

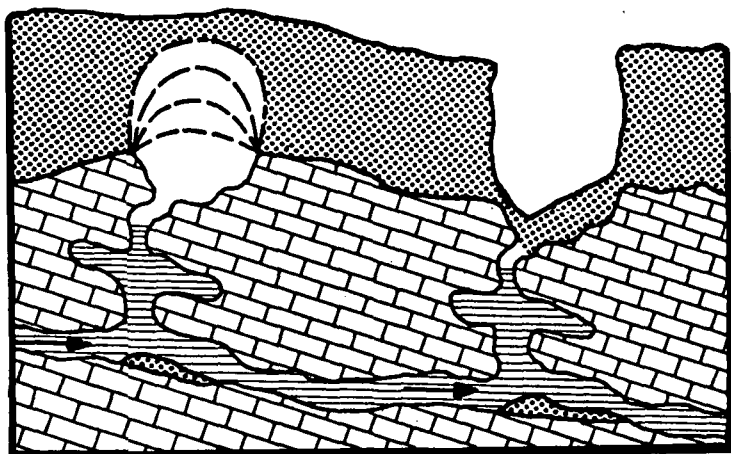
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A REMOTE SENSING EVALUATION of the POTENTIAL for Sinkhole OCCURRENCE



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January 1981

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SUMMARY

The Remote Sensing Applications Laboratory, University of Florida, was requested to investigate the area surrounding Pierson, Florida, where the development of sinkholes had created concern over their potential for damage to residences and other structures. It was anticipated that interpretation of features on aerial photography and other imagery, combined with information from the literature, would result in the development of a method for identification of areas having a high potential for cavity collapse.

The relationship between lineaments or fracture traces in karst terrain and the availability of water in the underlying limestone aquifers has been established by other investigators. These linear features are generally visible in aerial photography and satellite imagery. The greater degree of fracturing and water flow along these linears often creates a greater potential for development of subsurface cavities, which may collapse abruptly as the cavity enlarges and migrates toward the surface. The intersection of two or more linears often indicates even greater potential for sinkhole development.

Lineaments and fracture traces were mapped using three different types of imagery: LANDSAT (satellite), NASA's high altitude color infrared photography, and low altitude black and white aerial photography from the Agricultural Soil Conservation Service (ASCS). Sinkholes that had developed in recent years were accurately mapped to establish their location relative to linears and the intersection of linears.

During the course of the study it became apparent that the number of recent sinkholes were minimal and not nearly as numerous as originally implied. Field investigations revealed that a few fairly large sinkholes had apparently drawn much attention and the severity of the problem was considerably less than found in many other areas of Florida. Therefore, a second study area was selected for analysis in an attempt to obtain a more definitive correlation between linears and recent sinkhole development.

An area west of Plant City in Hillsborough County, Florida was the site of numerous collapses in January, 1977. Hydrologists had mapped the location of 22 new sinkholes within a seven square mile area. These sinkholes occurred during a period of heavy pumping for freeze protection of crops.

Lineaments were mapped from 1973 ASCS black and white aerial photography. The intersections of mapped lineaments corresponded quite well with the locations of the 22 sinkholes. Therefore supporting the belief that lineaments and lineament intersections delineate zones with a high degree of fracturing and a high permeability, which permits greater solution activity and cavity development. It is obvious that heavy well pumping and substantial drawdown of the water table was related to the high frequency of collapse. However, in this case, the triggering mechanism appeared to be related more to movement of the water sprayed on crops, which tended to saturate soils in the lower topographic areas or depressions.

It is impossible to halt or prevent sinkhole development by cessation of pumping since cavities already exist in the subsurface limestone formations. Drawdown of the water table, irrigation, freeze

protection, and natural conditions like drought and heavy rainfall only serve to minimize or accentuate the frequency of sinkhole occurrence. The potential for cavity collapse and/or damage to foundations and building structures still exists regardless of the conditions that may induce a collapse of subsurface cavities.

The area in the vicinity of Pierson does not appear to be a zone of frequent collapses or a high risk area for structural damage. Those areas falling along lineaments and fracture traces can be expected to have a greater potential for sinkhole development, particularly where topographic lows are encountered. It is recommended that the techniques and procedures outlined in this report be used in the evaluation of any portions of Volusia County where prior sinkhole development and urbanization growth trends indicate the need for zoning or special building code requirements. These requirements would serve to minimize future problems with cavities and sinkhole development.

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Special thanks to the Deland Sun for pictures and information that was used in documenting some of the cavity collapses.

INTRODUCTION

This investigation was initiated for the purpose of evaluating 1) the relationship between lowering of the water table and sinkhole development, and 2) the location of recently developed collapses in relation to lineaments or fracture traces that are expressed in the terrain and visible in aerial photography and satellite imagery. It was anticipated that these relationships would provide the basis for establishment of criteria for mapping those land areas that had the greatest potential for sinkhole development. Maps of this type could be used effectively in zoning or land use planning to limit or control land utilization. Modification of building codes to require more extensive investigation of subsurface foundation conditions could also be implemented. This would minimize the potential for structural damage due to the collapse of cavities.

The study evolved from information supplied to the Remote Sensing Applications Laboratory regarding the area in and around Pierson, Florida. Discussions with various individuals suggested that numerous collapses had occurred in recent years. It was implied that drawdown of the water table, during heavy pumping of wells for freeze protection of fern crops, was the major triggering mechanism in the collapse of cavities and development of sinkholes.

Details of the investigation are presented in this report. Background information on the geology and development of sinkholes in karst terrain was extracted from the literature to provide a basic understanding

of the mechanisms that contribute to the problem. The various types of data and remote sensing imagery utilized in the study, the analysis methods, and results are discussed in subsequent sections. Also, a summary of study procedures, findings, and recommendations has been provided for the reader's convenience.

SUMMARY

The Remote Sensing Applications Laboratory, University of Florida, was requested to investigate the area surrounding Pierson, Florida, where the development of sinkholes had created concern over their potential for damage to residences and other structures. It was anticipated that interpretation of features on aerial photography and other imagery, combined with information from the literature, would result in the development of a method for identification of areas having a high potential for cavity collapse.

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During the course of the study it became apparent that the number of recent sinkholes were minimal and not nearly as numerous as originally implied. Field investigations revealed that a few fairly large sinkholes had apparently drawn much attention and the severity of the problem was considerably less than found in many other areas of Florida. Therefore, a second study area was selected for analysis in an attempt to obtain a more definitive correlation between linears and recent sinkhole development.

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The area in the vicinity of Pierson does not appear to be a zone of frequent collapses or a high risk area for structural damage. Those areas falling along lineaments and fracture traces can be expected to have a greater potential for sinkhole development, particularly where topographic lows are encountered. It is recommended that the techniques and procedures outlined in this report be used in the evaluation of any portions of Volusia County where prior sinkhole development and urbanization growth trends indicate the need for zoning or special building code requirements. These requirements would serve to minimize future problems with cavities and sinkhole development.

APPLICATIONS OF REMOTE SENSING FOR KARST TERRAIN

Remote sensing encompasses various techniques for measurement and observation of an object of interest without being in direct contact with it. Methods available fall into three general groups (25): 1) direct observation of the of the object, or air reconnaissance, 2) interpretation of aerial photography (color, black and white, etc.) and 3) measurement of electromagnetic radiation by airborne sensors which convert the energy into an electronic signal, which can then be enhanced and evaluated. The last two groups have the advantage of providing a permanent record.

Air reconnaissance gives an observer the opportunity to observe the features of an area firsthand (25). Since subsurface features are often manifested in the surface characteristics, these features may be detected visually. While this technique is useful in allowing the observer to see the ground from different positions, it has the disadvantage of not providing a permanent record which can be reviewed later.

Air photo interpretation can be considered an extension of visual sensing, but in this case, a film record is made. Various film types are available, some of which are sensitive to electromagnetic wavelengths which cannot be seen by the unaided human eye. Films can record images over a wavelength range about twice the range detectable to the human eye (14). Discussion of various film types, sensors and their uses can be found in Appendix A. Aerial photographs also allow an

observer to view a large area at once, enabling him to develop a greater understanding of regional features.

Since aerial photographs provide a permanent record, it is possible to observe changes with time. Also possible is the recording of phenomena of short duration, such as floods, forest fires and oil spills (14). With the proper equipment, film, and atmospheric conditions, much more detail can be recorded on film than could be observed by eye. This detail can be seen when the photographs are magnified or viewed stereoscopically. With a correct ground reference system, information such as distances, heights, volumes, areas, directions and slopes can be obtained (14).

The third category of remote sensing techniques involves the measurement of different wavelengths of electromagnetic radiation by a sensor that is generally airborne and includes such methods as thermography. Multispectral scanning imagery (LANDSAT) is also available and is useful for delineating large scale regional features. While most aerial photographs must be taken during the daytime, some of these sensors may be used at night.

Methods involving the measurement of reflected energy, such as multispectral scanning, must generally be used during the daytime when reflected energy levels are greatest. Although radar measures reflected energy, it has its own radiation sources and is often used at night to avoid interference from other sources. Sensors detecting radiation emitted from an object, such as thermal or microwave radiation, are not dependent on high levels of radiation and may be used during the day or night.

In a recent review of remote sensing applications for the analysis of karst terrain, LaMoreaux (11) summarized the potential uses of remote sensing techniques. In addition to allowing relatively rapid analysis of large areas, potential applications of remote sensing include:

- 1) inventory of sinkholes;
- 2) monitoring sinkhole development;
- 3) mapping sinkhole alignments;
- 4) investigating the relationships among sinkhole development, groundwater movement, fracture traces, and lineaments;
- 5) preparing and updating base maps;
- 6) delineating incipient collapse zones;
- 7) detecting areas of abnormal surface drainage;
- 8) mapping regional geologic structure;
- 9) locating exposures of bedrock; and
- 10) aiding in general project planning.

(11, p. 388)

For the purpose of this study it is felt that mapping of linear features from available imagery has great potential in the evaluation of the possibility of sinkhole occurrence for an area. By mapping linear features, it is possible to locate highly fractured zones where these features intersect.

It has been shown that water wells are much more productive near the intersections of mapped linear features (13, 19), corresponding to more permeable zones in subsurface limestone. It is believed that the potential for cavity development and sinkhole formation is greatest in these zones since solution activity will be greater in a highly fractured zone with a large flow of water.

DEVELOPMENT OF KARST TERRAIN

Thornbury has defined "karst" as "a comprehensive term applied to limestone or dolomite areas that possess a topography peculiar to and dependent upon underground solution and the diversion of surface waters to underground routes" (30, p. 303). Nearly 15 percent of the contiguous United States (Figure 1) has some soluble rock at or near the surface (8), which could be subject to the development of karstic features under the proper conditions.

Areas in the United States exhibiting the greatest karst development include the Great Valley region of Pennsylvania, Maryland, Virginia, and Tennessee; the Salem-Springfield plateaus of Missouri; central Florida; and an area extending from south-central Indiana into west-central Kentucky (30). Other areas exhibit karst features, but not to such an extent as that areas already mentioned. Discussion of the various aspects of aerial interpretation as applied to karst terrain appears in Appendix B.

Carbonate aquifers in four karst regions are among the most productive aquifer systems in the United States and result from the high permeability developed secondarily by subsurface solution. These aquifers are: (1) the shallow Biscayne aquifer in southeastern Florida; (2) the artesian Floridan aquifer in Florida and southeastern Georgia; (3) the Edwards Limestone aquifer of the Edwards Plateau, Texas; and (4) the artesian aquifer in the Roswell Basin in southeastern New Mexico (8).

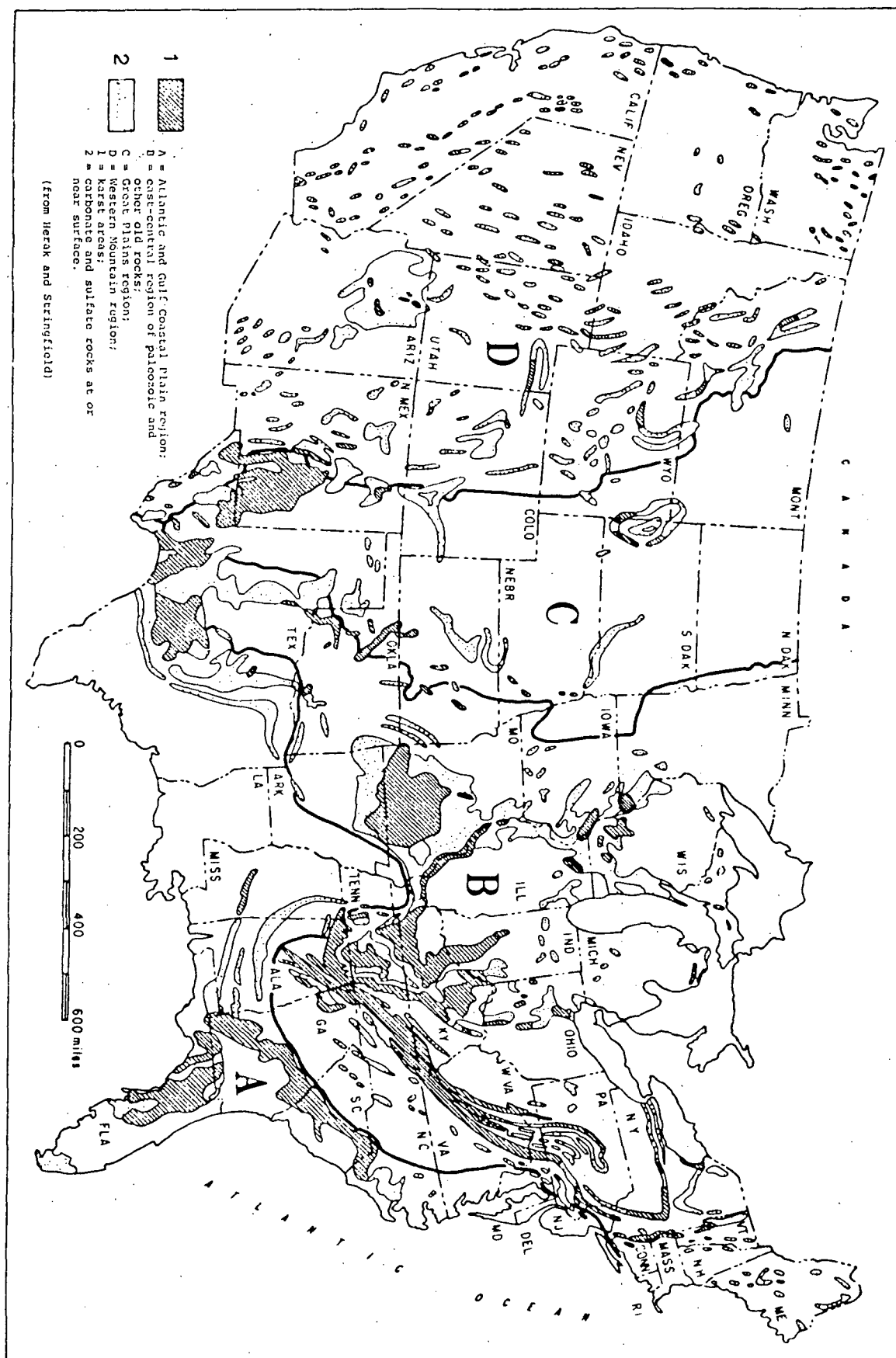


Figure 1 - Major karst regions of United States.

A region must also have at least moderate rainfall for the development of a karst terrain. Arid and semiarid regions generally do not exhibit significant karst development, and any features observed are believed to be remnants from periods of more humid climatic conditions (30).

For solution processes to occur, it is necessary that the rocks have some degree of permeability to allow flow of water. If the flow is more rapid and the water continually replaced, water that is saturated with the dissolved ions can be carried away and replaced by less saturated water, allowing more solution. The permeability is controlled by characteristics of the rock which have been termed "primary porosity" and "secondary porosity" (26).

Primary porosity is the result of interparticulate openings in the rock, such as in shell beds or coquina deposits, formed during deposition. This type of porosity is fairly uniform through the rock and results in solution features distributed throughout the limestone. Downward flow above the water table may form numerous small solution pits, while solution due to horizontal flow below the water table can result in irregular conduits or small caves (26). As these conduits develop, the flow rate of the water can increase, accelerating solution and producing larger and more contiguous conduits.

Secondary porosity is a result of flow along cracks and joints in the limestone which are probably caused by tectonic movements and flexure, and stress release in the rock. Highly fractured zones have been shown to yield large quantities of water in carbonate terrain (19, 13), and flow along fractures and joints can be much more rapid than

that through interparticulate openings. Flow along bedding planes is also an element of secondary porosity.

As solution continues, joints and fractures become enlarged, increasing the water flow rate and the rate of solution of the limestone. Features such as chimney-like holes and rock pinnacles may develop. In rock with a high degree of both primary and secondary porosity, numerous enlarged holes may form, concentrated near the enlarged secondary cracks (26).

Conditions favoring downward flow of water are also necessary for karst development. One example of this condition is a valley below an upland underlain by well jointed soluble rock (30). The river in the valley serves as a local "base level" for flow through the soluble strata. In other areas, the base level may be a local stream or possibly a lake or ocean.

Springs and caverns are familiar features of karst regions, but the most potentially dangerous feature is a collapse of the ground surface, or sinkhole. These collapses are often quite sudden, and the potential for damage to structures may be substantial in developed areas. Property damage is not usually great in agricultural areas, but in some areas with highly developed karst, loss of livestock is considered commonplace (1). Sinkhole damage to roads is also common in some karst regions, including Florida.

Urban development is now spreading into many rural areas, and people are often unaware of the potential hazards. Several structures have been damaged or destroyed by sinkholes in Florida, and insurance companies in Florida have only been required to provide sinkhole insurance to homeowners since 1970 (1). In general, no zoning guidelines

exist for construction in a karst area, and the safety of a structure depends on adequate reconnaissance and subsurface exploration. The reader is referred to Appendix C, where a brief discussion appears on the problems associated with construction and other activities.

Sinkhole Development

The most common topographic feature of karst terrain is the sinkhole, a depression in the land surface. In Indiana, over 1000 sinkholes have been mapped within one square mile (30). Sinkholes commonly range from 10 to 30 feet deep, but may be more than 100 feet in depth. Sinkhole areas range from less than a few square yards to several acres. Although variation in form is considerable, funnel shaped sinkholes opening upward are common (30).

There are two primary types of sinkholes, "collapse" and "raveling", with the characteristic type depending on the proximity of the soluble limestone to the surface (27). Both "collapse" and "raveling" sinkholes require a well developed system of solution channels, cavities, or caves in the limestone. These channels often form along joints and fracture zones in the rock.

A "collapse" sinkhole (Figure 2) may occur when the limestone unit is at or near the surface. The "collapse" type forms when a cavity is enlarged in the rock to the point that the roof is no longer strong enough to support the material above it. This results in a collapse of the overlying material into the cavity, often leaving an overhang. The material often drops as a unit and it may still be possible to see the surface vegetation or trees in the bottom of the sinkholes (27). Eventually, the overhanging material will drop off or slump into the

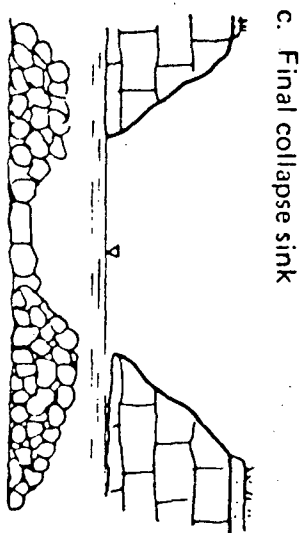
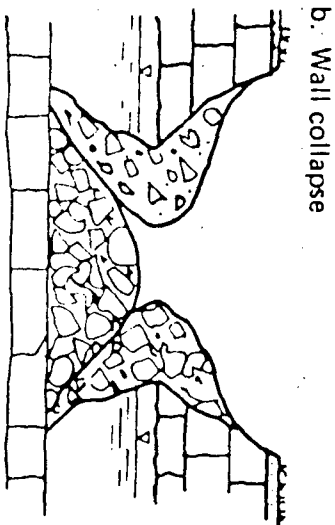
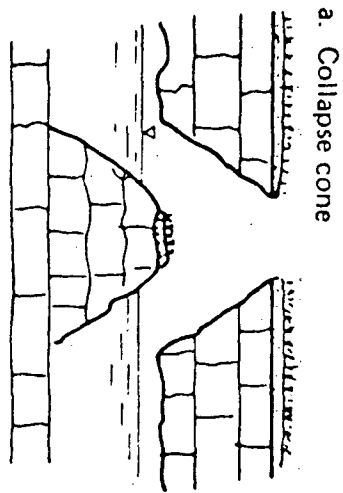


Figure 2 - Collapse sinkhole development.
(from Sowers, 1976)

sinkhole, and if there is flowing water, the material may be carried away, leaving a funnel shaped depression.

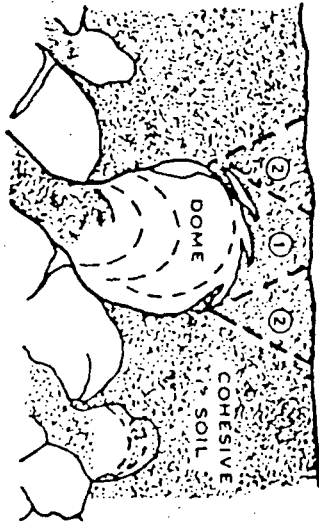
Much more common in Florida is the "raveling" sinkhole (Figure 3). This type of sinkhole usually occurs where the limestone is overlain by thick, uncemented soils. These failures are usually initiated over openings in the limestone that may have been previously plugged or covered. One dangerous characteristic of this type of sinkhole is that it does not require a large opening in the limestone, but just an opening large enough to allow flowing water to remove the soil that is eroded into it.

As soil is carried into the opening by groundwater, a cavity develops in the unconsolidated material and the soil arches over the opening. As water seeps in, small portions of the roof drop off, and eventually, slabs of the roof begin to peel off. This action is called "roofing" (27). This is caused by a combination of stresses in the internal shell of the domed roof, changes in soil moisture producing volume changes and loss of shear strength, and softening of the surface by percolating water.

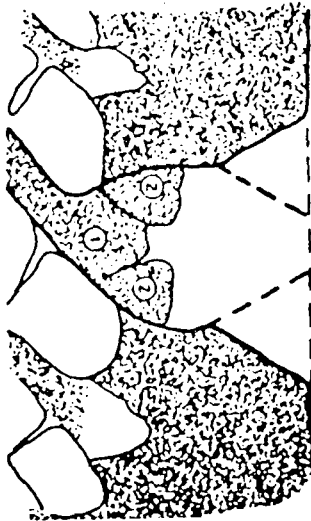
As with the "collapse" sinkhole, eventually the cavity of the "raveling" sink will become large enough that the roof cannot support the material above it, and it collapses into the cavity. The development of a "raveling" sinkhole requires that the soil have some degree of cohesion. It may be difficult to distinguish this type from a "collapse" sinkhole by observation.

In a cohesionless soil, a typical hourglass shaped "raveling" sinkhole may develop (Figure 3c). All that is necessary is a small opening in the rock below and circulation of water to carry away the

a. Dome formation by raveling and spalling into openings



b. Dome dropout (1) followed by rim collapse (2)



c. Hourglass erosion

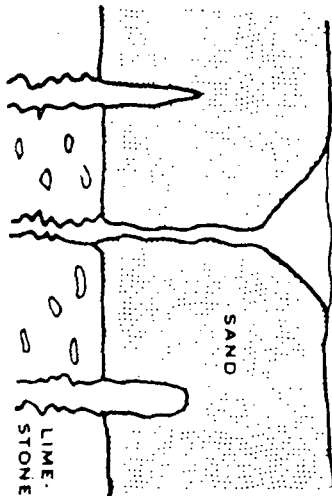


Figure 3 - Raveling sinkhole development.
(from Sowers, 1976)

material. A thin pipe may work its way to the surface with a cone shaped surface depression appearing, as cohesionless soil falls into the pipe (27).

Triggering Mechanisms for Cavity Collapse

Many different events can trigger the collapse of a cavity in soil or rock, resulting in a sinkhole. One major cause of sinkhole formation is a lowering of the water table (Figure 4). When the water table is high, the water has a buoyant effect on the rock or soil of a cavity, but a lowering of the water table removes this buoyant effect. This results in an increase in effective stresses in the already weakened structure of the cavity walls and roof. Under certain conditions this increase in effective stress can cause collapse of the cavity (27).

Lowering of the water table occurs either naturally as a result of periods of drought or from pumping from wells. Sudden drawdown due to excessive pumping from water wells has received much blame for sinkhole occurrence. Water levels may also be lowered by dewatering for construction (27).

Increased seepage through the soil is another important factor in sinkhole occurrence. This flow may be downward through the soil or laterally along an impervious bed until an opening is found (27). When the water flows into an opening in the limestone, particles of soil may be carried with it. This piping action enlarges cavities in the soil above the limestone, eventually resulting in collapse.

Piping of the soil into subsurface voids may be caused by increasing seepage from a number of sources, including: (1) increased rainfall; (2) broken or leaky water lines; (3) broken drainage lines; (4) flow of water toward wells; and (5) flow of water toward drainage

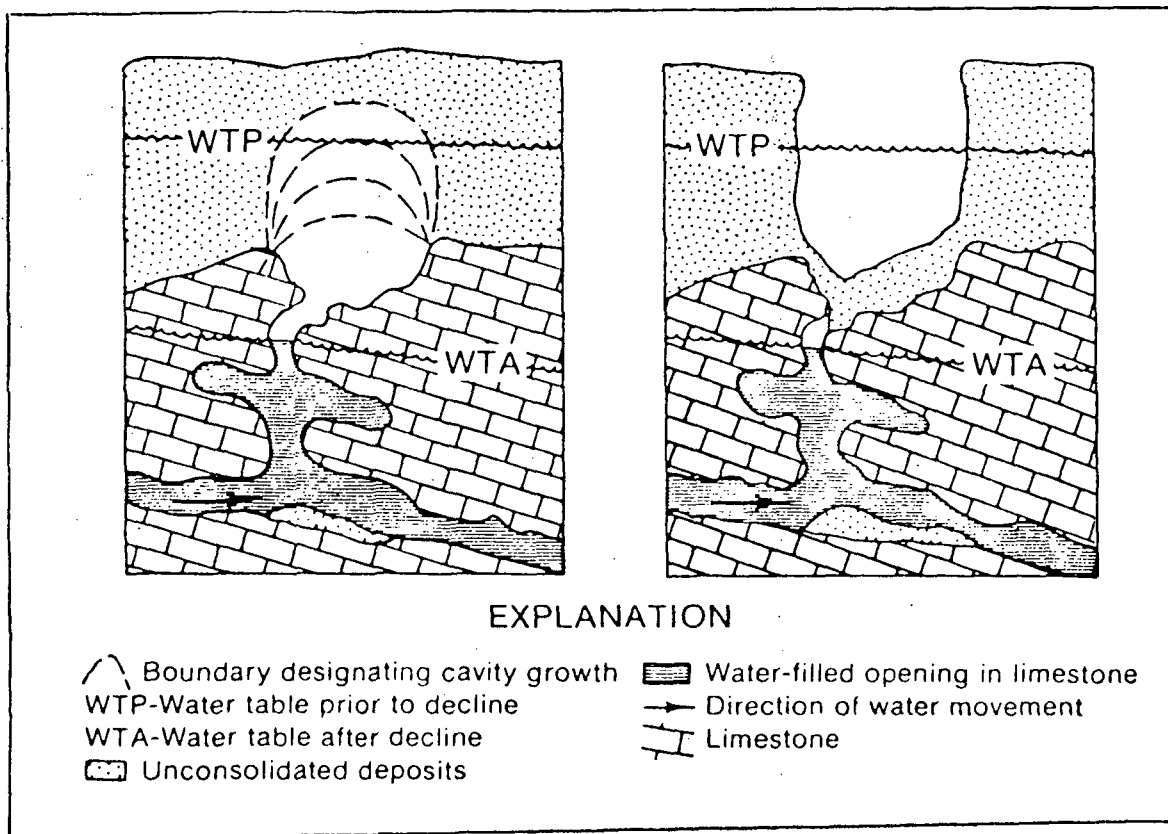


Figure 4 - Effect of water table decline
in sinkhole formation.
(from Warren)

systems with poorly constructed filter systems (34). Increased sinkhole occurrence has been reported after heavy rainfall (20), and infiltration from heavy irrigation may also be an important contributing factor.

Increased surface loading, especially when combined with a lowered water table, is another possible cause of sinkhole occurrence. Subsidence may also occur as a result of a general deterioration of soil and rock, expressed by either a gradual subsidence related to the degree of deterioration, a sudden collapse of the opening, or a raveling and shallow collapse (27).

GENERAL DESCRIPTION OF FLORIDA KARST TERRAIN

Most of the sinkholes in Florida occur where the Tertiary limestone of the Floridan aquifer (Figure 5) is at or near the surface. The Floridan aquifer is one of the most productive in the United States (8), and recharge of the aquifer takes place at several locations, including those where sinkholes have breached the confining layers over the aquifer (Figure 6). Many of Florida's lakes are sinkholes, some approaching 200 feet in depth (28).

Most Florida sinkholes occur during April and May, corresponding to the end of the dry season when water levels are lowest (2). Increased rainfall at this time increases downward flow of water, which may trigger cavity formation. However, the study areas considered here have experienced greatest sinkhole occurrence during the winter months, in conjunction with pumping for freeze protection of crops.

The major structural control in the Tertiary limestone of Florida is the Ocala uplift (Figure 7). From this feature the limestone surface dips slightly toward each coast. Movement of groundwater is generally toward the coast to points of discharge, but the movement does not always follow the dip direction (29).

In 1951, Vernon (33) presented a map of the fracture pattern for the northern portion of peninsular Florida (Figure 8). In general, two dominant fracture trends are apparent: a north/northwest pattern and a northeast trending pattern. The patterns are probably controlled by structural features such as the Ocala uplift and the Peninsular arch.

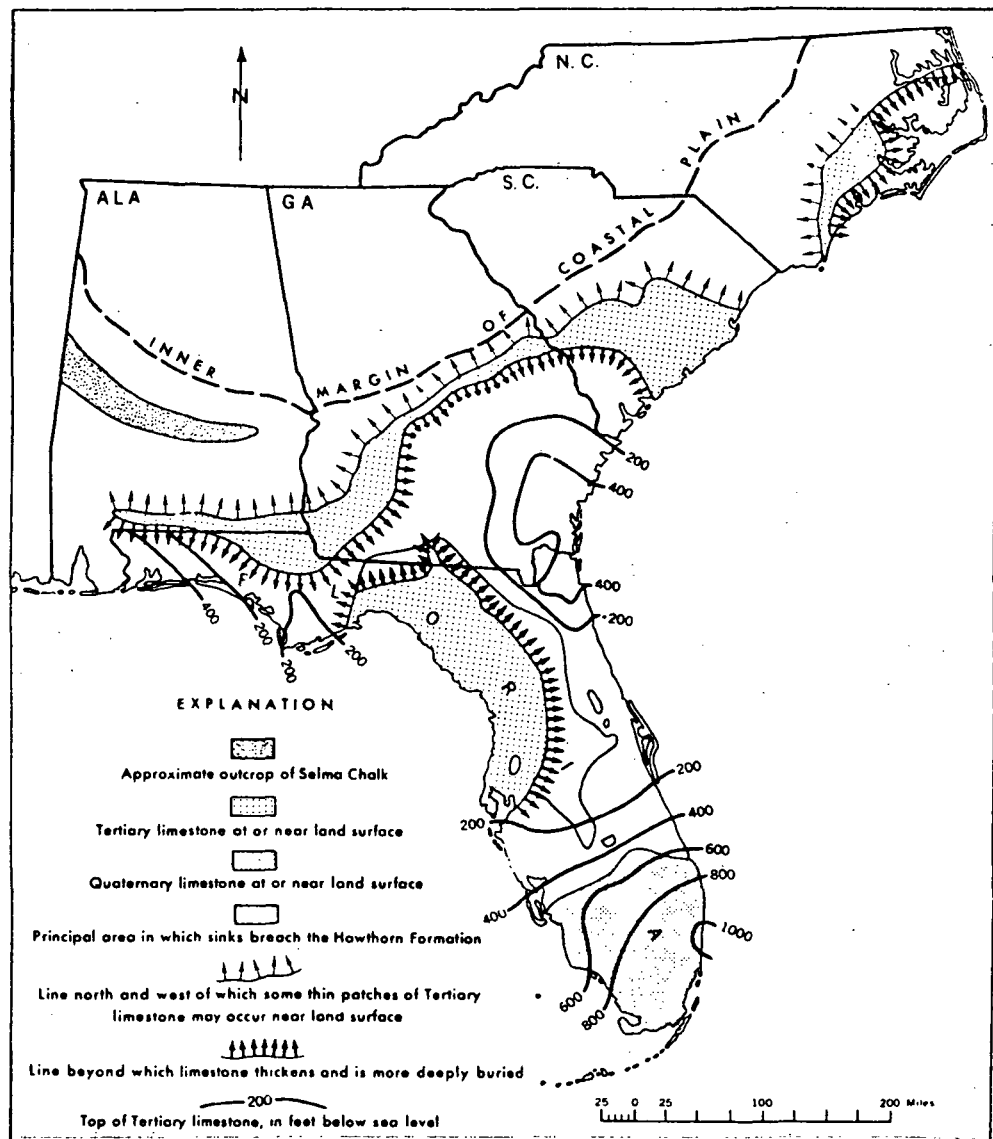


Figure 5 - Outcrop and contours of limestone in the southeastern United States.
(from Stringfield and LeGrand)

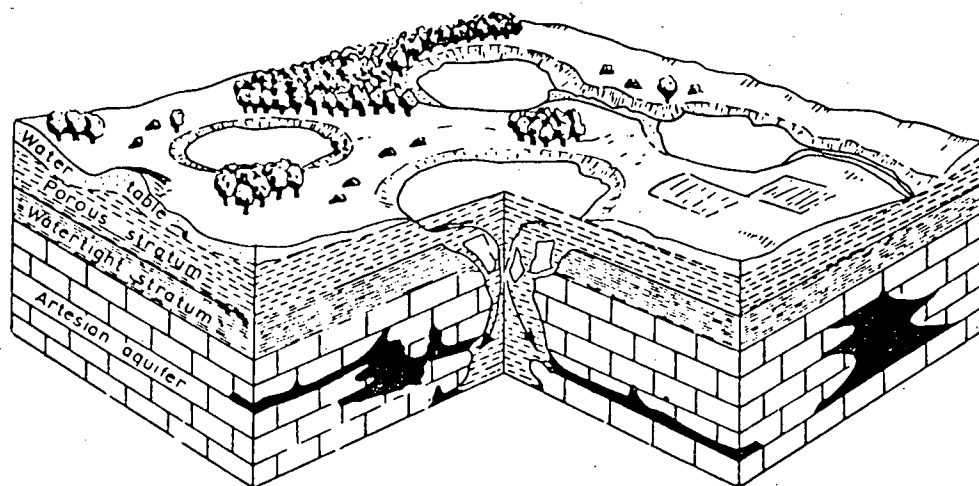


Figure 6 - Recharge of aquifers through sinkholes.
(from Herak and Stringfield)

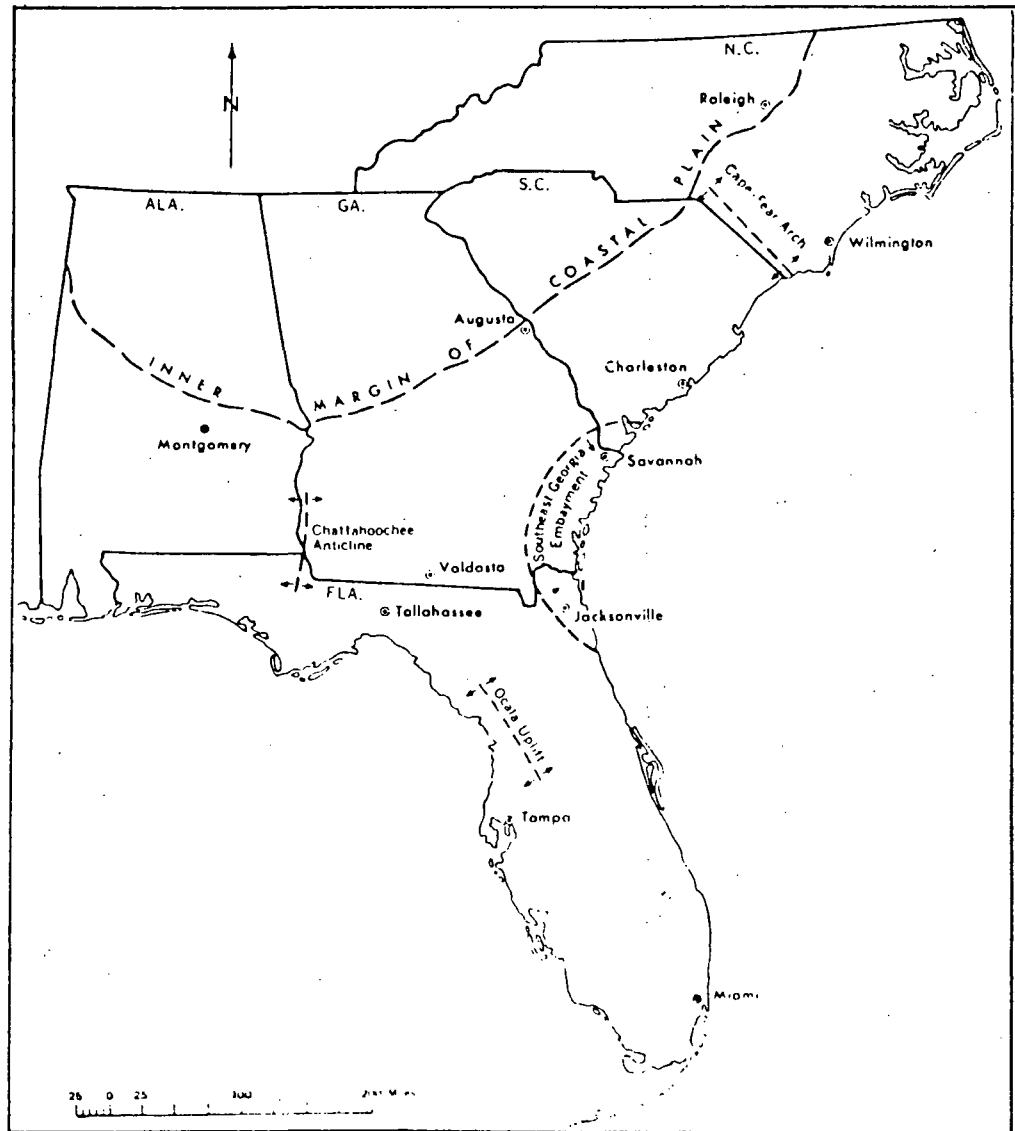


Figure 7 - Major structural features of Tertiary limestones. (from Stringfield and LeGrand).



Figure 8 - Fracture patterns of northern peninsular Florida. (from Vernon)

The Peninsular arch is an uplifted feature in Paleozoic sediments, roughly paralleling the Ocala uplift and forming the axis for the upper two thirds of the Florida peninsula (28). The regional trends mapped by Vernon (Figure 8) also show up in more detailed analyses of smaller portions of the state.

A brief history of the use of aerial photography to map linear features appears in Appendix D. Discussions on fracture trace mapping and lineament mapping also appear in this Appendix.

PIERSON STUDY AREA

Introduction

During the winter months of the past several years the community of Pierson (Figure 9) has been the site of several newly developed sink-holes. Their occurrence appears to be greatest in an area dominated by several irregularly shaped lakes. These collapses were believed to be associated with severe periodic drawdown of water levels by heavy pumping from many high capacity wells.

Volusia County is an area of subtropical climate, with an average annual temperature near 70°F and an average annual rainfall of about 50 inches. Winters are generally mild except for brief periods of freezing temperatures (32).

The mild climatic conditions and soil conditions near Pierson have made the community an ideal center for growing ornamental ferns, cultivated originally in the humid conditions beneath oak trees (Figure 10). As the fern industry expanded beyond the naturally available shade, artificial cover such as cedar slats or cut brush (Figure 11) was required. In the past decade, synthetic woven materials for shade (Figure 12) have been introduced, allowing further expansion of the fern industry in the area*. Most of the county's ferneries are near Pierson, and the fern industry accounts for half of the agricultural income for Volusia County. Fern sales in 1976 amounted to almost 20 million dollars (32).

*Fern industry information from conversations with Larry Loadholtz, Volusia County Agricultural Extension Service.

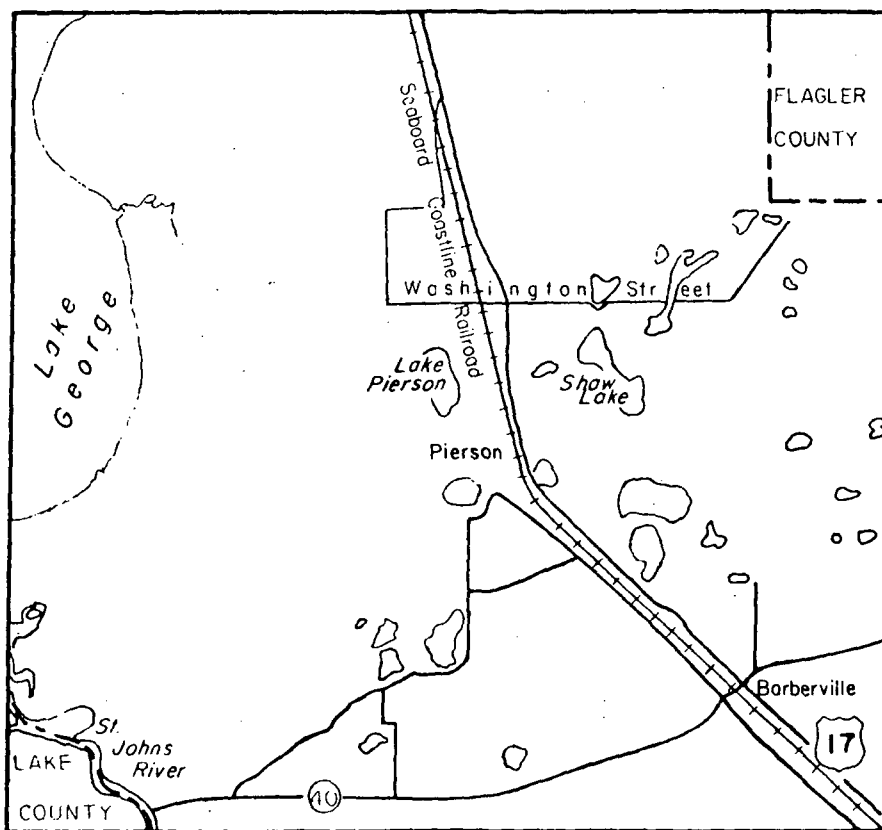
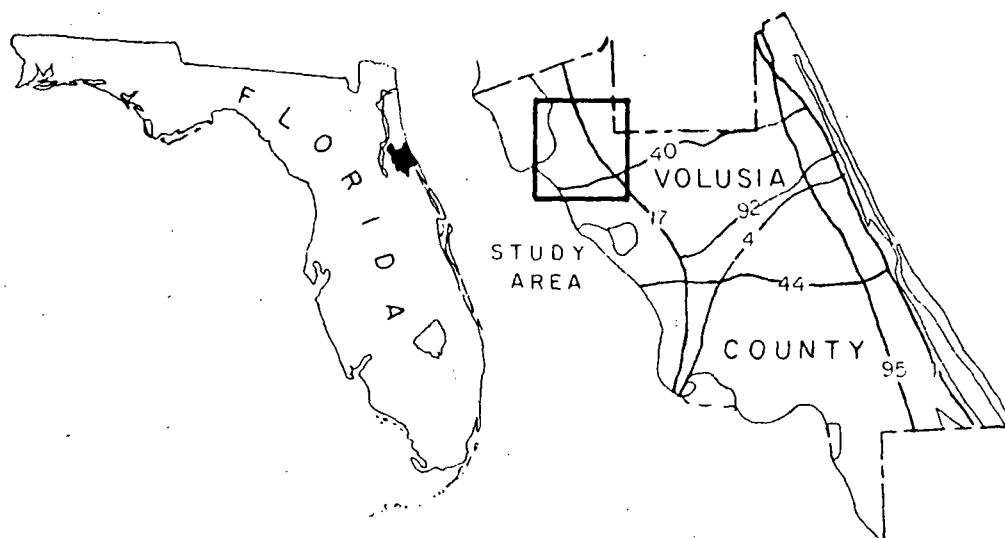


Figure 9 - Location Map (from Casper, et al.)



Figure 10 - Ferns growing in the shade of oak trees.



Figure 11 - Ferns growing under cut bush cover.

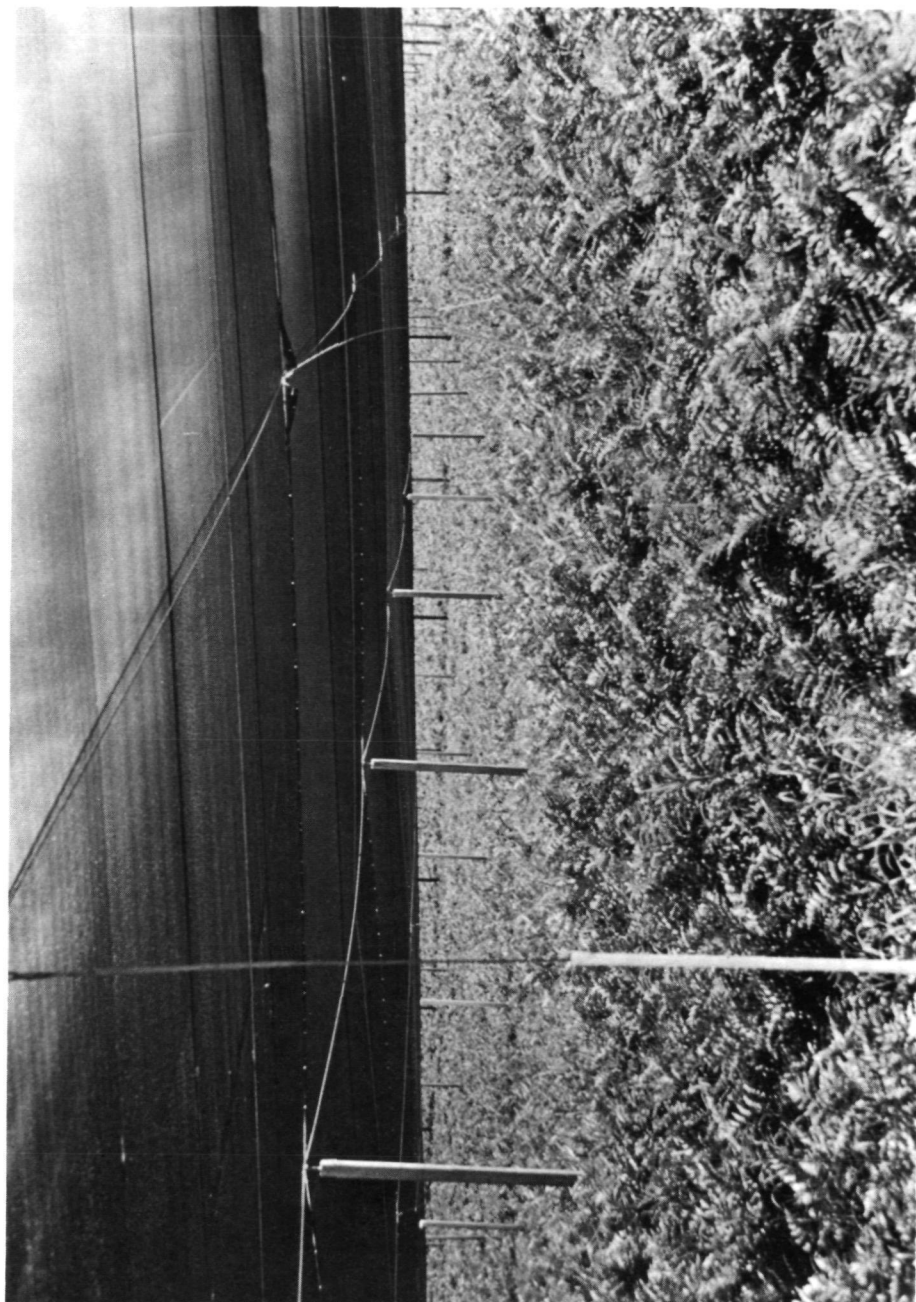


Figure 12 - Ferns growing under woven synthetic cover.

The fern crops, primarily the leatherleaf variety, are very sensitive to changes in climatic and soil conditions, being especially susceptible to damage by freezing. To protect the crops from freezing, water is usually pumped from deep wells, drawing water from the Floridan aquifer. By spraying the water as a mist or fog over the crops, high humidity conditions are maintained which prevent the temperature of the air in the ferneries from dropping below freezing. Tremendous quantities of water are pumped during freeze protection, with shallow, private wells sometimes running dry.

Most of the sinkholes in the Pierson area have occurred after a few days of continuous pumping. Well drawdown of 50 feet or more have been reported*, and changes in water level of almost 20 feet during one day have been reported in U.S. Geological Survey well records. This water level drawdown may be a major contribution to sinkhole formation, especially at locations where solution widened joints intersect in the subsurface limestone. The large quantities of water sprayed over the fern crops may also play an important role in sinkhole development, increasing seepage and the potential for loss of soil into limestone cavities.

Physiography

The Pierson study area is located in northwestern Volusia County and lies on a physiographic feature known as the Crescent City Ridge, a topographically high area which is part of a well developed series of Pleistocene marine terraces. Four terraces have been recognized (Figure 13), and the characteristic sinkholes of karst topography are exhibited by the highest, the Penholoway Terrace. This terrace, rising approximately

*Deland Sun News, January 21, 1977.

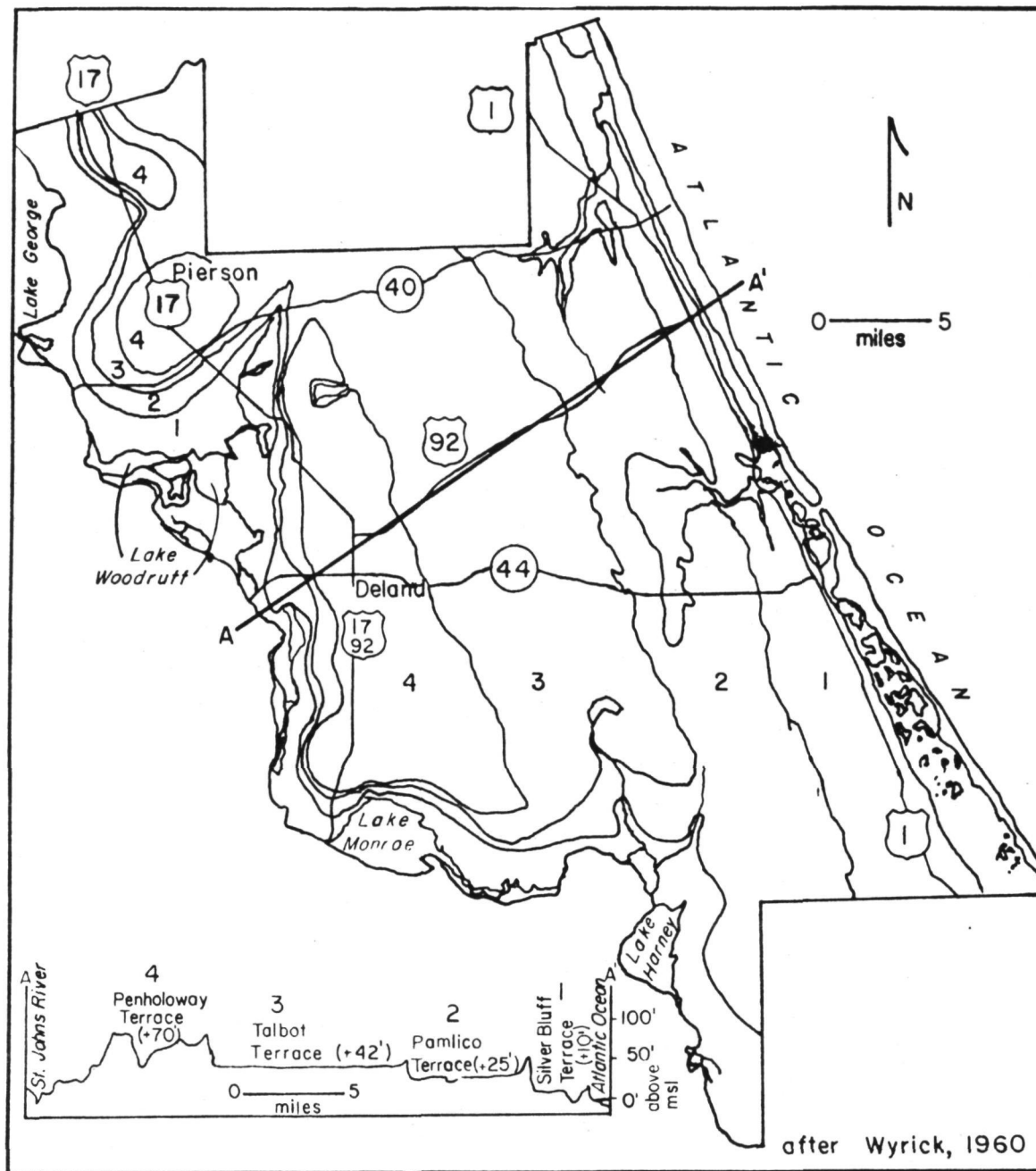


Figure 13 - Pleistocene marine terraces in Volusia County, Florida. (from Wyrick)

70 feet above mean sea level, is believed to have formed during the Sangamon interglacial stage, when sea level was 70 to 80 feet above the present level (37). Due to erosion and the occurrence of sinkholes, only a few small areas remain at or above 70 feet. These areas are along the highest terraces illustrated in Figure 13.

The Crescent City Ridge and the adjacent Deland Ridge roughly parallel the coast. Lakes in this area also show some parallelism, indicating some structural control by former shorelines (36).

Stratigraphy

In the Pierson area, the soluble limestone lies approximately 100 feet below the land surface. At the surface is the nonartesian sand aquifer (Figure 14), which has a minimum thickness range of 20 to 60 feet at Pierson. This is underlain by a clay layer 10 to 40 feet thick and a shell layer 0 to 20 plus feet thick. Next are the limestones that make up the principal artesian aquifer*.

The Floridan aquifer, which provides the fresh water supplies of Volusia County and most of Florida and southeastern Georgia, consists of limestones of Eocene age. Uppermost is the Ocala Group, which has been separated into three distinct formations by the Florida Geological Survey (37). The most recent deposit is the Crystal River Formation, a white to cream colored, chalky, massive limestone. Underlying this is the Williston Formation, a tan to buff granular limestone, followed by an Inglis Formation, consisting of tan to buff granular limestones and dolomites (28).

The Crystal River and Williston formations are not distinct in the Pierson area (Figure 14), and of three Pierson wells referred to by

*Conversation with Al Rutledge, U.S.G.S., Orlando, Fla.

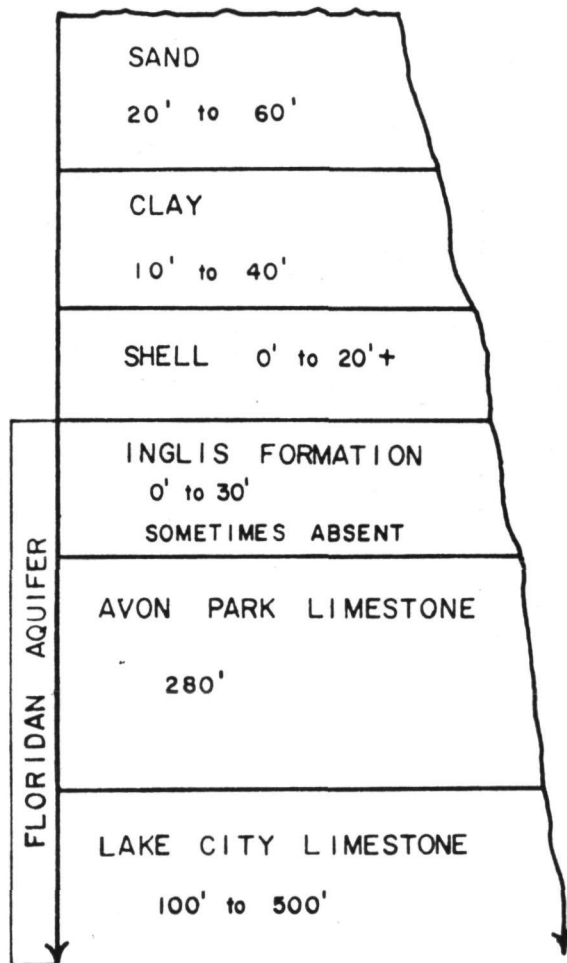


Figure 14 - Stratigraphy of the Pierson, Florida vicinity (from Casper, et al.)

Wyrick (37), the Inglis Formation is recognized in only two. In these two wells, the Inglis Formation is 18 and 30 feet thick at depths of about 110 feet. In the third well, the Avon Park Limestone is the first limestone recognized and occurs at a depth of 90 feet.

The Avon Park Limestone, immediately below the Ocala Group (Figure 14), is a white to reddish brown, dense, hard limestone and dolomite with some porous and chalky zones. In Volusia County, the Avon Park Limestone is approximately 280 feet thick.

Below the Avon Park Limestone is the Lake City Limestone (Figure 14), a buff to brown, porous limestone and white to brown, massive limestone, along with gray to tan dolomites (23).

Dolomitization of the limestone makes it more dense, decreasing permeability. The dolomitization is selective, however, and highly permeable zones remain. This is the major water source from the Floridan aquifer for western Volusia County, where the Ocala Group is thin or absent (28).

Aquifer and Recharge

The top of the Eocene limestones in Volusia County is at its highest elevations in the areas of the karstic Crescent City and Deland ridges (Figure 15). At Pierson (on the Crescent City Ridge), the surface of the limestone is domed, with a maximum elevation about 30 feet below mean sea level. The locations of these highest elevated limestone surfaces correspond roughly to the highest marine terraces. Practically all of the fresh water recharge within the county occurs on these karst ridges, through sinkholes penetrating the confining beds and leakage through these beds.

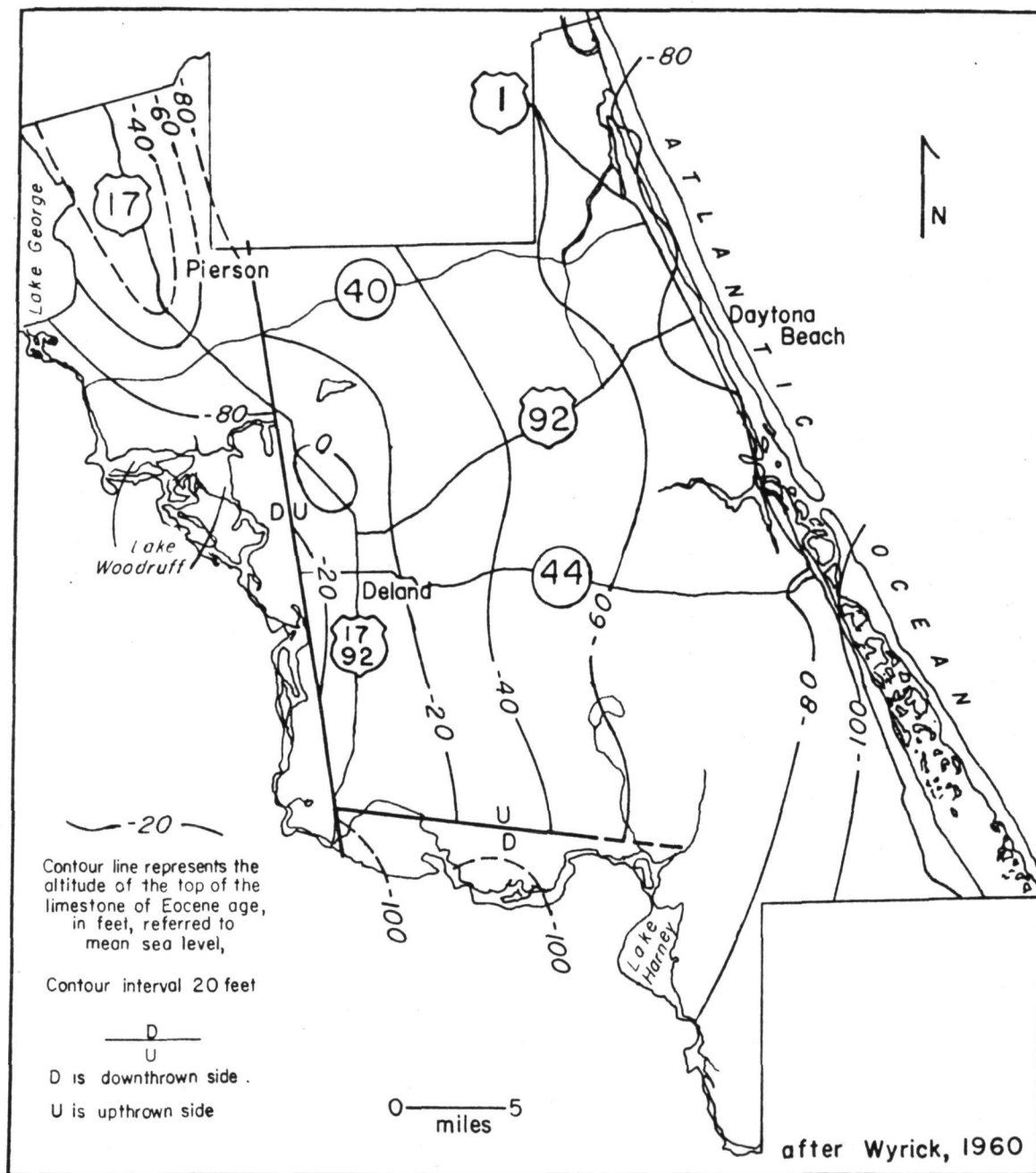


Figure 15 - Top of Eocene limestone. (from Wyrick)

Figure 16 shows the difference between the ground surface and the piezometric surface for the Floridan aquifer. It can be seen that the greatest difference in these levels occurs in the areas of the karst ridges, near Pierson and on the Deland Ridge. These areas also correspond to the recharge zones for Volusia County. In addition to providing rapid recharge, the formation of sinkholes is accelerated by flow of water which carries loosened soil into openings in the limestone.

Examples of Recent Collapses

The most publicized sinkhole in Pierson (Figure 17) in recent years occurred on December 13, 1973, after a period with temperatures of 28°F to 32°F. The low temperatures necessitated pumping for freeze protection of the fern crops. The sinkhole grew to more than 60 feet in diameter and was believed to be more than 110 feet deep.

Just four days later, on December 17, 1973, another sinkhole appeared across the road from the first (Figure 18). The two sinkholes were nearly on a direct line connecting two lakes, Shaw and Tuey Lake. Another sinkhole was reported near Shaw Lake on December 25, 1975.

On January 19, 1977, another sinkhole developed nearby, which enlarged to a diameter of 25 feet. Several other sinkholes and depressions in roads were reported during this time. Once again the cold temperatures required heavy pumping from most of the 500 wells in the area to protect fern crops from freezing. One report stated that enough water was being pumped every hour during this period to supply the city of Daytona Beach for two days. During pumping, the water level in some wells was reported to have been drawn down 60 feet below normal levels, with several shallow wells running dry.

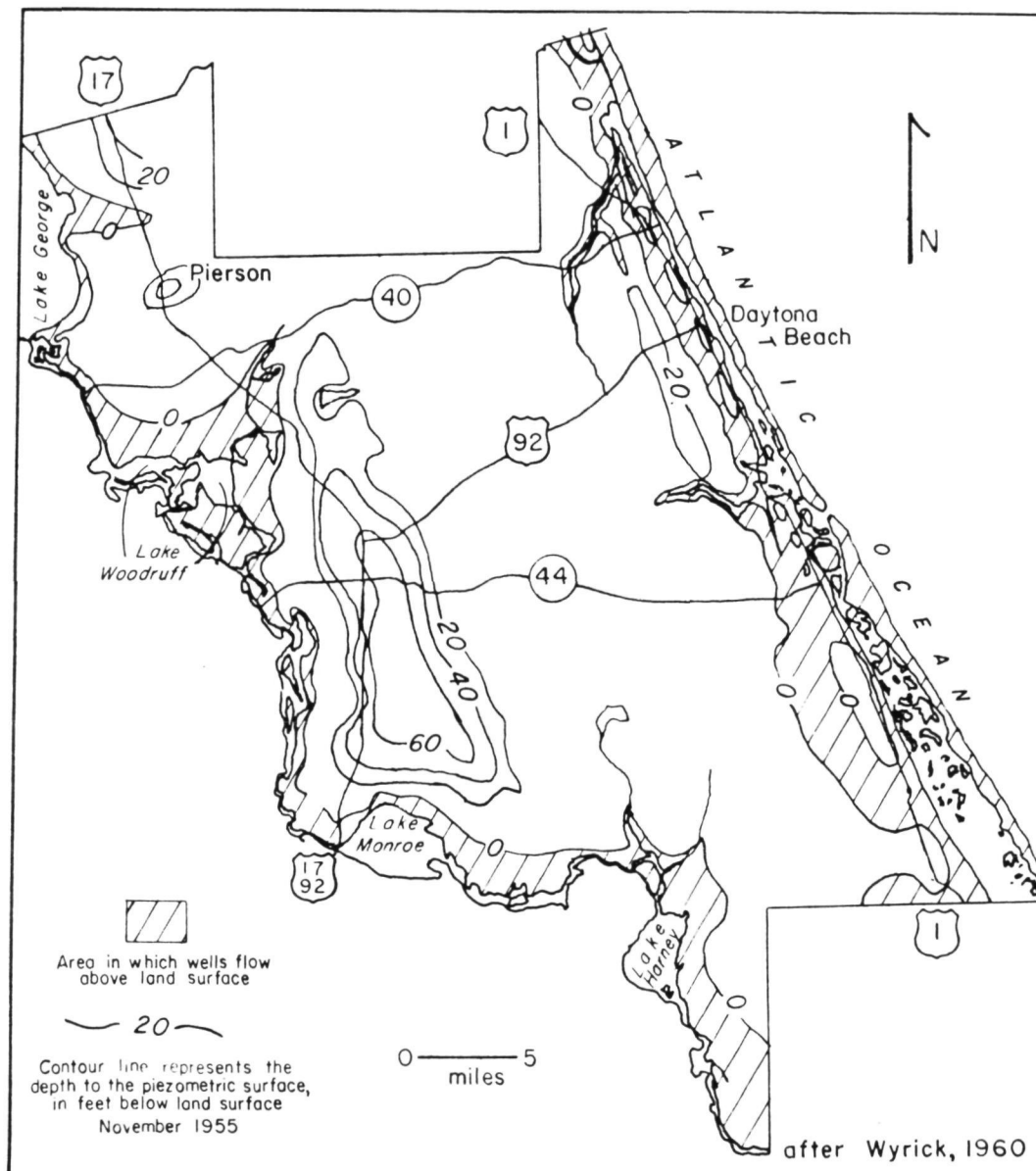


Figure 16 - Contour map of difference between the piezometric surface of the Floridan aquifer and the ground surface.
(from Wyrick)

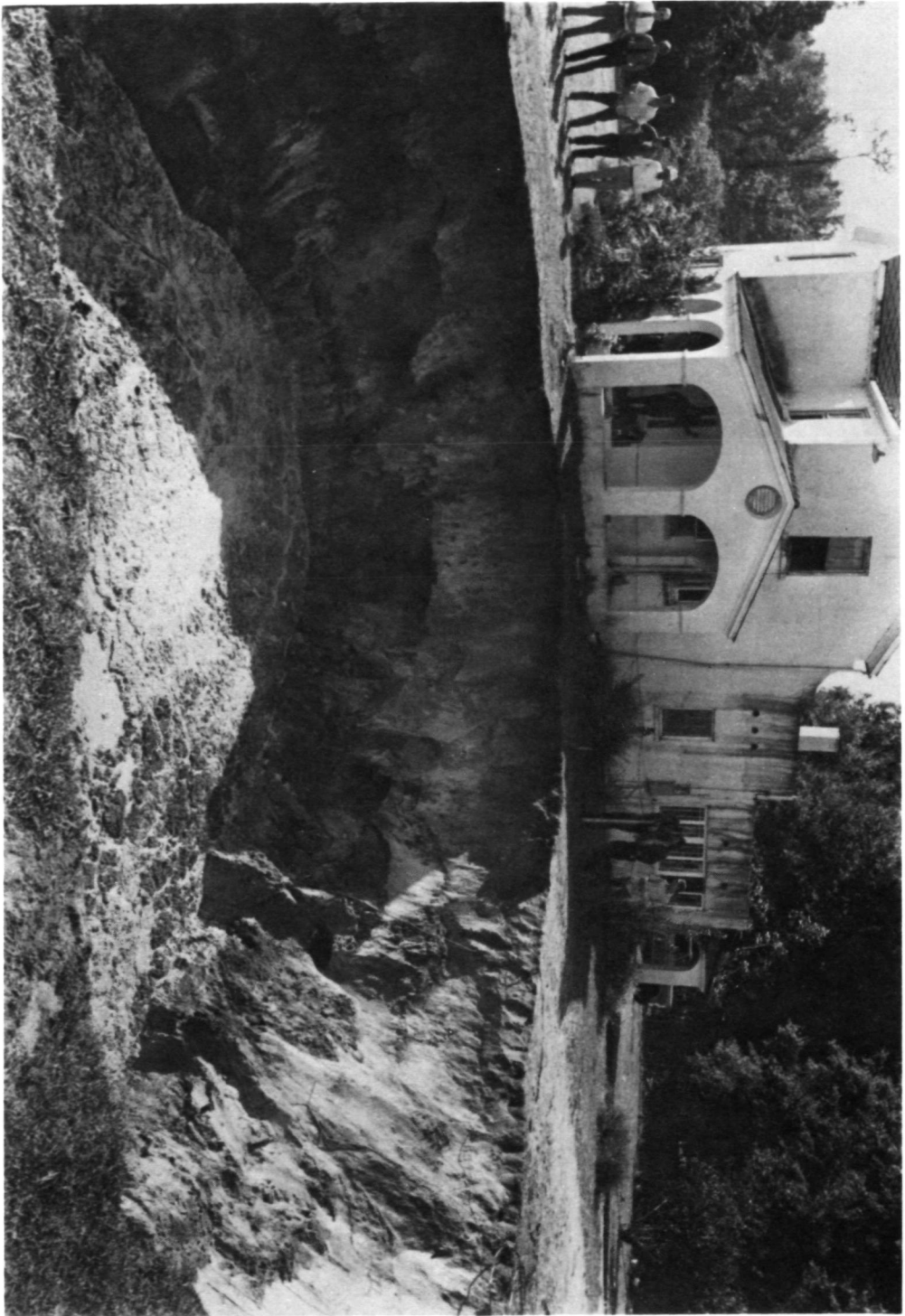


Figure 17 - Sinkhole at Pierson, Florida on December 13, 1973.
(Deland Sun News)

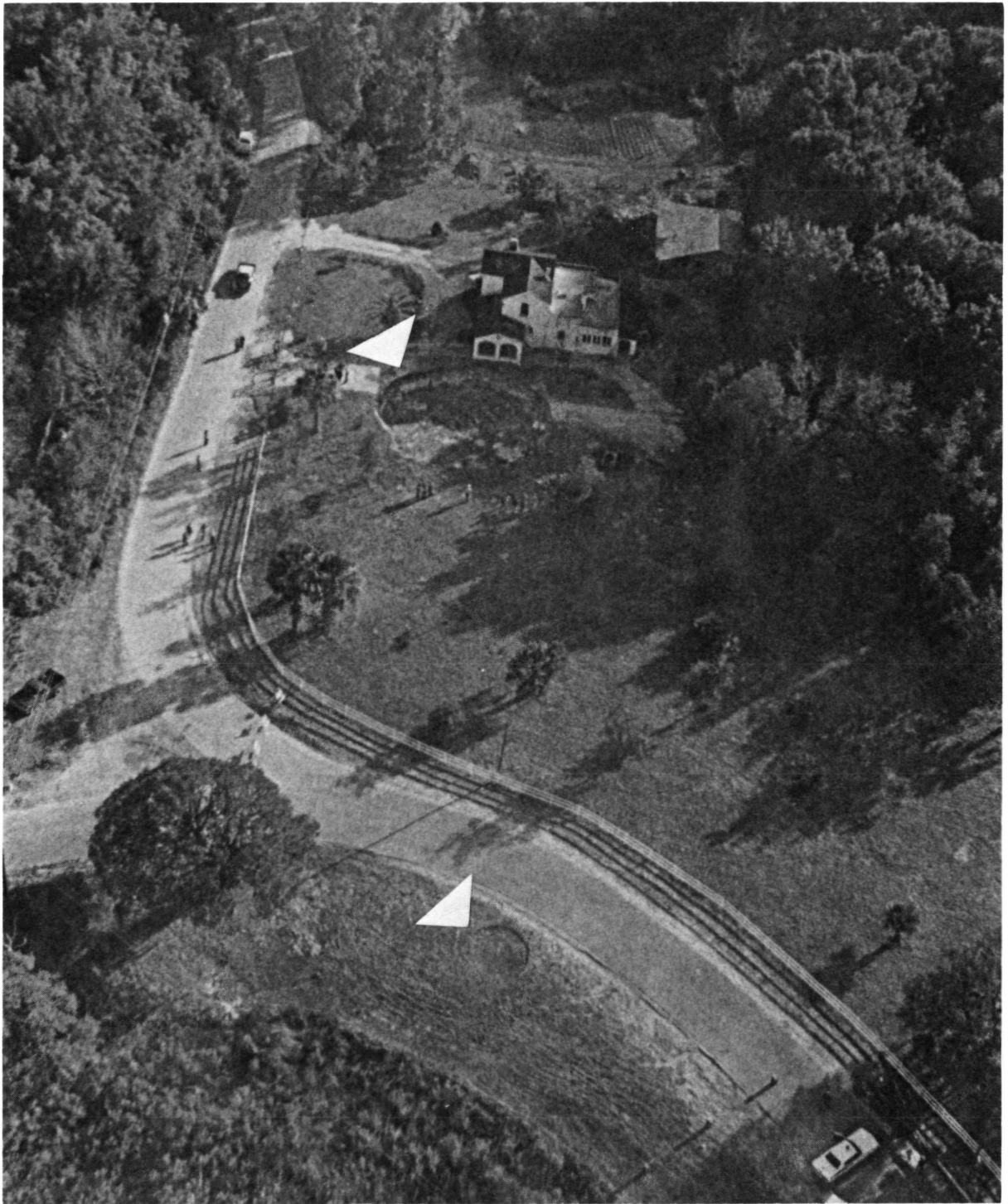


Figure 18 - Two sinkholes (at arrows) at Pierson, Florida
in December, 1973 (Deland Sun News)

On January 9, 1979, another sinkhole occurred on Washington Street, just past a neck of land separating two lakes (Figure 19). This also occurred during a period of freezing temperatures.*

Methods of Imagery Analysis

The types of imagery used in this study include Agricultural Stabilization and Conservation Service (ASCS) black and white aerial photography, NASA high altitude color infrared (CIR) photography, and NASA enhanced and unenhanced satellite imagery (LANDSAT).

While the LANDSAT imagery (scale 1:250,000 and 1:500,000) is useful for identifying large scale linear features and tonal variations, the CIR photography (scale 1:132,000) is useful for more detailed examination and allows the evaluation of smaller features and shorter lineaments. The tonal contrasts on the CIR photography also make it possible to locate and identify features which may not be detected on imagery such as the ASCS black and white photography (scale 1:20,000 and 1:40,000).

The color infrared photography and LANDSAT imagery were used primarily to locate regional features. ASCS photos were used to locate individual features, such as sinkholes and depressions. All features were analyzed to determine linear trends. The Bausch and Lomb Zoom Transfer Scope, Zoom Stereoscope, mirrored stereoscope, and Richards light table were employed in the analysis of imagery and transfer of data to base maps.

The results of the imagery analysis for this area are illustrated in Figure 20. The lineaments identified on LANDSAT imagery were recognizable by discontinuous lines of lakes or by tonal (color) patterns (Figure 21) different from surrounding areas. The skewed lineaments

* Data on sinkhole occurrence courtesy of the Deland Sun News.



Figure 19 - Sinkhole at Pierson, Florida on January 9, 1979.
(Deland Sun News)

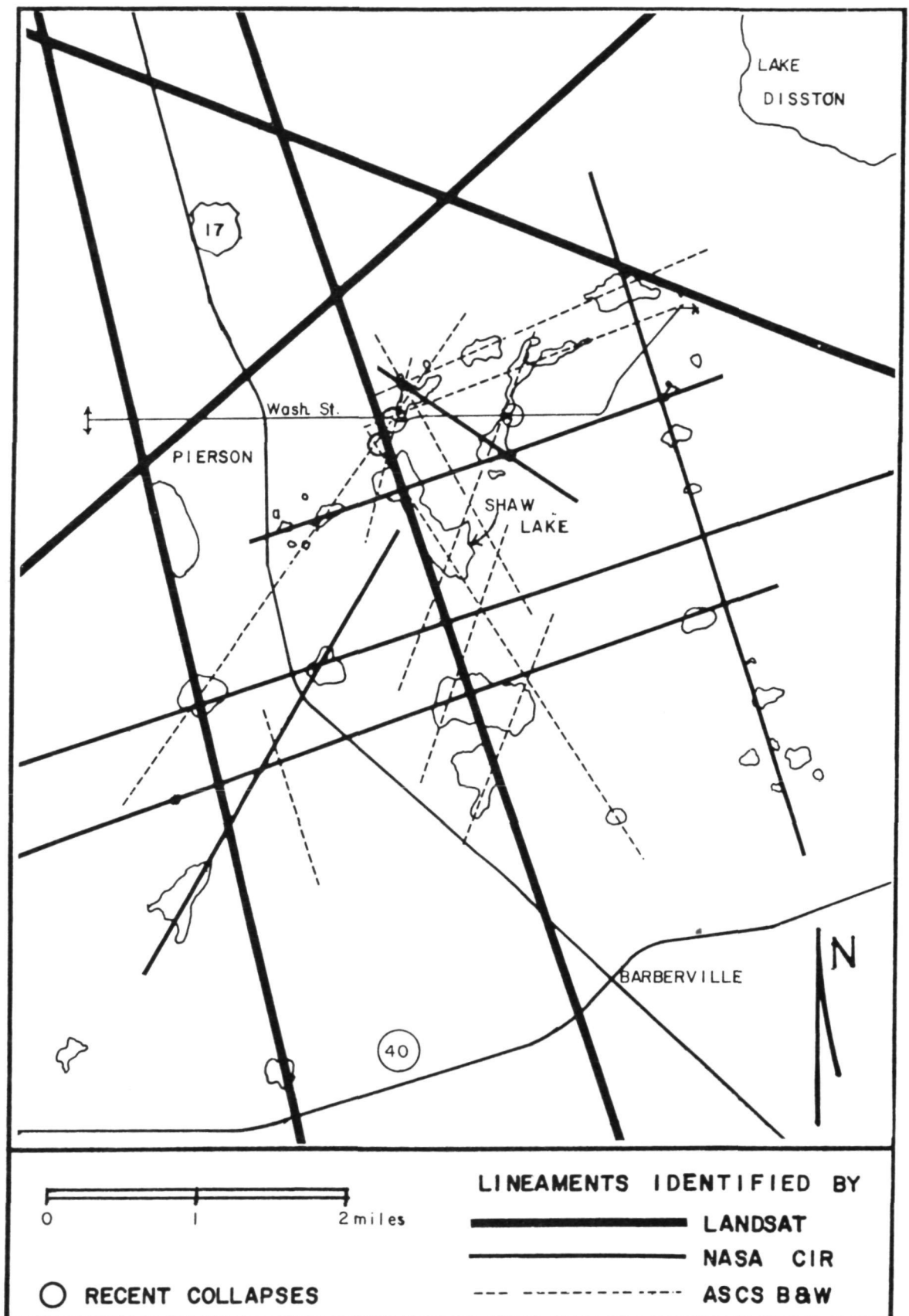


Figure 20 - Lineament map for the Pierson, Florida area.
(from Casper, et al. 1980)

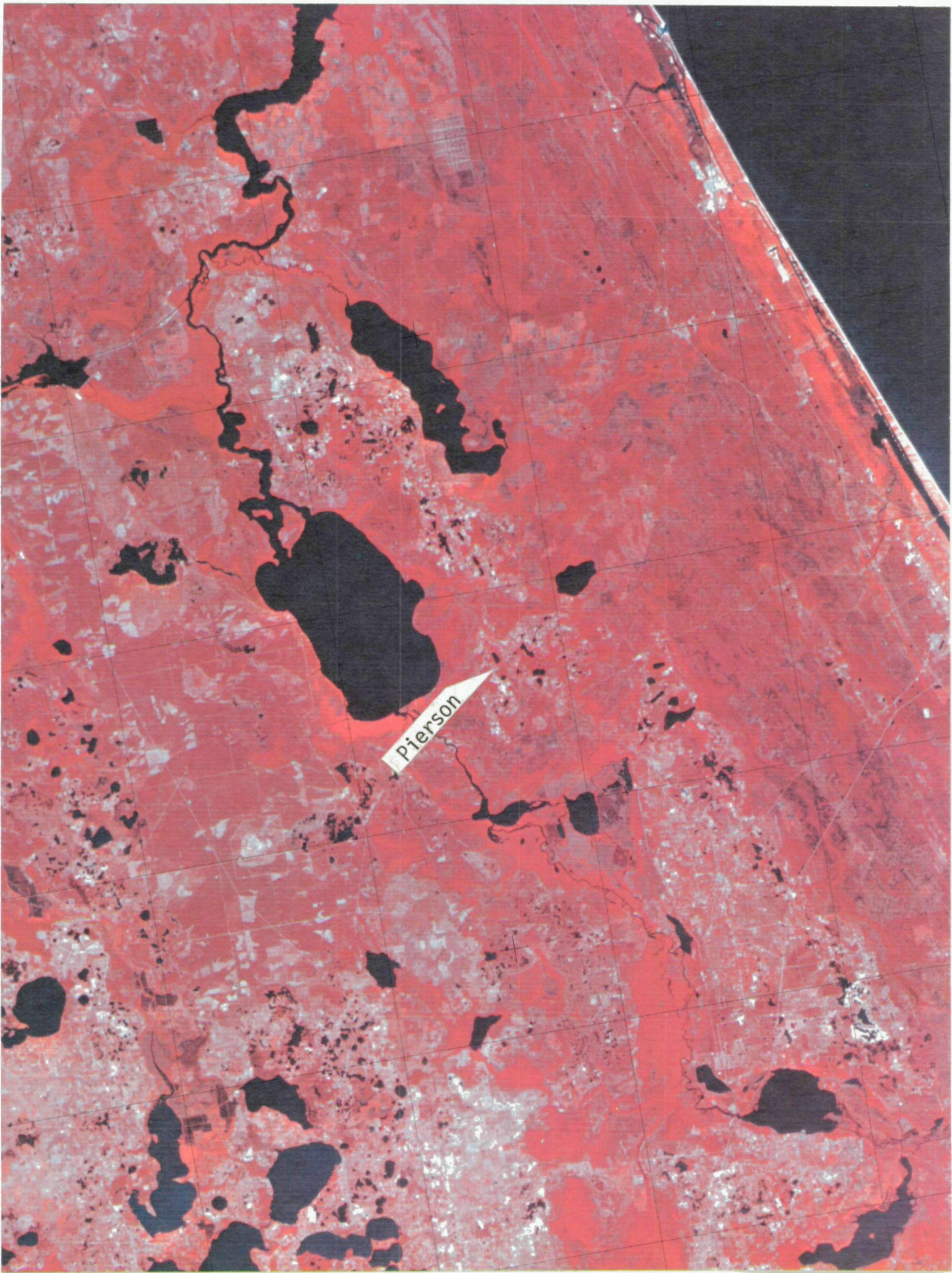


Figure 21 - 1973 LANDSAT scene of central Florida and the Pierson study area.

identified using LANDSAT imagery represent a topographic low. These were mapped on the basis of the photo tones resulting from dense vegetation. The reader is once again referred to Appendix B, which discusses the analysis of karst terrain using aerial photography, and Appendix D, which discusses the use of aerial photography in mapping linear features such as fracture traces and lineaments.

Lineaments were identified from the CIR imagery using tonal patterns and alignments of irregular lakes in the area. Some of the lineaments from CIR imagery were verified by locating individual sinkholes and lakes from the ASCS black and white photographs.

Figure 22 is presented as an example of the method used for mapping the lineaments in this area. The photograph is a portion of an ASCS black and white aerial photograph. The short solid line represents a lineament running northwest/southeast and was first noticed on the CIR imagery by aligning the irregular shapes of the lakes. Also, sinkholes creating projections of the lakes near the two ends of this lineament, were observed on the ASCS photographs. This lineament was mapped through these two small projections from the lakes.

The lineament expressed as the longer solid line (Figure 22) was mapped using alignments of soil tonal patterns and the lakes through which the lineament runs. This lineament runs through an arrowhead shaped lake in the lower left, through another lake, and then through a topographically low area which appears as a darker tonal pattern. This pattern is very noticeable on the CIR imagery, but can also be seen on the black and white photography.

The dashed line represents a lineament trending east/northeast (Figure 22) and was first noticed on the CIR imagery by alignment of



Figure 22 - ASCS aerial photograph of the Pierson, Florida area and example of lineament mapping.

lakes. Final location for this lineament was determined with the aid of the black and white photographs. The black and white photographs showed some sinkholes east of Shaw Lake (Figure 20), and the lineament was mapped through these sinkholes and the lakes.

The dashed lineament trending north/northeast was mapped primarily from the black and white photography. This lineament runs through some circular areas in the trees south of Shaw Lake, through a point on the lower portion of Shaw Lake, and through an irregularly shaped lake northeast of Shaw Lake. Several sinkholes can be observed near this lake on the ASCS black and white photographs.

All of the lineaments for this study area were plotted in a similar manner and transferred to a base map, which was a Florida Department of Transportation county map. U. S. Geological Survey topographic maps were also used to locate topographic low points to help locate the lineaments more precisely. Imagery used for the study area included:

LANDSAT enhanced imagery-Orlando sheet
4-18-75, # 81999150915N

LANDSAT unenhanced imagery-Lake George sheet
1973

NASA high altitude color infrared imagery
4-30-74, # 5740017438645-8648 & 8649
4-30-74, # 5740017438653-8655 & 8656

ASCS black and white photographs
1-13-73, Code 12127
13-19, 27-33, 50-55

Evaluation

A major north/northwest trend is visible on LANDSAT imagery and passes through large lakes in and near the Pierson study area (Figure 20). The larger lakes are elongated along this axis. Paralleling this trend are lakes on the Deland Ridge and major lakes along the St. Johns

River. These lineaments roughly parallel the east coast of Florida and were also observed by White (36).

A northeast trend is also visible, originating south of Lake George and extending northeast through a topographic low at the north end of Pierson, and above Lake Disston to the northeast. This lineament is partially recognized by tonal variation visible on the LANDSAT imagery and high altitude CIR photography. Another lineament is observed just north of Pierson trending northwest towards Lake George. Some of these trends may actually indicate major zones of fracture and solution. However, the intersecting lineaments just north of Pierson probably represent erosional features of the marine terraces.

From the CIR photography, northeast trending lineaments, based on tonal patterns and alignment of lakes, can be seen in addition to the lineaments observed on the LANDSAT imagery (Figure 20). Also, an uneven line of lakes roughly parallels the major north/northwest trends observed on the LANDSAT imagery. With the larger scale of the CIR photos, lineaments were detected through some of the irregularly shaped lakes near Pierson.

Much more detail can be observed on the ASCS photography (see Figure 22 for an example). Smaller features are easily seen and general lineaments can be located with greater accuracy. Lineaments have been determined using individual sinkholes and the orientation of irregular features (Figure 20). The area east of Pierson around Shaw Lake shows a high density of lineaments, primarily running northwest, north/northeast, and northeast. It should be noted that major trends in this area are close to the statewide trends mapped by Vernon (Figure 8).

Several of the recent sinkholes have occurred in close proximity to some of these lineaments. It is likely that additional collapses will

also occur in zones with high densities of fracture traces or lineaments, especially at their intersections.

The apparent higher density of lineaments on the topographically high areas near Pierson is one factor contributing to recent sinkhole formation. The doming of the surface of the Eocene limestone (Figure 15) may be in part responsible for this higher density. Lowering of the water table during pumping for freeze protection of fern crops is certainly a factor in sinkhole formation, along with increased seepage due to the great quantities of water sprayed over the crops.

The highest elevations in the area (at or above 70 to 75 feet) occur in a small (less than one half square mile) area near the intersection of Washington Street and U. S. Highway 17. Interestingly, this area shows little evidence of sinkhole development, while the area with the most severe problem is just to the east. It is possible that a dolomitized or less fractured zone is present in the limestone below this area. In a well near this area, the Avon Park Limestone was uppermost, and this limestone is usually dolomitized in Volusia County (37), although it has some extremely permeable zones.

The zones surrounding the irregular lakes in Pierson are apparently highly fractured, and cavities are probably abundant in the subsurface limestone. The potential for collapse is great in such a highly fractured zone, particularly just north of Shaw Lake (Figure 20). Although some residents have been concerned that pumping for freeze protection has been causing the sinkholes, the potential for collapse has existed for some time and will continue to exist. Pumping and irrigation for the fern crops may only cause sinkholes to develop more quickly than they would under natural conditions.

HILLSBOROUGH COUNTY STUDY AREA

General Description

Many sinkholes were reported near Dover, Florida, west of Plant City in Hillsborough County, in January of 1977. During a period of subfreezing temperatures, water levels were severely lowered during pumping for freeze protection of strawberry and other crops. This study area was selected for investigation because of the potential to relate newly developed sinkholes to lineaments and fracture traces.

Strawberry farmers began pumping from wells, tapping the Floridan aquifer to spray irrigate the strawberry crops when temperatures fell below 4°C (39°F), and continued pumping until the temperature rose above 4°C (39°F). Figure 23 compares temperature variations with water levels in an observation well (#1) located in the proposed Thonotosassa well field (Figure 24). Periods of drawdown correspond to periods with temperatures below 4°C (39°F). The drawdown in the well was almost three meters (10 feet) in about four days, but drawdowns of as much as 18 meters (60 feet) were also reported. Figure 23 also indicates that the natural recovery of the water table was much lower than the drawdown produced by pumping of the wells.

Many sinkholes were reported to have developed during this period of cold weather. Sinkholes occurred in strawberry fields, citrus groves, roads and near a fish farm. One caused major structural damage to a house (7). A total of 22 sinkholes were documented, but others probably occurred that were not detected.

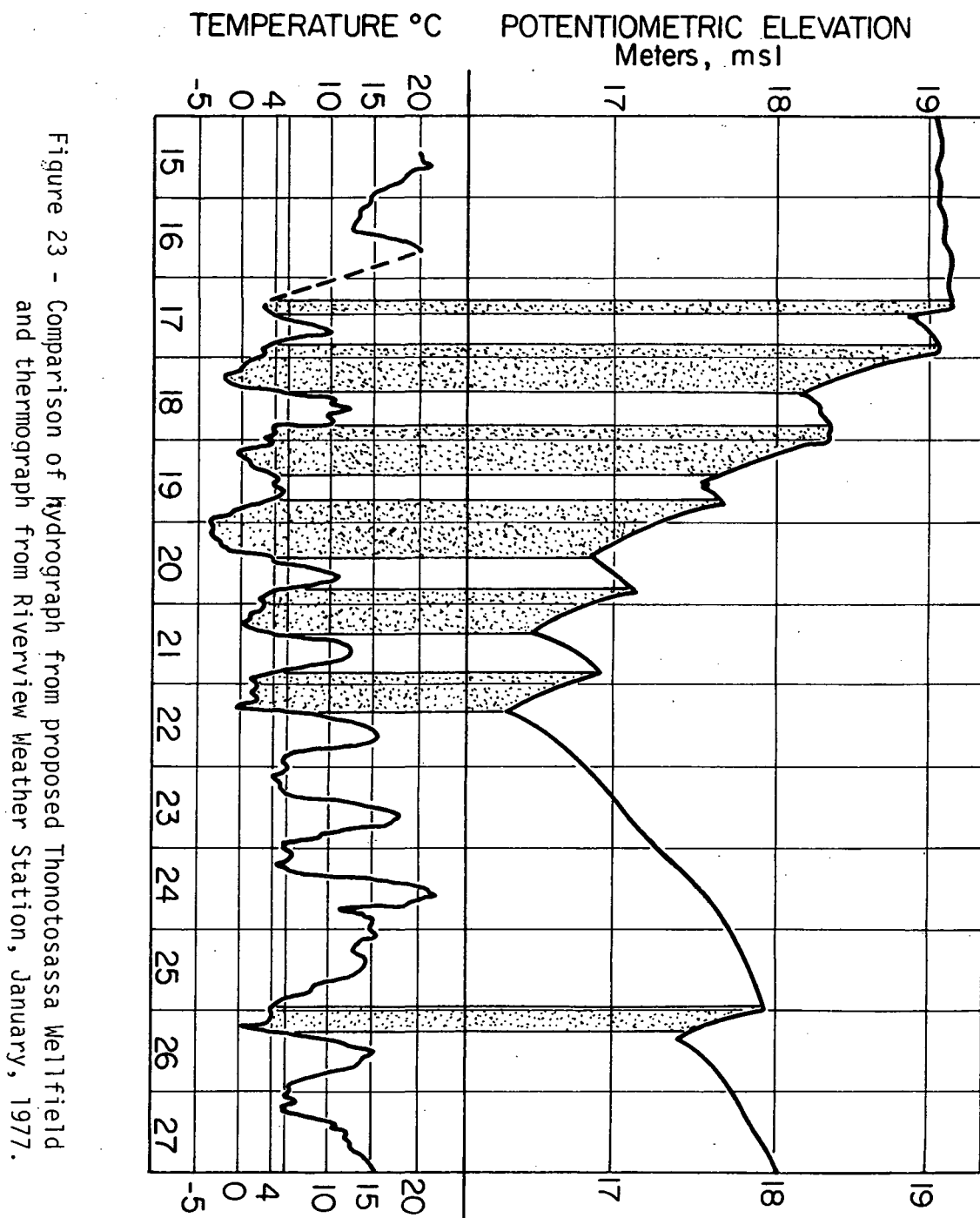


Figure 23 - Comparison of hydrograph from proposed Thonotosassa Wellfield and thermograph from Riverview Weather Station, January, 1977.

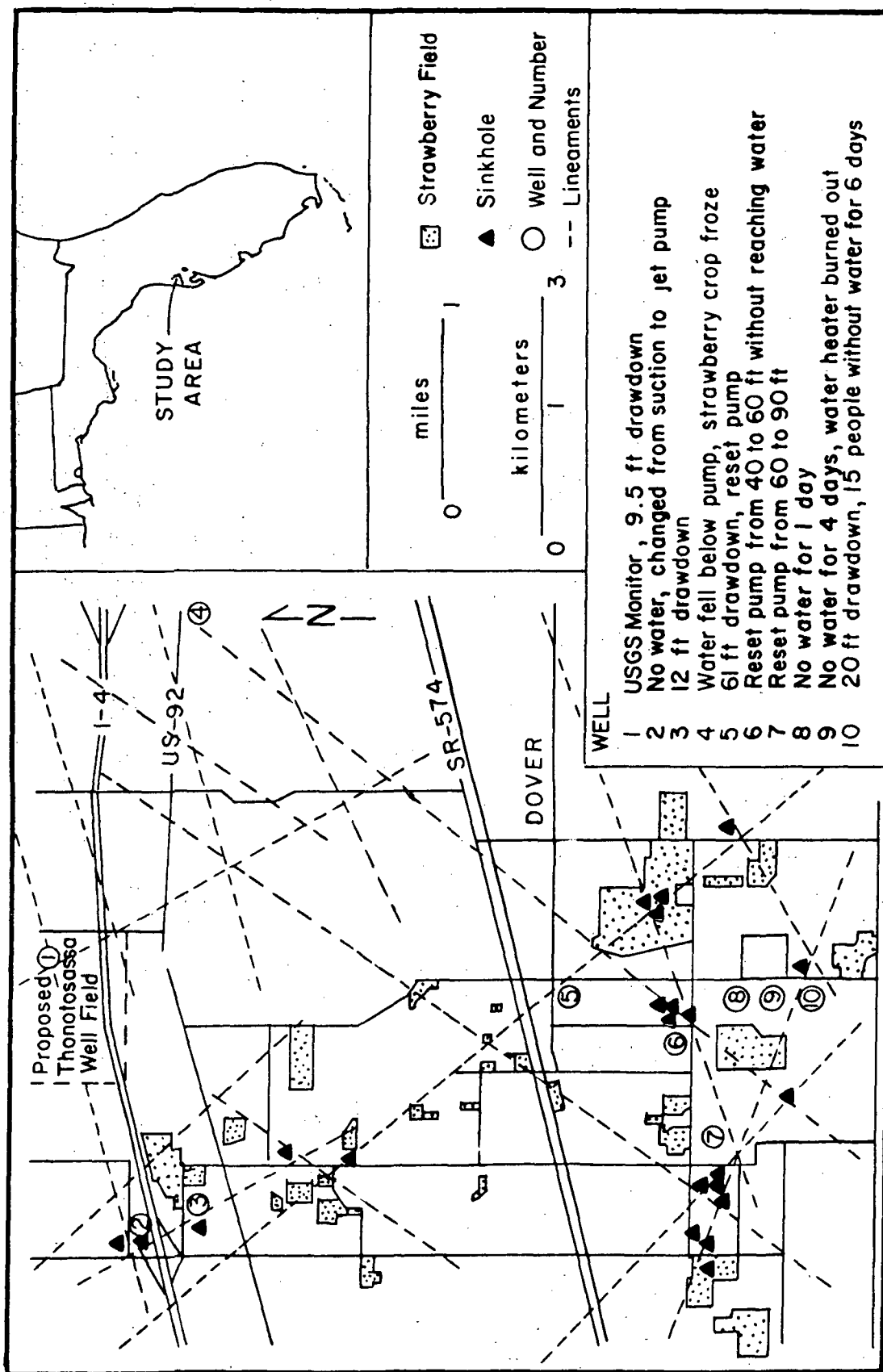


Figure 24 - Lineament and sinkhole map for study area west of Plant City, Florida
(modified from Hall and Metcalf)

The collapse of these cavities may have been initiated by increased stresses in the soils supporting the overburden above the cavities or by increased flow of groundwater, which may have washed additional soil into cavities of the underlying limestone strata. During freeze protection, large quantities of water are sprayed over the crops, and this water then percolates through the soil, causing more subsurface erosion.

Stratigraphy

Hall and Metcalfe (7) have described the stratigraphy of this area as 3 to 6 meters (10 to 20 feet) of sands, 7 to 15 meters (23 to 50 feet) of clay, phosphate, clayey sand and clayey limestones, underlain by over 1000 meters (3300 feet) of limestone. The stratigraphic column for this area is shown in Figure 25. The Tampa and Suwannee limestones yield up to 1000 gallons per minute (gpm) and the Inglis Formation of the Ocala Group, the Avon Park, and Lake City limestones sometimes yield over 5000 gpm.

Evaluation of Study Area

The analysis of this study area was carried out using primarily ASCS black and white aerial photographs, along with limited use of LANDSAT and NASA high altitude color infrared imagery. The ASCS photos used were:

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1-21-68
BQF-4JJ #32-37, 84-89, 153-159

The lineaments shown in Figure 24 were plotted primarily from soil and vegetation tonal alignments, and the alignment of a few old sinkholes that were observed on the imagery.

These lineaments approximately follow the northeast and northwest trends mapped by Vernon in 1951 (Figure 8). Many of the new sinkholes

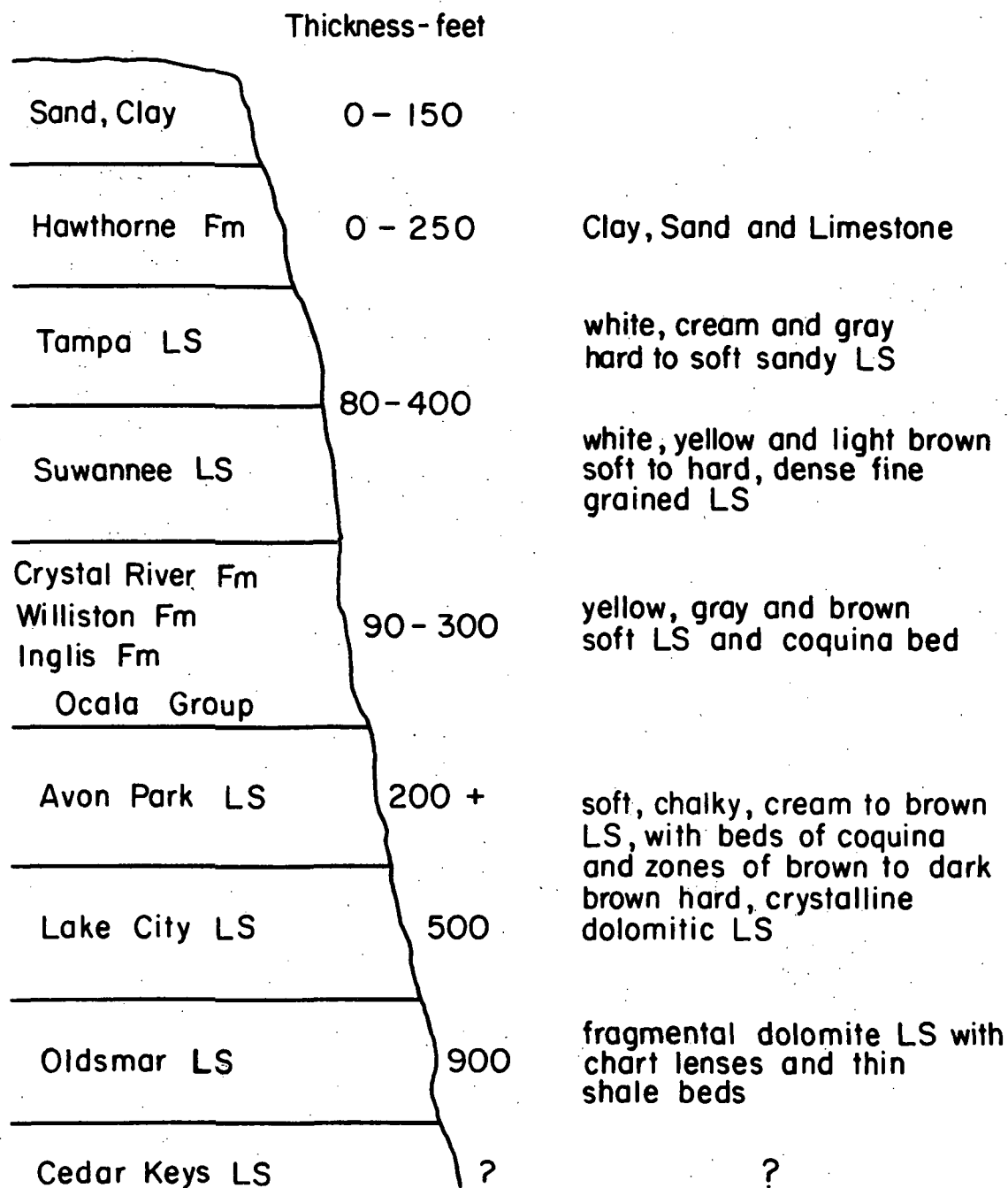


Figure 25 - Stratigraphic column of the study area in Hillsborough County, Florida.
(from Hall & Metcalfe)

(triangles on Figure 24) are located very near the intersections of the mapped lineaments. Many of these intersections also corresponded to high risk moisture conditions in depressions and areas of low topographic elevation. Comparison of the new sinkhole locations and mapped lineaments appears to support the concept that sinkholes are more likely to occur in highly fractured zones, as indicated by intersecting lineaments and fracture traces.

CONCLUDING REMARKS

A very good correlation was found between mapped lineament intersections and known locations of sinkhole occurrence for both study areas evaluated in this investigation. This indicates that lineament and fracture trace mapping may be very useful in locating zones with the greatest potential for sinkhole development. Although it is not possible to predict sinkhole occurrence based solely on such maps, the information could be beneficial in land use planning.

Information from lineament and fracture trace maps would be useful in a developing area in order to avoid those zones with potential problems. These maps could indicate zones requiring more detailed subsurface exploration for adequate evaluation of structural foundation requirements. Also, since sinkhole insurance has been available to homeowners in Florida since 1970 (1), the information could be used as guidelines for setting insurance rates. Appendix E reviews several studies of sinkhole occurrence that has employed remote sensing techniques.

Sinkhole formation in many areas is accelerated by increased flow of water through soil overlying cavernous limestone, causing piping loss of soil into cavities in the limestone. The potential for sinkhole occurrence is increased when this is compounded by a lowering of the water table. Cessation of pumping may slow the rate of sinkhole development, but sinkholes occur only where openings already exist in the subsurface limestone.

Sinkholes may eventually occur in an area due solely to seasonal fluctuations of the water level and increased rainfall, so prevention of excessive pumping will probably not actually prevent the development of new sinkholes. The best method to minimize sinkhole damage is to locate areas with high collapse potential and to plan for land use that is compatible with the specific site conditions. Mapping of lineaments and fracture traces using available remote sensing methods can provide an excellent basis for further detailed analyses of the potential for sinkhole formation.

The Remote Sensing Applications Laboratory recommends that local or state governmental agencies, with the assistance of the U. S. Geological Survey, prepare lineament and fracture trace maps. These maps could be used to delineate areas that are most likely to have a high frequency of cavity collapse. Records should be kept of sinkhole occurrences and potentiometric elevations in observation wells. The analysis of this data may provide the basis for delineating and rating land areas according to their potential for damage to structures.

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APPENDIX A

Uses of Various Film Types and Sensors

Black and white (panchromatic) film, sensitive at ultraviolet and visible wavelengths from 0.3 to 0.7 μm , is the most common film used in aerial photography, because it is relatively inexpensive and readily available. This film type is used for topographic surveys, soil surveys, and most interpretation purposes. Other film types have more specialized applications.

Black and white (or monochrome) infrared sensitive film, sensitive to the reflected or near infrared portion of the spectrum from 0.7 μm to 0.9 μm , is useful in plotting shorelines and water boundaries. Since most of the near infrared is absorbed by water, there is a better distinction between land and water than with panchromatic film (16). This type of film is also useful in distinguishing between plant types and locating areas where the vegetation is under stress since it helps reveal the structure and condition of the plant tissues. Infrared wavelengths are also less subject to scattering by haze, thus giving infrared film a better capacity to penetrate haze than photography in the visible range of the spectrum (16).

True color photography has gained in popularity because it reveals more subtle tonal variation, enabling an interpreter to better identify individual features. However, it does cost more than the panchromatic film and has more narrow requirements for exposure and development (16).

False color film is more versatile, combining the advantages of infrared and color films in identifying wet areas and stressed vegetation. This film offers greater ease in evaluating photo tones (16).

Multispectral cameras and scanners are available with the capability of simultaneously recording images in different visible and infrared wavelength ranges. By analyzing these images separately, combined, or in digital form, it is possible to make more detailed evaluations of an area than could be done with a single photograph.

Thermal infrared radiation (wavelengths of 3.0 μm to 14.0 μm) is emitted from the surface of the earth (or from other objects or bodies) and may be detected by a scanner and recorded electronically (14). This type of information can show temperature differences that provide additional information about surface and subsurface conditions. Thermal scanning is often used at night, since different objects emit different relative amounts of radiation during the day and at night.

Information can be obtained from recording reflected or emitted energy in the microwave region (wavelengths of 1.0 mm to 1.0 m). One method utilizing microwaves is radar (for RAdio Detection And Ranging) which transmits microwave impulses and records the strength and origin of the reflected radiation. Radar is an active system, while a passive system, such as a microwave radiometer, records low energy emissions of microwave wavelengths from the earth's surface. Microwave sensors can be operated during the day or night and under most weather conditions. Radar has been useful in mapping major rock units, surface drainage patterns, geologic structure, and vegetation types, and even in determining sea ice types (14). Microwave radiometry and scanning is useful in oceanography and meteorology, and is potentially useful in hydrologic studies (14).

APPENDIX B

Aerial Photographic Analysis of Karst Terrain

Commonly available aerial photographs are useful for a wide variety of engineering and agricultural purposes. Using aerial photographs, it is possible to inventory crops, forests, animal populations, and to map cultural features and land use. Information useful for engineering purposes such as soil types, drainage features, erosional characteristics, and structural controls may also be obtained by an experienced airphoto interpreter. Some information may be directly recognizable on the aerial photographs, while other features must be inferred from more subtle visible characteristics by an experience interpreter.

The surface expression of a karst terrain is extremely variable from region to region and even within a particular region. Karst terrain is normally characterized as having a poorly developed surface drainage pattern (few or no streams), along with numerous pits or depressions of various shapes and sizes. These depressions, or "sink-holes" are often roughly circular and are formed when the ground surface collapses into a subsurface cavity. The size, shape, and number of sinkholes in any particular area depend on such factors as solubility of the carbonate rock, proximity of the rock to the surface, types of soils overlying the rock, fractures, joints in the rock, and hydrologic conditions.

The sinkholes in an area may be dry or water filled, dependent upon the water levels and water table conditions. If the water table is at

a level higher than the bottom of the sink, it may be water filled. Also, clay plugs in the bottom of old sinkholes may cause "perched" water tables by holding water in the sinkhole.

When analyzing aerial photographs of karst terrain, or any terrain, certain features aid in the evaluation of a region. These include the expression of the physiographic landforms, such as the sinkholes and other physical features of a karst terrain. Another important feature on the aerial photographs is the photographic tone, which is observed as varying shades of gray on a black and white product. The photo tone is dependent upon the intensity and wavelength of light reflected from the surface, and is therefore influenced by the soil type, vegetation, and the amount of water present.

Vegetative cover is also very important in evaluating a region. Although vegetation may mask some features, subtle tonal variations in the vegetative cover allows identification of other features. The presence of water affects the vegetation. Usually the areas receiving more water tend to have more thriving vegetation. Time of year has an effect also, since vegetation thrives during the summer and may mask terrain features. These features may be more evident at times of year when the vegetation is not thriving.

Vegetative cover can be evaluated in three ways: "as an index for the recognition of terrain types, as an attribute in their definition, and as a natural resource physically attached to them." (16). In other words, some types of vegetation may be peculiar to a particular type of terrain, some may aid in identifying features in an area, and some may be viewed as a resource, such as timber or crops.

The surface drainage patterns are valuable in evaluating a particular area. The shapes of gullies, absence of streams, and pattern of streams give clues to the subsurface conditions. Poorly developed surface drainage, for instance, is a clue in the identification of a karst terrain, where most of the drainage is through the available sinkholes and underground openings.

In evaluating the soil types and water conditions of an area, it is noted that well drained soils generally have a lighter gray photographic tone on black and white photographs than do poorly drained or wetter soils. Vegetative growth is usually more dense where more water is present, and in these areas the photo tones will also appear darker. A well drained, sandy soil will generally appear the lightest in photo tone with a wet, sandy soil appearing somewhat darker. Clayey soils will generally appear darkest since they do not permit quick drainage of water.

All available information should be used in evaluating the landscape of any area, since individual elements can be misleading. Relative differences in photographic tone must be considered solely within the area being viewed, and should not be used as a general index for soil types or water conditions. For terrain underlain by horizontally bedded limestone in a humid climate, Kiefer and Lillesand present this summary of key elements for terrain evaluation:

Topography: A gently rolling surface broken by numerous roughly circular sinkholes that are generally 3 to 15 m in depth and 5 to 50 m in diameter.

Drainage: Centripetal drainage into individual sinkholes. Very few surface streams. Surface streams from adjacent landform or rock types may disappear underground via sinkholes where streams reach the limestone.

Erosion: Gullies with gently rounded cross sections develop in the fine textured residual soil.

Tone: Mottled tone due to extensive sinkhole development.

Vegetation and Land Use: Typically farmed, except for sinkhole bottoms that are often wet or contain standing water a portion of the year.

Other: ...Dolomitic limestone ($(\text{Ca}, \text{Mg})\text{CO}_3$) is more difficult to identify than (the more) soluble (CaCO_3) limestone. It is generally well drained and has subtle sinkholes.

(14, pp. 210-211)

APPENDIX C

Problems Associated with Construction and Other Activities

A variety of construction and foundation problems may be encountered in a karst terrain. Foundation problems encountered in karst areas include: (1) collapse of a cavity in limestone below a structure (Figure C1); (2) differential settlement over rock and a soil filled cavity which may not have been detected by exploratory borings (Figure C2); and (3) foundations placed on an isolated boulder mistaken for the bed-rock surface (Figure C3) (34).

Poor or careless construction practices may also cause subsurface cavity development. Losses of soil by piping into limestone cavities can lead to subsidence at the ground surface (Figure C4), and infiltration of concentrated storm runoff may cause subsurface erosion and the formation of a void below a structure (Figure C5) (34).

Pollution of groundwater is also a potentially serious problem where fluid retention ponds overlie cavernous limestone. Failure may occur when leakage from the retention basin washes soil into cavities in the limestone, causing upward migration of a cavity in the overburden soil (Figure C6).

Increased sinkhole occurrence due to dewatering for mining operations has also been reported in Shelby County, Alabama (34). Progressive decline of the water table (as a limestone quarry deepened) increased the frequency of sinkhole occurrence in the area (Figure C7).

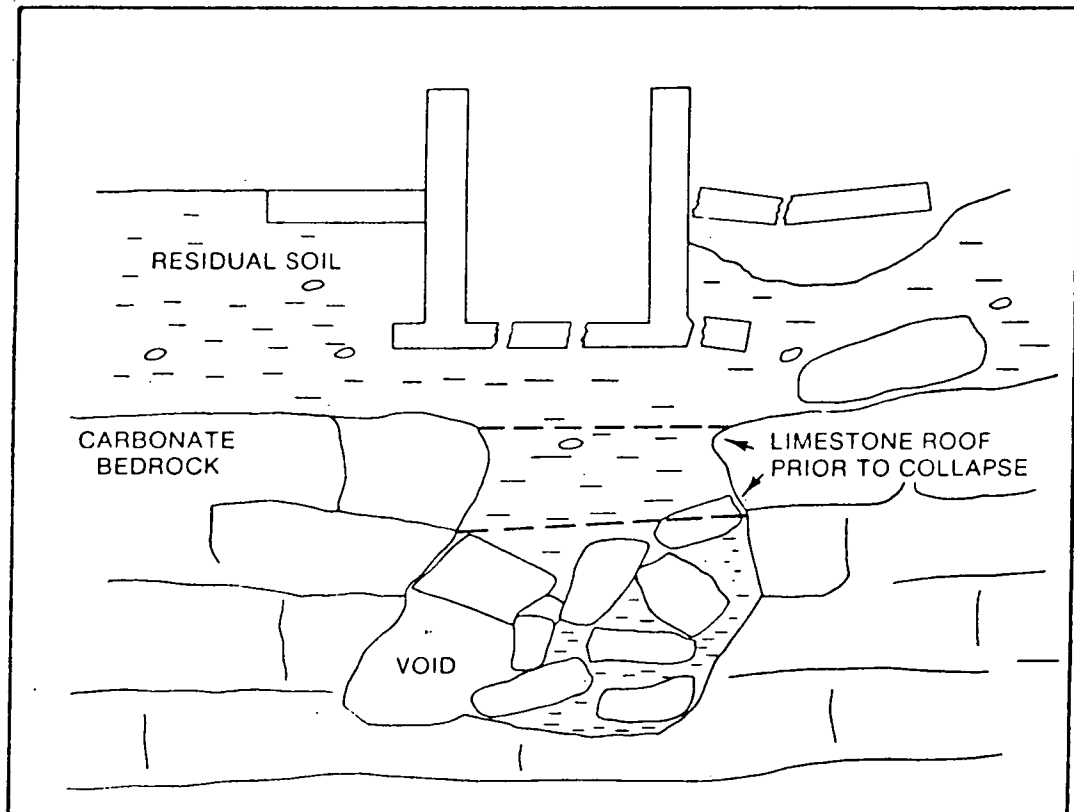


Figure C1- Foundation failure due to collapse of
a bedrock cavity.
(from Warren)

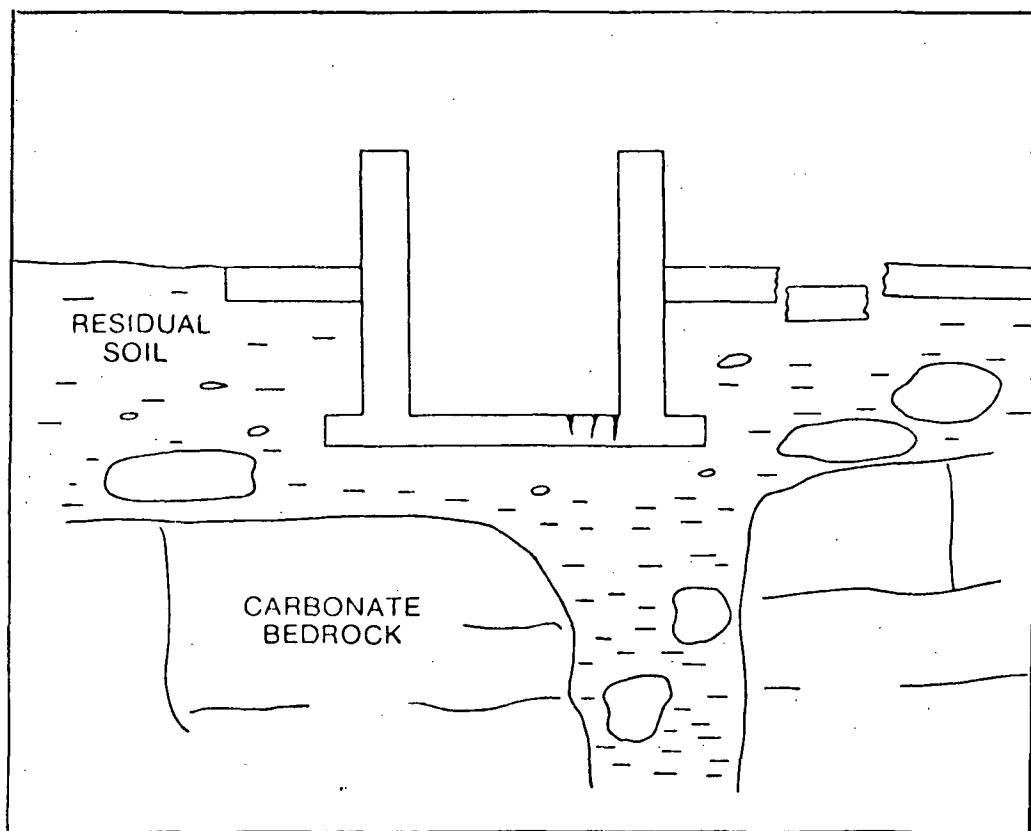


Figure C2 - Foundation failure due to differential settlement over a solution feature.
(from Warren)

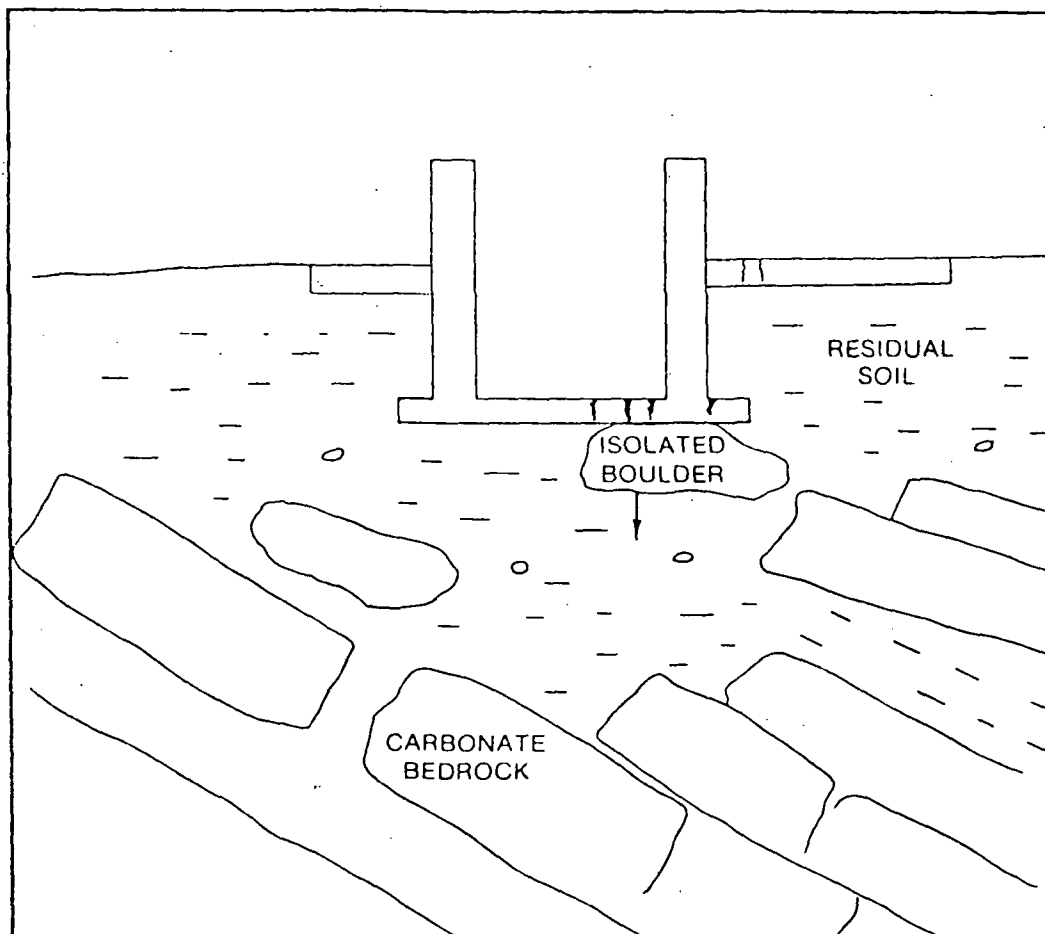


Figure C3 - Foundation failure due to placement on
a floating boulder.
(from Warren)

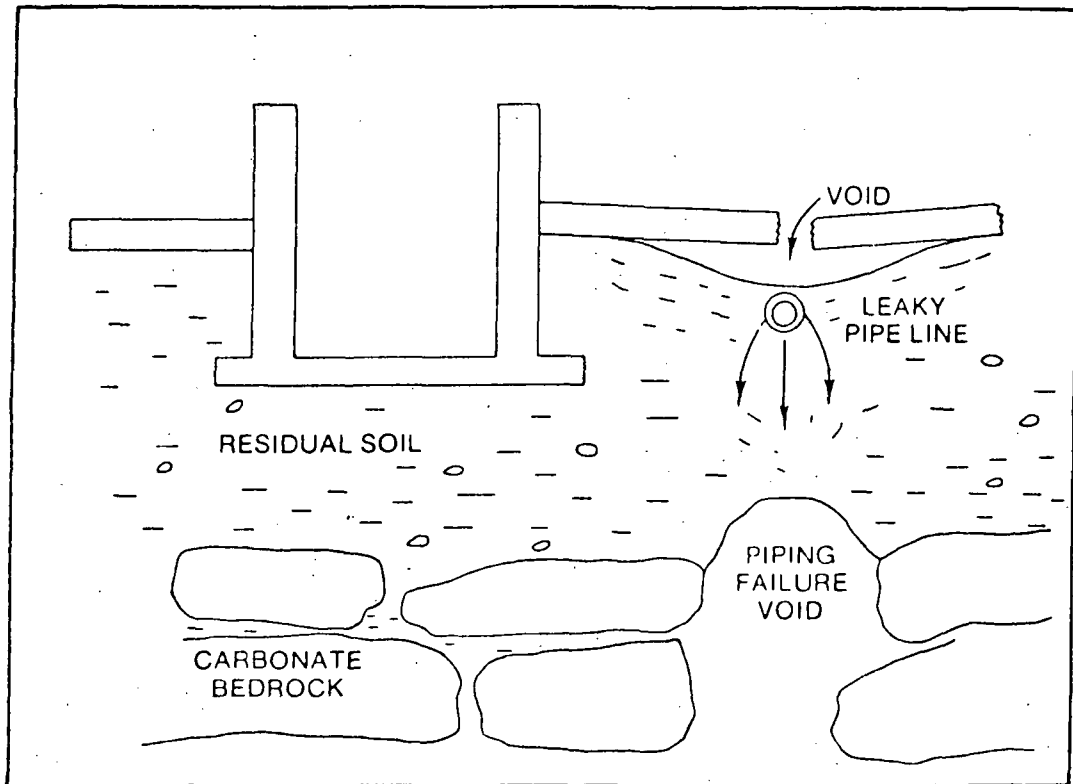


Figure C4- Foundation failure due to subsurface erosion by a leaking pipeline.
(from Warren)

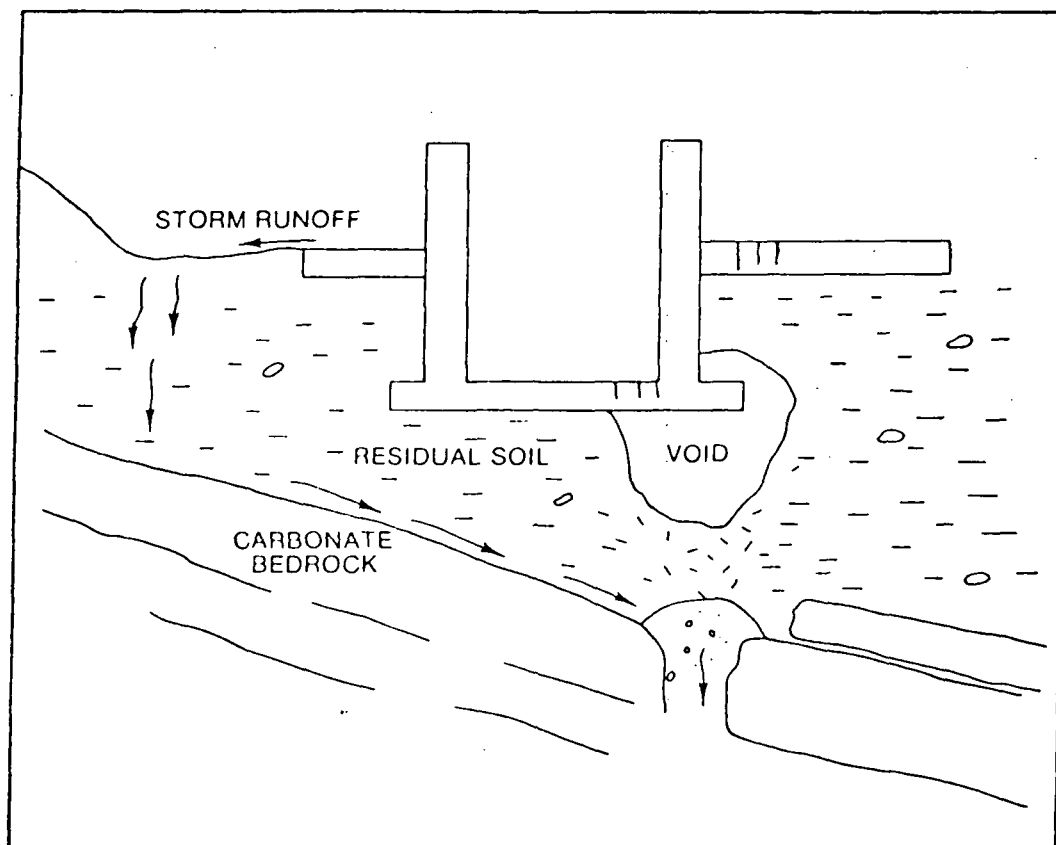


Figure C5--Foundation failure due to subsurface erosion by infiltrating storm runoff.
(from Warren)

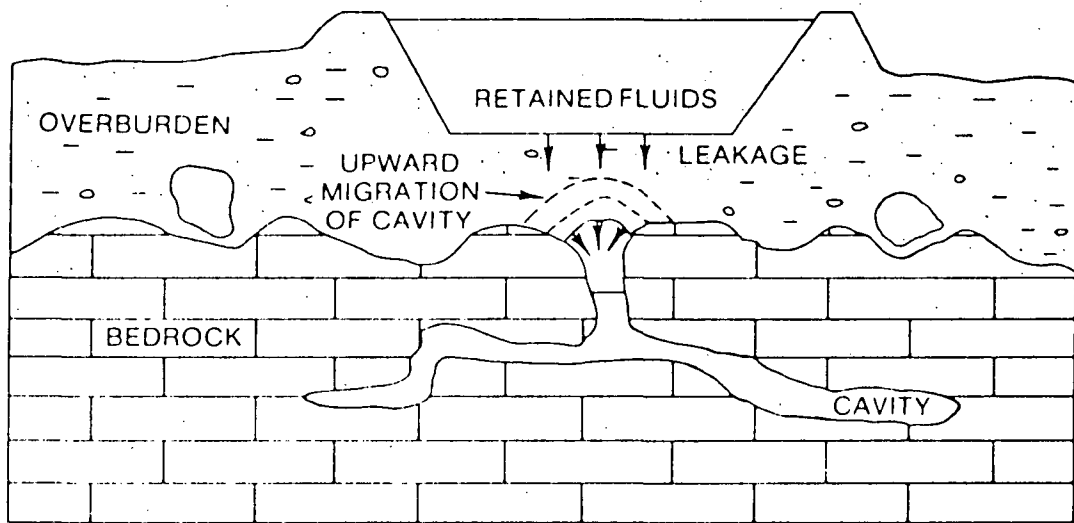


Figure C6 - Subsurface erosion under a leaking retention basin caused by spalling of clay into a bedrock cavity.
(from Warren)

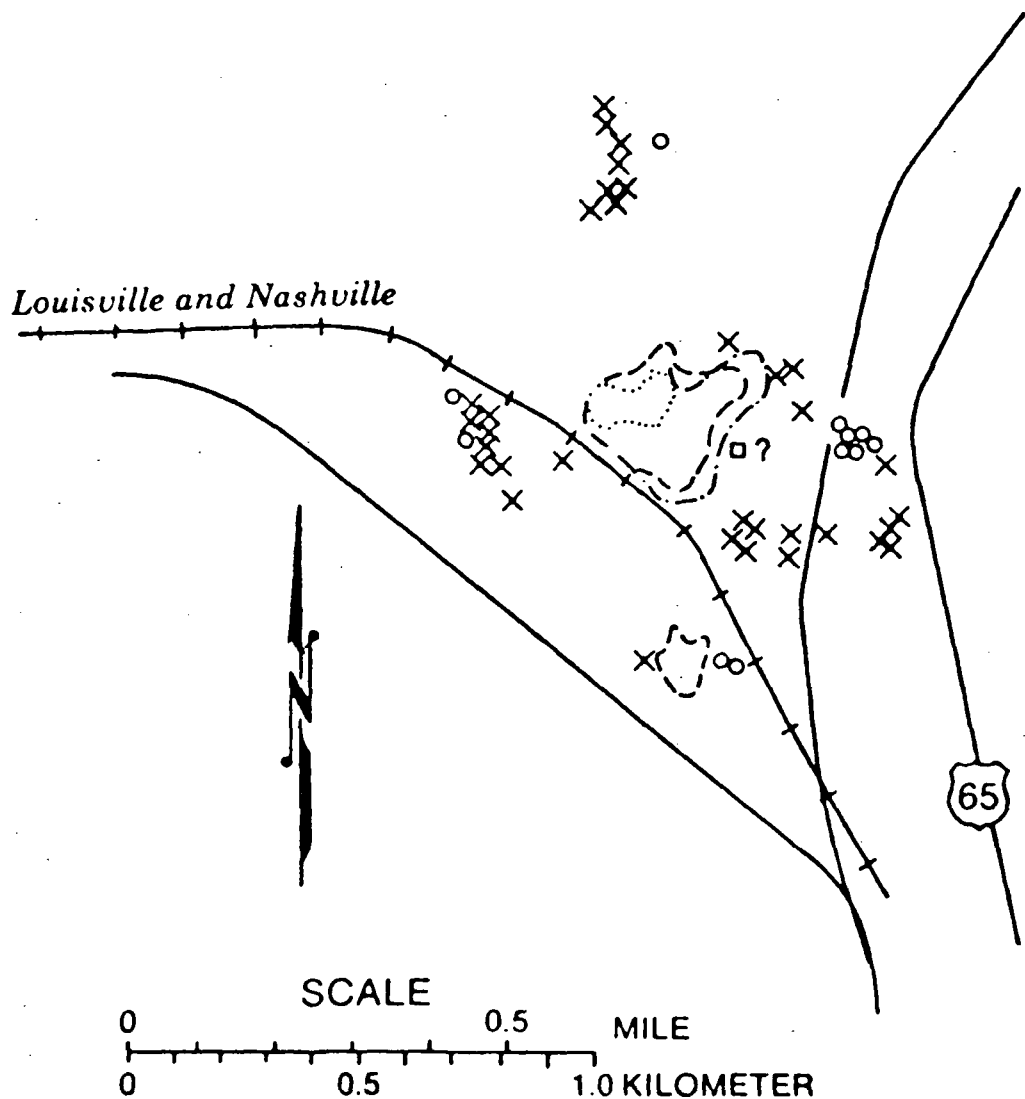


Figure C7 - Historical sinkhole activity around an abandoned limestone quarry near Pelham, Alabama.
(from Warren)

After this quarry was abandoned in 1967 the water level recovered and sinkhole development apparently stopped (34).

Increased sinkhole activity in relation to lowered water levels has been recognized in other studies (17, 18). Newton et al. believed that "a recovery of the water table will probably result in a cessation of, or drastic decrease in sinkhole development" (17, p. 36). This may slow down the development of sinkholes, but the sinkholes only form where an opening already exists in the subsurface limestone. Cessation of pumping may only postpone sinkhole formation.

APPENDIX D

Aerial Photographic Analysis of Linear Features

Use of aerial photography to map linear features on the surface of the earth was first suggested by J. L. Rich in 1928 (24). Noticing from the air the prominent effect of jointing on limestone mesas in northern Oklahoma, he suggested that photographing and analyzing areas with known structural patterns might yield information that could be applied in areas with poorer exposures. Little was done in this area until after World War II, when major oil companies realized the potential of using fracture analysis in their exploration programs (24).

This interest in fracture analysis by aerial photography led to many published articles in the 1950's, and in 1958, Lattman saw a need to standardize the terminology and method of air photo analysis for linear features. He defined fracture traces and lineaments as:

Photogeologic fracture trace (or simply fracture trace):

A photogeologic fracture trace is a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces. Included in this term are joints mapped on aerial photographs where bare rock is observed.

Photogeologic lineament (or simply lineament):

A photogeologic lineament is a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaics, and expressed continuously or discontinuously for many miles. The restrictions placed on the term "fracture trace" as regards origin apply equally to the term "lineament."

(12, p. 569)

The major difference in the two features is their magnitude, lineaments often being extremely long. Fracture traces are viewed more easily in stereoscopic study of photographs, while lineaments are more evident in photo mosaics or high altitude photography. It is possible that some mapped fracture traces may be parts of lineaments, but Lattman felt that the majority of fracture traces are not parts of lineaments (12).

A genetic distinction between fracture traces and lineaments can be made, while not necessarily entirely accurate. While fracture traces are believed to be the surface expressions of localized bedrock jointing and small faults, lineaments are believed to be due to major faults and fracture zones (12). Many theories have been proposed for the development of lineaments and fracture traces. One suggests oscillatory stresses, such as earth tides, for the formation of lineaments, while another attributes them to adjustment to stresses from earth and tides along Precambrian zones of weakness. Another suggests "isostatic adjustment" to tectonic forces (24). Fracture traces are believed to be the result of local adjustment to regional stress conditions, and may be the surface expression of minor faults, solution zones, concentrated jointing, or separation of strata during folding (24).

Fracture Trace Mapping

Fracture traces are most easily observed on "stereo pairs" of photographs (consecutive photographs in the reconnaissance plane's flight path) with a magnifying lens stereoscope. By systematically viewing small portions of the area, it is possible to locate fracture traces, expressed by continuous or discontinuous tonal variations or surface features, which should be marked with a grease pencil (which

is easily cleaned from the photograph, if necessary). If too large an area is viewed, there is a danger of drawing diagonals which do not represent true feature traces to the corners of any existing rectangular pattern, such as roads or fields (12).

Many fracture traces may be expressed by subtle tonal variations, so it is better to mark directly on the photograph than on an overlay, since the overlay could mask variations. Some interpreters also feel that transmitted light is better for viewing fractures traces, so it may be beneficial to view the photograph or transparencies on a light table. Fatigue will also reduce the efficiency of the interpreter, making it desirable to hold viewing time to two hours or less (12). The mapped fracture traces may later be transferred to a regional mosaic or base map to develop the fracture trace map for the entire area.

Lineament Mapping

Since lineaments are at least one mile long, and quite often many miles long, they are seen more easily on photographic mosaics or on the now available high altitude photography or LANDSAT imagery. Lineaments may be expressed by a single pattern element for their entire length, but often are expressed in different sections by stream segments, tonal variations, vegetation, or rock outcrop. It is also possible that the same lineament will not be observed in some segments. Lighting is important in viewing mosaics, and it should be uniform and of low to medium intensity. Viewing on a light table may also prove successful (12).

When mapping photogeologic lineaments, it is also useful to view the photo mosaic from different vantage points. Some of the more subtle

tonal variations may be viewed more easily at an angle from perpendicular to the mosaic. It is helpful to put the mosaic on a table and walk around, raising and lowering one's head to see patterns not visible at other positions. The lineaments mapped by oblique viewing may require further evaluation since they were not readily observable. Of course, it is also helpful to have more than one person working on a given mosaic (12).

APPENDIX E

Review of Previous Remote Sensing Analyses

Remote sensing has been used with some success for water resource investigations in recent years, including some studies in typical karst terrain. Regional features, as well as faults, other surface lineations, and localized surface features may be plotted using the various remote sensing techniques. This data base makes it possible to infer or derive information about the subsurface geology.

A study in the early 1960's by Lattman and Parizek explored the usefulness of aerial photography in searching for underground water sources. By mapping surface fracture traces, which are usually the surface manifestations of concentrated fracture zones in the rock below, it is possible to identify zones with a greater potential for high yield water wells. Lattman and Parizek (13) mapped fracture traces using panchromatic aerial photographs (scale 1:20,000) and then compared these mapped fracture traces with known well locations and well yield. By comparison of the locations of high yield wells and dry holes with respect to the fracture traces, they hoped to be able to show that the surface fracture traces indeed implied the locations of subsurface fracture zones in the limestone and dolomite, which provided a higher water yield.

The results obtained by Lattman and Parizek showed that well yields, or specific capacities (expressed as gallons per minute per foot of drawdown per foot of saturated rock penetrated), from wells at or

near a mapped fracture trace were more than ten times higher than the specific capacities for wells in zones between fracture traces. This demonstrated that more water flowed through the highly fractured (and possibly cavernous) zones than through the less fractured zones. Bore hole caliper surveys for wells on fracture traces also showed numerous cavernous openings, while those for wells away from fracture traces showed few openings.

From this research Lattman and Parizek concluded that the results from well yield data, caliper surveys, drillers logs, and overburden thickness indicated that fracture traces observed on aerial photographs do indeed "reflect zones of increased permeability, weathering, and solution which further supports the contention that fracture traces reflect nearly vertical zones of fracture concentration." (13, p. 90). They also concluded that "fracture traces delineate solution zones which have varied and pronounced effects on the local and regional hydrology of carbonate terrain," and the "zones of fracture concentration as revealed by fracture traces undoubtedly markedly affect the occurrence and movement of ground water to varying degrees in a number of rock types..." (13, p. 90).

In a study undertaken in the Shenandoah Valley, Virginia, Trainer and Ellison (31) found that fracture traces formed mainly along vertical joints, and that the type of rock had a great deal of influence on the frequency of occurrence of fracture traces. In studies on sandstone, shale, and limestone or dolomite formations, fracture traces were significantly less abundant in shale and more numerous in the carbonate rocks. Among the carbonate rocks, those that were primarily limestone

(calcium carbonate) showed more fracture traces than the carbonate rocks which were more shaly, cherty, or dolomitic (31).

Sabins (22) obtained thermal infrared scanner imagery at night in the Indio Hills, California, in an attempt to differentiate between different stratigraphic units based on their radiometric characteristics. He was able to separate the materials into three distinct groups (Figure E1): (1) alluvium which appeared to be uniformly cooler than the exposed bedrock; (2) poorly stratified bedrock, which was uniformly warm and (3) well stratified bedrock, which exhibited alternating warmer and cooler bands, corresponding to sandstones and siltstones, respectively. Sabins also found that it was possible to locate faults from the thermal imagery. Faults were expressed as "offsets of the stratigraphic-radiometric units", or "as radiometric temperature anomalies related to blockage of ground water." (22, p. 750). Using this method it may be possible to detect potentially dangerous faults which are covered by alluvium or areas of fairly shallow ground water in arid regions (22).

In a 1973 study in the Camuy Cave area in Puerto Rico, Rinker used black and white photography to map lineaments and fracture traces in an effort to locate the path for the underground channel of the Camuy River. Portions of the cave through which the river flows were mapped along with the locations of some large sinkholes. By combining mapped sinkholes with fracture trace mapping, Rinker was able to predict possible routes of the subsurface channel (Figure E2). The results of his study correlated well with portions of the cave that had previously been mapped (Figure E3) (21).

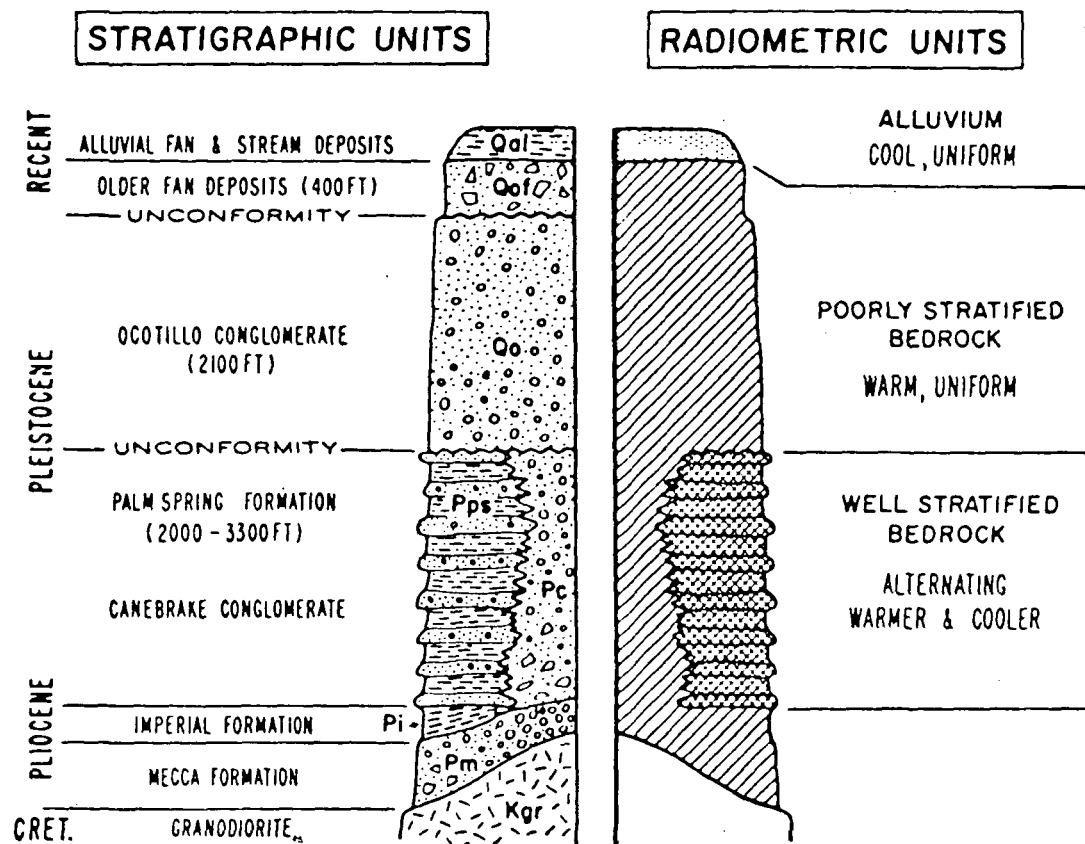


Figure E1:- Stratigraphic and radiometric units for the Indio Hills, California.
(from Sabins)

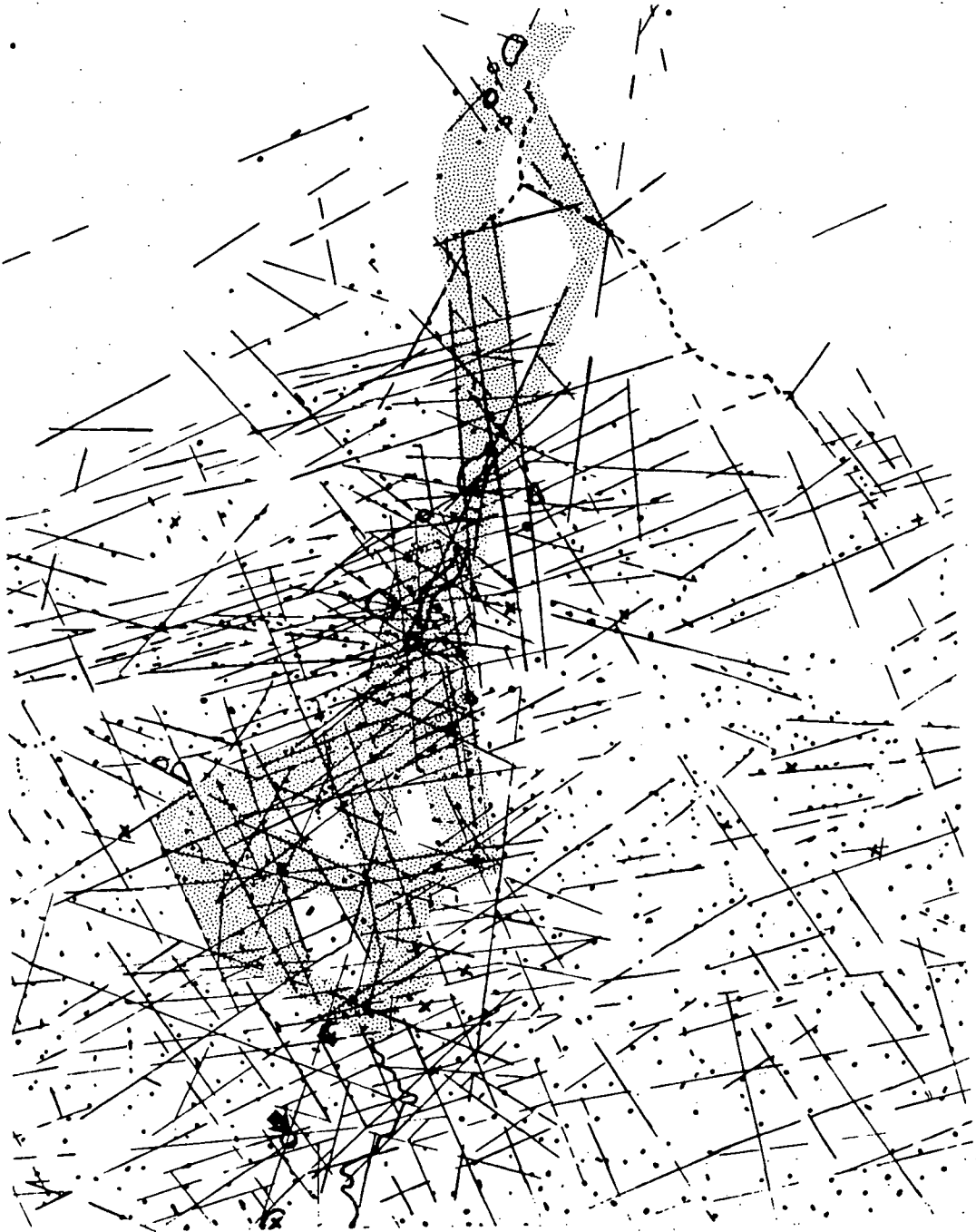


Figure E21- Map of lineaments and sinkholes for Camuy Cave area. The gray stippled area represents the most probable locations of the underground system of the Camuy River. (from Rinker).



Figure E3 - Map of lineaments and sinkholes in the Camuy Cave area showing the approximate location of the known part of the cave. The agreement with the predicted probable location (gray stippled area) is generally good. (from Rinker).

Parizek (19) has discussed the use of large scale lineaments as mapped from imagery from LANDSAT and other high altitude platforms. Most of the previous studies have primarily mentioned fracture traces, which are shorter linear features (less than one mile in length). With the LANDSAT and other high altitude imagery it is possible to map lineaments greater than 150 kilometers. Whereas fracture traces were found to indicate subsurface fracture zones of two to 20 meters in width, Parizek assumed a one kilometer wide fracture zone to be associated with major lineaments. He has also suggested that large scale lineaments could be used for the same purposes as fracture trace mapping. It may be more difficult to establish ground reference points from the high altitude imagery.

Figure E4, presented by Parizek (19), shows the relative productivity of wells located on and off lineaments. It can be seen that wells located on the lineaments (assumed to be one kilometer wide) show a generally higher trend in productivity (gallons per minute per foot of drawdown per foot of static saturated thickness of rock penetrated) than wells not located on lineaments. It can be seen, however, that some wells had a high productivity whether they fell on a lineament or not. The results presented here do not necessarily verify the assumed one kilometer width for a lineament, so the zone of fracturing could be narrower or wider.

Parizek also presented data (Figure E5) for wells located on fracture traces, at the intersection of fracture traces, and away from fracture traces, with no distinction between lineament and nonlineament wells. As might be expected the wells at fracture trace intersections show productivities twice as high as wells located on fracture traces

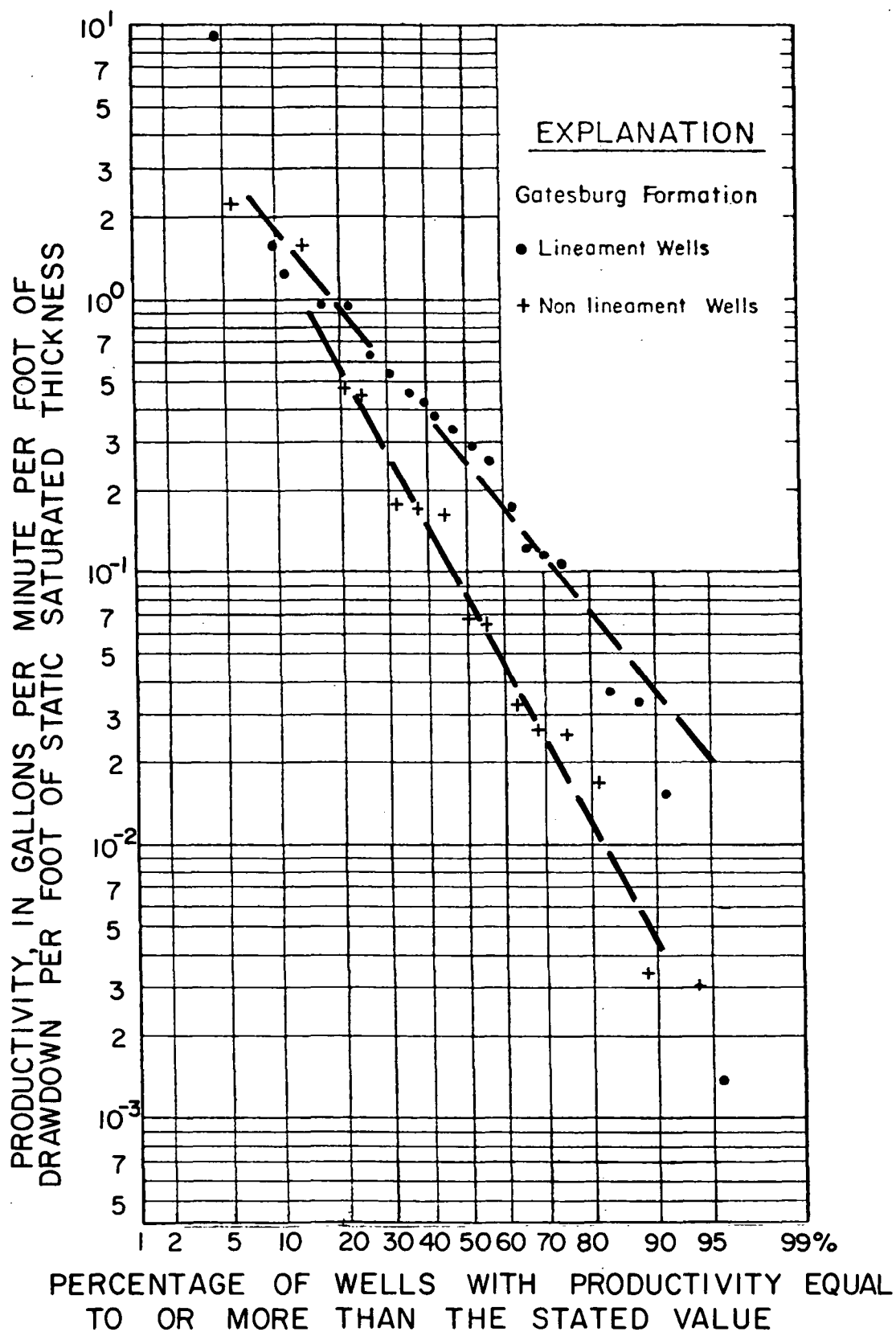
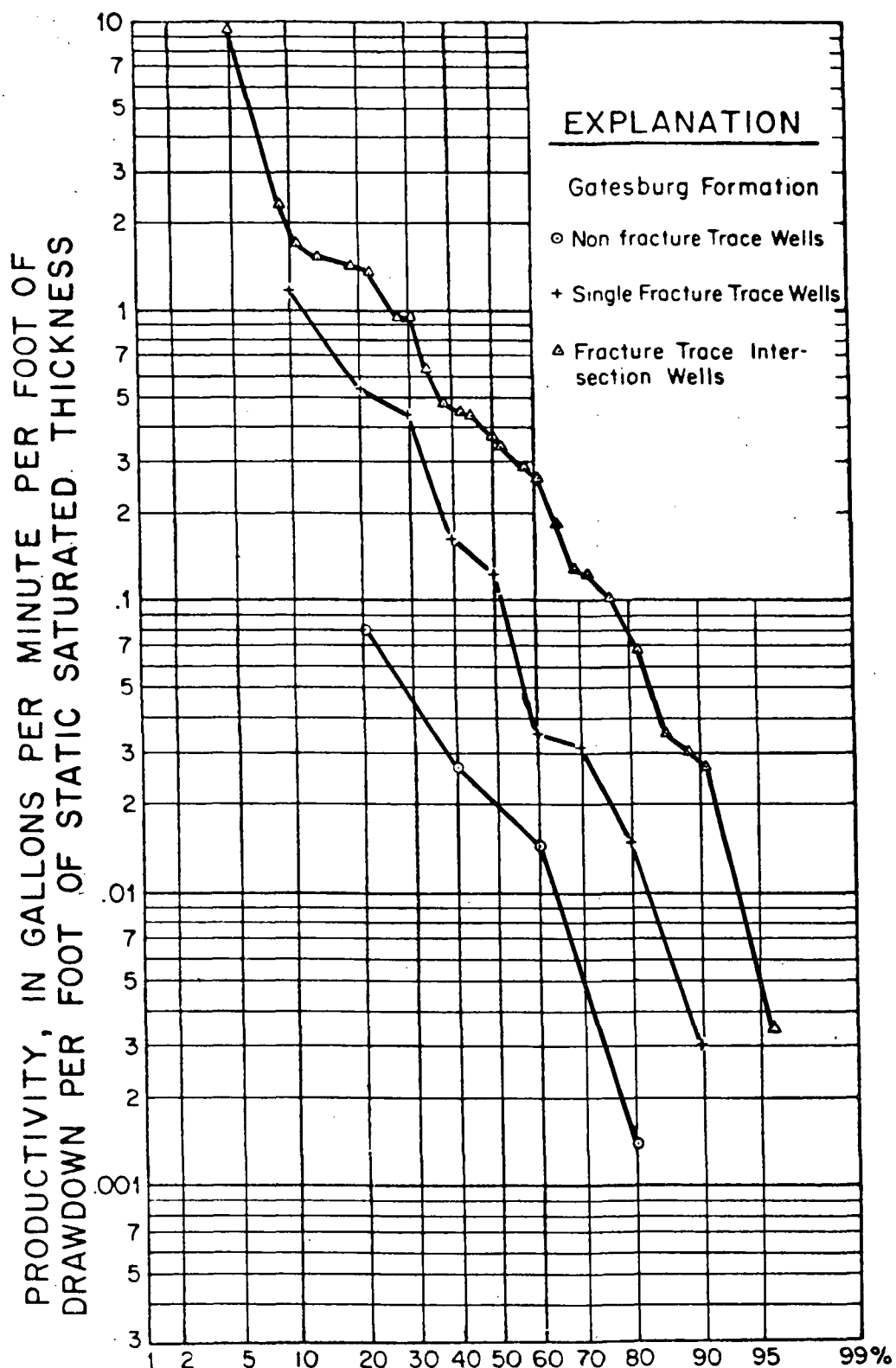


Figure E4 - Productivity of lineament and non lineament wells (value multiplied by 10³). (from Parizek)



PERCENTAGE OF WELLS WITH PRODUCTIVITY
EQUAL TO OR MORE THAN THE STATED VALUE

Figure E5 - Productivity values for fracture trace intersection, single fracture trace, and non fracture wells (multiplied by 10^3). (from Parizek)

but not at intersections. Wells at the intersections of fracture traces had specific capacities ten or more times higher than nonfracture trace wells. Parizek suggested that a combination of lineament and fracture trace mapping may be beneficial in locating potential high yield wells.

Parizek (19) has also noted that certain features such as sink-holes, swallow holes, caves entrances, and ground subsidence have been observed along major lineaments and at lineament intersections. He believes that lineament maps, combined with information such as depth of water table, surface and subsurface drainage characteristics, soil characteristics, rock type, and structural features may help define potential subsidence and leakage zones. He also stated that

Lineament maps will help to delineate risk areas for various structures but in themselves cannot be used to predict when and where subsidence and cave-in's and severe leakage are precisely going to occur. However, they can be used to flag areas where caution should be exercised in land use planning and where more detailed test drilling and foundation exploration work are justified.

(19, p. 94)

In 1969 Coker, Marshall, and Thomson (5) made an analysis of sink-hole prone areas near Bartow, Florida using computer processed multispectral scanner imagery which consisted of 18 bands at wavelengths between 0.4 and 14.0 microns. The computer was "trained" to use the multispectral data to help locate zones of moisture stressed vegetation, which were thought to be areas with potential for collapse. The vegetation may show moisture stress when water levels decrease, such as during the dry season, and after prolonged drought or excessive removal of water by pumping. They hypothesized the greatest potential for collapse to be in areas with ancient buried sinkholes, "during and

shortly after times of greatest hydrostatic pressure or water level decline." (5, p. 66). When a cavity is under a high hydrostatic pressure, the water "buoys" up the roof, which could collapse when the pressure decreases, especially if a rapid reduction in pressure occurs due to a rapid water level decline.

Coker et al. collected multispectral data during a drought in September 1967 that produced a large decline in the shallow water table. Measurement in wells showed water levels to be lowest near the center of relic sinkholes. Thermal data from early morning showed lower temperatures in the center of relic sinkholes, and the temperature contours approximated the subsurface water conditions (cooler at the center with water far below the surface, and warmer on the edges where the water table was closer to the surface). the coolest zones corresponded to zones of active subsidence. Other known sinkhole areas were observed as oval patterns in the processed multispectral data. Also, one area was located before subsidence started the following year.

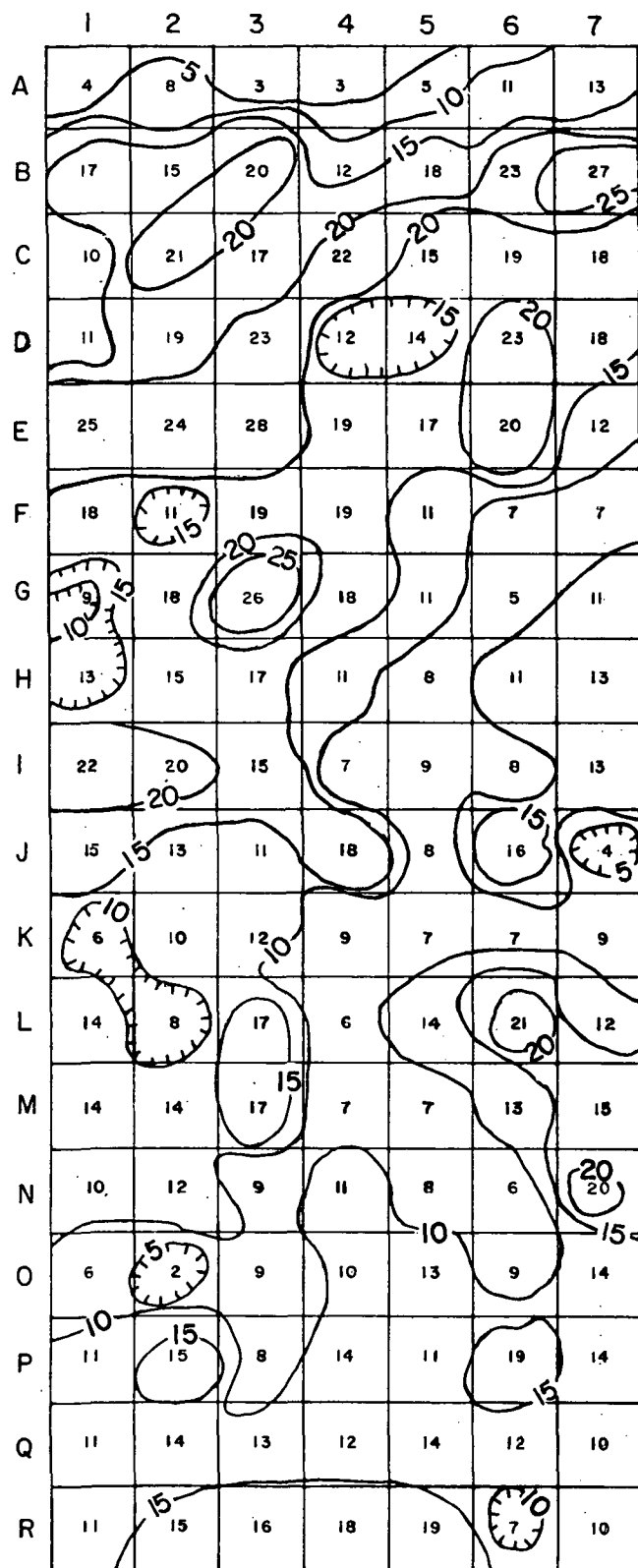
Coker et al. concluded that multispectral scanning may become a very valuable tool in studies of karst areas, particularly for locating zones of potential subsidence (5). Zones exhibiting vegetative stress due to lower water levels near the center of a sand filled sinkhole could be detected using multispectral or thermal imagery.

In a study published in 1970 by the Geological Survey of Alabama, Sonderegger used panchromatic (black and white), color, and infrared photography for mapping lineaments and fracture traces in Limestone County, Alabama. The area studied was divided into a grid system and contours of fracture trace densities (number of fracture traces in a grid unit) were plotted separately for each type of photography

(Figures E6, E7, E8). It should be noted that different results were obtained from each photo type. Comparison of water yields from test wells shows that wells drilled on fracture traces exhibit significantly higher yields than the average of all wells (24), apparently corresponding to highly permeable zones.

Sonderegger concluded from his study that: (1) locating wells using fracture traces is much more effective than a random approach; (2) thickness of overburden did not affect fracture trace concentration in his study area; (3) color and infrared transparencies did not seem to be better than black and white prints for locating well sites, but they increased interpreter confidence; and (4) color and infrared transparencies were superior in showing the influence of the rock basement structure. Sonderegger also agreed that color and infrared transparencies were better for mapping of vegetation and drainage characteristics, while black and white photographs appeared better for mapping cultural and soil features (24).

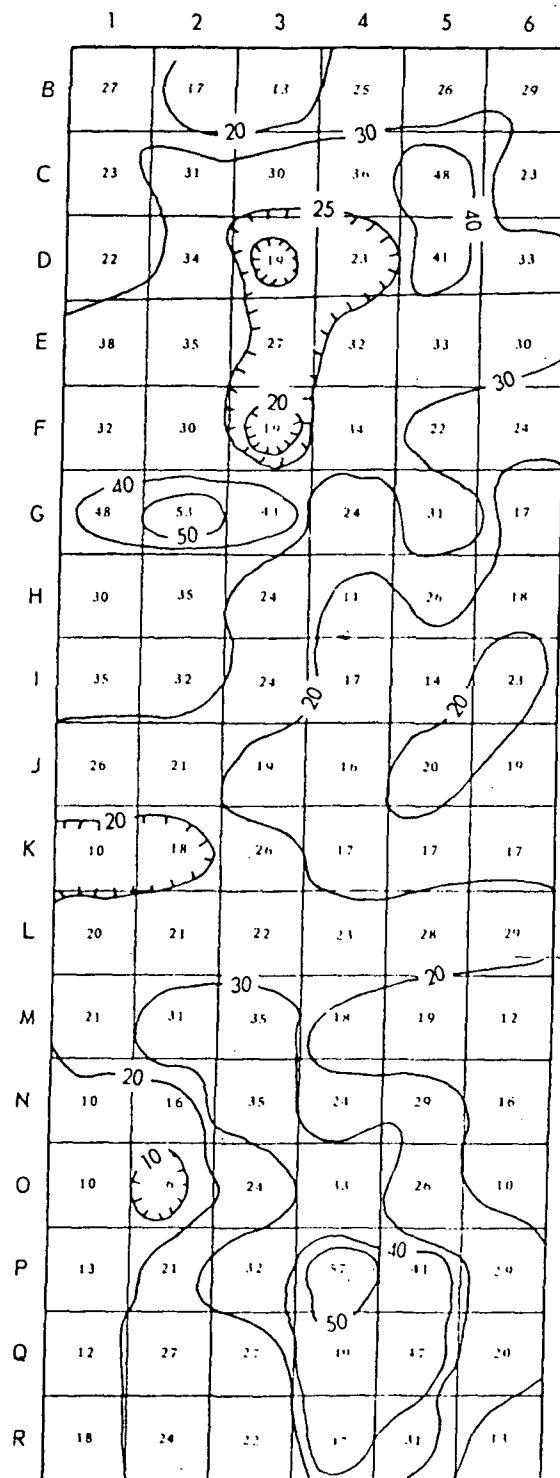
A study by Newton, Copeland and Scarbrough (17) in Jefferson County, Alabama, in 1973 used color infrared and color Ektachrome aerial photography to locate areas of vegetative stress due to subsidence and drainage in subsurface cavities. The vegetative stress proved to be a good indication of potential collapse zones in the residual clay soils, and in one case, an auger penetrated a cavity in the clay soils beneath a zone where vegetative stress was apparent. Infrared black and white photography was used to define water and land boundaries; and daytime thermal infrared imagery was useful in mapping faults and points of water loss, such as streams flowing into sinkholes.



Contour Interval: 5 fracture traces per grid unit

0 10,000 20,000 feet

Figure E6 - Fracture trace density based on panchromatic photographs
(from Sonderegger)



Contour interval: 10 fracture traces per grid unit

0 10,000 20,000 feet

Figure E7 - Fracture trace density based on panchromatic photographs (from Sonderegger)

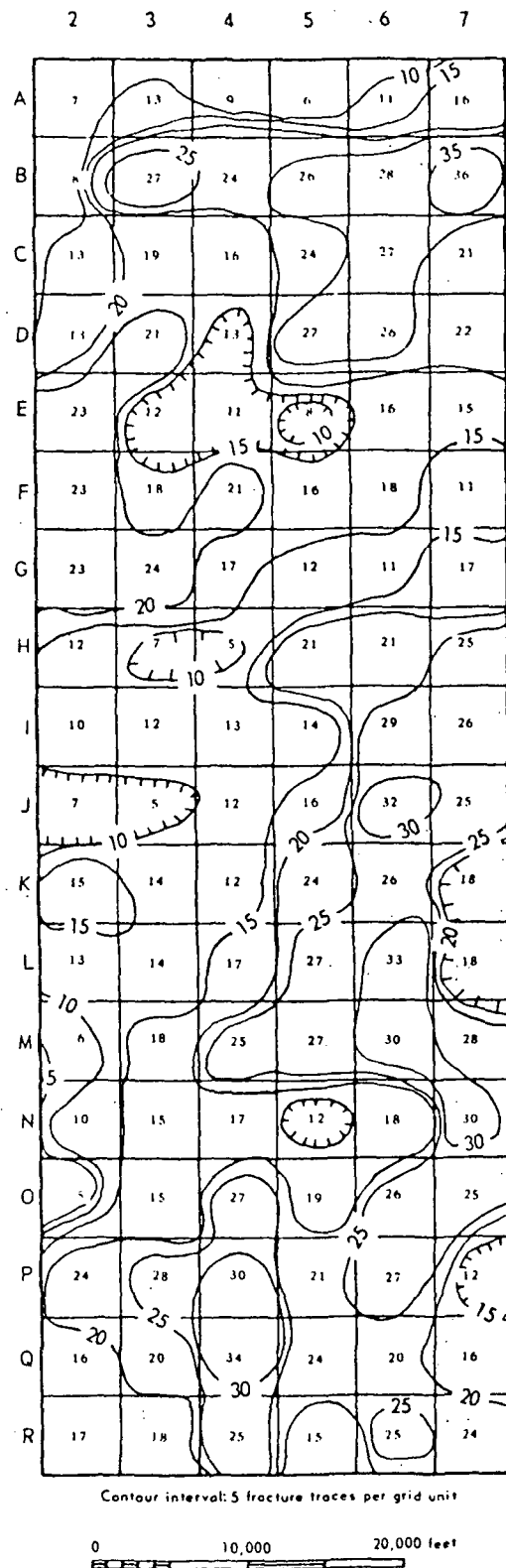


Figure E8 - Fracture trace density based on color transparencies.
(from Sonderegger)

In another study in Shelby County, Alabama, Warren and Wielchowsky (35) suggest that high altitude photographs at regular time intervals can be invaluable tools in tracing the history of sinkhole problems. This provides information on past and present subsidence activity, eliminating inaccuracies which may be the result of relying on personal interviews. They also suggest that black and white infrared photography and thermography is useful in locating zones where water enters sinkholes. As mentioned in relation to other studies, they feel that indications of vegetative stress may also provide clues for location of subsurface cavities (35).

Brown (3) conducted a thermal infrared study of a drainage basin in Alberta, Canada in an effort to locate air vents from subsurface cavities and to possibly find the spring outlets for two large lakes with drainage through openings in the lake bottoms. The use of the thermal infrared imagery was based on the characteristics of the water and air from subsurface cavities and springs. The water and air temperatures from these sources have small diurnal and seasonal variations. The temperatures in most karst regions approximate the average annual temperature (3). Using thermal imagery, taken late in the morning in early October, 1971 by a line scanning infrared sensor (wavelength range 8 to 14 microns), a large intermittent spring was identified in a water filled karst polje, or karst plain. This spring had not previously been identified on aerial photographs or during field investigations, even those conducted after the water level in the polje had declines. This spring would probably not have been identified without the use of the thermal infrared imagery since it flowed only when the water level in the polje was above the spring outlet (3).

In an area of Kansas City, Kansas, in 1970 Dedman and Culver (6) conducted an airborne microwave radiometric study to evaluate the potential of microwave radiometry to detect subsurface voids. By recording the radiometric "temperatures" for an area and plotting them on an isotherm map, they were able to locate temperature anomalies, or zones with lower radiometric temperatures. By superimposing a known mapped cave over their isotherm map, they were able to show a fairly good correlation between radiometric temperature anomalies and cavity occurrence. However, not all areas showed good correlation. They concluded that microwave radiometry has some definite potential for the detection of subsurface cavities, but more studies are needed to determine the causes of microwave anomalies (6).

