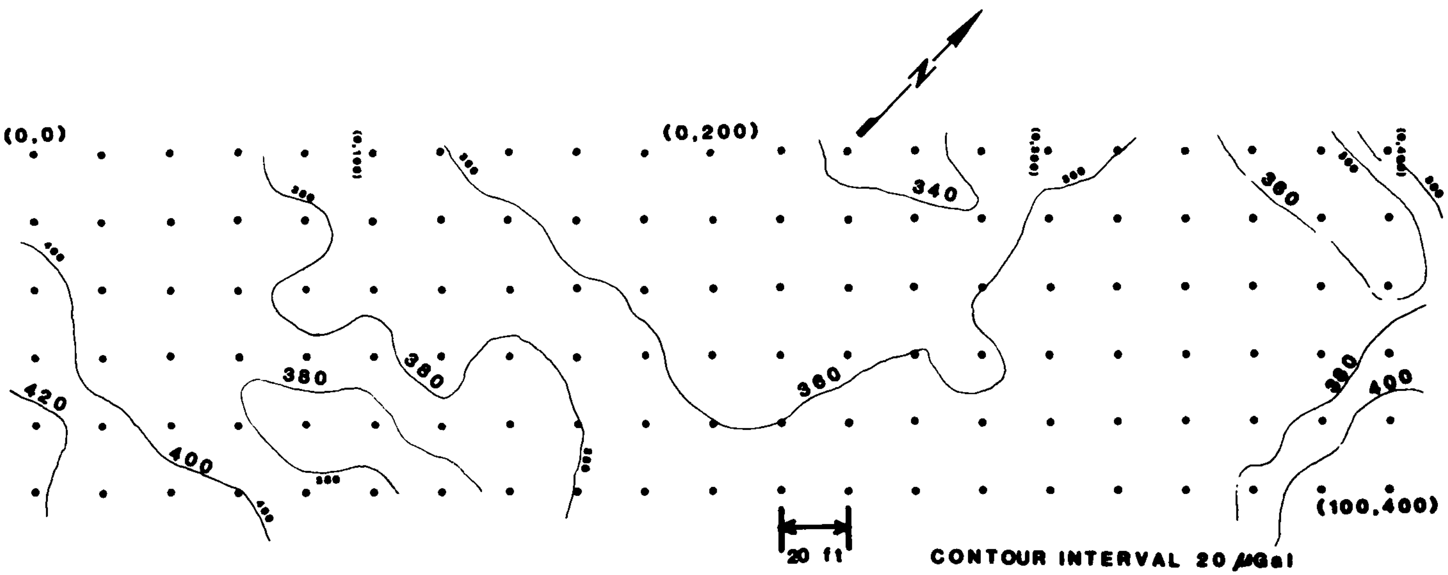

Figure 13. Bouguer gravity anomaly map, Manatee Springs site

on the scale of the survey (Telford et al. 1976, Butler 1980). For small-scale surveys, microgravimetric surveys, like the Medford Cave and the Manatee Springs survey, the regional component can usually be satisfactorily approximated as a constant or as a planar surface. This procedure is called the regional-residual separation, and two methods of accomplishing it will be investigated here: (a) a planar regional will be determined by inspection; and (b) a planar regional, as well as regionals of higher orders, will be determined by polynomial surface fitting of the data.

Bouguer anomaly (residual) map;
planar regional field
determined by inspection

42. The observed general trend of the Bouguer gravity values to decrease along profile lines from SE to NW, discussed previously, is used to specify a planar regional variation. Using mean values of Bouguer gravity along the bounding SW-NE survey lines, a linear variation of 0.22 μGal/ft (0.72 μGal/m) is determined, decreasing SE to NW. Clearly this procedure is subjective in nature; the effect of determining a best-fit planar regional field in a least-squares sense will be examined later.

43. Subtracting this planar regional field from the Bouguer gravity map (Figure 13) gives the residual or Bouguer anomaly map shown in Figure 14. Several anomaly features appear in the residual gravity map. The most prominent feature is a broad negative anomaly region (A) trending from SW to NE across the center of the map. Obvious correlation of this negative feature with the known location of the main cavity is demonstrated by the dashed outline of the cavity system in Figure 14. The apparent width of the negative feature is considerably greater than the width of the cavity itself, as expected from examination of Figure 10. Also, the magnitude of the negative anomaly, -20 to -30 μGal, is similar to that predicted by the model study of Figure 10; however, if the concentric positive anomaly values (particularly evident to the SW of the negative feature) are considered part of the anomaly caused by the cavity, the anomaly magnitude becomes -50 to -60 μGal. This larger

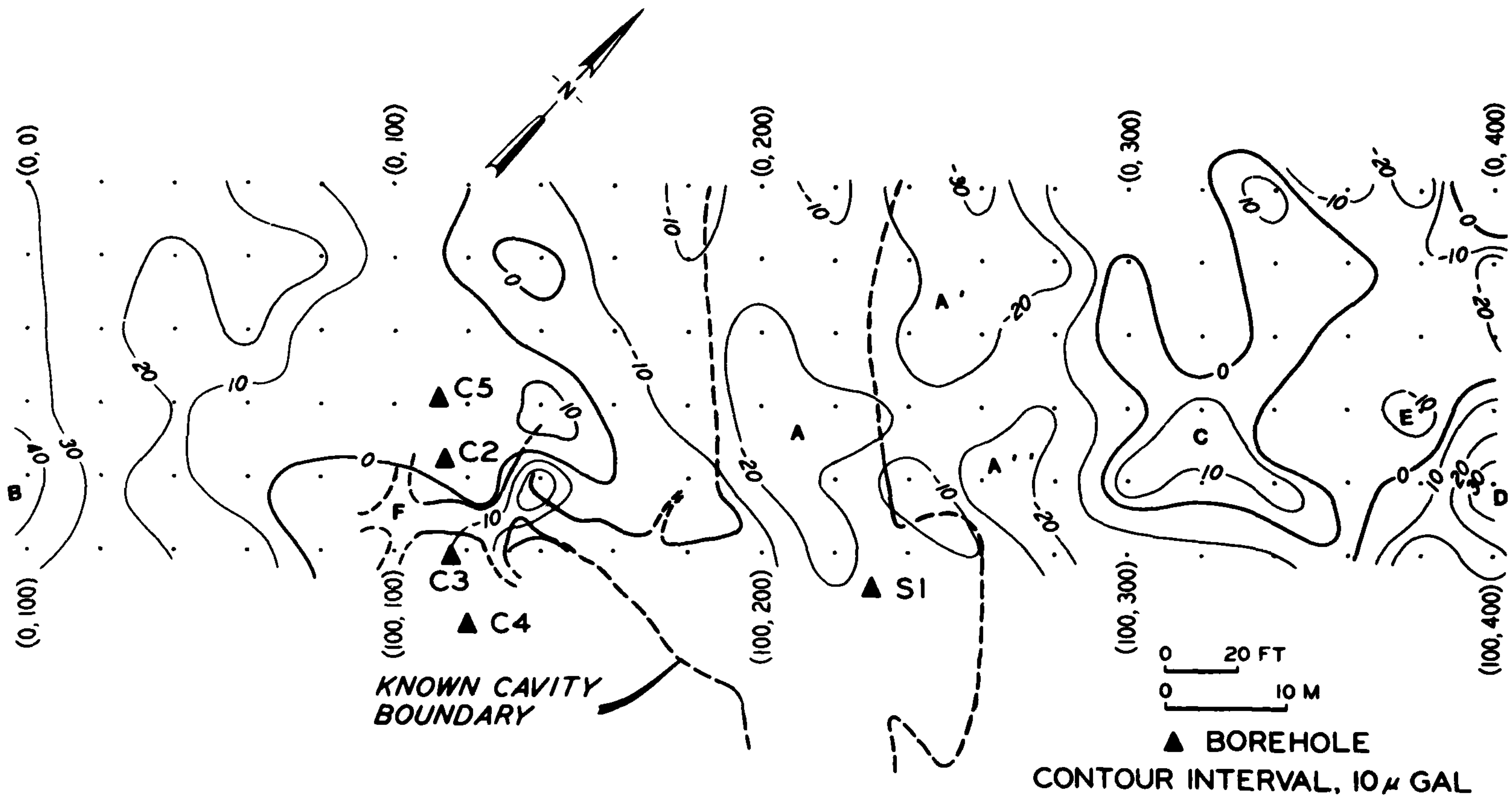

Figure 14. Residual gravity anomaly map, Manatee Springs site

anomaly magnitude is more consistent with the observation that anomalies associated with cavities in karst regions are frequently larger by factors of two than that predicted on the basis of the cavity dimensions alone (Butler 1980, Neumann 1977). Two areas within the broad negative region (A' and A") to the NE of the mapped cavity location exhibit closure, indicating anomalous features in addition to the known cavity system.

44. Other features of the anomaly map (Figure 14) are the positive area in the SW area of the map which attains 40 μGal magnitude (B). A positive anomaly area exhibiting closure (C) is adjacent to the central negative feature to the NE and attains magnitude slightly in excess of 10 μGal. Another positive anomaly (D) occurs in the NE corner, attaining 30 μGal magnitude at (80,400). A negative region (E) with a magnitude of approximately -10 μGal separates anomalies C and D.

45. A negative feature (F) occurs as a small southwestern trending extension of the central negative feature (A), with a magnitude of approximately -10 μGal. This feature is interesting due to its very close correlation with the small secondary cavity feature mapped in this area (Figure 5) shown dashed in Figure 14. All of the other anomaly features can be expected to change only slightly in detail with a different choice for a planar regional; however, a narrow, elongated anomaly such as F could be altered considerably by the choice of planar regional. This association of F with the small cavity feature will be discussed further after presentation of the regionals determined by polynomial surface fitting.

Bouguer anomaly (residual) map; regional field determined by polynomial surface fitting

46. A more objective procedure for determining the regional cavity field is by fitting a low-order polynomial surface to the Bouguer gravity values (Coons, Woolard, and Hershey 1967, Nettleton 1971). The Bouguer gravity values g_B are considered to be a function of the station coordinates (X,Y), i.e., $g_B(X,Y)$. For example, the equation for a planar surface can be written as $g_B(X,Y) = C_1X + C_2Y + C_3$, where the

constants C_1 , C_2 , and C_3 are determined so that the plane best fits the gravity data in a least-squares sense. In principle, surfaces of increasingly higher order can be fit to the Bouguer gravity data. Subtracting any polynomial surface from the Bouguer data results in residual gravity values relative to that surface; residual gravity maps will correspond to shallower anomalous features as higher order polynomial surfaces are subtracted.

47. Figure 15 contains polynomial surface fits to the Bouguer gravity data (Figure 13) through fourth order. The plane determined by inspection dips from right to left through the grid compared to the best-fit planar surface which dips from lower right to upper left. It is worthy of note, however, that the right-to-left gradient through the grid is the same for both surfaces (~0.23 μGal/ft). The second-order surface (as well as the third and fourth) show the second prominent feature discussed earlier in regard to the Bouguer gravity values, i.e., that the Bouguer gravity values along SW-NE profile lines decrease from the SW, reaching minimum values near the center, and then increase to the NE. Higher order polynomial surfaces (not shown) will account for increasingly smaller scale features of the Bouguer gravity values, until ultimately a surface is generated for which the residuals will approach zero.

48. Residual gravity maps will be presented only for the first- and second-order polynomial regionals of Figure 15. The residual gravity map referenced to the first-order polynomial regional is given in Figure 16. Comparison of Figures 14 and 16 reveals that all the major details are similar. All of the lettered anomalies in Figure 14 can be identified in Figure 16. Of course, absolute values of anomalies have changed, but the important relative anomaly values are the same. The most obvious visual difference between Figures 14 and 16 is the shifting of the zero contour separating the anomalous regions A and F from B in Figure 14 further to the SW in Figure 16. Also, the pronounced "outlining" of the small secondary cavity feature by a continuous zero contour line (see anomaly F in Figure 14) is no longer present in Figure 16, although the presence of a relative negative anomaly apparently

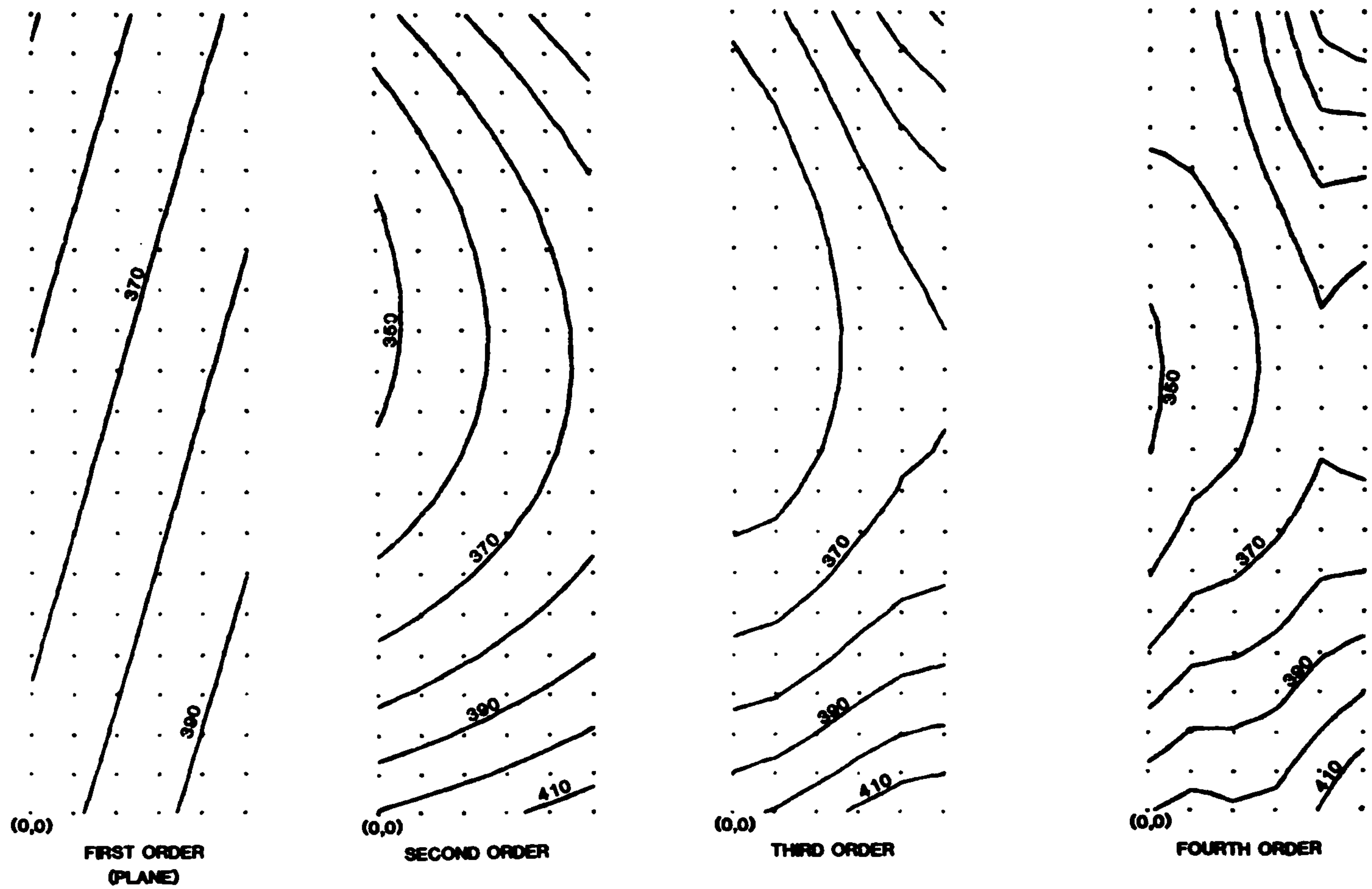

Figure 15. First- through fourth-order polynomial surface fits to the Bouguer gravity data (see Figure 13); contour interval, 10 μGal; 20-ft grid spacing

Figure 16. First-order residual gravity anomaly map

associated with the feature is still evident. Thus, observations made previously regarding Figure 14 and its correlation with the known cavity system are unaffected by the choice of the planar regional field (by inspection or by least-squares surface fitting).

49. Using the second-order polynomial surface of Figure 15 as a regional field results in the residual map shown in Figure 17. A comparison of Figure 17 with Figures 14 and 16 shows that anomalies A, B, and F are removed or significantly altered in character by subtracting the second-order regional field. The obvious interpretation is that the long wavelength anomaly caused by the known cavity system has been accounted for by the second-order regional. Within the area occupied by anomaly A (including A' and A") in Figure 14, negative anomalies apparently corresponding to A' and A" are present in Figure 17. Also, negative anomalies labeled A"' and A"" are identified in an area of otherwise very small negative values in Figure 17. Presumably, these four negative anomaly features are caused by conditions shallower than the main cavity system. For example, as noted in Part III, a wheel of the drill rig fell in a vertical solution pipe about 1.5 ft in diameter and 80 ft deep, creating a hole about 5 ft in diameter at the surface, while drilling boring S-1. Anomaly A"" in Figure 17 seems to be caused by this feature. This association suggests similar causes for anomalies such as E' and E"" in Figure 17.

Verification Drilling

50. Because of time and fiscal constraints, only a very limited number of verification borings was possible. These borings, E-1 through E-6 shown in Figure 17, were placed subsequent to the microgravimetric survey and several cross-borehole surveys in the vicinity of the small secondary cavity feature. These borings were not logged in detail; cuttings were monitored and ease of drilling noted to indicate soft or hard zones or tool drops.

51. Simplified boring logs for these verification borings are given in Figure 18. Boring E-1 was placed to verify the mapped location

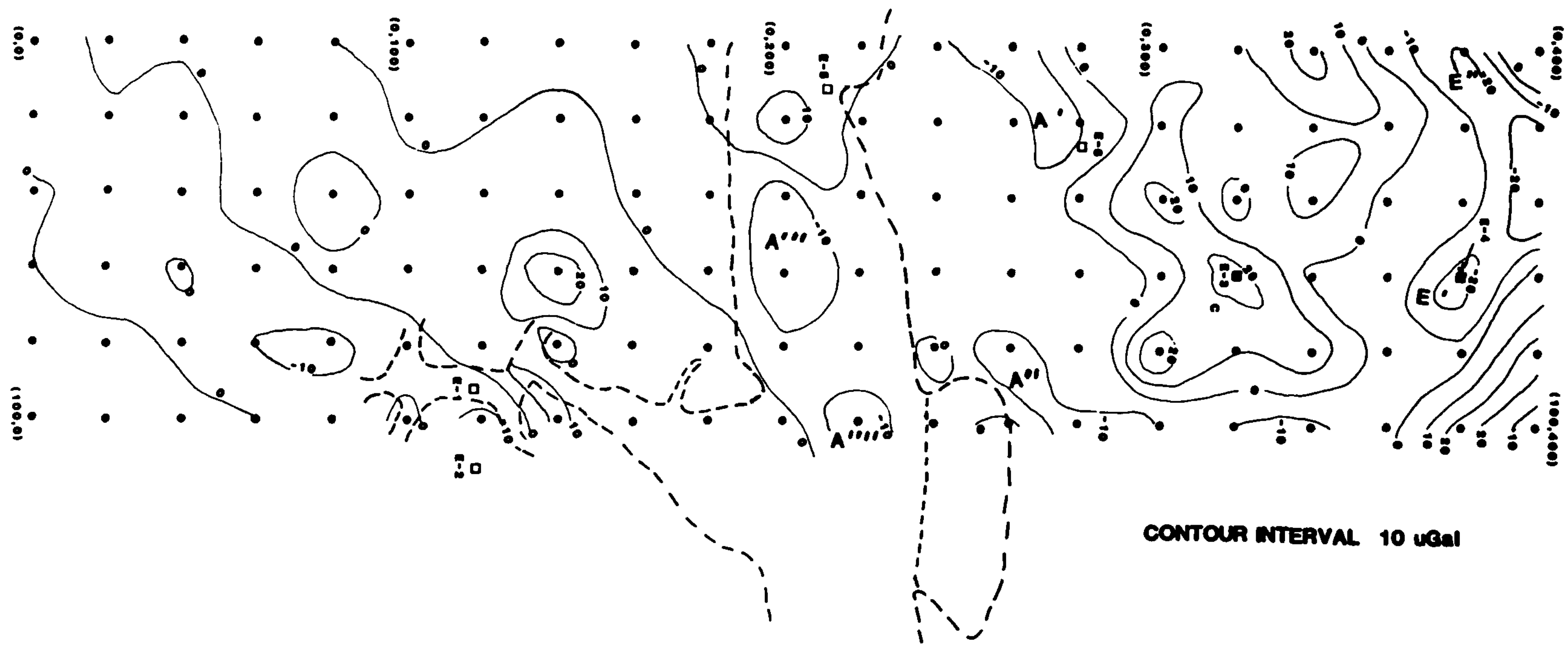

Figure 17. Second-order residual gavity anomaly map

E-1	
0-1.5	Silty sand w/original material
1.5-15	Silty sand w/clay
15-16.5	Residual clay w/LS nodules
16.5-125	Limestone, soft, white
91.5-107	Cavity

E-2	
0-1	Silty sand w/original material
1-8	White, silty sand
8-9	Residual clay w/LS nodules
9-125	Limestone, soft, white
114-114.2	Tool drop

E-3	
0-1	Silty sand w/orig. material
1-14	White, silty sand
14-15.5	Residual clay w/LS nodules
15.5-50	Limestone, soft, white

E-4	
0-1.5	Silty sand w/original material
1.5-5.5	White, silty sand
5.5-50	Limestone, soft, white

E-5	
0-10	Silty sand w/original material
10-13	Sandy clay s/LS nodules
13-96	Limestone, soft, white
89.5-95.9	Cavity

E-6	
0-1	Silty sand w/or g. material
1-13	White, silty sand
13-16	Residual clay w/LS nodules
16-105	Limestone, white, soft
90-105	Noticeably softer material, possibly sand- or clay-filled pocket
101-101.3	Tool drop

Figure 18. Simplified boring logs for verification borings (depth intervals in feet)

and depth of the secondary cavity feature between borings C-2 and C-3. Figure 19 shows the location, depths, and geometry of the secondary cavity feature as confirmed by boring E-1 and cave divers. The secondary cavity feature is somewhat shallower and larger than originally thought. Boring E-2 was placed to investigate an anomalous response indication on a crosshole electromagnetic survey between borings C-3 and C-4. Borings E-5 and E-6 were placed to verify the mapped location of the main cavity as it crosses under the northeastern side of the survey grid. Finally, borings E-3 and E-4 were placed to investigate the cause of anomalies C and E (Figure 14).

52. Boring E-5, placed at (10,210), intercepted the main cavity, and the dashed cavity location in Figure 14 reflects the proper borehole location relative to the cavity as verified by cave divers. Boring E-6 was originally planned to investigate anomaly A' at (0,260) and the possibility that the main cavity might turn and pass out of the survey area at this location, but it was relocated due to presence of large trees at the desired location. As seen from Figures 14 and 17, boring E-6, as finally located, is at the periphery of anomaly A'. From the boring logs in Figure 18, two features are apparent: (a) 3 ft of residual clay was intercepted by boring E-6 but not by boring E-5; and (b) a soft zone was intercepted in boring E-6 from approximately 90- to 105-ft depth, possibly a clay- or sand-filled pocket. Feature (a) above suggests that anomaly A' itself may be due to a clay-filled depression or pocket which extends to the west in the top of the limestone. The positive anomaly centered at (20,200) in Figure 17 (near boring E-5) may be a limestone high or pinnacle. The broader negative area around A' in Figure 17 and NE of the main cavity location may be due to the clay- or sand-filled pocket below boring E-6, which, due to its depth range, may be a filled cavity connected to the main cavity.

53. Results of borings E-3 and E-4 present a paradox which cannot be readily resolved. On the basis of the nature of the anomalies C and E' in Figure 17 (Figures 14 and 16), it could be expected that the anomalies associated with C are caused by limestone highs (pinnacles) or limestone with greater than typical density contrast while E' would

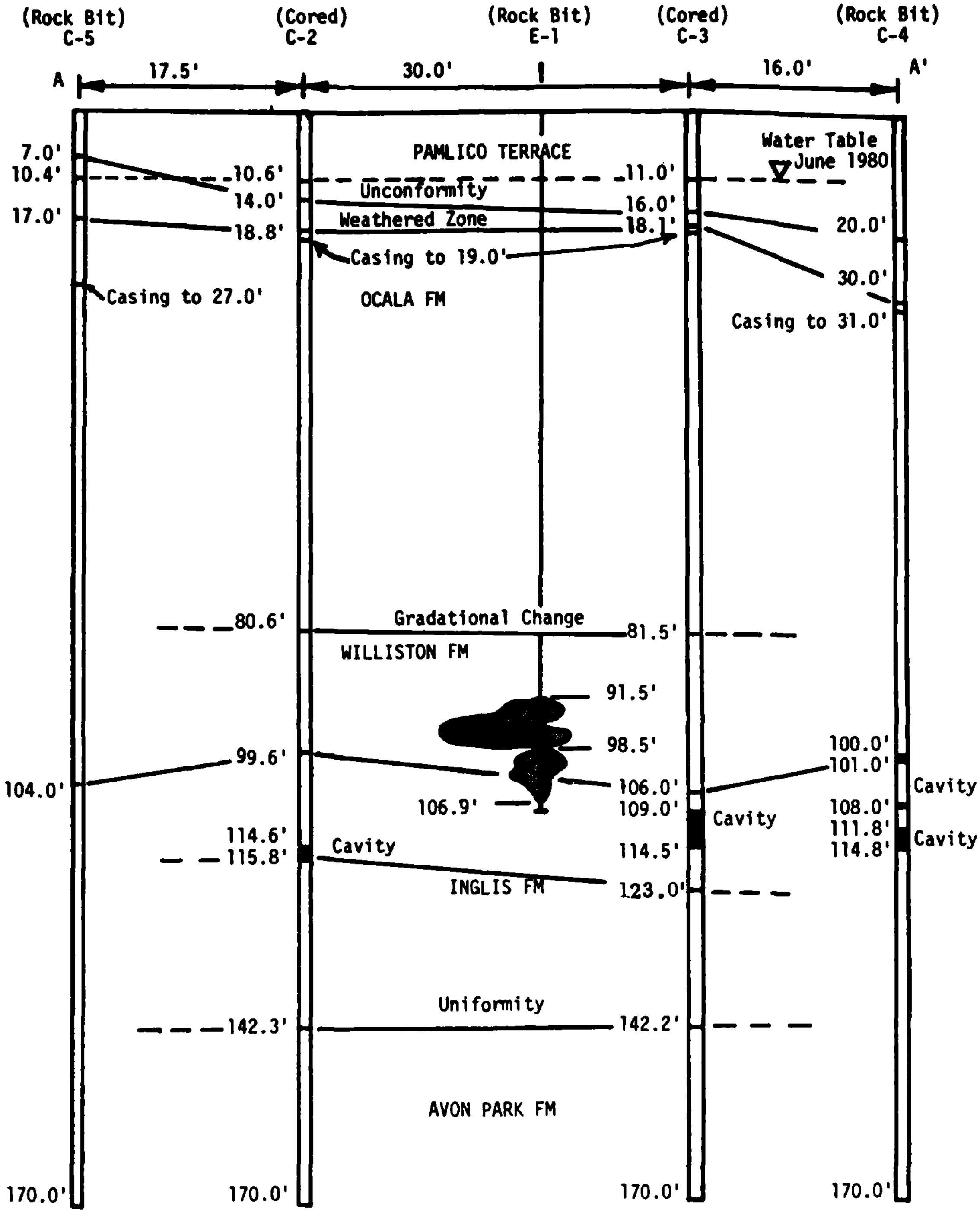

Figure 19. Location and geometry of secondary cavity feature at cross section AA' (see Figure 7)

be a clay pocket, vertical pipe, or other form of shallow cavity. If the feature causing E' is a vertical pipe similar to the one encountered near S-1, it is easy to imagine how a single borehole could miss the feature. The top of rock at boring E-3 is at 15.5-ft depth, which is typical for the site. At E-4, the top of rock is at 5.5 ft. Thus, except for the possibility of missing a vertical pipe with boring E-4, the results seem inconsistent. The possibility of denser limestone at boring E-3 cannot be verified since the boreholes were not cored.

PART V: SUMMARY AND CONCLUSIONS

54. This report presents the results of a microgravimetric survey over a known cavity system at the Manatee Springs site, Fla. The cavity system is water-filled and is at a nominal depth of 90 ft to top, with cavity height ranging from 6.5 ft at boring E-5 to 17.6 ft at S-1 and nominal width of 40 ft. A smaller cavity feature (15 ft in vertical dimensions with a highly irregular cross section ranging up to 10 ft maximum horizontal dimension) branching at about 90 deg to the main cavity was discovered by cave divers during work at the site.

55. Detection of the cavity system by microgravimetric methods was expected to be difficult due to the predicted low amplitude (~-35 μGal) and long spatial wavelength (~200 ft) of the anomaly caused by the cavity system. The survey was planned primarily for the detection of the anomaly caused by the main cavity system. Thus, while the 20-ft station spacing used in the survey is certainly adequate to delineate* larger solution features, 6-ft effective diameter and larger, at depths from 2 to 4 times the effective diameter (depending on geometry),** small solution features such as the small-scale, shallow limestone pinnacles and clay pockets encountered at the Medford site likely would not be delineated (Butler 1980, 1983). Small solution features as well as other small-scale density variations will appear as "lithological gravity noise" on the gravity maps.

56. Results of the microgravimetric survey clearly indicated the location and trend of the main cavity system across the survey area. Anomaly magnitude and width were consistent with predictions based on known geometry and depth of the main cavity system. Also a closed

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* Delineation refers to mapping of the details of the anomaly caused by a subsurface feature. Detection of the anomaly caused by a subsurface feature can be accomplished, however, without this detailed mapping.

** Actually, these size/depth rules of thumb will generally be conservative since gravity anomalies will often be greater than that calculated based on measurable dimensions due to secondary effects around the solution features.

negative anomaly superimposed on the broad negative caused by the main cavity satisfactorily delineated the small secondary cavity feature. Mapped locations of the main and secondary cavities were verified by borings and cave divers. These two anomalies were apparent despite a fairly high level of lithological noise.

57. Several other anomalies were apparent on the gravity maps. One small negative anomaly can be correlated to a vertical solution pipe discovered during drilling operations. Only a very limited verification drilling program was possible at the site (six borings) and these were not cored. Of the total of 12 borings at the site, the gravity data were consistent with the subsurface conditions revealed by all but two of the borings. These two borings were in the NE half of the survey area away from the area above the main cavity system. Two gravity anomalies (one positive and one negative), which these borings were to investigate, indicated the possibility of a limestone pinnacle or extended high rock area for the positive anomaly and the possibility of a clay pocket, very shallow cavity, or vertical solution pipe for the negative anomaly. The borings confirmed neither of these possibilities and, in fact, indicated conditions somewhat contradictory to the stated possibilities. Narrowly missing a small-diameter vertical pipe could explain the contradiction for the case of the negative anomaly, but a similar explanation for the contradiction between gravity anomaly indication and boring results is not possible for the positive anomaly, in the absence of core data for the boring.

58. Approximately 12 man-days were required for establishing the site grid system, conducting the elevation survey, conducting the microgravimetric survey, processing data, and producing a hand-drawn residual gravity contour map (Figure 14). At this stage, i.e., after the residual gravity contour map is produced, recommendations regarding site suitability for a given use could be made, assessment of the possibility of solution features at the site could be made, and/or a site drilling program layout could be recommended. For comparison, a two-man rotary rig drill crew (no geologist or inspector) could only produce approximately six 100-ft-deep NX core drill holes for the same

investment of man-time. Six borings at random could do little to characterize a 100- by 400-ft site in a karst region. Microgravimetric surveys coupled with selective drilling are seen to be a time- and cost-effective site investigation procedure for karst areas.

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APPENDIX A

BORING LOGS

Hole No. S-1

DRILLING LOG	DIVISION: Geotechnical Lab	INSTALLATION: WES	SHEET 1 OF 1 SHEETS

1. PROJECT	Manatee Springs Site
2. LOCATION (Coordinates or Station)	
3. DRILLING AGENCY	Mobile District Corps of Engineers
4. HOLE NO. (As shown on drawing title and file number)	S-1
5. NAME OF DRILLER	Herbert Owens
6. DIRECTION OF HOLE	[x] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	6.6 ft
8. DEPTH DRILLED INTO ROCK	99.0 ft
9. TOTAL DEPTH OF HOLE	105.6 ft
10. SIZE AND TYPE OF BIT	6-1/2" rock bit
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
12. MANUFACTURER'S DESIGNATION OF DRILL	Failing 1500
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED: -- ; UNDISTURBED: --
14. TOTAL NUMBER CORE BOXES	0
15. ELEVATION GROUND WATER	
16. DATE HOLE	STARTED: 5 May 80 ; COMPLETED: 7 May 80
17. ELEVATION TOP OF HOLE	
18. TOTAL CORE RECOVERY FOR BORING	0 %
19. SIGNATURE OF INSPECTOR	

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Pamlico fm.	0		sand, fine to very fine, gray to light tan			Flight auger to 6.6 ft
Ocala fm.	6.6		--6.6' Ls, white, soft, fossiliferous			
	8.4					Lost water return at 8.4 ft
	10					
			--very soft zone			
			--alternating hard and soft zones			No cuttings from 8.4 ft to 72.1 ft
	20–60		No cutting from 8.4 to 72.1 ft			
	70		--Ls, white to reddish tan			Water return at 72.1 ft
? - ?	80					
Williston fm.						Lost water at 88.4 ft
	90	X	Cavity from 88.0 ft to 105.6 ft; Manatee Springs cave			
	100		Bottom of hole at 105.6 ft			

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE (TRANSLUCENT)

PROJECT: Manatee Springs Site | HOLE NO. S-1

Hole No. C-1

DRILLING LOG	DIVISION Geotechnical Lab	INSTALLATION WES	SHEET 1 OF 2 SHEETS

1. PROJECT: Manatee Springs Site
2. LOCATION (Coordinates or Station):
3. DRILLING AGENCY: Mobile District Corps of Engineers
4. HOLE NO. (As shown on drawing title and file number): C-1
5. NAME OF DRILLER: Carl Moon and Herbert Owens
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN: 24.5 ft
8. DEPTH DRILLED INTO ROCK: 148.5 ft
9. TOTAL DEPTH OF HOLE: 173.0 ft
10. SIZE AND TYPE OF BIT: 4" rock bit
11. DATUM FOR ELEVATION SHOWN (TBM or MSL):
12. MANUFACTURER'S DESIGNATION OF DRILL: Failing 1500
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED -- UNDISTURBED
14. TOTAL NUMBER CORE BOXES: none
15. ELEVATION GROUND WATER: 7.6 ft on 6 May
16. DATE HOLE: STARTED 5 May 80 COMPLETED 17 June 80
17. ELEVATION TOP OF HOLE:
18. TOTAL CORE RECOVERY FOR BORING: 0 %
19. SIGNATURE OF INSPECTOR:

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Pamlico fm.	0		sand, fine, white	No Samples		
	7.0		7.0 ft			
Ocala fm.	10		clay, brown, sandy, ls nodules			water table at 7.6 ft on 6 May 80
	20		—ls, weathered			
	30		ls, white, unweathered, fossil fragments abundant			white water return
	40					
	50					thin hard zone at 53.5 ft
	60					
	70					
	74.0		74.0 ft			
Williston fm.			ls, creamy to grey, macro-forams abundant and other fossil fragments			tan to pink water return
	80					
	90					soft, cuts very easy
	100					

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE | **Hole No.** C-1

PROJECT Manatee Springs Site | INSTALLATION WES | SHEET 2 OF 2 SHEETS

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Williston fm.	100		-102.5 harder drilling, chert fragments			
		☒	void from 105.5 to 108.0			lost water at 105.5'
	110		Ls and chert fragments			
?						
Inglis fm.	120					
	130		soft zone 2'			rock bit hung up at 129.0 ft
						pulled plastic casing and set 26.5 ft of 6" steel casing on 12 May and left hole as was until 16 June; cleaned out hole to 129.0' and drilled to 173.0'
?			- soft zone at 137.0'			
Avon Park fm.	140		Ls, brown, few fossil fragments			
			alternating hard and soft zones			
	150					had water return all the way to 173.0' but had to run pump at high speed and continuously add water, 20% water return at 173.0'
	160					
	170					water table at 10.7 ft on 16 June
			Bottom of hole at 173.0'			

Hole No. C-2

DRILLING LOG	DIVISION: Geotechnical Lab	INSTALLATION: WES	SHEET 1 OF 2 SHEETS

1. PROJECT: Manatee Springs Site	10. SIZE AND TYPE OF BIT: 4" core and 6-1/2" rock bit
2. LOCATION (Coordinates or Station):	11. DATUM FOR ELEVATION SHOWN (TBM or MSL):
3. DRILLING AGENCY: Mobile District Corps of Engineers	12. MANUFACTURER'S DESIGNATION OF DRILL: Failing 1500
4. HOLE NO. (As shown on drawing title and file number): C-2	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED -- ; UNDISTURBED --
5. NAME OF DRILLER: Herbert Owens	14. TOTAL NUMBER CORE BOXES: 13
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER: 7.4 ft on 14 May
7. THICKNESS OF OVERBURDEN: 18.8 ft	16. DATE HOLE: STARTED 12 May 80; COMPLETED 20 May 80
8. DEPTH DRILLED INTO ROCK: 151.2 ft	17. ELEVATION TOP OF HOLE: --
9. TOTAL DEPTH OF HOLE: 170.0 ft	18. TOTAL CORE RECOVERY FOR BORING: 98 %
	19. SIGNATURE OF INSPECTOR:

ELEVATION (a)	DEPTH ft (b)	LEGEND (c)	CLASSIFICATION OF MATERIALS (Description) (d)	% CORE RECOVERY (e)	BOX OR SAMPLE NO. (f)	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) (g)
Pamlico fm.	0		sand, fine to very fine, white to yellowish brown, becoming silty with depth	No Sample		8" ID plastic casing set to 20 ft
	13.3		— 13.3 —			
Ocala fm.			Ls residue - sandy clay with ls nodules			
	19.9		--19.9			
	20		Ls, white to creamy, granular, slightly cemented, fossiliferous, very weak and soft, pasty, gastropods, pelecypods, and macroforams.	Run 1 94%	Box 1	limonitic stained joint; RQD = 94%
				Run 2 100%		RQD = 94%; weathered zone with joints
	30		--vugs up to 1/2" in diam.		2	
	40			Run 3 98%		RQD = 96%
					3	
	50			Run 4 100%		RQD = 80%
			—concentrated fossil zone		4	
	60			Run 5 99%		RQD = 20%
				Run 6 96%	5	RQD = 24%
	70			Run 7 95%		Watertable 7.4 ft on 14 May; RQD = 49%
	80.5		— 80.5 —	Run 8 97%	6	losing water return; RQD = 23%
Williston fm.			Ls, slightly cemented, granular, massive, grayish brown to white, vuggy, hard, predominance of macroforams with some pelecypods and gastropods			
	90			Run 9 100%	7	RQD = 53%
	99.6		--99.6 irregularly silicified ls, brown hard, fossil., hard and soft zones	Run 10	8	
	100					

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PROJECT: Manatee Springs Site | HOLE NO. C-2

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE | **Hole No.** C-2

PROJECT: Manatee Springs Site | INSTALLATION: WES | SHEET 2 OF 2 SHEETS

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Williston fm.	100		irregularly silicified ls.	Run 10 31%		
				100%		RQD = 33% - Run 13
	110			Run 12 16%	8	RQD = 62% - Run 14 lost all water return core barrel stuck in hole; overreamed with 4" steel casing to retrieve barrel
				Run 13 63%		
			115.7			
Inglis fm.			Ls, hard, partially dolomite, grey to brown, porous, vuggy, hard and soft zones, fossiliferous, friable zones.	Run 14 92%		
	120			Run 15 92%	9	Ls has appearance of vesicular basalt RQD = 24% - Run 15
	130			Run 16 100%		RQD = 61%
				Run 17 96%	10	RQD = 51%
			Laminated dolomite clasts in base	Run 18 92%		RQD = 60%
	140		142.3			
Avon Park fm.			Ls, brown, friable, hard and soft zones, indurated partially dolomitized, scattered carbonaceous materials	Run 19 100%	11	RQD = 38%
	150			Run 20 100%		RQD = 60%
				Run 21 100%	12	RQD = 38%
	160			Run 22 82%		RQD = 30%
				Run 23 84%	13	RQD = 40%
				No core		
	170		Bottom of hole 170.0			

Hole No. C-3

DRILLING LOG

DIVISION	Geotechnical Lab
INSTALLATION	WES
SHEET	1 OF 2 SHEETS
1. PROJECT	Manatee Springs Site
2. LOCATION (Coordinates or Station)	
3. DRILLING AGENCY	Mobile District Corps of Engineers
4. HOLE NO. (As shown on drawing title and file number)	C-3
5. NAME OF DRILLER	Carl Moon
6. DIRECTION OF HOLE	☒ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	18.1 ft
8. DEPTH DRILLED INTO ROCK	151.9 ft
9. TOTAL DEPTH OF HOLE	170.0 ft
10. SIZE AND TYPE OF BIT	3" core and 6" rock bit
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
12. MANUFACTURER'S DESIGNATION OF DRILL	Failing 1500
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED: -- UNDISTURBED: --
14. TOTAL NUMBER CORE BOXES	10
15. ELEVATION GROUND WATER	9.5 ft on 15 May
16. DATE HOLE	STARTED: 13 May 80 COMPLETED: 22 May 80
17. ELEVATION TOP OF HOLE	--
18. TOTAL CORE RECOVERY FOR BORING	71 %
19. SIGNATURE OF INSPECTOR	

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Pamlico fm.	0–16.0		sand, fine, white to tan, silt and clay increase with depth	no sample flight auger		8" plastic ID casing set to 18.1 ft; casing crooked so reset to 19.0 ft on 14 May -- Run 1 was cave-in
	16.0		clay tan to brown, with ls nodules		19.0	
Ocala fm. (Crystal River fm.)	19.0		Ls, pink to gray, hard, weakly cemented, friable, massive, fossiliferous (gastropods, pelecypods and macro-forams)	Run 2 88%	Box 1	RQD = 88% lost circulation at 22 ft; cemented hole, have water return
				Run 3 44%	29.5 Box 2	RQD = 35%
				Run 4 26%		losing more water RQD = 18% - Run 4
	44.5		Ls, soft, white to creamy, friable, massive, scattered chert fragments, fossiliferous as above	Run 5 100%	49.6	RQD = 87% - Run 5 cemented around outside of casing to stop wash
				Run 6 100%	Box 3	Add revert to stop water loss RQD = 35% - Run 6
				Run 7 86%	60.4 Box 4	RQD = 43%
				Run 8 45%		RQD = 25%
	76.5		Ls, hard, cream to pink, well cemented, massive, fossil. as above	Run 9 84%	76.0 Box 5	RQD = 39%
Williston fm.	81.5		Ls, grey, hard, massive, friable, abundance of macroforams gives granular appearance, some gastropods and pelecypods	Run 10 100%	87.7	RQD = 57%
	100			Run 11 ?%		RQD = 26% still losing water

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PROJECT: Manatee Springs Site HOLE NO. C-3

DRILLING LOG (Cont Sheet) ELEVATION TOP OF HOLE — **Hole No.** C-3

PROJECT: Manatee Springs Site | INSTALLATION: WES | SHEET 2 OF 2 SHEETS

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Williston fm.	100				Box 6	void from 106.0 to 106.5; lost all water
		Void	106.0		106.0	
			Ls, irregularly silicified, brown to gray, hard and soft zones, fossiliferous (gastropods, pelecypods, macroforams), friable, massive	Run 12		RQD = 6%
	110	Void		17%	Box 7	void from 109.0 to 114.5
				Run 13	126.3	RQD = 38%
	120			70%		
Inglis fm.			115.7			
			Ls, grey to brown, porous, partially dolom., hard, few gastropods and pelecypods, some granular zones	Run 14		RQD = 44%
	130			62%	Box 8	
			laminated dolomite clasts	Run 15	138.0	core barrel stuck in hole; overreamed with 4" steel casing to retrieve barrel.
	140			67%		
Avon Park fm.			142.3		Box	RQD = 48%
			Ls, brown to grey, friable, hard and soft zones, partially dolomitized, carbonaceous material scattered in upper section	Run 16	9	RQD = 69%
	150			92%	153.0	
						1 RQD = 52%
				Run 17	Box 10	
	160			92%		
				no core		hole reamed to 170.0 ft with 6" rock bit
	170		Bottom of hole 170.0 ft			

ENG FORM 1836-A

PROJECT: Manatee Springs Site | HOLE NO. C-3

Hole No. C-4

DRILLING LOG	DIVISION: Geotechnical Lab	INSTALLATION: [illegible]	SHEET 1 OF SHEETS

1. PROJECT: Manatee Springs Site	10. SIZE AND TYPE OF BIT: " rock bit
2. LOCATION (Coordinates or Station)	11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
3. DRILLING AGENCY: Mobile District Corps of Engineers	12. MANUFACTURER'S DESIGNATION OF DRILL: Failing 1500
4. HOLE NO. (As shown on drawing title and file number): C-4	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED -- UNDISTURBED --
5. NAME OF DRILLER: Carl Moon and Herbert Owens	14. TOTAL NUMBER CORE BOXES --
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ___ DEG. FROM VERT.	15. ELEVATION GROUND WATER 11.0' on 16 June
	16. DATE HOLE: STARTED 27 May 80 COMPLETED June 80
7. THICKNESS OF OVERBURDEN 30.0 ft	17. ELEVATION TOP OF HOLE --
8. DEPTH DRILLED INTO ROCK 150.0 ft	18. TOTAL CORE RECOVERY FOR BORING 0 %
9. TOTAL DEPTH OF HOLE 180.0 ft	19. SIGNATURE OF INSPECTOR

ELEVATION (a)	DEPTH ft (b)	LEGEND (c)	CLASSIFICATION OF MATERIALS (Description) (d)	% CORE RECOVERY (e)	BOX OR SAMPLE NO. (f)	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) (g)
Pamlico fm.	0		sand, fine, white	No Samples		8" ID plastic casing set to 31 feet
Ocala fm.	20		clay, sandy, ls nodules			casing bent at 20 ft joint
	30		Ls, white, fossiliferous			
	40		hard ledge			lost all water at 40 ft; cemented hole with 9 sacks cement; have some water return
	65		hard ledge			
?—?—	80		soft zone at 81 ft			
Williston fm.	100		Silicified williston fm.			Drilling much harder

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PROJECT: Manatee Springs Site HOLE NO. C-4

DRILLING LOG (Cont Sheet) ELEVATION TOP OF HOLE

Hole No. C-4

PROJECT: Manatee Springs Site | INSTALLATION: WES | SHEET 2 OF 2 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
Williston fm.	100		101.0			
			cavity			
			108.0			
	110		hard drilling			
			111.8			
			cavity			
			114.8			
			hard drilling			
?—?—	120		alternating hard and soft zones to bottom of hole	No Samples		--120' - cemented hole with 30 sacks of cement mixed with 1/2 sack drilling mud; cement set up to 105.0'
Inglis fm.	130					
?—?—	140					
Avon Park fm.	150					
	160					--165.0 ft - cemented hole with 40 sacks of cement, set up to 105.0 ft, cemented hole with additional 85 sacks cement, set up to 102.2 ft
	170					
	180		Bottom of hole			Note: hole is crooked Water table at 11.0 ft on 16 June

Hole No. C-[illegible]

DRILLING LOG	DIVISION: Geotechnical Lab	INSTALLATION: WES	SHEET 1 OF [illegible] SHEETS

1. PROJECT: Manatee Springs Site	10. SIZE AND TYPE OF BIT: [illegible]-1/2" [illegible] bit
2. LOCATION (Coordinates or Station)	11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
3. DRILLING AGENCY: Mobile District Corps of Engineers	12. MANUFACTURER'S DESIGNATION OF DRILL: [illegible]iling 1500
4. HOLE NO. (As shown on drawing title and file number): C-5	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED: -- UNDISTURBED: --
5. NAME OF DRILLER: [illegible]	14. TOTAL NUMBER CORE BOXES: --
6. DIRECTION OF HOLE: ☐ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER: 11.[illegible] ft on 1[illegible] June
7. THICKNESS OF OVERBURDEN: 17.0 ft	16. DATE HOLE — STARTED: 27 May 80 COMPLETED: 30 May 80
8. DEPTH DRILLED INTO ROCK: 153.0 ft	17. ELEVATION TOP OF HOLE: --
9. TOTAL DEPTH OF HOLE: 170.0 ft	18. TOTAL CORE RECOVERY FOR BORING: 0 %
	19. SIGNATURE OF INSPECTOR

ELEVATION a	DEPTH ft. b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
[illegible] Fm.	0		sand, white, fine			8" ID plastic casing set to 27.0' --
			7.0 ft			hole started 2.5 ft west drilled to 26.5 ft before hitting rock; lost 8" rock bit in hole; filled with sand and 1 sack cement and moved to present location
	10		clay, sandy with ls nodules			
			17.0' --Ls, creamy to white, soft, fossiliferous			
	20					
Ocala Fm.	30					Lost all water return
						Cemented hole with 4 sacks cement; 60 to 80% water return after cementing and using drilling mud
	40					
	50		--hard zone			
			--very soft zone			
	60					
	70		hard zone at 71 and 74 ft			
						20% water return
—?—?—	80					
[illegible]	90					
	[illegible]					

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PROJECT: Manatee Springs Site HOLE NO. [illegible]

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE | **Hole No.** C-5

PROJECT: Manatee Springs Site | INSTALLATION: WES | SHEET 2 OF 2 SHEETS

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	100					
Williston fm.			--top of silicified Williston at 104 ft			very hard drilling
	110					
? ?						lost all water at 114.0 ft; cemented with 4 sacks of cement; lost all water return after drilling through cement
	120		alternating hard and soft zones to bottom of hole			
Inglis fm.	130					
? ?	140					
	150					
Avon Park fm.	160					
						water table at 11.5 on 16 June
	170		Bottom of hole			cemented hole with 8 sacks of cement to help hold it open; cement set up to 120 ft but questionable how good top 25 ft was set up

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Butler, Dwain K.
Cavity detection and delineation research : Report 4 : Microgravimetric survey : Manatee Springs Site, Florida / by Dwain K. Butler, Charlie B. Whitten, and Fred L. Smith (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1983.
47, [12] p. : ill. ; 27 cm. -- (Technical report ; GL-83-1, Report 4)
Cover title.
"March 1983."
"Prepared for Office, Chief of Engineers, U.S. Army under CWIS Work Unit 31150."
Bibliography: p. 47.

1. Geophysical research. 2. Gravimeter (Geophysical instruments). 3. Manatee Springs (Fla.) I. Whitten, Charlie B. II. Smith, Fred L. III. United States. Army. Corps of Engineers. Office of the Chief of Engineers. IV. U.S. Army Engineer Waterways Experiment Station.

Butler, Dwain K.
Cavity detection and delineation research : ... 1983.
(Card 2)

Geotechnical Laboratory. V. Title VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-83-1, Report 4.
TA7.W34 no.GL-83-1 Report 4

4-8

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