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RELATIONSHIP OF GROUND WATER CHEMISTRY TO PHOTOLINEAMENTS IN A KARST AQUIFER

by

Sheila R. Williams

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in
the Department of Geology in
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Major Professor: Sam B. Upchurch

In memory of Joseph R. Wadsworth, Jr., PhD.

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RELATIONSHIP OF GROUND WATER CHEMISTRY TO PHOTOLINEAMENTS IN A KARST AQUIFER

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An Abstract

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Factor analysis is a useful, statistical technique for identifying underlying hydrogeochemical processes that govern complex relationships observed among ground-water quality data. When investigating the geochemistry of a fractured, karst aquifer, photolineament analysis allows recognition of the influence of solution-enlarged joints, fractures and faults on the areal distribution of geochemically-distinct ground-water masses identified by factor analysis.

These techniques were applied to geochemical data available for 307 wells completed in the upper 300 m of the Floridan aquifer, northwest-central Pasco County, Florida. For all ground-water samples, pH, color, bicarbonate alkalinity, total alkalinity, total hardness, and the concentrations of Ca^{+2}, Mg^{+2}, SO_4^{-2}, Cl^{-}, and total iron (Fe^{+2} + Fe^{+3}) were determined by Standard Methods. R-mode factor analysis was used to cluster those chemical variables that reflect areally-significant hydrogeochemical processes.

Surface expressions of vertical to near-vertical, subsurface zones of fracture concentration were identified and mapped as photolineaments on several scales of aerial photography. Criteria employed in the identification of individual photolineaments include combinations of; soil tone, sinkhole, elongate sinkhole, sinkhole alignment, tree alignment, vegetation body, elongate vegetation body, vegetation body alignment, and straight water-course segment. The reliability or confidence in identification of each segment of an individual photolineament was recorded by assigning numerical subscripts to the

identifying criteria; (1) definite photolineament, (2) definite photolineament, but precise location indeterminable, (3) probable photolineament, and (4) possible photolineament. Photolineament length and orientation were also recorded, and photolineament density patterns were examined.

Three factors, which represent different geochemical processes, were identified using factor analysis. These processes are: (1) dissolution of the aquifer limestone, (2) leaching of surface organics and mobilization of iron in the surficial units, and (3) weathering of a discontinuous, semi-confining layer that overlies portions of the aquifer.

The magnitude of Factor 1 scores increases with residence time, or depth, except where sinkholes, considerably enlarged by dissolution, isolate recharge from reaction with the limestone or where extensive pumping draws up water from deeper within the aquifer.

Local intensities of Factor 2 depend on the abundance of surface organics and iron-bearing minerals in the surficial sediments and the presence of solution-enlarged fractures that provide rapid and direct recharge to the Floridan aquifer.

For Factor 3, low fracture densities, thus relatively-restricted ground-water circulation, provide the proper geochemical environment for the weathering of Mg^{+2} from the semi-confining clays.

In general, photolineaments are more easily detected in the semi-confined regions of the Floridan aquifer since conditions are more favorable for sinkhole development. In unconfined regions of the Floridan aquifer, where conditions for sinkhole development are less favorable, it is difficult to trace photolineaments over long distances.

As a result, the areal distribution of photolineaments shorter than 2 km appears relatively uniform over the area of study. The majority of these shorter photolineaments most likely reflect tidal-stress joints and appear to have little to no effect on the areal distribution of the three geochemical factors identified by factor analysis. This suggests that tidal-stress joints, typically shorter than 2 km, either do not penetrate the aquifer matrix for a sufficient depth, are not sufficiently enlarged by dissolution to affect water quality in the Floridan aquifer, or they are diffuse and abundant enough that at a macroscale they function as a homogeneous system.

Photolineaments longer than 2 km generally indicate fractures of tectonic origin. These long photolineaments do not appear to be uniform in distribution over the study area. Instead, photolineaments longer than 2 km are closely grouped forming distinct zones of photolineament concentration. The extensive fractures, which these photolineaments represent, appear to penetrate the Floridan aquifer much deeper and are more enlarged by dissolution than surficial tidal-stress joints since they have a significant affect on local ground-water movement and thus, on the areal distribution of the ground-water quality parameters used in factor analysis. Therefore, when locating potential well sites in high fracture density zones, it is important to examine the origin and character of the constituent fractures in order to ensure high well yield.

In conclusion, the ground-water chemistry of the Floridan aquifer, as represented by local intensities of the hydrogeochemical processes identified by factor analysis, is dependent upon source, stratigraphy, residence time and flow path, with the latter two being strongly

influenced by fracture type, distribution, and enlargement by dissolution.

Abstract approved: _____

Sam B. Upchurch

Professor, Geology

_____

Date

INTRODUCTION

Karst ground-water systems are among the most productive aquifers. The wide range in permeability of a karst aquifer, however, gives rise to many significant hydrogeologic problems, including; (a) poor predictability of ground-water supplies, (b) scarcity of surface streams, (c) instability of the ground, (d) leakage of surface-water reservoirs, (e) an unreliable waste-disposal environment, and (f) variable water quality (LeGrand, 1977).

There have been many well-productivity studies concerning the occurrence of ground water in karst aquifers (Lattman and Nickelson, 1958; Lattman and Parizek, 1964; Parizek 1976; Leggette, Brashears & Graham, 1974-1977; LaRicca and Rauch, 1977; Siddiqui and Parizek, 1977; Moore et al., 1977). However, as the numbers of ground-water contamination incidents increase, it has become apparent that there exists little knowledge on the background water quality of karst ground-water systems.

It is difficult to ascertain the influence karst conduits have on ground-water chemistry. Vertical to near-vertical, solution-enlarged zones of fracture are, generally, the easiest to assess since they are often discernable at the land surface as fracture traces and on aerial photographs as photolineaments. Vertical solution conduits often serve as recharge pathways to the aquifer. Understanding the affects various types of vertical, solution-enlarged fractures have on local

ground-water movement is necessary to understand the karst ground-water system as a whole.

An extensive, karst, artesian aquifer system underlies a significant portion of the southeastern United States (Stringfield, 1966, fig 23). Within Florida this ground-water system is commonly referred to as the Floridan aquifer, which is predominately comprised of a thick sequence of fractured, Tertiary limestones and dolostones. The Floridan is the source of nearly all artesian water in Florida and serves as that state's primary reservoir of potable water (Stringfield, 1966).

Recharge to the Floridan aquifer occurs through streams, lakes, sinkholes, and permeable materials overlying the aquifer. The quality of the ground water is continuously affected by artificial, as well as by natural recharge processes. Potable ground-water supplies may be susceptible to contamination by urban storm runoff, treated municipal sewage, agricultural wastes, and leachate from solid waste disposal (Lawrence and Upchurch, 1982). The potential for ground-water contamination is especially high in the proximity of solution-enlarged, vertical to near-vertical fractures that provide direct hydraulic connection between surface- and ground-water bodies. Identification of those fractures that serve as recharge pathways, and thus are potential sites of pollutant introduction to the aquifer, is important in preserving the water quality of this karst aquifer.

Objective

The principal objective of this study is to investigate relationships of ground-water quality to photolineaments, which

represent fracture traces, in a heavilly-used, karst aquifer.

The study employs factor analysis to examine and to describe the areal distribution of selected ground-water quality parameters in the Floridan aquifer. Photolineament analysis is used to locate fracture traces in order that subsurface zones of vertical fracture concentration can be evaluated as to their impact on the areal distribution of the selected ground-water quality parameters used in factor analysis.

Study Area

The study was conducted within a 186 km^2 area in and around the Cross Bar Well Field, northwest-central Pasco County, Florida (Figure 1). The area of study lies within the region designated as the broad, karst Coastal Plain Province by Fenneman (1938), the Terraced Coastal Lowlands by Vernon (1951), and the Middle Gulf recharge area by Cherry et al. (1970). The study area includes the Talbot and Penholoway coastal terraces of Pleistocene age (Cooke, 1945). Beneath the Pleistocene surficial sands there are several hundred meters of Tertiary carbonate formations and possibly one or more, discontinuous, semi-confining layers of Miocene age.

Two distinct physiographic provinces are identifiable on aerial photography of northwest-central Pasco County (Figure 2). The southern province is characterized by numerous lakes, sinks and cypress heads (Gilboy and Moore, 1982). The northern province is characterized by the lack of wetlands and the abundance of scrub oaks and pasture land. Leggette, Brashears & Graham, Inc. (1976) noted much higher transmissivities accompanied by very low water-table elevations in the northern province. A higher degree of confinement in the southern

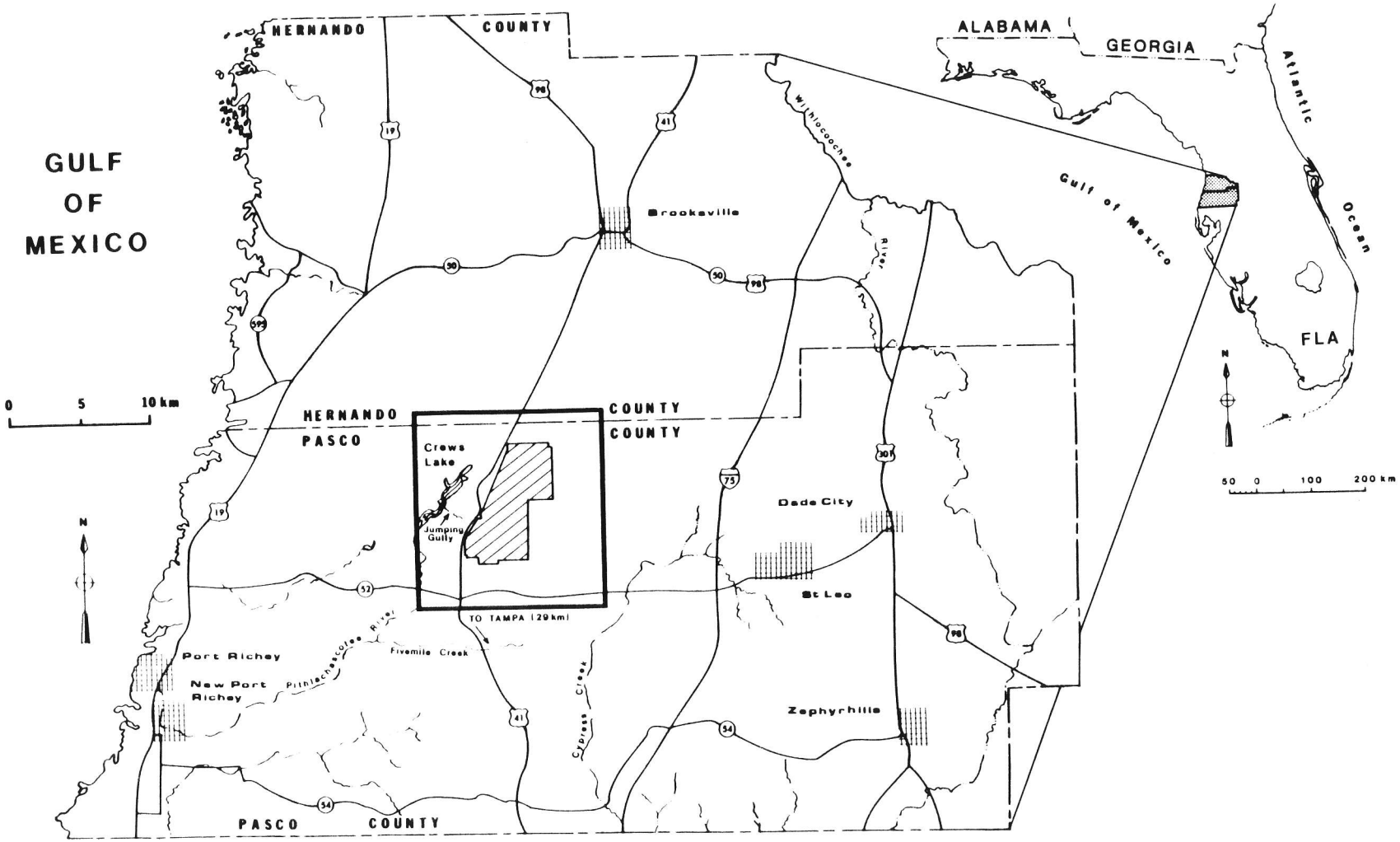


Figure 1. Location of study area. Shaded area is the Cross Bar Well Field.

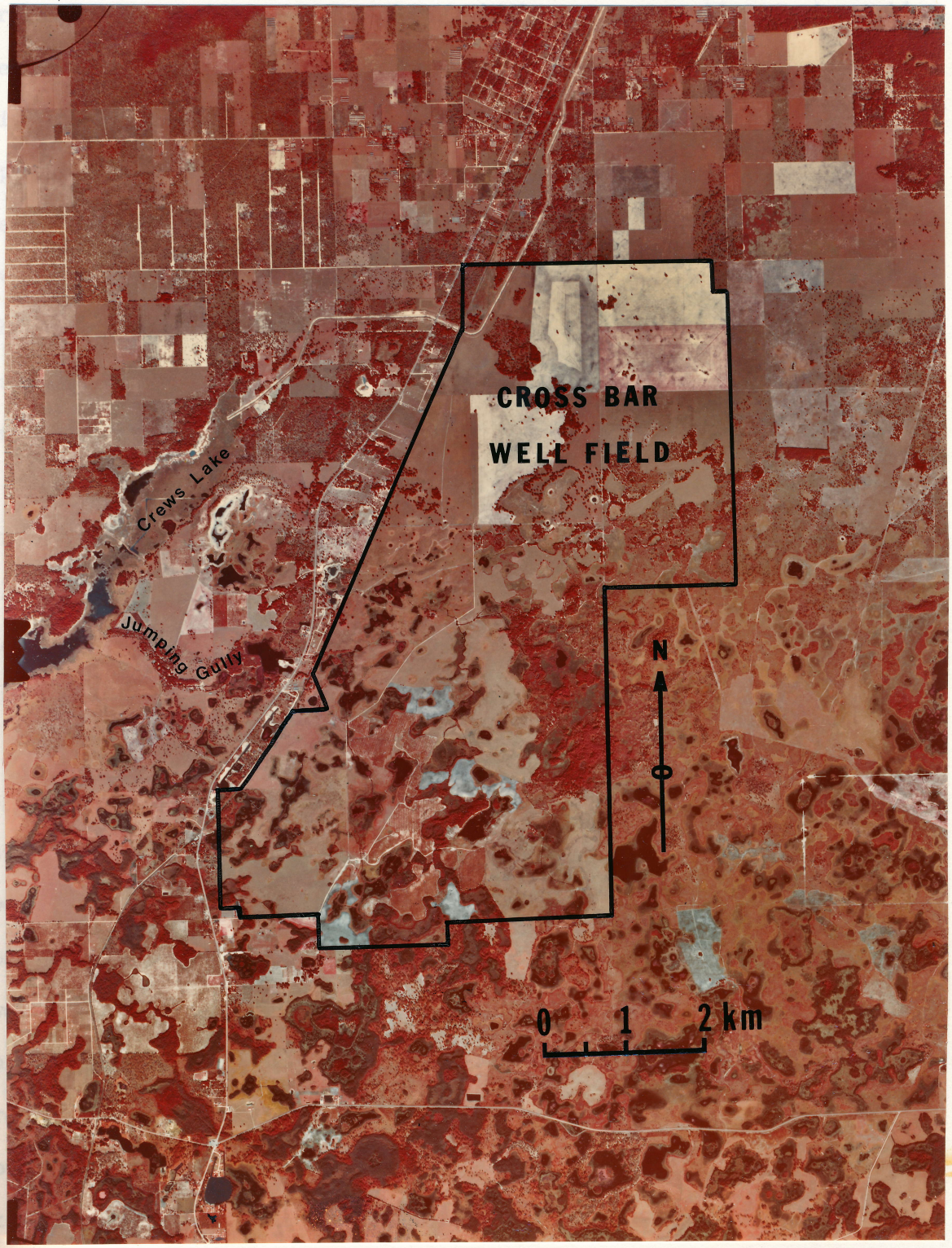


Figure 2. 1:80,000 scale, color-infrared aerial photograph of study area.

province allows this area to maintain higher water tables and stable wetlands (Gilboy and Moore, 1982). Miller (1977) attributes the difference in water-table elevations to faulting or pinching out of the uppermost, Miocene semi-confining unit in the northern section of the well field. Gilboy and Moore (1982) contend that the boundary of the two provinces trends northeast and coincides with the boundary between the Talbot and Penholoway Terraces (Figure 3). There is insufficient data to detail the areal extent of the uppermost, Miocene semi-confining unit for this region.

The study area includes the towns of Masaryktown, Loyce, Greenfield, Fivay Junction and Gowers Corner. Residences are clustered along U.S. Highway 41 and State Highway 52. Most residences in the area have private wells. Outside the well field and towns, the land is used predominately for agricultural purposes (Moore, 1981).

The West Coast Regional Water Supply Authority oversees operation of the Cross Bar Well Field and monitoring of ground-water quality. A preliminary water-quality study of domestic wells, which surround the well field (Figure 4), was made shortly after initiation of municipal-well drilling in 1978. Three hundred and seven selected wells, which consititute a majority of the domestic and municipal wells present in the area, were used in this study. Chemical analyses for the remaining wells were incomplete, and were not used in this study. All private wells are completed in the upper Floridan aquifer to depths up to 145 m below land surface. The municipal wells drilled within the well field penetrate the Floridan to depths between 145 to 220 m below surface level.

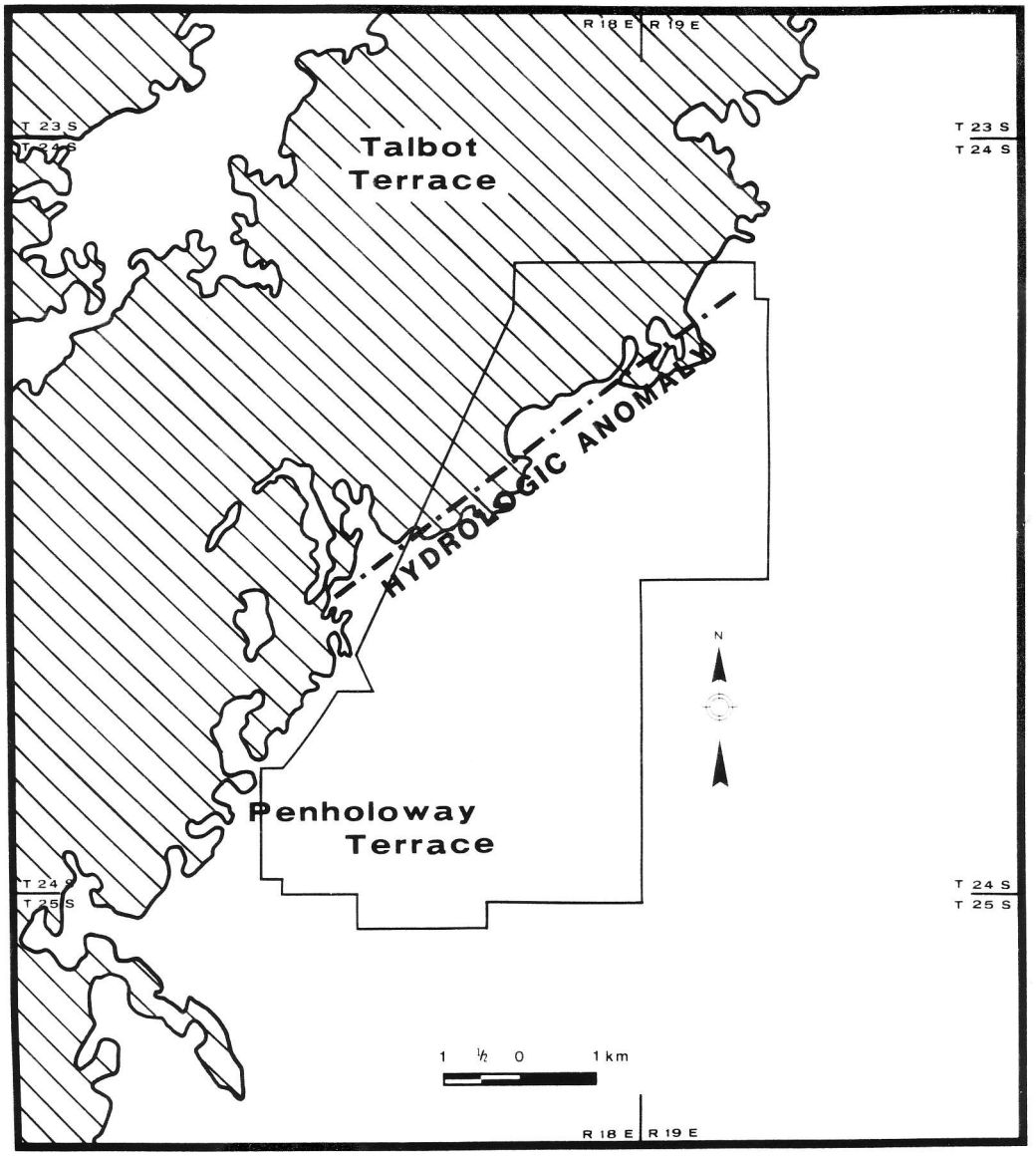


Figure 3. Areal distribution of Pleistocene marine terraces within the study area (After Gilboy and Moore, 1982, fig. 3). Outlined area is the Cross Bar Well Field.

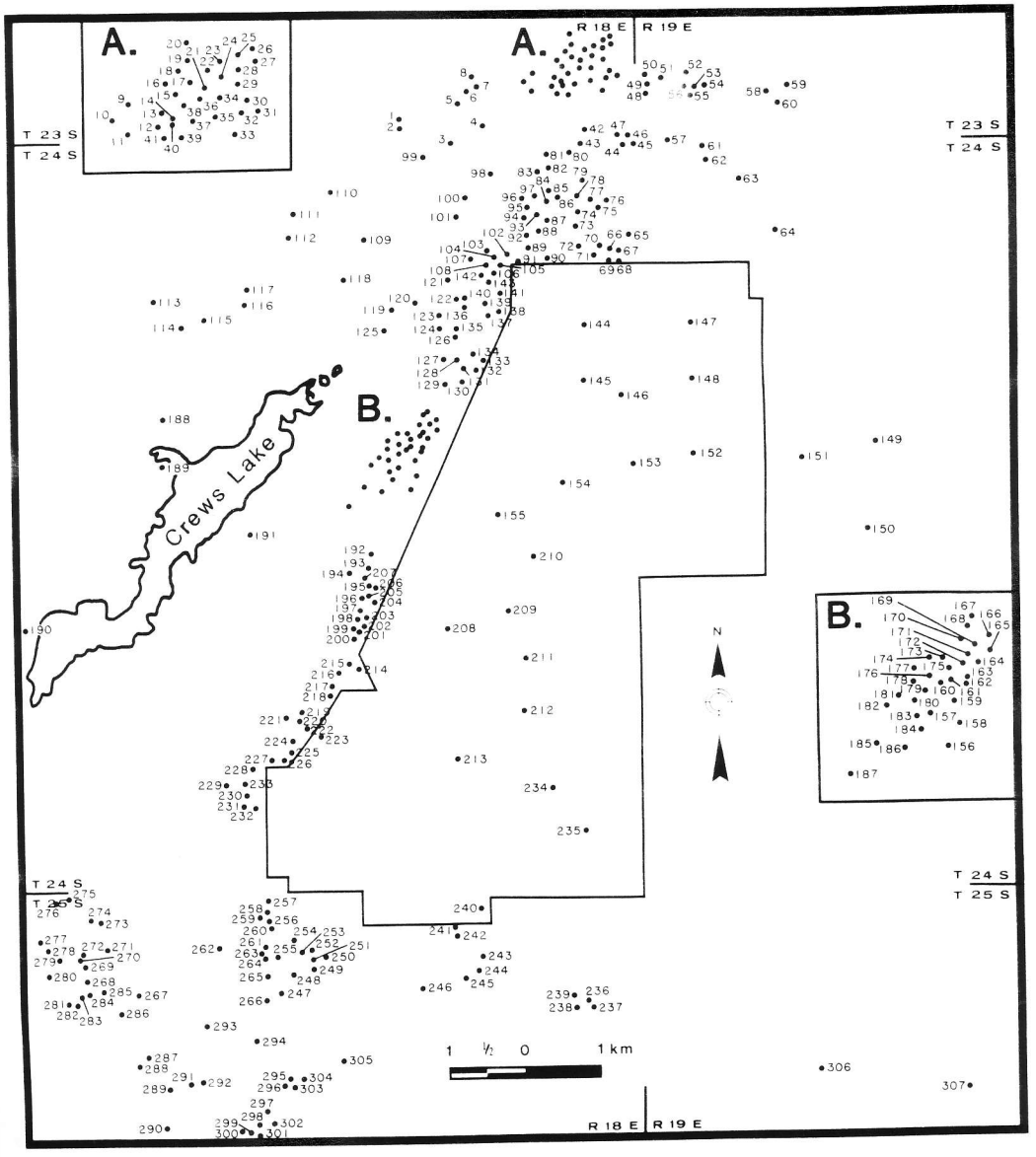


Figure 4. Location of wells sampled. Outlined area is the Cross Bar Well Field.

Stratigraphy

The chief water-bearing formations of the Floridan aquifer include, from bottom to top, the Lake City Limestone and the Avon Park Formation of Middle Eocene age; Ocala Group of Late Eocene age: Suwannee Limestone of Oligocene age; and the Tampa Limestone of Miocene age (Table 1) (Stringfield, 1966). These formations consist chiefly of limestone, dolostone and marl. The Lake City and Avon Park contain some anhydrite and gypsum. Clastic interbeds are found in several horizons throughout the limestone section. Despite differences in lithology and texture, however, the entire section may be considered a limestone which now acts as a single hydrologic system (Davies and LeGrand, 1971).

Lake City Limestone

As described by Wetterhall (1964), the Lake City Limestone of Middle Eocene age is a soft to hard, chalky, fossiliferous, tan/brown limestone with dark brown beds of dolomitic limestone at irregular intervals. The thickness of the formation beneath Pasco County averages about 150 m. The formation is, in part, highly permeable and will yield large quantities of water to wells. Before initiation of production at the Cross Bar Well Field in 1978, the Lake City was not commonly used as an aquifer in Pasco County because its depth below land surface made it economically impractical for domestic use.

Avon Park Formation

The Avon Park Formation of Middle Eocene age overlies the Lake City Limestone. It is a soft, chalky, fossiliferous, white to tan limestone with interbeds of brown, crystalline dolostone. Within the region, the Avon Park ranges from 15-120 m in thickness. The dolomitic zone, about

Table 1. Generalized stratigraphy of Cross Bar Well Field (After Cherry et al., 1970).

System	Series		Formation	Approximate thickness (m)	Lithology
Quaternary	Holocene and Pleistocene		Undifferentiated sand and clay	0-30	Sand and shell; alternating with clay, blue-gray, and clay, gray-green sandy, calcareous, phosphatic; interbedded white layers of limestone, gray, white and tan, sandy, phosphatic.
Tertiary	Pliocene				
	Miocene		Hawthorn Formation		
			Tampa Formation	30-50	Limestone, white to gray, sandy; locally crystalline; contains dolomite and silicified layers.
	Oligocene		Suwannee Limestone	0-100	Limestone, cream to tan, thin-bedded, fine grained, dense, hard.
	Eocene	Ocala Group	Crystal River Formation	0-100	Coquina, white to cream, soft, massive with pasty calcite matrix.
			Williston Formation	10-20	Coquina, cream-colored, or limestone, cream to tan, detrital; - loosely cemented calcareous matrix; locally silicified
			Inglis Formation	15-50	Limestone, cream to tan, granular, porous, medium-hard, massive, dolomite, locally tan to brown near base
			Avon Park Limestone	15-120	Limestone, white to tan, soft, chalky, granular; dolomite, tan to brown, hard, crystalline.
			Lake City Limestone	120-350	Limestone, tan to cream, soft, granular, pasty; locally interbedded with layers of dolomite and bentonitic clay; some gypsum

30 m below the top of the formation, is permeable and, like the Lake City, yields large quantities of water to the municipal wells within the Cross Bar Ranch.

Ocala Group

The Ocala Group of Late Eocene age is comprised of the Inglis, Williston, and Crystal River Formations. The Inglis Formation, a cream to gray, fossiliferous, hard, dolomitic limestone, overlies the Avon Park Formation and attains a thickness of 15-50 m in the area. The formation is highly permeable over much of the region and yields large quantities of water to municipal and deep domestic wells.

The Inglis Formation is overlain by the Williston Formation, which is in turn overlain by the Crystal River Formation. The Williston and Crystal River Formations are lithologically and hydrologically similar. The Williston and Crystal River Formations are generally white, to tan, soft, chalky, bioclastic limestones comprised of the remains of foraminifera and other fossils loosely cemented in a calcareous matrix. The formations generally attain individual thicknesses of 30-40 m within the study area. Only a few domestic wells produce water from cavities in these formations.

Suwannee Limestone

The Suwannee Limestone of Oligocene age overlies the Crystal River Formation. The formation is generally a cream to tan, fine-grained, fossiliferous limestone. Within the study area, the Suwannee attains a maximum thickness of 100 m. The lower part of the formation is generally harder, denser, and less fossiliferous than the upper part. The Suwannee Limestone is a very permeable, productive aquifer. Most

domestic and many irrigation wells produce from the lower part of this formation.

Tampa Formation

The Tampa Formation of Miocene age overlies the Suwannee Limestone. The Tampa Formation is a white to gray, sandy and clayey, finely granular, and locally fossiliferous limestone. Some of the sand and clay previously mapped as the Hawthorn Formation in northeastern Pasco County belongs to the Tampa. Within the study area, clayey units often act as semi-confining layers. The thickness of the Tampa Formation in the study area is variable because both the top and bottom surfaces are irregular, erosional surfaces. The formation is not a major source of water in Pasco County.

Hawthorn Formation

During the Miocene, the Hawthorn Formation was deposited over the pre-existing limestone. The Hawthorn is a source of silica, through leaching of clays and sedimentary opal, and of fluoride, by means of dissolution of fluorapatite (Lawrence, 1976), in the ground-water of the Floridan aquifer. These minerals are abundant in the Hawthorn.

The Hawthorn Formation, as described by Carr and Alverson (1959) and Wetterhall (1964), is comprised of four units from bottom to top:

(1) Lower limestone unit - yellow to white, soft, irregularly sandy and clayey, massive, dolomitic limestone and calcitic dolostone, with a few clay lenses and sparse phosphate nodules.

(2) Upper limestone unit - gray to white, slightly sandy and clayey, soft, massive, dolostone, limestone and calcitic dolostone, with sparse phosphate nodules.

(3) Phosphate unit - semipermeable, gray/green to tan, generally unfossiliferous, locally calcareous, sand and clay, with abundant phosphate nodules.

(4) Sand unit - semipermeable, gray to red and orange/brown, often mottled sand and clay, with traces of phosphate nodules and locally abundant secondary phosphate.

In that part of the study area where the Hawthorn is present, the basal limestone and dolostone units form the upper part of the Floridan aquifer. The overlying clayey units act as additional semi-confining layers.

Post-Miocene Sediments

Sea level fluctuated during the Pliocene and Pleistocene and ranged from as much as 80 m above the present level to 150 m below sea level (Davies and LeGrand, 1971). Change in sea level has had a significant dissolutional effect on the water-bearing formations and has caused erosion of most of the Miocene Hawthorn Formation. Undifferentiated deposits of Pliocene to Recent age overlie the entire region. These sediments consist of interbedded sands and clays which reach a maximum thickness of 45 m within the study area. A few small domestic wells produce water from the sands. The water generally contains objectionable concentrations of iron and is likely to be highly colored (Wetterhall, 1964).

A generalized, near-surface, lithologic cross section, constructed using data from well logs and soil borings, is illustrated in Figure 5. The Hawthorn Formation is typically absent and the surficial sediments are generally underlain by clay and limestone units of the Tampa

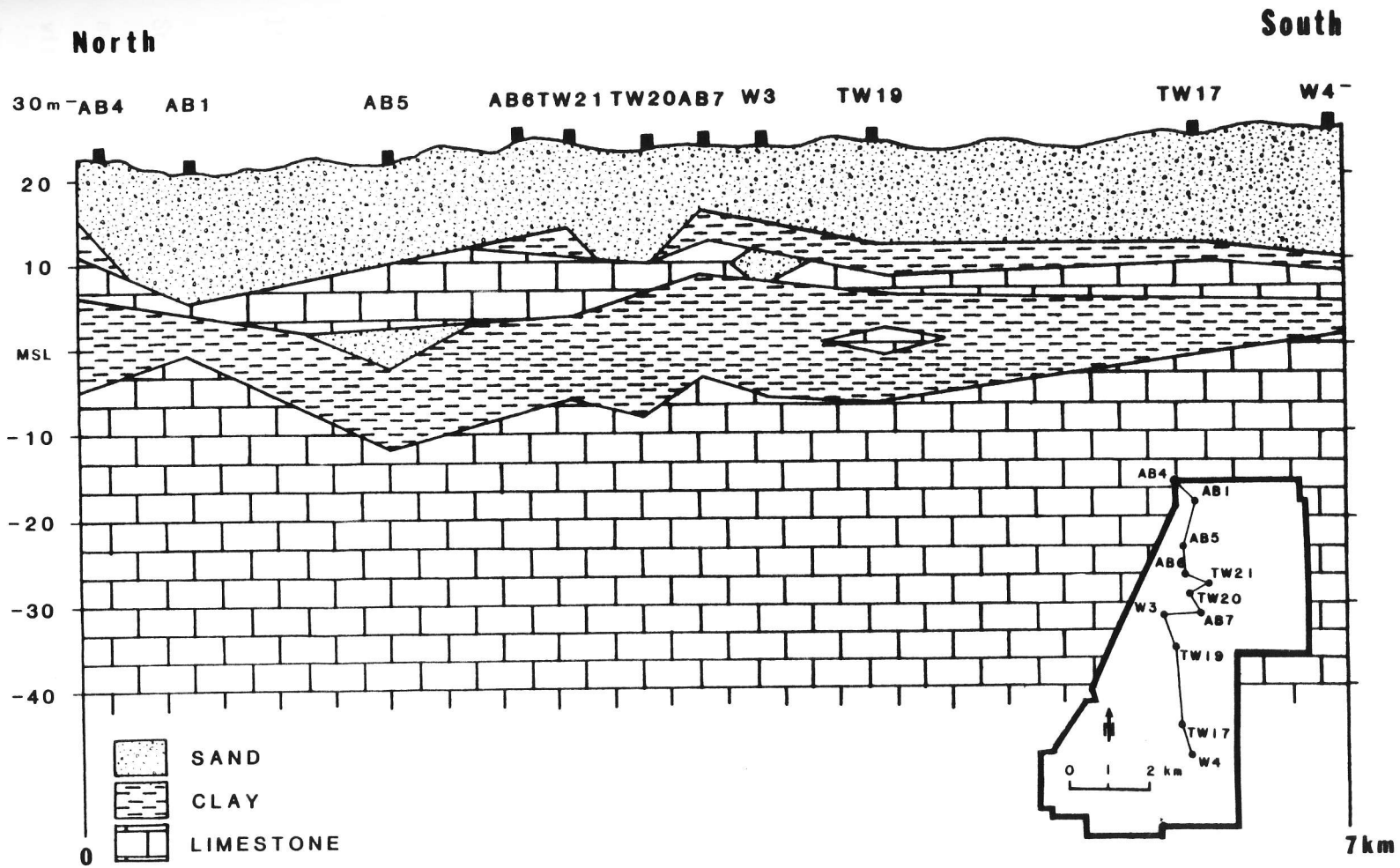


Figure 5. Generalized, near-surface lithology. Cross Bar Well Field, Pasco County, Florida (After Gilboy and Moore, 1982, fig. 6).

Formation. It is important to note the discontinuous nature of the upper semi-confining clay layer.

Geologic Structure

The Floridan Peninsula is comprised of a complex, Pre-Cretaceous basement, overlain by hundreds of meters of Tertiary carbonate formations, Miocene sands and clays and unconsolidated Pliocene and Quaternary sands (Applin and Applin, 1944). The Tertiary carbonate formations form a relatively thick, broad belt of nearly flat-lying units, which extend along the Atlantic Coastal Plain from North Carolina to Florida, and along the Gulf Coast to Alabama. The carbonate units tend to dip gently and thicken slightly in a coastal direction and are commonly concealed by the Miocene Hawthorn Formation or equivalent formation. The entire region is blanketed by a relatively thin veneer of Pliocene and Quaternary sands that range in thickness from a few meters near the inner margin of the coastal plain to several tens of meters along the coast (Davies and LeGrand, 1971). The general anticlinal structure (commonly referred to as the Peninsular Arch) is interrupted by scattered, minor normal faults; tidal-stress joints; extensive, north-south, basement-controlled features; and the Ocala Uplift in west-central Florida. At the crest of the uplift the limestone is exposed at the surface.

The Ocala Uplift began to rise near the end of the Oligocene. Stringfield (1966) proposed that it was produced by compressive crustal stresses. Conversely, Winston (1976) suggests that the arch was passive with subsidence on each side. The uplift resulted in a broad, elongate dome that trends southeast. Deposition on the flanks of the rising dome

resulted in thickening of the Oligocene and Miocene formations away from the structure. Some of the effects of the regional structure on the distribution, thickness, and lithology of the sedimentary formations have been described by Applin and Applin (1965).

Longitudinal, tensional fractures, oriented parallel to the Ocala Uplift, are common in the Cenozoic rocks. These fractures developed as stress-relief fractures in response to the forces that produced the uplift. The area of study lies on the southwestern flank of the Ocala Uplift where the limestone units dip towards the Gulf of Mexico.

The geologic history of the region has had a significant affect on the water-bearing properties of the geologic formations, the quality of the ground water, the present topography and drainage, and areas of recharge of the Floridan aquifer (Stringfield, 1966). Changes in sea level during the Pleistocene modified recharge and discharge patterns of the Floridan aquifer from one glacial epoch to another (Stringfield, 1966). Extensive, horizontal solution cavities developed chiefly in the upper part of the zone of saturation under water-table conditions as the water rose and fell with changes in base level (Davies and LeGrand, 1971). This created various horizons of extensive cavity development throughout the Tertiary limestone section. During high stands of the sea, recharge areas of the aquifer were submerged and some sinkholes and solution cavities in the limestone were filled with unconsolidated sediments. The present cycle of karstification renewed circulation of water and developed additional secondary permeability by solution and removal of unconsolidated deposits in the buried karst (Davies and LeGrand, 1971). Some of the salt water that entered the system during the Pleistocene has not been completely flushed from the aquifer

(Stringfield, 1966).

Horizontal layering and vertical jointing of the limestone has resulted in variable horizontal and vertical permeabilities. Vertical permeability depends primarily on void size from small cracks to solution-enlarged pipes more than 30 m in diameter. Hard zones in the limestone are capable of maintaining small or large openings, but small openings in the soft, friable and chalky limestones generally are filled by surrounding material. Larger openings, which locally penetrate the softer zones, result from collapse or dissolution of the harder, underlying limestone. Although the soft layers may tolerate some vertical movement of water, horizontal permeability is restricted principally to hard zones in the limestone (Wetterhall, 1964). In the Floridan aquifer, the highest permeabilities usually occur in or near such hard zones. These hard zones are common in the base of the Suwannee Limestone, within the Inglis Formation, and to about 30 m below the top of the Avon Park Limestone (Wetterhall, 1964).

Hydrology

Central Pasco County receives 130-142 cm of precipitation annually (Cherry et al., 1970). About 86 cm of it falls during a five month period from May to September. Lakes, streams, and aquifer levels are highest in late summer or early fall following the rainy season and are lowest in late May or early June. Inflow to the aquifer system occurs when precipitation exceeds evapotranspiration, generally from June to September.

Surface Hydrology

Surface drainage is poorly developed and the region is primarily

drained by seepage into the underlying several hundred meters of sedimentary rock. The Pithlachascotee River is the principal stream within the study area (Figures 1 and 2). Its upper reaches contain many lakes, sinks, and depressions, while its middle to lower sections are swampy and ill defined. Its major tributaries are Jumping Gully and Five Mile Creek. An average of 1.65 m^3/sec discharges from the Pithlachascotee River (Cherry et al., 1970). Jumping Gully and Five Mile Creek account for 0.75 m^3/sec and 0.15 m^3/sec, respectively. The remaining 0.75 m^3/sec comes from base flow downstream from these tributaries. In general, over 70% of the annual stream flow from the area is water derived from the Floridan and surficial aquifers (Cherry et al., 1970).

Crews Lake, in the headwaters of the Pithlachascotee River (Figures 1 and 2), has an active sinkhole in its northern section. This sink, the Hernasco Sink, is hydraulically connected to the Floridan aquifer and transmits vertically about half of the yearly outflow of the lake. Surface depressions occupied by lakes and swamps appear to be the result of either the subdued, original karst surface, the unequal compaction of surficial sands, or the solution of the subadjacent limestone and consequent lowering of the surface. As with Crews Lake, many lakes are hydraulically connected to the Floridan aquifer through sinkholes. In a three year study by Cherry et al. (1970), lake levels within the study area fluctuated from 0.6 to 1.2 m (Cherry et al., 1970) depending, in part, on annual precipitation, degree of hydraulic interconnection between surface- and ground-water bodies, and location with respect to the surface-water divide between the coastal rivers and Hillsborough drainage basins (Yobbi and Schiner, 1981).

Surficial Aquifer

The saturated, fine-grained surficial deposits overlying the limestone constitute the shallow or surficial aquifer. It recieves water almost entirely from local precipitation, with minor recharge from irrigation, and effluent from septic tanks and cesspools (Stringfield, 1966). Within the study area, the water table of the shallow aquifer ranges from slightly below to as much as 5 m above the potentiometric surface of the Floridan aquifer (Stringfield, 1966; Cherry et al., 1970). Throughout much of the area, water moves downward from the shallow aquifer and recharges the Floridan.

Floridan Aquifer

In the area of study, the Floridan aquifer consists of all or part of the Lake City Limestone, the Avon Park Formation, the Ocala Group, the Suwannee Limestone and the Tampa Formation. The aquifer contains a number of thick, permeable zones, which, despite their range in permeability, function as a single aquifer. The top of the Floridan is taken to be the top of the first consistent limestone, usually the Tampa Formation, but in some places the basal limestone components of the Hawthorn Formation may be included. Recharge occurs over the entire area through streams, lakes, sinkholes, and permeable materials overlying the aquifer. The local, high points on the potentiometric surface of the Floridan aquifer (Yobbi and Schiner, 1981; Yobbi et al., 1981) are mounds informally referred to as the Pasco Highs (Wetterhall, 1964). Water moves from these highs to the northwest across the study area to the Gulf of Mexico. The "hydrologic anomaly" shown in Figure 3 is defined by a change in potentiometric-surface elevations of up to 1 m

in as little as 100 m of horizontal distance (Gilboy and Moore, 1982). According to Miller (1977) the "anomaly" reflects the transition of the Floridan from artesian to water-table conditions.

Cherry et al. (1970) show that the potentiometric surface of the Floridan aquifer fluctuated from less than 1.2 to more than 2.4 m in different regions of the study area over 3 years (Cherry et al., 1970). Seasonal variation in recharge rates is responsible for regional fluctuation of aquifer levels. Local, large-scale fluctuations of the water levels observed in the surficial and artesian aquifers, as well as many of the lakes in the study area, are attributed to the discontinuous nature of the upper semi-confining unit and direct hydraulic interconnection of surface- and ground-water bodies through sinkholes.

PREVIOUS WORK

Carbonate Aquifer Systems

Carbonate rocks are among the most productive aquifers, even though their permeability and porosity may vary enormously from the time of their origin in the marine environment to their development as a fresh-water aquifer after emergence (Stringfield, 1966; Hanshaw and Back, 1979). Some aquifers in carbonate rock possess intergranular porosity, however, in most carbonate aquifer systems, the openings in which ground water is stored and through which it moves have been dissolved by the water itself (Thrailkill, 1972). Initially, carbonate strata can develop appreciable secondary permeability as a result of openings along bedding planes, joints, fractures and fault zones (Lattman and Parizek, 1964; Parizek, 1976). Secondary openings in carbonate rock may be enlarged as a result of calcite and dolomite dissolution by the circulation of weakly acidic ground water undersaturated with respect to these minerals (Thrailkill, 1972; Freeze and Cherry, 1979).

Garrels and Christ (1965) and Thrailkill (1972) discuss the principles of carbonate equilibrium, the driving force behind dissolution. Studies by Back (1963), Back and Hanshaw (1970), Langmuir (1971), and Thrailkill (1972) investigate the hydrogeochemistry of several karst regions. Their studies show that the chemistry of ground water in carbonate aquifers is a function of source, infiltration

history, movement, and residence time within the ground-water flow system. Dissolution of calcium carbonate causes prevailing hard ground-water conditions with somewhat higher mineral concentrations occuring in zones of restricted flow and unconnected pore space (Filipovic and Dimitrijevic, 1967). Lower dissolved-solids concentrations are usually associated with regionally flowing water within karst conduits, such as fractures and joints.

Karst aquifers generally have two modes of fluid transport; (1) conduit fow and (2) diffuse flow. Foremost, flow through interconnected, secondary pore space, or conduit flow, provides direct hydraulic connection between recharge and discharge areas. There is little attenuation of pollutants by filtration, sorption, or microbiological decomposition (Todd, 1980). Contaminated water that infiltrates the matrix enters the diffuse-flow system and is stored there for relatively long periods of time, discharging slowly into the conduit-flow system (Werner and Medville, 1977). Fractured carbonate aquifers are generally highly susceptible to pollution because of high transmissivity values in the network of interconnected, solution openings and the lack of effective chemical means of attenuating the contaminants.

Geochemical-Data Processing

Geochemistry has played an essential part in hydrogeochemical interpretations. In addition to residence time within the system, the chemical composition of ground water reflects the chemical nature of the geologic formations with which the water is in contact at the sampling point as well as along its flow path (Lawrence and Upchurch, 1982).

Back (1961) and Lawrence (1976) review a variety of conventional hydrogeologic techniques that are commonly employed in hydrogeochemical studies. When ground water mixes, however, it is difficult to identify separate recharging water masses using such conventional techniques. Factor analysis has been successfully used to sort out the hydrogeochemical processes that account for the relationship among commonly-collected, ground-water quality data (Dawdy and Feth, 1967; Hitchon et al., 1971). It has been applied to the Floridan aquifer system by Lawrence (1976), Lawrence and Upchurch (1977), Ceryak (1977), Dalton (1978), Dalton and Upchurch (1978), Kaufmann (1979), and Lawrence and Upchurch (1982). Lawrence (1976) has shown that the areal distribution of ground-water quality data can reflect recharging water masses indicative of zones of increased fractured density.

Photolineaments

Photolinear features have been studied in oil, gas, mineral and ground-water exploration, and in structural/tectonic contexts using aerial photography and satellite imagery since the early 1950's. In carbonate terrains, natural, systematic, rectilinear patterns of bedrock fracture are often visible at the land surface as fracture traces and on aerial photographs as photolineaments. These features are generally straight or slightly curving in plan, are unaffected by topography, and hence, are considered to be surface manifestations of vertical to near-vertical zones of fracture concentration (Kaiser, 1950; Blanchet, 1957; Lattman, 1958; Lattman and Metzke, 1961; Lattman and Parizek, 1964; Wobber, 1967). Fracture traces are often discernable on aerial photography as long, narrow, relatively-straight alignments of

vegetation, soil tones, surface depressions, and drainage patterns. These identifying features may reflect underlying zones of localized bedrock weathering and increased permeability and porosity that may serve as hydrogeologic recharge pathways (Blanchet, 1957; Lattman and Nickelson, 1958; Lattman and Parizek, 1964). Subsurface fracture zones are often detectable on aerial photography even when covered by as much as 30 m of regolith. Moore (1981) has demonstrated that several geophysical techniques can be used to delineate subsurface zones of increased fracture density. Within a fracture zone, these techniques show increased depths to the limestone and thickening of the weathered mantle and regolith.

Hydrogeologic studies of the Cambrian-Ordovician carbonates of the Fredrick Valley, Maryland (LaRicca and Rauch, 1977) and the Nittany Valley in central Pennsylvania (Lattman and Parizek, 1964) have shown that photolineaments are often associated with zones of high well yield. Similar conclusions were drawn in photolineament studies by Lattman and Nickelson (1958), Parizek (1976), Siddiqui and Parizek (1977), and Moore et al. (1977). Setzer (1966) found a similar relationship in wells penetrating abundantly-fractured Devonian gneiss and mica schist overlain by more than 100 m of unconsolidated strata, and Wobber (1967) had similar results in jointed Precambrian basement rock buried by 46 m of glacial sediment.

Fracture patterns in the northern part of the Floridan peninsula where first described and mapped based on physiographic features and on mosaics and contact prints of aerial photography by Vernon (1951). In a similar study by Ritchie (1983), photolineaments were mapped within an area of approximately 9,000 km^2 in central Florida. In Cypress Creek

Well Field, 13 km south of Cross Bar Well Field, Leggette, Brashears & Graham, Inc. (1974-1977) have shown that wells of higher yield tended to be drilled in highly fractured rock, and the depths required for sufficient yields were considerably less than in wells with less fractured rock. Consequently, for the Cross Bar Well Field, Miller (1977) applied photolineament analysis as an economic means of selecting favorable sites for additional large-capacity, municipal wells. Miller identified photolineaments on sinkhole features. Favorable drilling sites were chosen at locations where a number of photolineaments intersect on the premise that these were zones of intense fracturing and solution of the limestone. Miller was not able to trace photolineaments into the northermost part of the Cross Bar Well Field, which is an area lacking sinkholes. Moore (1981) confirmed by geophysical means that photolinear features in the Cross Bar Well Field are a result of subsurface zones of vertical fracture in the aquifer limestone.

PROCEDURE

Sample Collection and Laboratory Analysis

Over a three year period from April, 1979, to December, 1981, the West Coast Regional Water Supply Authority collected and analyzed 307 ground-water quality samples from 290 domestic wells and 17 municipal supply wells. Nearly all of the private wells are completed at various depths within the Suwannee Limestone. The municipal wells within the Cross Bar Ranch penetrate the Avon Park Formation and the Lake City Limestone.

Most of the wells are cased through the surficial deposits and semi-confining clays, and are open hole in the aquifer. Cross Bar wells are screened, however, due to the soft, coquinoid limestone within the Williston and Crystal River Formations and the presence of clastics, interbedded throughout the limestone section. Available subsurface geologic information gives no evidence of discrete producing zones at various depths of formation heterogeneity.

Water samples were analyzed at the Water Authority's Cypress Creek Water Quality Laboratory. For all samples, pH, color, bicarbonate alkalinity, total alkalinity, total hardness, and the concentrations of Ca^{+2}, Mg^{+2}, SO_4^{-2}, Cl^{-} and total iron (Fe^{+2} + Fe^{+3}) were determined according to Standard Methods. Data are listed in Appendix A along with other pertinent well data.

Data Processing

Numerous hydrogeochemical studies have been conducted employing a variety of approaches that deal with the extraction of information from chemical ground-water data. Since this study involves the collection of spatially-distributed, multivariate observations, R-mode factor analysis was utilized to extract hydrogeochemical information from the raw ground-water quality data provided by the West Coast Regional Water Supply Authority. This numerical technique transforms the data into an easily interpretable form by filtering the data and identifying data clusters that reflect different hydrogeochemical processes (Davis, 1973).

This study employed routine FACTOR of the Statistical Package for the Social Sciences (Nie et al., 1975) with factoring method PA2, or principal components factoring with iterations (Figure 6). The final factor solution generated and employed was the orthogonal, varimax rotation factor solution with Kaiser normalization. All statistical analysis were preformed on the IBM 360/65 computer at the Unversity of South Florida.

Prior to factor analysis, the data are generally normalized according to criteria presented by Howarth and Earl (1979). This is recommended since the first step in factor analysis is computation of a correlation coefficient matrix, which requires normal distributions in all variables (Lawrence and Upchurch, 1982). Lawrence (1976) has shown that the ground-water quality parameters examined in his study of the Floridan aquifer exhibit nearly normal distributions and correlation coefficients did not change upon normalization and recomputation. This suggests that the raw chemical data used in this study are in a

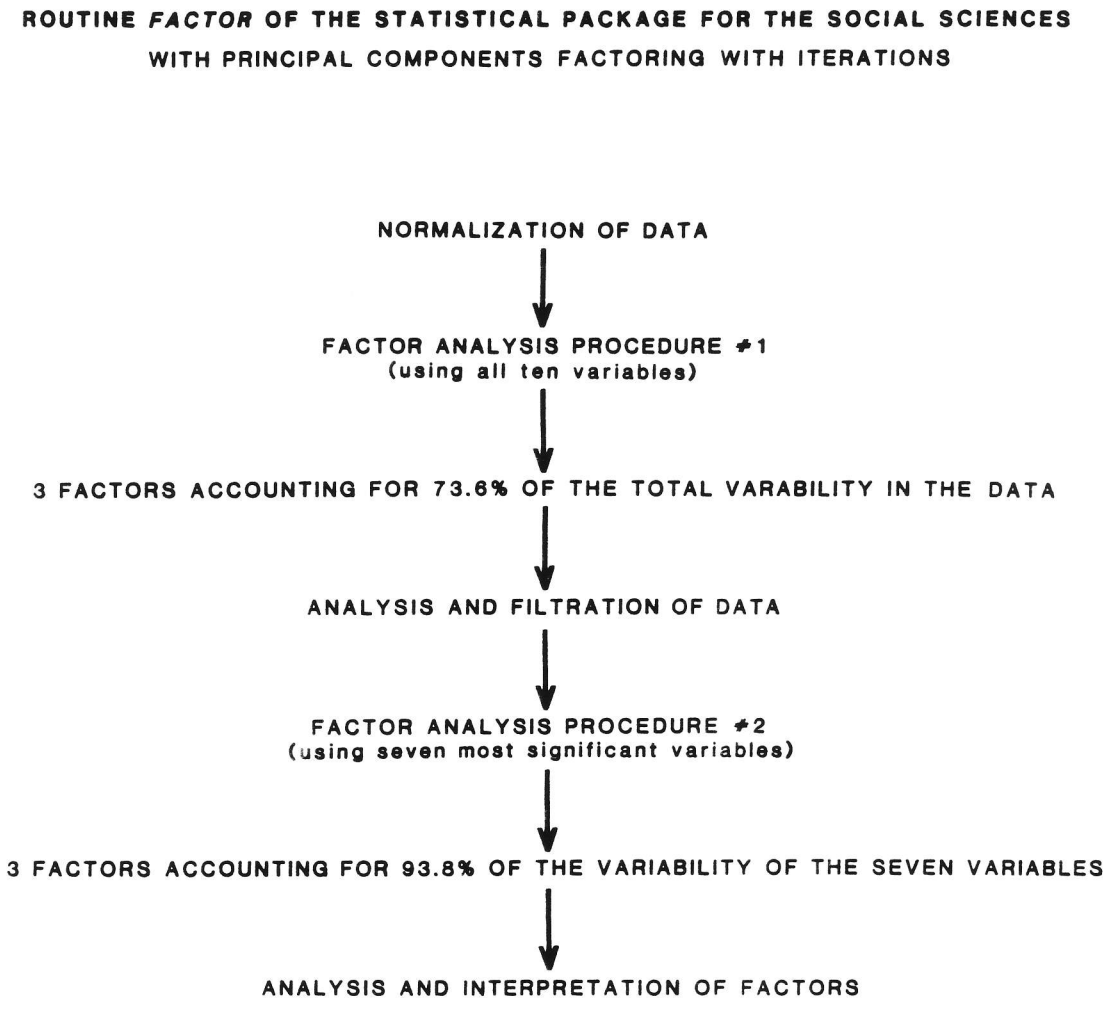


Figure 6. R-mode factor-analysis procedure.

sufficient form for further analysis.

The ten chemical variables (Table 2) were standardized and correlated by means of Pearson product-moment correlation coefficients (Table 3). The matrix lists only those correlations significant at alpha values less than or equal to 0.05.

Table 4 shows the eigenvalues for the initial factor solution using all ten variables. The critical eigenvalue for factor extraction was 1.0. The analysis reduced the ten variables to three factors. These factors accounted for 73.6% of the total variability in the data (Figure 6).

While all of the variables have some pattern of distribution, they most probably do not represent seven separate processes. The distribution pattern of each variable contains regional information plus "noise" due to local conditions, sampling, and analyitical error (Lawrence, 1976). The difference between the calculated communality and 1.0 is attributed to the error term, so analytical and other random noise can be evaluated and filtered from the factoring procedure (Lawrence and Upchurch, 1982). Each of the factors generated by factor analysis represents a filtered and weighted, linear combination of the variables based on the physical and chemical controls imposed by the system.

Figure 7 is a graph showing the percent of the variability, based on communalities, of each parameter that was accounted for by the three factors after final varimax rotation. The distribution of the variables is distictly bimodal. Calcium, magnesium, iron, color, bicarbonate alkalinity, total alkalinity, and total hardness show some pattern of distribution over the study area and contributed significant information

Table 2. Physical and chemical variables used in factor analysis.

Name	Number of Samples	Units	Maximum Value	Minimum Value	Mean	Standard Deviation
pH	307	---	8.11	6.90	7.59	0.21
Color	307	PCU*	75.0	0.0	10.9	14.6
Bicarbonate Alkalinity	307	mg/1 as $CaCO_3$	267.0	48.0	131.9	33.8
Total Alkalinity	307	mg/1 as $CaCO_3$	267.0	48.0	131.9	33.8
Total Hardness	307	mg/1 as $CaCO_3$	252.0	65.0	143.0	33.5
Calcium	307	mg/1	98.0	21.0	52.6	13.0
Magnesium	307	mg/1	10.9	0.0	3.2	1.8
Iron	305	mg/1	0.80	0.00	0.14	0.19
Sulfate	306	mg/1	51.0	0.0	2.4	4.8
Chloride	306	mg/1	36.5	7.0	11.5	2.8

*Platinum Cobalt Units

Table 3. Correlation coefficient matrix. Coefficients not significant at $\alpha > 0.05$ are omitted.

	pH	Color	Bicarbonate Alkalinity	Total Alkalinity	Total Hardness	Calcium	Magnesium	Iron	Sulfate	Chloride
pH		-0.33	-0.52	-0.52	-0.54	-0.53		-0.39		-0.24
Color			0.26	0.26	0.20	0.17	0.20	0.71		
Bicarbonate Alkalinity				1.00	0.92	0.91	0.19	0.25	-0.20	
Total Alkalinity					0.92	0.91	0.20	0.25	-0.20	
Total Hardness						0.98	0.23	0.21	-0.17	0.16
Calcium								0.20	-0.17	0.15
Magnesium										0.19
Iron										
Sulfate										
Chloride										

significant at $\alpha = 0.05$ (%P = 99.0%); degrees of freedom = 305

Table 4. Eigenvalues and percent variability for R-mode factor analysis using all ten variables.

Factor	Eigenvalue	Percent of Variability	Cumulative Percent Variability
1	4.48729	44.9	44.9
2	1.66304	16.6	61.5
3	1.20943	12.1	73.6
4	0.96091	9.6	83.2
5	0.75522	7.6	90.8
6	0.50728	5.1	95.8
7	0.28229	2.8	98.7
8	0.13158	1.3	100.0
9	0.00240	0.0	100.0
10	0.00055	0.0	100.0

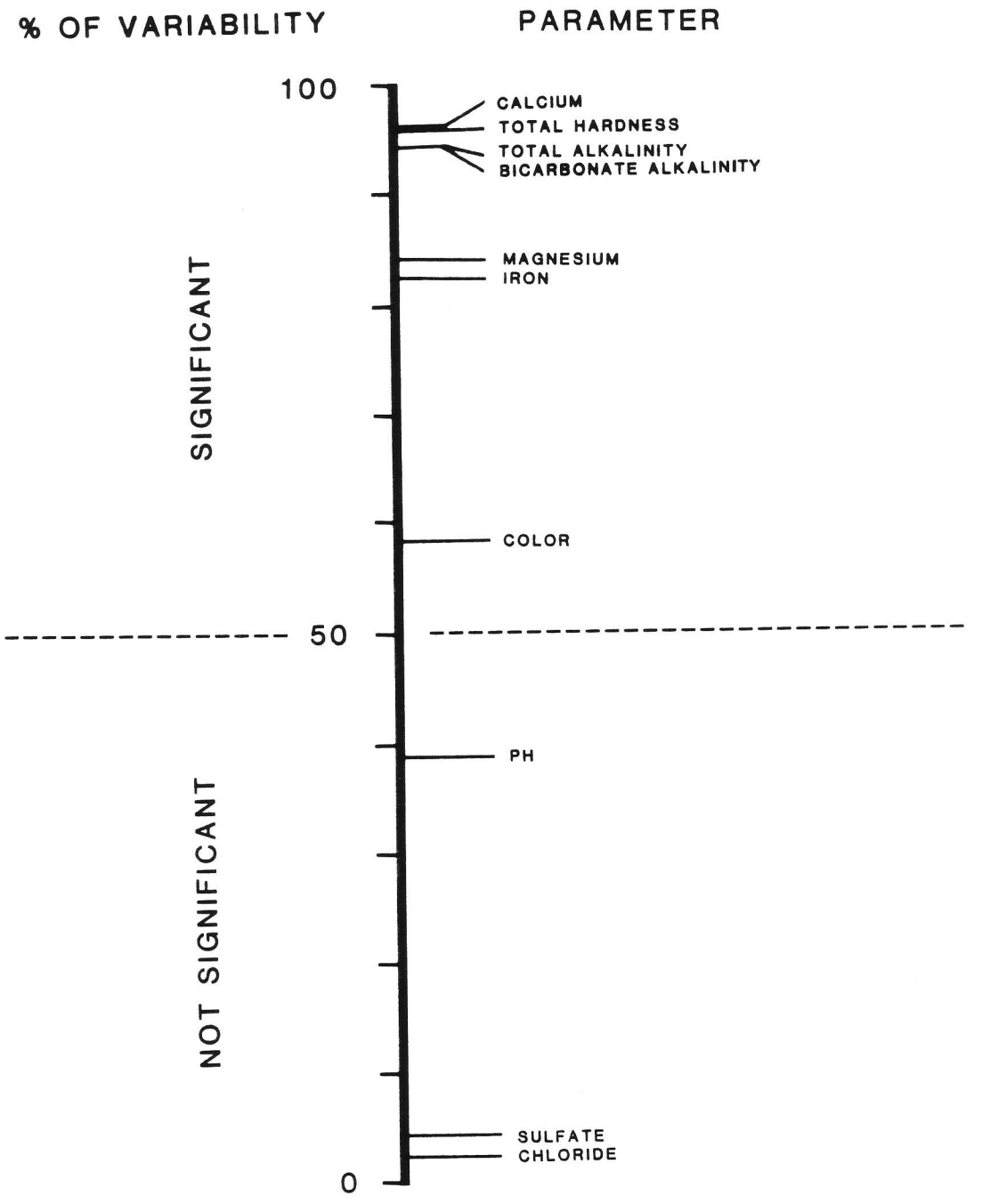


Figure 7. Graph showing percent of variability of each variable accounted for by factor analysis using all ten variables. Level of significance chosen at 50 percent.

towards identification and interpretation of the underlying hydrogeochemical processes.

The analysis accounted for less than 40% of the variability of the variables, pH, sulfate, and chloride. For these parameters, the pattern of distribution over the study area was weak, which suggests that the variables are either distributed randomly or are uniform (Lawrence, 1976). Since these three variables have little or no pattern, they contribute little hydrogeochemical information to an interpretation. For this reason they were deleted from the rest of the analysis, and the remaining seven variables were used as input for another factor analysis (Figure 6).

Table 5 shows the eigenvalues for the initial factor solution using only the seven chemical parameters that had greater than fifty percent of the variability accounted for in the previous analysis. In this case, the critical eigenvalue for factor extraction was 0.90. Three factors were extracted, accounting for 93.8% of the variability of the seven variables. These factors represent three chemically-distinct, overlapping processes, which are lithologically controlled. Table 6 shows the final Varimax rotated factor matrix which lists the variables, the loading of each variable on each factor and the communalities.

Table 7 shows the factor-score coefficient matrix. From these coefficients, the value in standard form of each of the three factors can be calculated for each sample location. If the original data are normal, the scores have a similar distribution and structure and reflect the importance of a given factor at that sample site. Factor scores may be contoured for each factor and evaluated as to the areal importance of the chemical processes represented by the factor (Lawrence and Upchurch,

Table 5. Eigenvalues and percent variability for R-mode factor analysis using seven most significant variables.

Factor	Eigenvalue	Percent of Variability	Cumulative Percent Variability
1	4.04702	57.8	57.8
2	1.56931	22.4	80.2
3	0.94786	13.5	93.8
4	0.28784	4.1	97.9
5	0.14496	2.1	100.0
6	0.00243	0.0	100.0
7	0.00057	0.0	100.0

Table 6. R-mode factor loadings using Varimax rotation for the seven most significant variables.

Variable	Communality h^2	Rotated Orthogonal Factors 1	2	3
			FACTOR 1	
Bicarbonate Alkalinity	0.950	0.956	0.163	0.102
Total Alkalinity	0.951	0.956	0.164	0.101
Total Hardness	0.951	0.962	0.096	0.127
Calcium	0.952	0.976	0.084	-0.066
			FACTOR 2	
Color	0.726	0.112	0.837	0.113
Iron	0.697	0.127	0.825	0.024
			FACTOR 3	
Magnesium	0.890	0.091	0.106	0.933

Table 7. Factor score coefficient matrix.

Variable	Factor 1	Factor 2	Factor 3
Color	-0.06639	0.52207	-0.01517
Bicarbonate Alkalinity	0.17813	-0.09126	0.19480
Total Alkalinity	0.31389	0.14656	-0.12856
Total Hardness	0.08459	-0.38165	2.50595
Calcium	0.46191	0.22459	-2.58104
Magnesium	-0.01961	0.00867	0.45674
Iron	-0.05616	0.47643	-0.06134

1982). Put more simply, factor scores can be related to the intensity of the chemical processes described by each factor (Dalton and Upchurch, 1978). Low factor scores (less than -1) reflect areas essentially unaffected by the process and high factor scores (greater than +1) reflect areas most affected. Near zero scores approximate areas affected to an "average" degree by the chemical process or factor (Lawrence and Upchurch, 1982).

Photolineament Analysis

This study takes advantage of photolineament analysis, a relatively quick, inexpensive, regional method for locating vertical fracture zones that may serve as recharge pathways to the Floridan aquifer. Moore (1981) used several geophysical techniques to confirm that selected photolineaments in the Cross Bar Well Field are surface manifestations of subsurface zones of vertical to near-vertical fracture concentration.

Surface expressions of fracture zones were mapped as photolineaments identified on three scales of aerial photography:

(1) 1:24,000 scale stereo panchromatic 9"x9" contact prints: March 22, 1951 and March 26, 1979, Florida Department of Transportation.

(2) 1:80,000 scale stereo color-infrared 9"x9" contact prints: December 10,1972, Mark Hurd Aerial Survey, Inc.

(3) 1:130,000 scale color infrared diapositive: October 14, 1969, Mark Hurd Aerial Survey Inc.

The 1:24,000 scale photographs was used primarily to map photolineaments shorter than 2 km. The 1951 set of photography were used specifically for mapping photolineaments in areas that have been obscured by recent development. Photolineaments longer than 2 km were mapped using smaller

scale (1:80,000 and 1:130,000) photography. Photographs were interpreted individually by simple visual examination, and in stereo using a mirror stereoscope and a Bausch and Lomb Stereo Interpretation System. These processes are subjective. Moore (1982) discusses biases introduced in photolineament interpretation processes.

Photolineaments were mapped using procedures developed by Wadsworth (1982, pers. comm.) in which individual photolineaements are identified by a single or a combination of identifying criteria. Criteria used in this study were soil tone, sinkhole, elongate sinkhole, sinkhole alignment, tree alignment, vegetation body, elongate vegetation body, vegetation body alignment and straight water-course segment (see Appendix B for individual photolineament descriptions). The reliability or confidence in identification of each segment of a photolineament is expressed by a subscript representing a ranking system: (1) definite photolineament; (2) definite photolineament, precise location indeterminable; (3) probable photolineament; and (4) possible photolineament.

The identifying criteria and confidence ranking for each photolineament can thus be expressed as a series of abbreviations and subscripts describing a single or combination of segments. For example, st_1, $ta_{3,4}$, denotes a two component photolineament. The first, most prominent component is a definite photolineament of known location, expressed by a soil tonal pattern (st); the second component denotes a probable grading into a possible photolineament expressed by tree alignement (ta).

This photolineament characterization scheme has many advantages: (1) it improves clarity and reproducibility of the data; (2) its

versatility facilitates revision and/or further photoanalysis; (3) it facilitates correlation of results between independent studies; and (4) it permits extraction of various data subsets for more detailed interpretation.

The aerial photographs used in this study commonly displayed some distortion resulting from irregularities in flight path. This distortion was minimized by registering individual scenes to a smaller scale base map prepared from a single image. In this study, control points were located on a 1:130,000, scale color-infrared diapositive that completely images the study area. These control points were then located on twenty 1:24,000 scale panchromatic 9"x9" contact prints, with at least three control points lying on each of the larger scale photographs. A composite photolineament map was constructed by reducing individual lineament overlay sheets prepared from each of the 1:24,000 scale photographs to fit the control points on the 1:130,000 scale base map using a Map-O-Graph reflecting projector, and transferring all mapped photolineaments onto the base map. Prior examination of several sets of photography of differing scales showed correspondence of control points between the individual scenes and the base map to be best when the differences between the two was greatest, providing that all control points could be identified clearly.

RESULTS AND INTERPRETATIONS

Analysis of Raw Ground-Water Quality Data

The quality of water in the upper 300 m of the Floridan aquifer, northwest-central Pasco County, Florida (Table 2), meets, in general, U.S. Public Health Service Drinking Water Standards. The mineral content is less than 300 mg/l and is satisfactory for domestic and most industrial uses except for difficulties which may result from the hardness (Stringfield, 1966). Most of the mineral content is calcium bicarbonate, which causes the water to be alkaline and moderately hard to very hard. Sulfate, iron, and magnesium occur in concentrations generally less than 10 mg/l. Chloride concentrations are slightly higher.

pH

Water in the Floridan aquifer tends to be slightly alkaline (Table 2). The pH of water samples collected from the upper 200 m of the Floridan aquifer range from 7.5 to 8.0. Below 200 m, pH is generally less than 7.5. However, field pH measurements of ground-water samples taken at the point of discharge may only approximate actual pH conditions within the aquifer. The carbon dioxide-bicarbonate-carbonate equilibrium and buffer systems existing in the water sampled from the Floridan may be disturbed upon release of the confining pressure (Hem, 1959).

Iron

Iron, generally in the form of ferrous bicarbonate, $Fe(HCO_3)_2$, remains in solution in ground water until it is exposed to air in the well pumping system (Stringfield, 1966). The iron then oxidizes to the ferric state and precipitates as the hydroxide $Fe(OH)_3$;

$$2Fe^{+2} + 4HCO_3^- + H_2O + 0.5O_2 \rightleftharpoons 2Fe(OH)_3 + 4CO_2. \quad (1)$$

or the oxyhydroxide FeOOH;

$$2Fe^{+2} + 4HCO_3^- + 3H_2O + 0.5O_2 \rightleftharpoons FeOOH + 4H_2CO_3. \quad (2)$$

Since bicarbonate ions are removed from solution and, in equation (1), carbon dioxide is given off, the conversion of iron to the ferric state may have had a marked effect on the pH of the samples (Hem, 1959).

Iron is objectionable in water in concentrations greater than 0.3 mg/l (Stingfield, 1966) because it gives the water a disagreable taste and stains laundry and bathroom fixtures.

Iron in small amounts, generally not exceeding a few mg/l, is present in some places in the surficial sands. Over most of the area, it is present only in trace amounts in the water of the Floridan aquifer (Figure 8). Where isolated, high iron concentrations occur, there is a possibility that some of the iron reported in the chemical analysis may be from rusty well casings or pipes through which the water flowed.

The source of iron in solution in the Floridan aquifer is thought to be derived from the oxidation of pyrite and the leaching of iron-bearing clays and/or organics found in varying amounts throughout the Miocene to Recent deposits.

Sulfate

The concentration of sulfate, in the Floridan aquifer, is generally

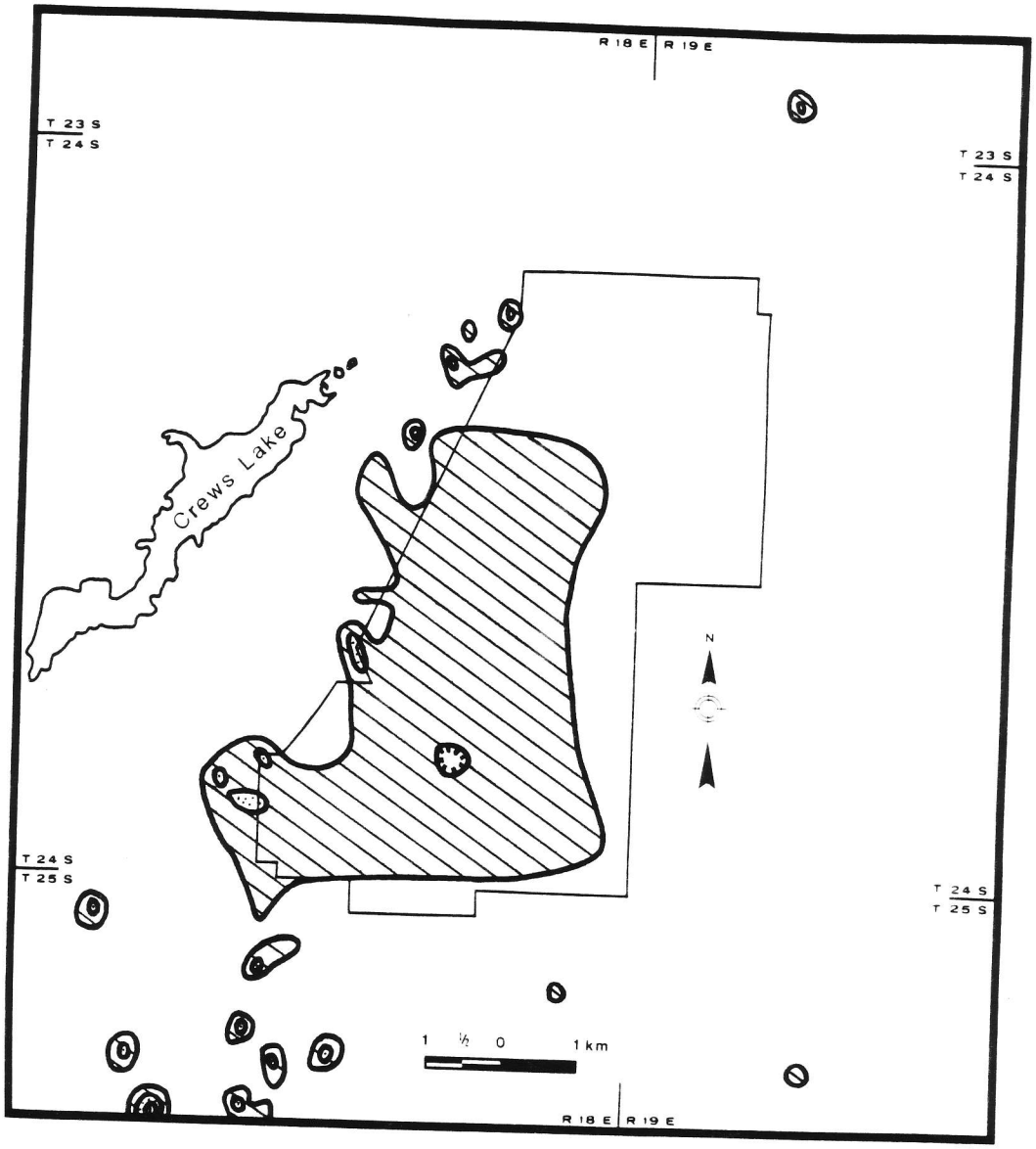


Figure 8. Distribution of iron in mg/l. Contour interval is equal to 0.25 mg/l. Unshaded, diagonal, stippled and vertical patterns denote areas in which water samples contain 0.00 to 0.25, 0.25 to 0.50, 0.50 to 0.75, and 0.75 to 1.00 mg/l iron, respectively. Outlined area is the Cross Bar Well Field.

less than 10 mg/l and is relatively uniform over the study area (Figure 9). Four possible sources of sulfate in the ground water of the area and their relative importances are, respectively, (1) oxidation of pyrite and/or organics, (2) dissolution of gypsum or anhydrite, (3) sea water which has not been completely flushed from the aquifer, and (4) rainfall in a coastal area.

Chloride

As with sulfate, the concentration of chloride in the water of the Floridan aquifer is relatively uniform over the study area (Table 2). Most of the water-quality samples contain 8 to 15 mg/l chloride. Chloride in ground water can be dissolved in small quantities from most geologic formations. It is encorporated in the phosphate mineral apatite, which is locally abundant in the Hawthorn Formation.

Calcium

Calcium is dissolved in large quantities from the limestone. The lower formations of the Floridan also contain significant anhydrite ($CaSO_4$) and gypsum ($CaSO_4 \cdot 2H_2O$). Concentrations of calcium range from 21 to 98 mg/l (Figure 10). The Ca-Mg ratio of the water samples suggests that the aquifer, in the area of study, consists chiefly of limestone. Well logs show, however, the presence of dolostone at two levels in the stratigraphic sequence of the Cross Bar Ranch.

Magnesium

Magnesium concentrations in water of the Floridan aquifer range from 0.0 to 10.9 mg/l. Highest values occur along U.S. Highway 41 and in the southeastern section of the study area (Figure 11). Dolomitic

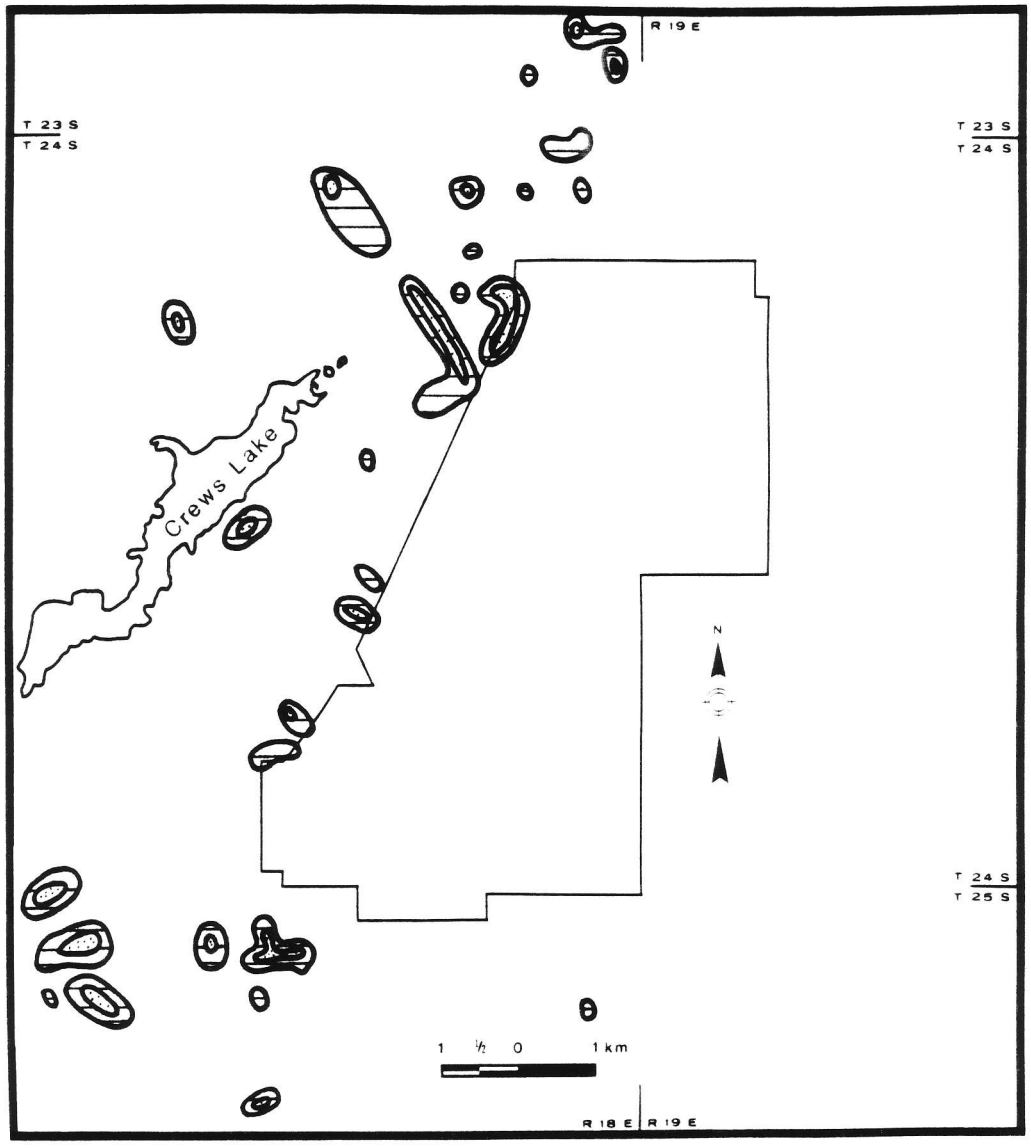


Figure 9. Distribution of sulfate in mg/1. Contour interval is equal to 2.5 mg/1. Unshaded, horizontal, and stippled patterns denote areas in which water samples contain 0.0 to 2.5, 2.5 to 5.0, and greater than 5.0 mg/1 sulfate, respectively. Outlined area is the Cross Bar Well Field.

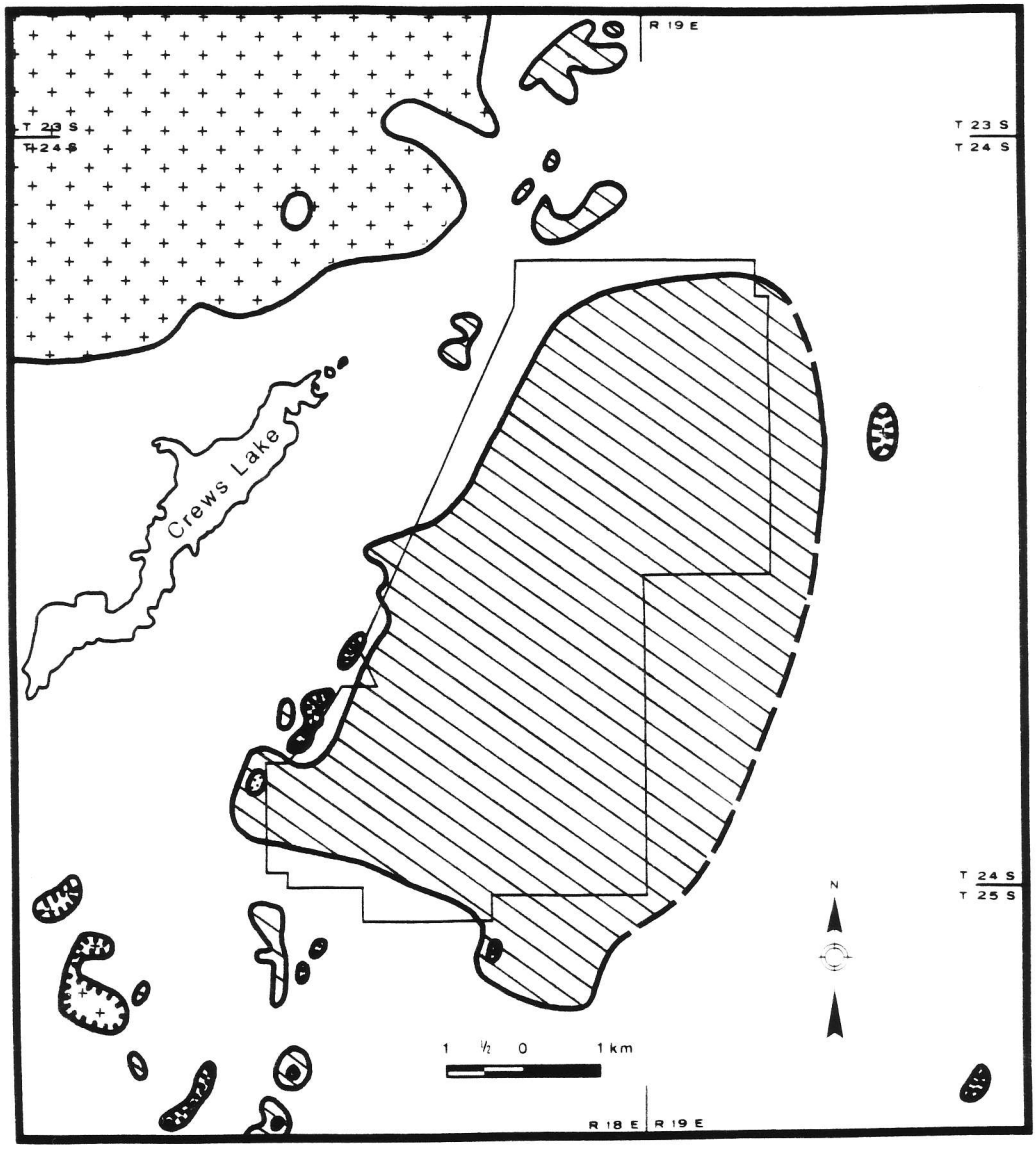


Figure 10. Distribution of calcium in mg/1. Contour interval is equal to 20 mg/1. Cross, unshaded, diagonal, and stippled patterns denote areas in which water samples contain 0 to 20, 20 to 40, 40 to 60, and 60 to 80 mg/1 calcium, respectively. Outlined area is the Cross Bar Well Field.

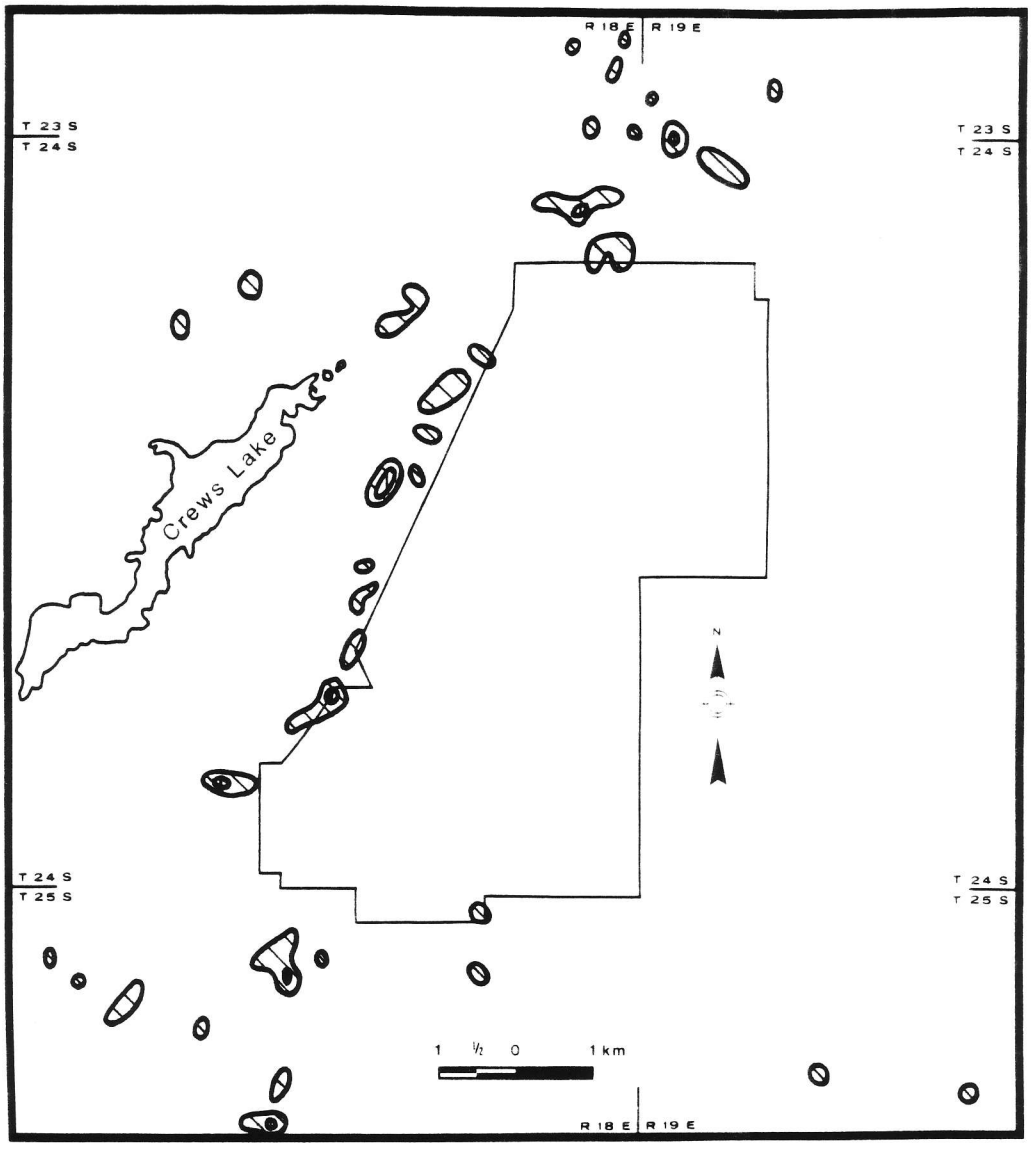


Figure 11. Distribution of magnesium in mg/l. Contour interval is equal to 4 mg/l. Unshaded, diagonal, and vertical patterns denote areas in which water samples contain 0 to 4, 4 to 8, and 8 to 12 mg/l magnesium, respectively. Outlined area is the Cross Bar Well Field.

interbeds within the Floridan may account for the distribution of magnesium observed in the water of the Floridan aquifer. Additional sources of magnesium may include the clay-rich zones within the surficial deposits and the semi-confining, clay layer(s) that overlie portions of the aquifer.

Alkalinity

Total alkalinity of ground water is the sum of hydroxide (OH^-), carbonate (CO_3^{-2}), and bicarbonate (HCO_3^-) alkalinity (Stringfield, 1966). For most well water sampled in the region, bicarbonate alkalinity and total alkalinity are the same since the presence of hydroxide and carbonate ions in the well water in amounts sufficient to affect alkalinity determinations directly are very rare (Hem, 1959). Alkalinity values range from 48 to 267 mg/1. Shallower, domestic wells generally exhibit alkalinities between 100 to 150 mg/1. However, lower values are found in ground-water samples from the northwestern region of the study area. Higher values are restricted to the deeper wells within the Cross Bar Well Field.

Hardness

Total hardness, expressed as calcium carbonate, is a measure of calcium and magnesium in water. Water having a hardness between 60 and 120 mg/1 is generally regarded as moderate. Hardness between 120 and 200 mg/1 is regarded as troublesome for many industrial and domestic uses. Such water generally requires treatment to prevent scale when used in steam boilers. Water with a hardness of more than 200 mg/1 is regarded as very hard. Most domestic wells exhibit moderate hardness values, between 100 to 150 mg/1. Values below 100 mg/1 are not abundant

and, where they do occur, they appear to be random in distribution. Hardness values between 150 to 200 mg/l occur in the deep wells throughout the Cross Bar Well Field. Single, very high hardness values, above 200 mg/l, appear scattered over the study area.

Factor Analysis

Through the use of the factor-analysis technique, hydrogeochemical information contained within the ten original parameters was filtered and redistributed among three, new, parsimonious variables called factors. The factors represent geochemical processes that are responsible for and adequately describe the areal distribution of chemical species in the Floridan aquifer. However, factor analysis can only demonstrate the complex relationship among the variables, it can not explain it. The processes, which the factors represent, have to be deduced from geologic and hydrogeologic evidence (Dawdy and Feth, 1967; Hitchon et al., 1971).

Factor 1 includes the variables calcium, total hardness, bicarbonate alkalinity and total alkalinity. These variables are redundant and most likely reflect dissolution of carbonate material in the upper Floridan aquifer. Figure 12 shows the areal distribution of factor scores for Factor 1. Low Factor 1 scores (less than -1) in the north and southwestern corners of the study area, indicate that the intensity of the dissolution process is locally low. This geochemical condition is most likely due to the relatively brief residence time of water within the aquifer system. Crews Lake, located up hydraulic gradient from the northernmost affected area, is hydraulically connected with the Floridan aquifer, primarily through the Hernasco Sink. Surface

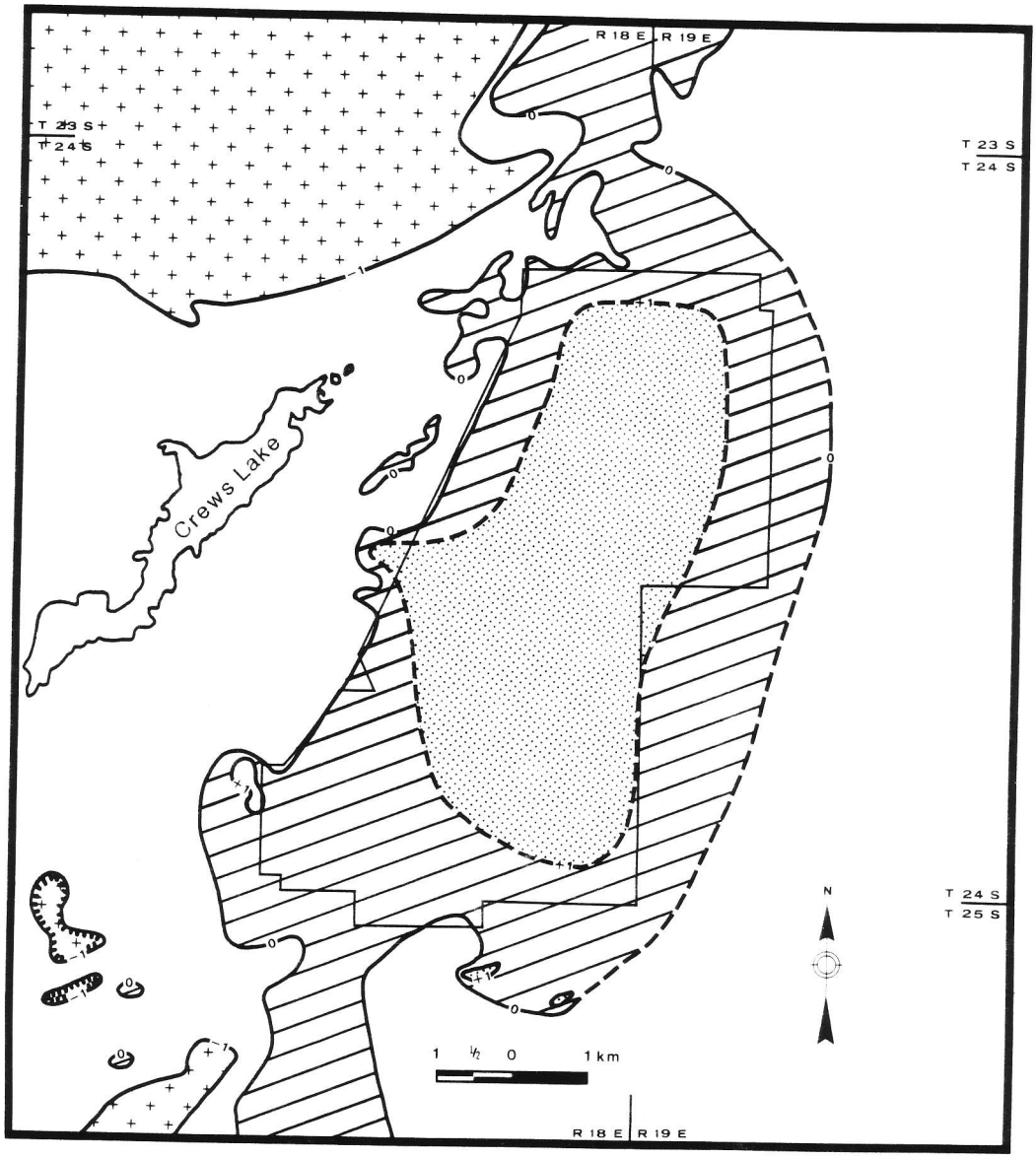


Figure 12. Factor-score map showing distribution of Factor 1. Factor 1 represents the variables calcium, bicarbonate alkalinity, total alkalinity and total hardness. Cross, unshaded, diagonal and stippled patterns denote areas in which factor scores are less than -1, -1 to 0, 0 to +1, and greater than +1, respectively. Outlined area is the Cross Bar Well Field.

water that seeps through the lake bottom and drains through the sink moves relatively rapidly northwestward along karst conduits within the aquifer. In a similar fashion, sinkholes to the south may serve as rapid and direct recharge pathways to the Floridan aquifer.

The large area of high factor scores (greater than +1) directly coincides with the Cross Bar Well Field. High intensities indicate longer residence times where deeper wells tap the regional flow of the Floridan. There are a few, isolated areas of restricted flow, characterized by singularly high factor scores.

The remainder of the study area exhibits moderate Factor 1 scores (-1 to +1). In the more developed regions of the study area, slightly elevated Factor 1 scores (0 to +1) may reflect upwelling of deeper water due to extensive pumping.

Figure 13 shows the areal distribution of factor scores for Factor 2 (iron and color). Factor 2 most likely reflects leaching of surface organics and mobilization of iron in the surficial sediments. Positive Factor 2 scores are distributed over those regions of the study area where there are significant local sources of surface organics and/or iron-bearing minerals in the surficial sediments, and where there exists hydraulic interconnection between surface- and ground-water bodies. Sinkholes may act as sites of concentrated recharge by which surface water, discolored by organics and surficial aquifer water discolored and enriched in iron, is introduced into the aquifer. The abundance of surface organics and iron-bearing minerals (i.e. clay and pyrite) in the surficial sediments varies over the study area as does its impact on the areal distribution of Factor 2 scores. Therefore, it is possible to have a breached semi-confining layer that provides direct and rapid

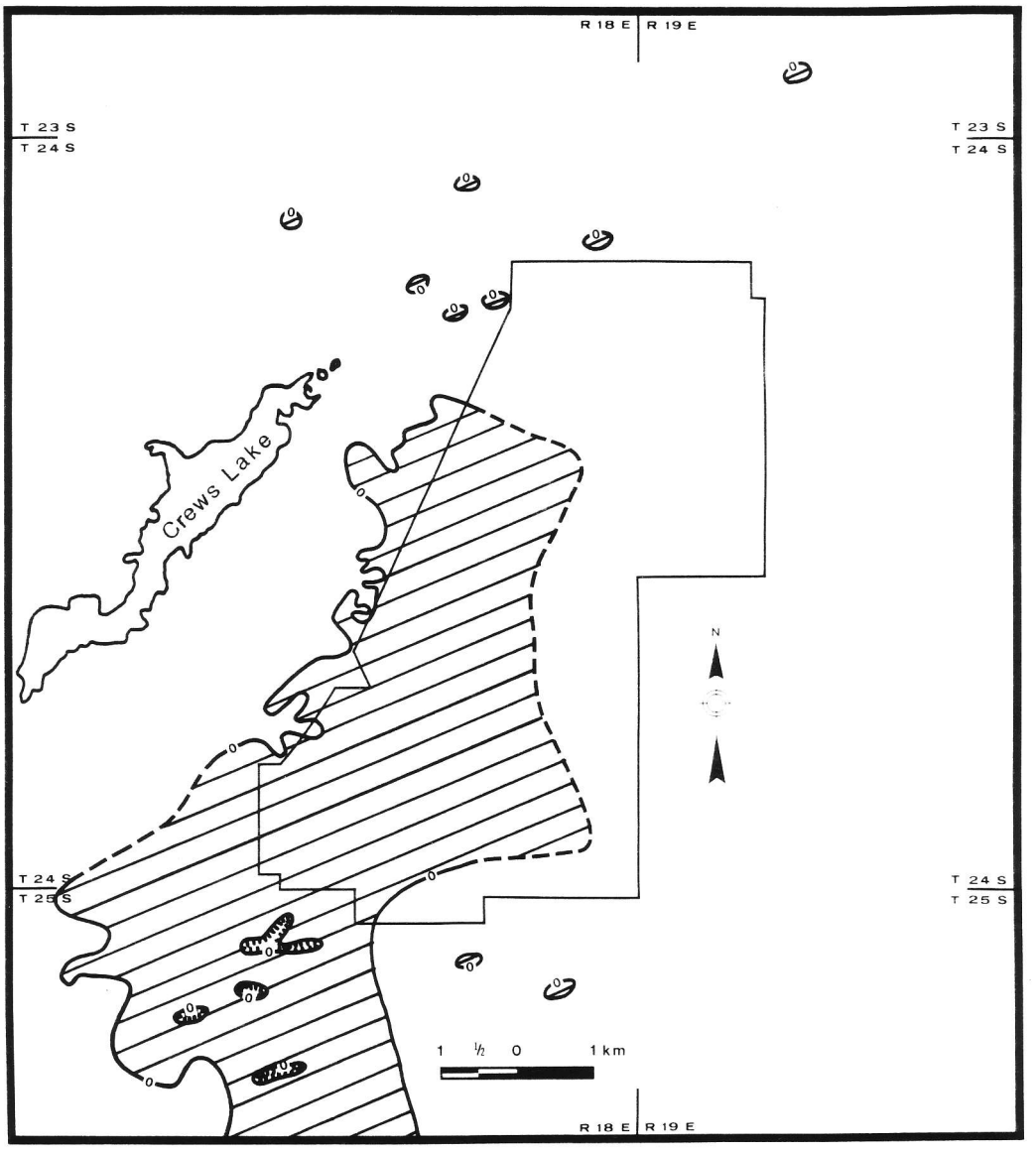


Figure 13. Factor-score map showing distribution of Factor 2. Factor 2 represents the variables color and iron. Diagonal pattern denotes area in which factor scores are positive. Outlined area is the Cross Bar Well Field.

recharge to the Floridan aquifer, but have no significant local source of surface organics and/or iron-bearing minerals.

Recharge is generally diffuse in nonsinkhole areas. This is most evident where the Floridan is unconfined and exhibits negative Factor 2 scores. Surface and surficial aquifer water, notably discolored and enriched in iron and organics, must infiltrate tens of meters of terrigenous sediments before recharging into the Floridan aquifer. As the water percolates down through the sediments, much of the free iron is rapidly bound up in the surficial deposits by natural, chemical, biological, and physical processes and is effectively removed from the hydrologic system.

Where isolated, high iron concentrations occur, there is a possibility that some of the iron reported in the chemical analysis may be from rusty well casings or pipes through which the water flowed.

Factor 3 includes only the variable magnesium and most likely reflects weathering of the upper, discontinuous, semi-confining clay unit (Figure 5). Figure 14 shows the areal distribution of factor scores for Factor 3. Positive factor scores are clustered along the zone where the semi-confining unit either pinches out or thins significantly.

Within the semi-confined region, precipitation that does not recharge directly to the Floridan aquifer through sinkholes or solution-enlarged fractures, infiltrates the surficial sediments where it eventually comes in contact with the semi-confining clays. Positive Factor 3 scores are present in the water of the Floridan aquifer where perched surficial aquifer water, which has been in contact and has been involved in weathering of magnesium clays, is able to recharge into the

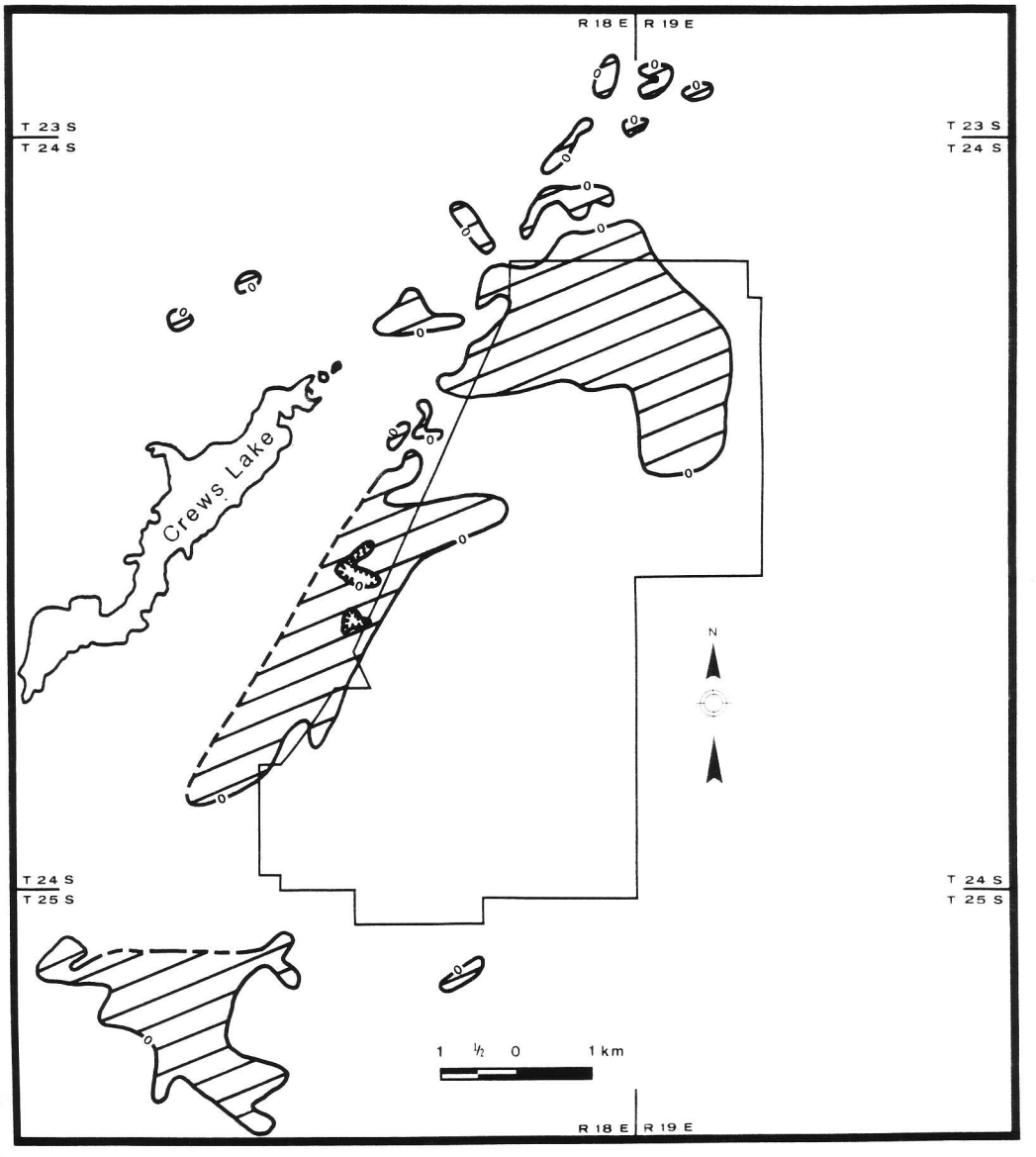


Figure 14. Factor score map showing distribution of Factor 3. Factor 3 represents the variable magnesium. Diagonal pattern denotes area in which factor scores are positive. Outlined area is the Cross Bar Well Field.

Floridan aquifer.

Photolineament Analysis

Six hundred and eighteen photolineaments (Figure 15) were identified according to the mapping technique previously outlined. The three scales of areal photography used in this study strongly bias the length of detectable photolineaments. A length-frequency diagram for the photolineaments that were detected is illustrated in Figure 16. Approximately 58% of the photolineaments are between 0.5 and 1.5 km in length. Only 7% are shorter than 0.5 km, and the remaining 35% are longer than 1.5 km, with a maximum length of just over 10 km.

The orientations of the photolineaments are illustrated in Figure 17. The diagram shows several apparent modes: (1) a distinct northeast mode, (2) a distinct northwest mode, with a subordinate west-northwest mode, (3) a weak complimentary east-west mode, and (4) a north-south mode. Similar results were obtained by Ritchie (1983) in a photolineament study of Pasco, Polk, Hillsborough, and Hardee Counties, Florida.

Together, 75% of all the photolineaments mapped fall within the northeast, northwest, and west-northwest modes (Table 8). Seventy nine percent of these photolineaments are under 2 km in length, 14% are between 2 to 3 km, and only 6% are longer than 3 km. Similarly, 85% of the photolineaments comprising the east-west mode are under 2 km in length, 15% are between 2 to 3 km, and none are longer than 3 km.

Vernon (1951) describes similar orientations of regional fracture systems in Citrus and Levy Counties, 20 km north of the study area. It is unclear if these fracture sets are the result of movement along the

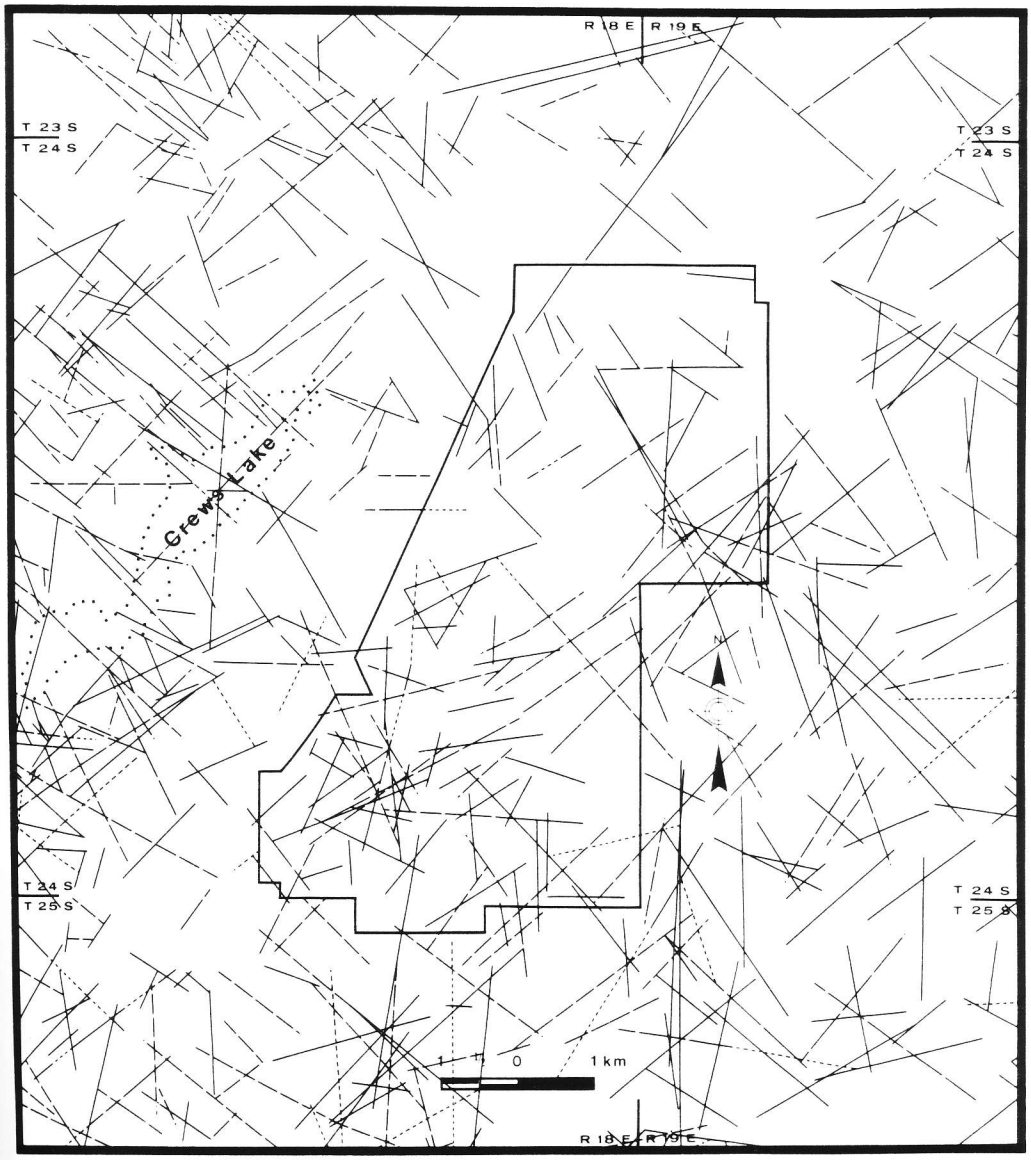


Figure 15. Map of photolineaments. Mapped according to the technique described in text. Solid, long dashed, medium dashed and short dashed lines denote definite, definite, but precise location indeterminable, probable and possible photolineaments, respectively. Outlined area is the Cross Bar Well Field.

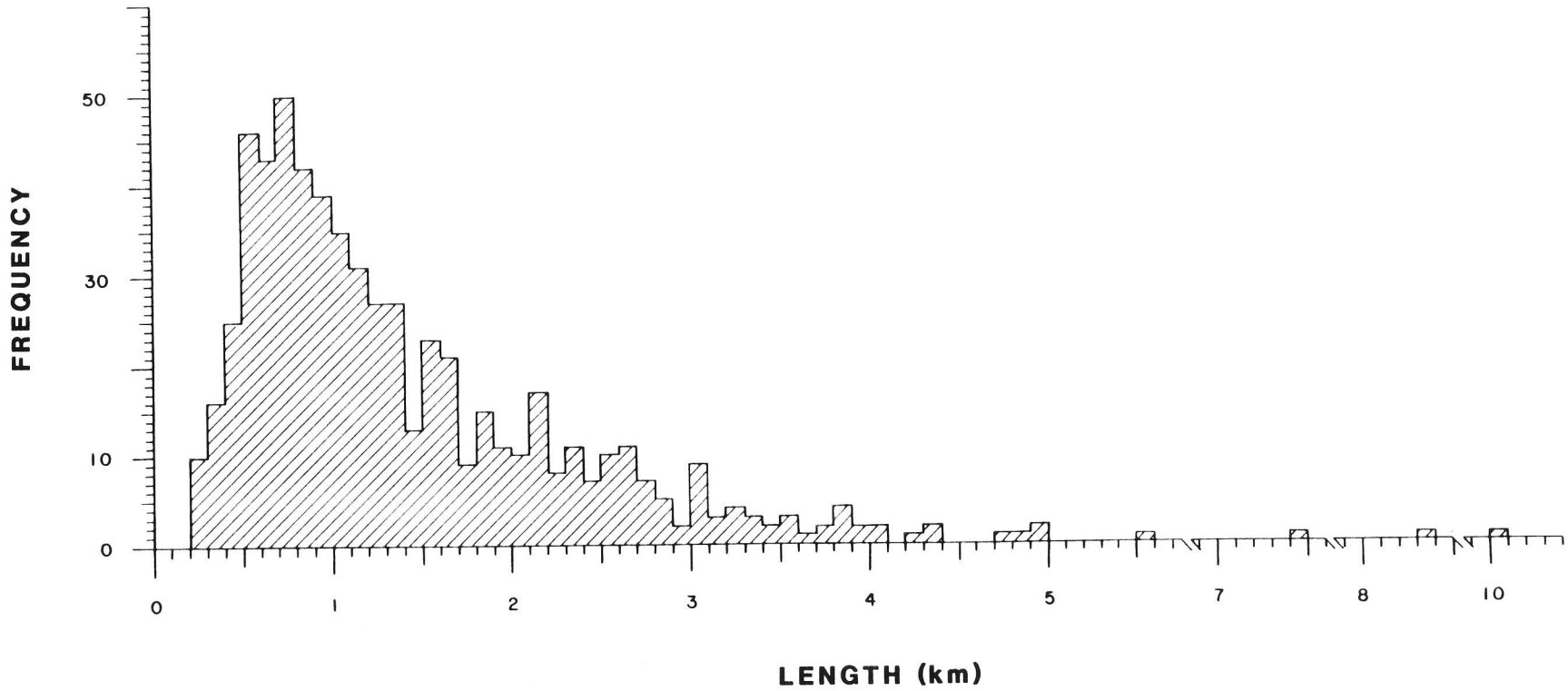


Figure 16. Length-frequency diagram of all photolineaments identified.

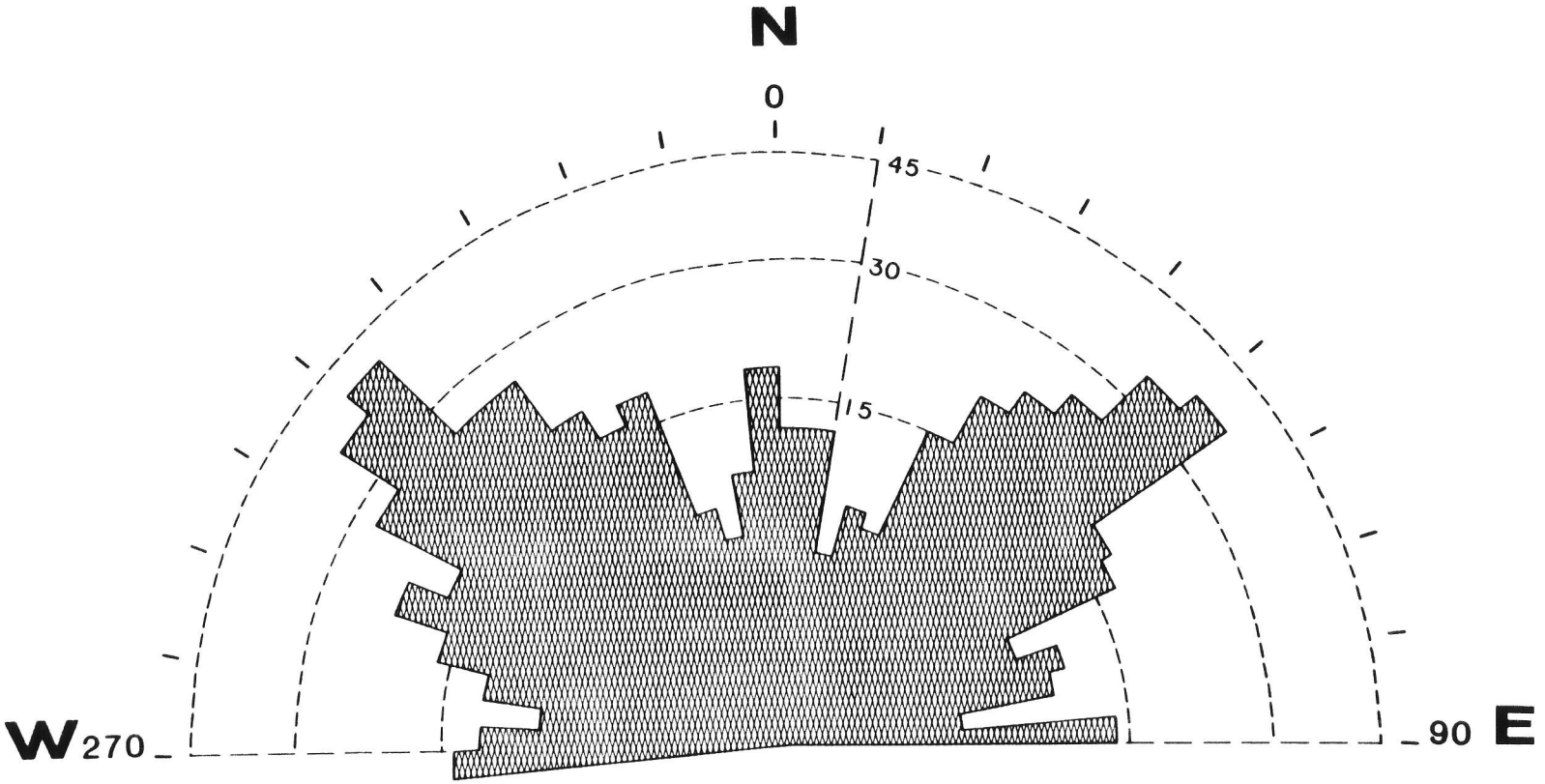


Figure 17. Relationship of photolineament number and orientation.

Table 8. Relationship of photolineament length and orientation.

Mode	WNW-ESE (280-300°)	NW-SE (300-340°)	N-S (350-10°)	NE-SW (25-65°)	E-W (85-95°)	INTERMODES* (COLLECTIVE)
Percent of total photolineaments mapped	10.7	33.7	8.6	30.7	4.2	12.1
Percent of these photolineaments that are shorter than 2 kilometers	84.8	76.0	77.4	76.8	84.6	78.7
Percent of these photolineaments that are between 2-3 kilometers in length	10.6	16.3	7.5	16.3	15.4	13.3
Percent of these photolineaments that are longer than 3 kilometers	4.6	7.7	15.1	6.9	0.0	8.0

*10-25°, 65-85°, 275-280°, and 340-350°

Peninsular Arch and/or Ocala Uplift, or the result of formation fatigue due to earth tides. In this study, photolineaments are presumed to reflect fractures of both origins. Histograms of photolineament orientation versus frequency for photolineaments shorter than 2 km (Figure 18-A) show broad north, northeast, and northwest maxima that probably represent tidally-induced joints (Ritchie, 1983). Longer photolineaments (Figure 18-B) are most likely fractures or faults of small displacement that reflect the regional geology. The Peninsular Arch and subparallel Ocala Uplift, the axes of which are north and east of the study area, trend approximately 320°. Photolineaments trending 305-313° are probably produced by fractures or normal faults subparallel to the axes of these positive features and 32-53° photolineaments represent cross-fractures on the same structures. Photolineaments trending 325-338° parallel the Gulf of Mexico coast and may represent down-to-the-coast normal faults or related joints (Ritchie, 1983).

The north mode (250-10°) includes only 9% of the total photolineaments mapped. Of these, 77% are under 2 km in length, 7% are between 2 to 3 km in length, and 15% are longer than 3 km. A greater percentage of photolineaments longer than 3 km describe the north mode. These extensive north-south photolineaments have been studied by Ritchie (1983) in Polk County, Florida. Preliminary results of a gravity study across a prominent, north-south photolineament indicates basaltic dikes at depth. Ritchie (1983) proposes that the photolineament was produced by fractures propagated vertically from normal faults parallel to the implied dike.

The photolineament density map (total length of photolineaments in each 1 km/km^2) shown in Figure 19 demonstrates the broad areal coverage

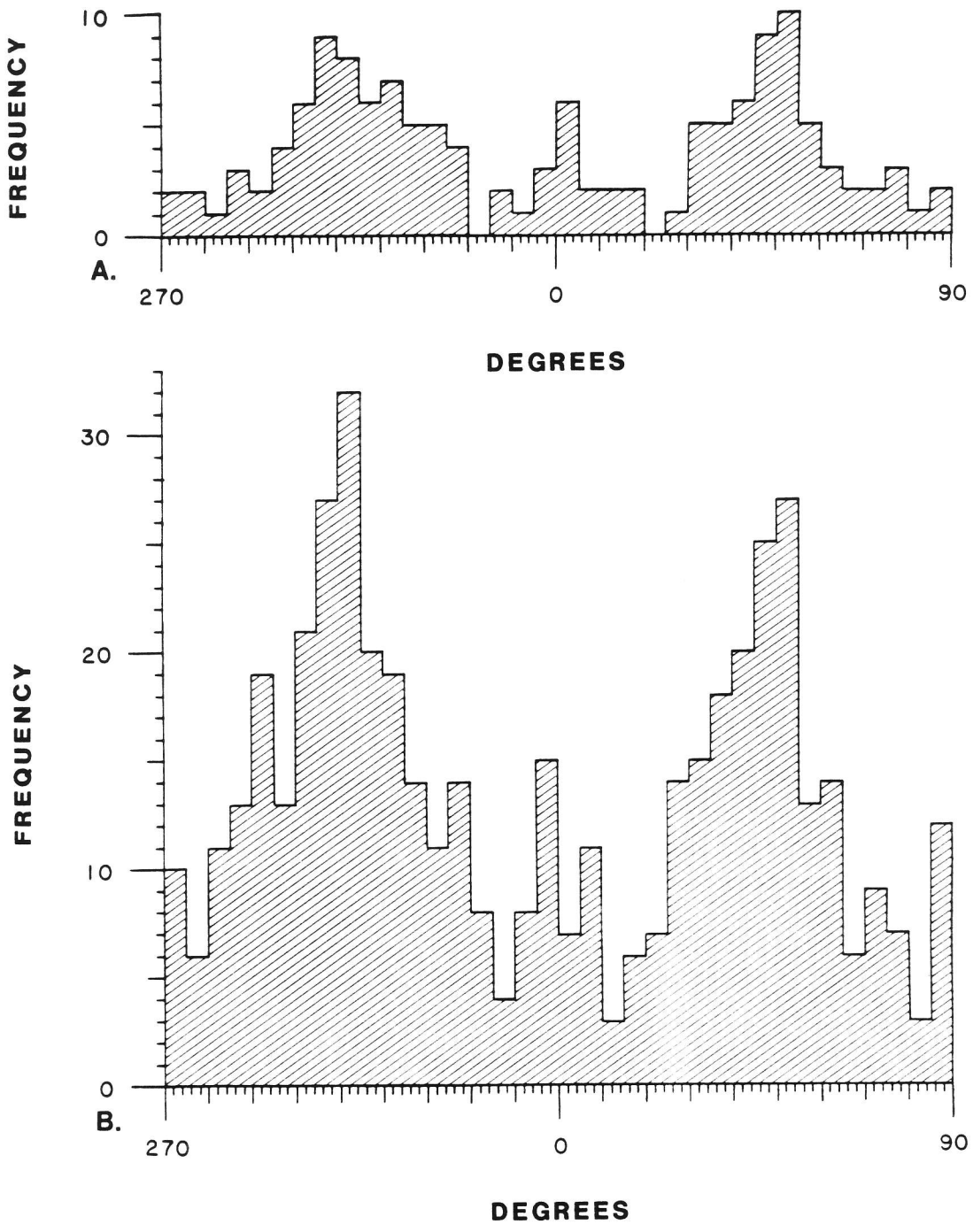


Figure 18. Histograms showing modes of orientation for photolineaments; (A) longer than 2 kilometers, and (B) shorter than 2 kilometers.

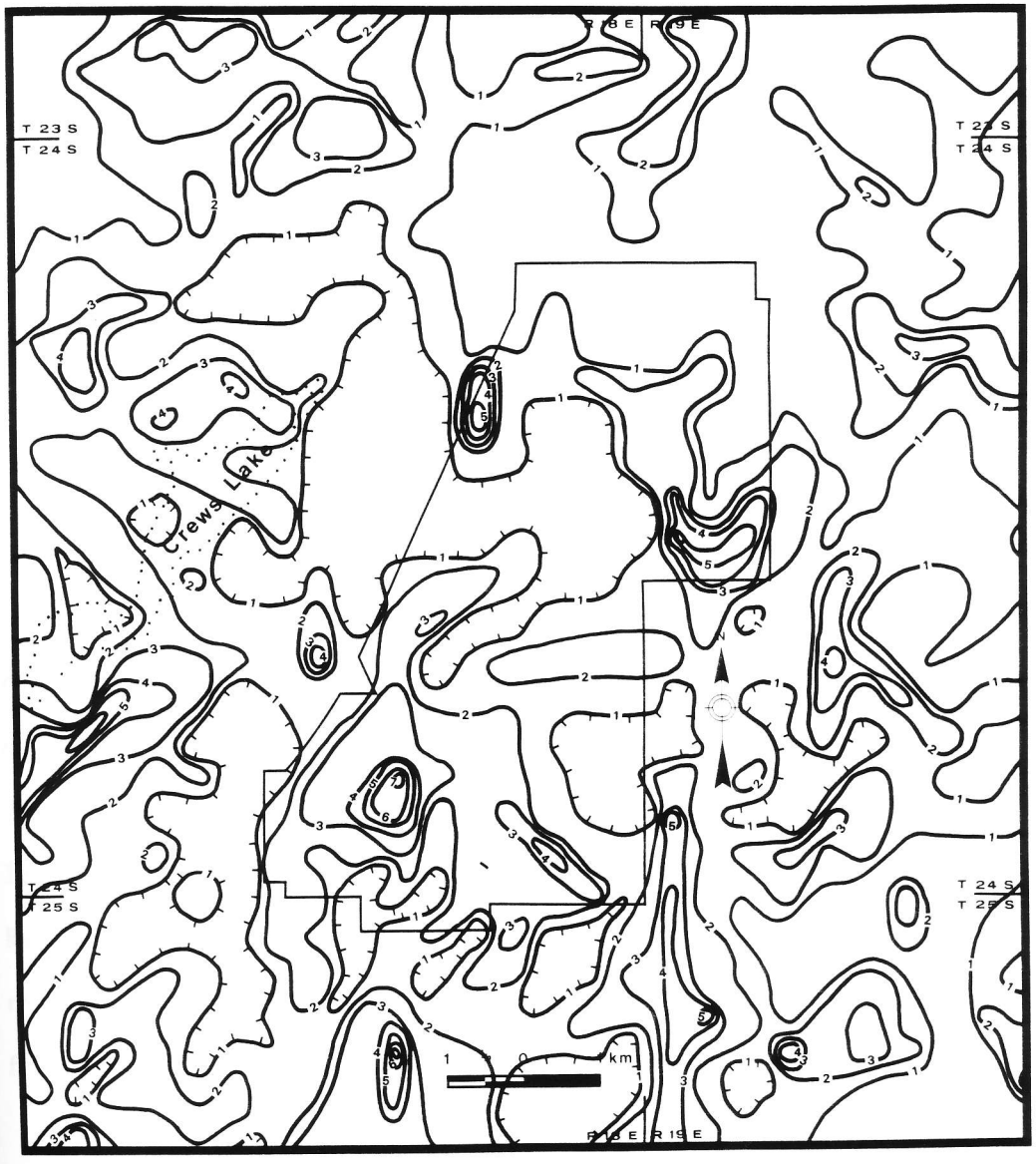


Figure 19. Map of photolineament density using all photolineaments identified. Contour interval is 1 km/km^2 (total length of photolineaments in each km.). Outlined area is the Cross Bar Well Field.

of the identified photolineament systems. Within the study area, the density of photolineaments is greater in the southern province or the semi-confined portion of the Floridan aquifer.

North, northeast and northwest photolineaments appear more regular and systematic when photolineaments shorter than 2 km are deleted (Figure 20). In addition, Figure 20 illustrates that photolineaments longer than 2 km, are more prevelant or at least were more readily identifiable within the semi-confined portions of the Floridan aquifer.

Throughout the study area, gradual dissolution of the limestone along subsurface fractures results in local increases in transmissivity values. In the semi-confined region, where surficial aquifer water-table elevations are high, erosion or ravelling of the surficial sediments and semi-confining unit occurs at these sites of concentrated recharge. This results in sinkholes at the land surface and good surficial expression of subsurface zones of vertical fracture.

In unconfined regions, where water-table elevations are much lower, conditions for sinkhole development are less favorable. Readjustment and settling of the unconsolidated surficial sediments results in a much more subtle surface expression of subsurface zones of fracture.

Some of the photolineaments shorter than 2 km detected in the unconfined region may actually be segments of longer photolineaments with interphotolineament areas being undetectable at the land surface.

Zones of high photolineament concentration tend to be associated with the intersection of fracture zones and with topographically low relief. Although zones of relatively high photolineament density may be comprised of both short and long photolineaments, some high density

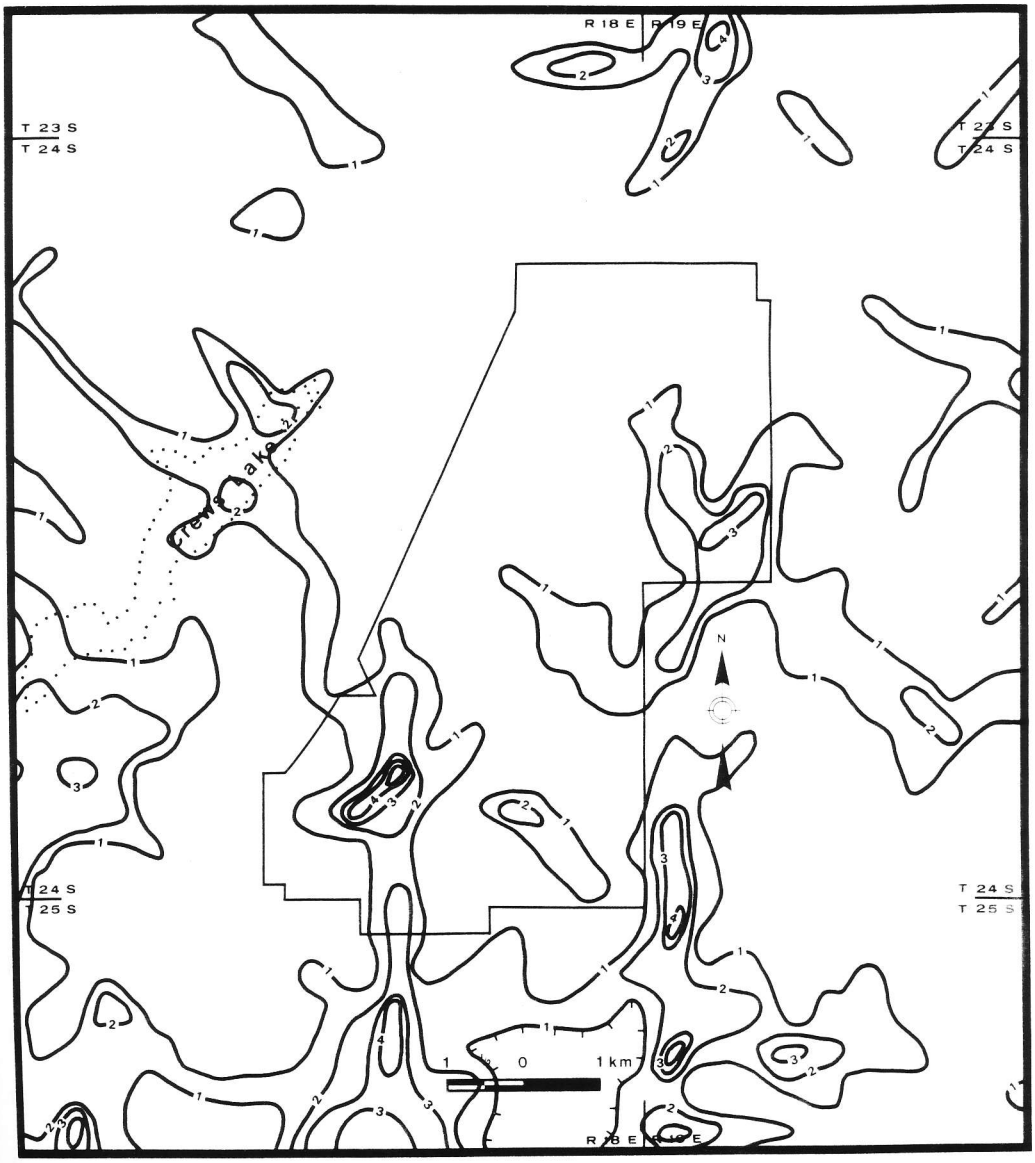


Figure 20. Map of photolineament density using only those photolineaments longer than 2 km. Contour interval is 1 km/km. (total length of photolineaments in each km^2). Outlined area is the Cross Bar Well Field.

zones shift position or are deleted when considering only those photolineaments longer than 2 km. This observation suggests that when locating potential well sites in high density fracture zones, it is important to examine the origin and character of the constituent fractures in order to ensure high well yield.

Comparative Analysis of Data

Comparison of factor maps with photolineament maps gives an indication of the relative importance of subsurface fracture zones to the areal distribution of the ground-water quality parameters. Factor 1 includes the variables calcium, bicarbonate alkalinity, total alkalinity and total hardness, and most likely reflects dissolution of the aquifer limestone. The areal distribution of low Factor 1 scores (less than -1) is controlled by surface water introduced into the Floridan aquifer through karst conduits (Figures 21 and 22). Crews Lake as well as sinkhole lakes and swamps in the southwestern corner of the study area are similar to those classified as "deep, water-filled sinkholes" by Miller (1977). These sinks are typically more enlarged by dissolution, thus, usually better hydraulically connected to the Floridan than sinkholes in other regions of the study area. Deep, water-filled sinkholes form a narrow band between sinkhole and nonsinkhole areas and most likely reflect pinching out of the semi-confining unit and transition of the Floridan aquifer from artesian to water table conditions. Deep, water-filled sinks form the dividing line between the northern and southern provinces of the Cross Bar Well Field. The Cross Bar wells are deep enough, however, that they do not show any affects from surface water recharging to the Floridan aquifer

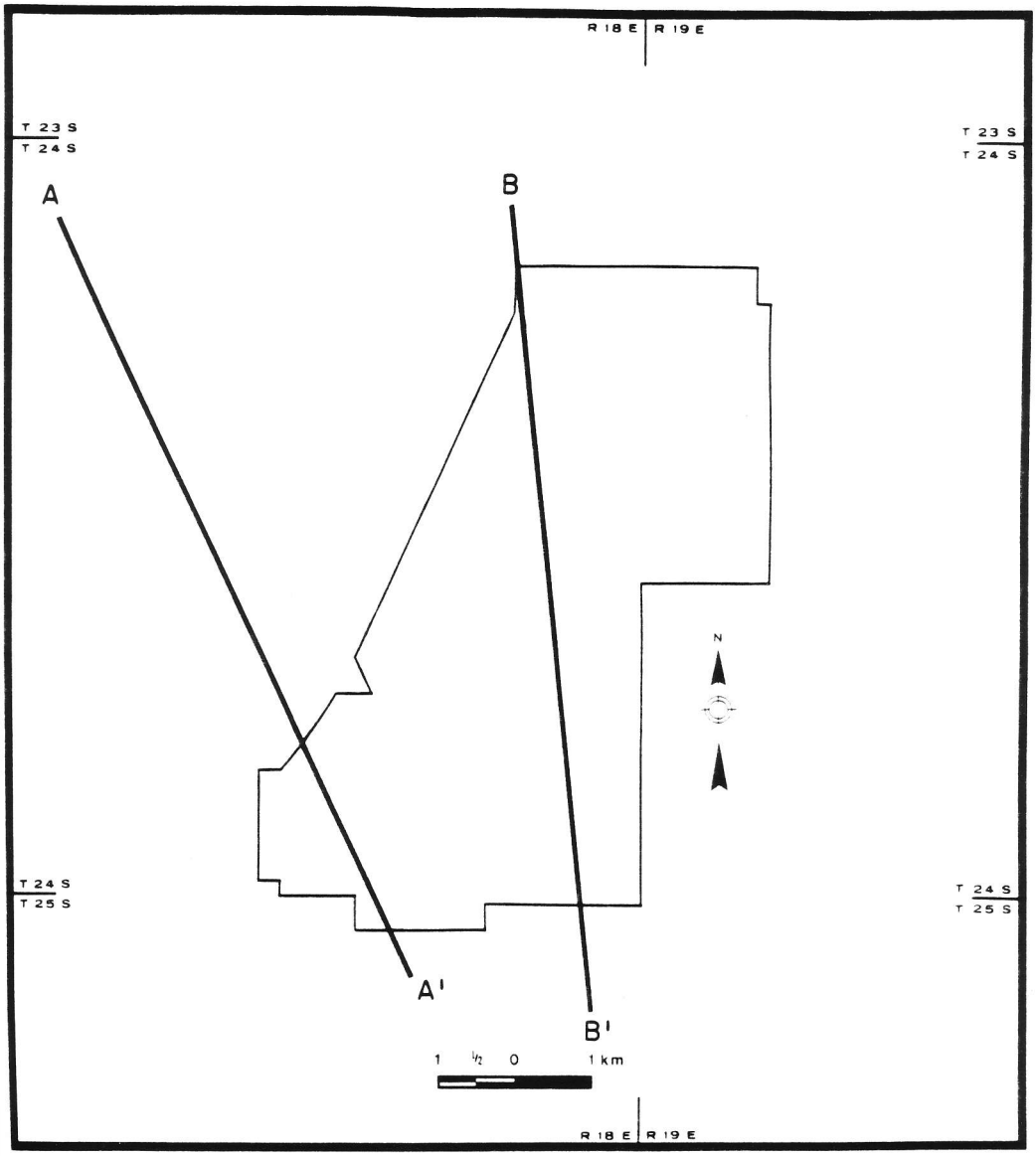


Figure 21. Location of cross sections A-A' and B-B', northwest-central Pasco County, Florida. Outlined area is the Cross Bar Well Field.

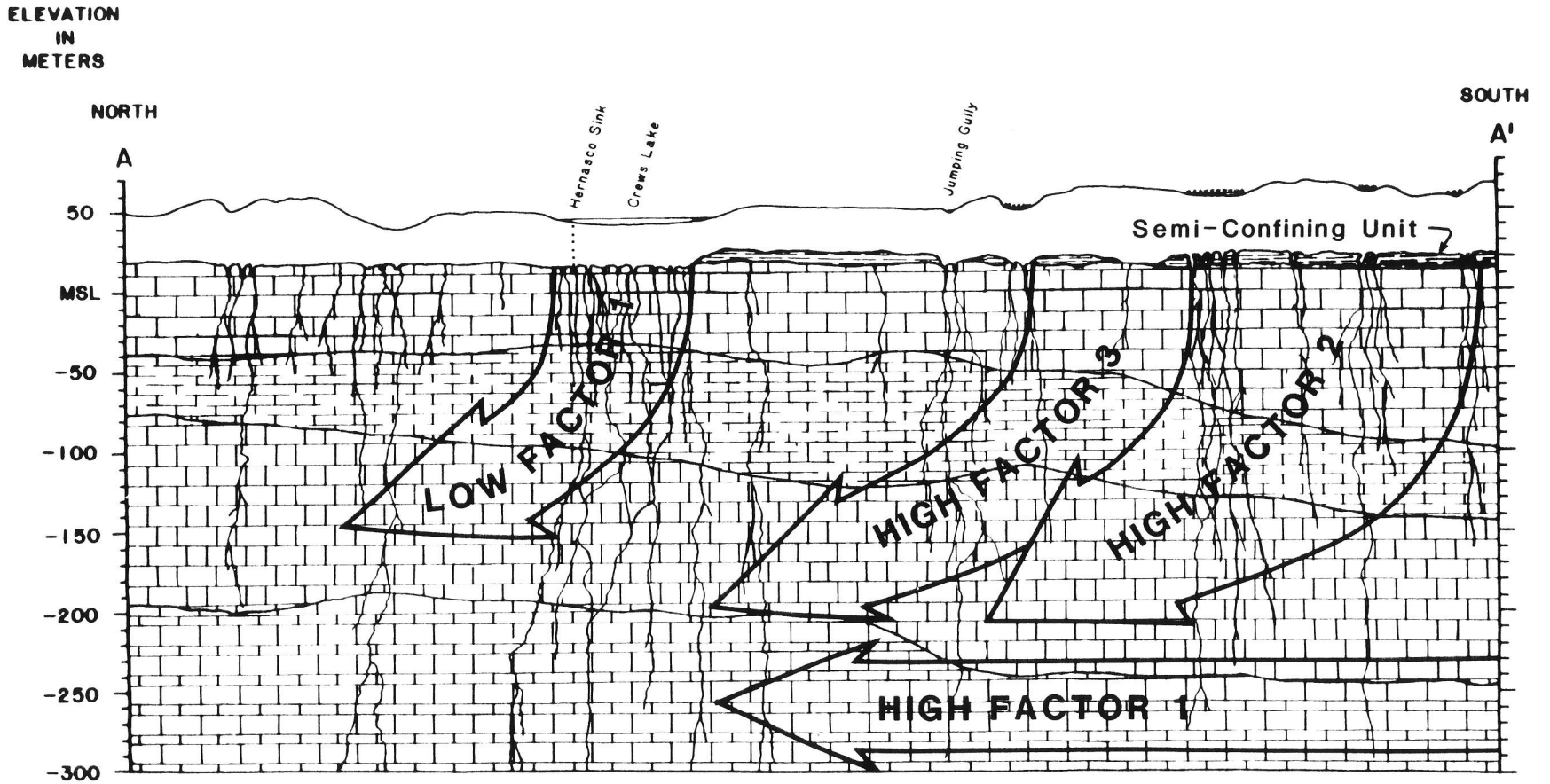


Figure 22. Hydrogeologic cross section A-A' of study area showing control of stratigraphy and fracture distribution on recharge to the Floridan aquifer.

through these sinkholes.

Figure 20 shows that Crews Lake and its counterpart deep, water-filled sinks in the southwestern region of the study area are located in high photolineament density zones when considering only those photolineaments longer than 2 km. These long photolineaments most likely reflect fractures in the limestone of tectonic origin.

The distribution of intermediate to high Factor 1 scores appears to be predominately a function of well depth, rather than stratigraphy and degree of solution enlargement of fractures. As a general rule, the intensity of Factor 1 increases with depth, since deeper ground water has a longer residence time (Figures 21, 22 and 23). In the vicinity of the Cross Bar Well Field and along U.S. Highway 41, Factor 1 values may be slightly higher than "average" due to upwelling as a result of extensive pumping.

Factor 2 includes the variables iron and color. Iron is most likely derived from the leaching of surface organics and mobilization of iron in the surficial sediments. Iron is present in the ground water in only minor amounts despite its variable distribution and abundance since iron tends to react with the surficial sediments and is readily removed from the hydrologic system. High intensities for Factor 2 reflect rapid and direct recharge (Figures 21, 22 and 23). In the semi-confined region of the Floridan aquifer, stratigraphy favors sinkhole development by solution enlargement of fractures in the limestones and subsequent subsidence of the overlying units. Sinkholes, as well as other fracture-related features, concentrate recharge and provide direct hydraulic connection between surface and ground-water bodies. This isolates recharge from reaction with the surficial sediments and

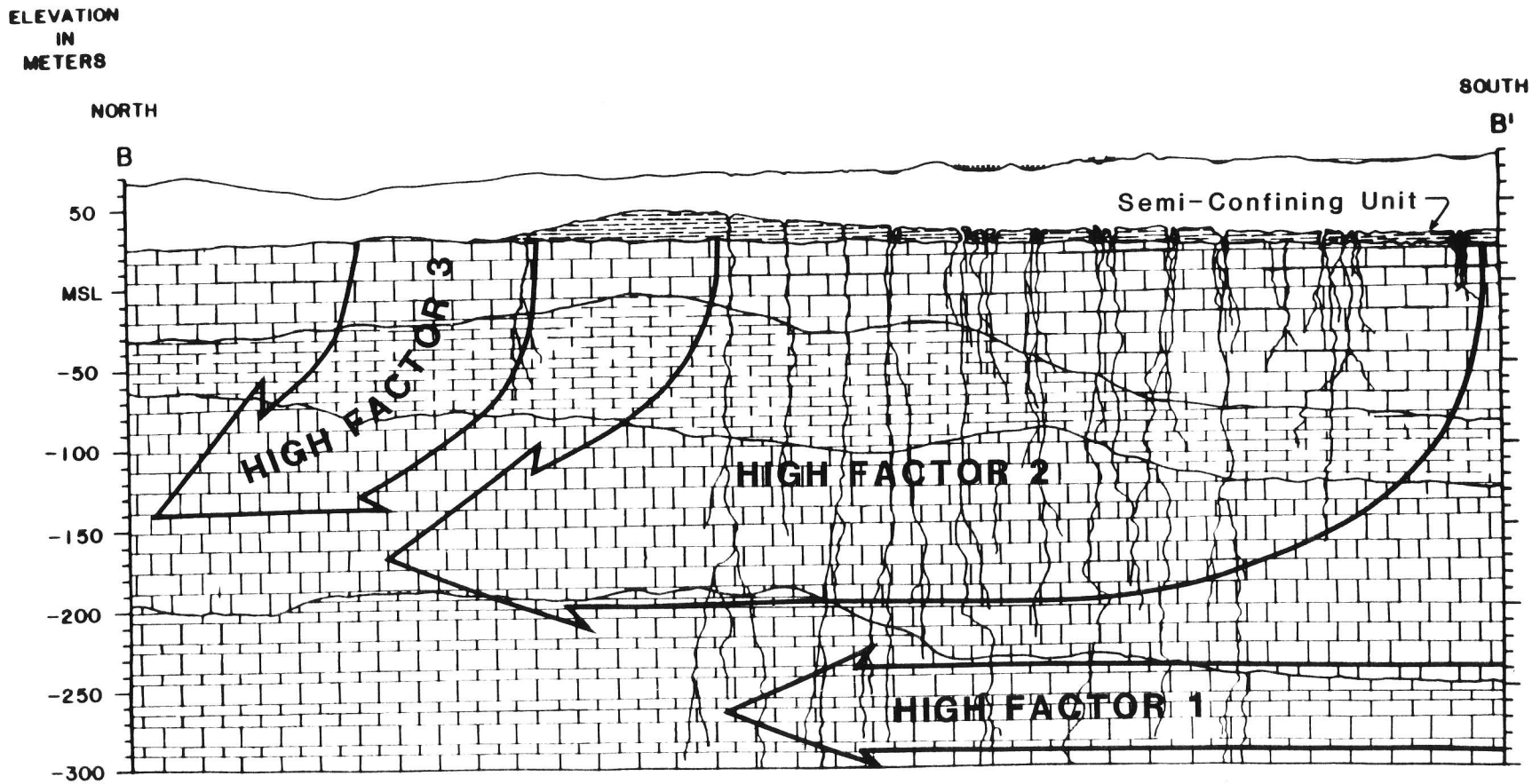


Figure 23. Hydrogeologic cross section B-B' of study area showing control of stratigraphy and fracture distribution on recharge to the Floridan aquifer.

semi-confining clays.

Although the deep, water-filled sinks provide direct recharge pathways to the Floridan aquifer, in several areas there appears to be an insufficient source of iron. In general, in regions of the study area where Factor 2 scores are negative there appears to be an insufficient source of iron and/or a lack of sinkholes that provide direct hydraulic interconnection. Recharge is diffuse in the unconfined region and as recharging water infiltrates the surficial sediments, much of the iron is either removed from the hydrologic system or is diluted.

Factor 3 most likely reflects weathering of magnesium clays in the semi-confining unit. Highest magnesium concentrations occur where perched surficial aquifer water, which has been in contact and has been involved in weathering of magnesium clays is able to recharge into the Floridan aquifer at the edges of the semi-confining unit or where it thins significantly (Figures 21, 22 and 23).

Positive Factor 3 scores are not found in the water of the Floridan aquifer where there are abundant sinkholes or other solution-enlarged fracture-related features. The weathering of magnesium from the clays requires higher dissolved-solids concentrations either as a result of relatively-restricted ground-water circulation or localized flow with long contact time. In general, positive Factor 3 scores are restricted not only to areas where the semi-confining unit pinches out or thins, but, also to areas of low photolineament density. The photolineaments that do exist within this area are generally shorter than 2 km and do not appear to have a significant affect on local ground-water movement.

In some regions of the study area, the areal distribution of Factor 3 scores exhibit a strong bias to sample distribution. This is most

evident along U.S. Highway 41. Positive Factor 3 scores are probably present in the ground water of the Floridan aquifer west of U.S. Highway 41 since the semi-confining unit is also found in portions of this region. It is difficult to speculate, however, since well coverage is inadequate.

SUMMARY AND CONCLUSIONS

The quality of water in the upper Floridan aquifer, northwest-central Pasco County, Florida, may vary significantly over a few kilometers due to the heterogeneity of the surficial sediments, discontinuous nature of the semi-confining unit, and various, solution-enalarged joint, fracture and fault systems that form a network of interconnected karst openings. It would have been difficult and cumbersome to try to determine the areal hydrogeochemistry of the upper Floridan aquifer using only the available well logs and spatially-distributed, raw, ground-water quality data. It would have been even more difficult to impossible to determine the underlying hydrogeochemical processes that are responsible for the areal distribution of chemical species in the upper Floridan aquifer without the aid of a computer technique such as factor analysis. Photolineament analysis serves to incorporate, into the study, the influence of solution-enlarged joints, fractures, and faults on the areal distribution of those hydrogeochemical processes identified by factor analysis.

In the first step of the study, factor analysis proved to be a useful technique for identifying the underlying hydrogeochemical processes that govern the complex relationships observed among the commonly-collected ground-water quality data. In the first reduction step of the factoring procedure, three of the original ten water quality

parameters (pH, sulfate and chloride) were eliminated from the remainder of the analysis since they exhibited no significant regional pattern and, therefore, could contribute little hydrogeochemical information towards the identification and interpretation of the hydrogeochemical processes. In a separate factor analysis, the seven remaining variables (bicarbonate alkalinity, total alkalinity, total hardness, calcium, magnesium, iron and color) were reduced to three clusters or groups of variables represented by three new variables called factors. The manner in which these seven variables were clustered reflect the hydrogeologic controls imposed by the system.

In the second step of the study, photolineaments were mapped according to a flexible, systematic technique that permits easy manipulation of the data. Three major modes of photolineament orientation were identified: north, northwest and northeast. These results correspond remarkably well with those of Ritchie (1983). Histograms of frequency versus orientation for photolineaments shorter than 2 km show broad north, northeast and northwest maxima that probably represent tidally-induced joints. Ritchie (1983) proposes that photolineaments longer than 2 km are most likely fractures or faults of small displacement that reflect the regional geology. Photolineaments trending 305-313° are probably tectonic features subparallel to the axes of the Peninsular Arch and the Ocala Uplift. Photolineaments trending 32-53° represent cross-fractures on these same structures. Photolineaments trending 325-338° parallel to the Gulf of Mexico and possibly represent down-to-the-coast normal faults or other sub-parallel basement features. A preliminary gravity survey of the north-south group of photolineaments elsewhere suggests that these photolineaments

are produced by fractures propagated vertically from normal faults parallel to basaltic dikes at depth (Ritchie, 1983). This theory has yet to be confirmed.

In step three of the study, information obtained by factor analysis and photolineament analysis was used for a comparative analysis. Comparison of factor maps with photolineament maps gives an indication of the relative importance of subsurface fracture zones to the areal distribution of ground-water quality parameters.

The three factors identified using factor analysis, represent three, different hydrogeochemical processes, each described by a chemically-distinct ground-water geochemical system.

Factor 1, represented by the variables alkalinity, hardness and calcium, most likely reflects dissolution of carbonate rock in the Floridan aquifer. Regionally, Factor 1 increases with residence time, or depth. However, in the more developed regions of the study area, upwelling of deep aquifer water due to extensive pumping has resulted in slightly elevated Factor 1 scores. Extremely low Factor 1 scores (less than -1), just west and northwest of the zone where the semi-confining unit pinches out, result from concentrated recharge of surface water to the Floridan aquifer through sinkholes considerably enlarged by dissolution. This localized hydraulic interconnection isolates recharge from reaction with the limestone.

Factor 2, which includes the variables iron and color, most likely reflects leaching of surface organics and mobilization of iron in the surficial sediments. Since iron cations are readily bound up as a result of chemical interaction with the surficial sediments, positive Factor 2 scores are present in only those iron-rich regions of the study

area that are underlain by a breached semi-confining unit, which provides direct and rapid recharge to the Floridan aquifer.

Factor 3 includes only the variable magnesium and most likely reflects weathering of magnesium clays. Along the perimeter of the semi-confining unit, low photolineament densities and thus relatively-restricted ground-water circulation, provides the proper geochemical environment necessary for the weathering of magnesium in the semi-confining clays.

Some general observations may be drawn from this study. The areal distribution of photolineaments shorter than 2 km is relatively uniform over the region. These photolineaments are presumed to reflect tidal-stress joints and appear to have little to no effect on the areal distribution of the three geochemical factors identified using factor analysis. This suggests that tidal-stress joints, typically shorter than 2 km, either do not penetrate the aquifer matrix for a sufficient depth, are not sufficiently enlarged by dissolution to affect water quality in the Floridan aquifer, or they are diffuse and abundant enough that at a macroscale they function as a homogeneous system.

Photolineaments longer than 2 km generally indicate fractures of tectonic origin. These long photolineaments do not appear to be uniform in distribution over the study area. Instead, photolineaments longer than 2 km are closely grouped forming distinct zones of photolineament concentration. The extensive fractures appear to penetrate the Floridan aquifer much deeper and are more enlarged by dissolution than surficial tidal-stress joints since they have a significant affect on local ground-water movement and thus on the areal distribution of the ground-water quality parameters used in factor analysis.

Factor analysis and photolineament analysis demonstrate that the distribution of chemical species in the upper 300 m of the Floridan aquifer, northwest-central Pasco County, Florida, is, in general, not random; rather it is controlled by source, stratigraphy, residence time, and flow path with the latter two being strongly influenced by fracture type, distribution and degree of enlargement by dissolution.

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