Fracture Trace Mapping of the Eldridge-Wilde Well Field, Pinellas County, Florida

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ABSTRACT

A photolinear analysis of the Eldridge-Wilde well field, Pinellas County, Florida, was conducted to identify zones of fracture concentration. Photolinear fracture traces and lineaments correspond to vertical zones of fracture concentration. Forty-three photolinears, ranging in length from 269 meters to 2.53 kilometers were mapped on four aerial photographs. The dominant azimuthal orientation of the photolinears is in the range of 041° to 050°.

The relation between well yield and well location relative to fracture trace location was investigated. Of the forty-eight production wells in the field study area for which specific yield data were available, seven are located on mapped fracture traces, one of which is on a fracture trace intersection. Boxplots of specific yields of wells "on" and "off" fracture traces show that the median productivity of the "on" group, 308 gallons per minute per foot of drawdown, is almost twice that of the "off" group, 160 gallons per minute per foot of drawdown. However, nonparametric statistical analysis could not reject the null hypothesis that both samples were from the same statistical population.

Application of this photolinear analysis to any subsequent water supply investigations would require supplementary inquiries, including field checking of the mapped photolinears and test drilling. In the course of the investigation, a list of sixteen hydrogeologic variables that can influence porosity and permeability at the Eldridge-Wilde well field was developed.

INTRODUCTION

Although many fracture traces have been mapped in West-Central Florida, to the best of the author's knowledge no rigorous quantitative demonstration of the relation between fracture zone and well yield has been published for the Upper Floridan aquifer. Water wells located on zones of enhanced fracture concentration in other areas of the United States have been shown to have significantly larger yields than similar wells not located on such zones (Siddiqui and Parizek, 1971). Photolinear mapping was conducted to investigate the relation between well yield and fracture trace location in the Upper Floridan aquifer at the Eldridge-Wilde well field.

The Eldridge-Wilde well field is located in sections 1, 2, 11, and 12, Township 27 S, Range 16 E on the U.S. Geological Survey (USGS) topographic quadrangle of Elfers, Florida, near the intersection of Pinellas, Pasco and Hillsborough counties on Florida's western coast (fig. 1). Maximum relief in the quadrangle is less than 20 meters. Most of this relief is due to the presence of paleodunes west of the study area. The area of investigation encompassed approximately 11 square kilometers. The well field is one of several that supplies water to west-central Florida. The geologic setting of the well field is dominated by thick, areally-extensive limestone with some dolomite. Karst features are pervasive and many sinkholes occur in the study area.

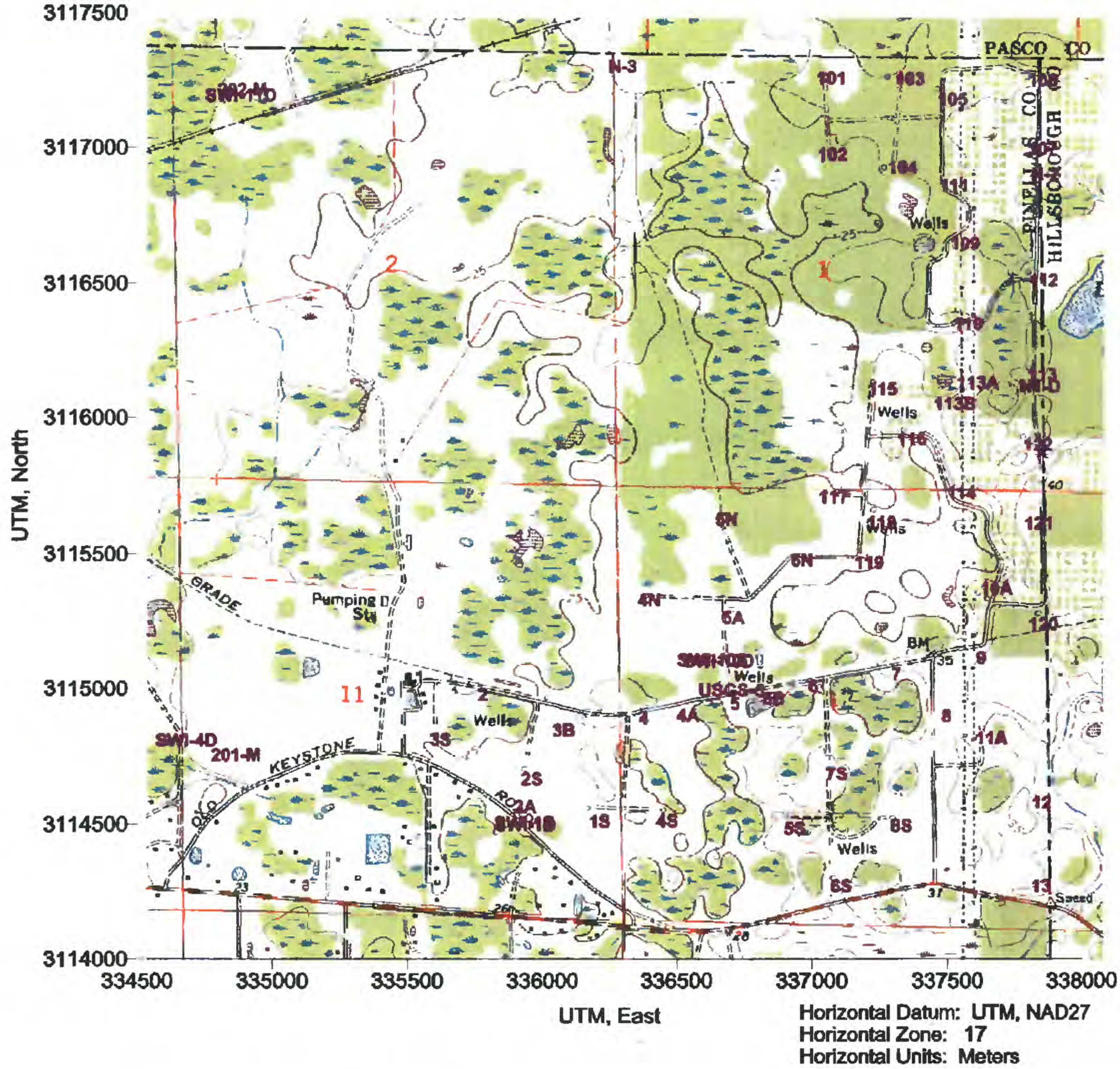

Figure 1. Map showing location of production and monitoring wells (shown in blue) in the study area at the Eldridge-Wilde well field, based on a 21 June 1999 global positioning system survey. See figure 2 for location within state of Florida. (Topographic map is not rectified to the well coordinates and is for reference only.)

HYDROGEOLOGIC SETTING

The wells in the Eldridge-Wilde well field produce water primarily from the Tertiary Upper Floridan Aquifer. The hydrostratigraphy of the Tertiary and Quaternary rocks in the study region is summarized in Table 1.

A map of the regional potentiometric surface of the Upper Floridan Aquifer in May 1980 was published by Meyer (1989). That map shows the approximate location of a prominent ground-water divide running down the central axis of the Florida Peninsula. Although the data synthesized on the map are not recent, the configuration of the potentiometric surface on a regional scale does not change apprecia-

Table 1: Generalized hydrostratigraphy in the study region (modified from Tihansky and others, 1996)

System	*Series*	*Hydrostratigraphic Unit*	*Generalized Lithology*
Quaternary	Pleistocene	Surficial Aquifer System	Fine to very fine sand, shelly in places, infrequent clay beds.
Tertiary	Pliocene	Intermediate Confining Unit	Fine-grained carbonate, variably dolomitic (Arcadia Formation) Sandy wackestone (Tampa Member)
	Miocene		
	Oligocene	Upper Floridan Aquifer	Fine- to medium-grained limestone with trace organics and variable dolomite and clay (Suwanee Limestone)
	Eocene		Chalky, fine- to very fine-grained limestone, changing with depth to medium to coarse-grained biogenic limestone, variable dolomite (Ocala Limestone)

bly with time (M.L. Merritt, USGS, oral comm., 1999). The stippled area indicates potable water.

The local geology consists of a karstic carbonate rock sequence with considerable heterogeneity with respect to dolomite content and the presence or absence of karst conduits, shelly beds, and clayey zones. As is typical of karst hydrogeologic settings, the thickness of the sedimentary overburden varies considerably but is up to 30 m in places. The sediments are dominated by sand, but also include clay-dominated and shelly zones on top of the carbonate rock sequence. Cypress swamps dot the landscape, and peat deposits are present in some of these swamps. Although topographic relief is negligible, the northern portion of the study area can be classified as "upland" based on the occurrence of relatively hydrophobic pine and palmetto, whereas the southern portion can be classified as "lowland" based on the scarcity of those plant types and the dominance of hydrophyllic cypress trees.

FRACTURE-TRACE MAPPING PRINCIPLES

Photolinear analysis is a type of remote sensing analysis wherein investigators map linear features ("photolinears") observable on aerial photographs or other remotely-sensed images. The use of photolinears for ground-water well siting was pioneered by Lattman and Parizek (1964). For linear features of geologic origin, *lineaments* are defined as those photolinear features greater than one mile in length, whereas *fracture traces* are the same type of feature having a total length of less than one mile. The width of these zones of fracture concentration can vary from a few to tens of meters. In general, longer lineaments tend to have wider surface expressions of the zone of fracture concentration and wider zones of fracture concentration at greater depths. Because the fracture

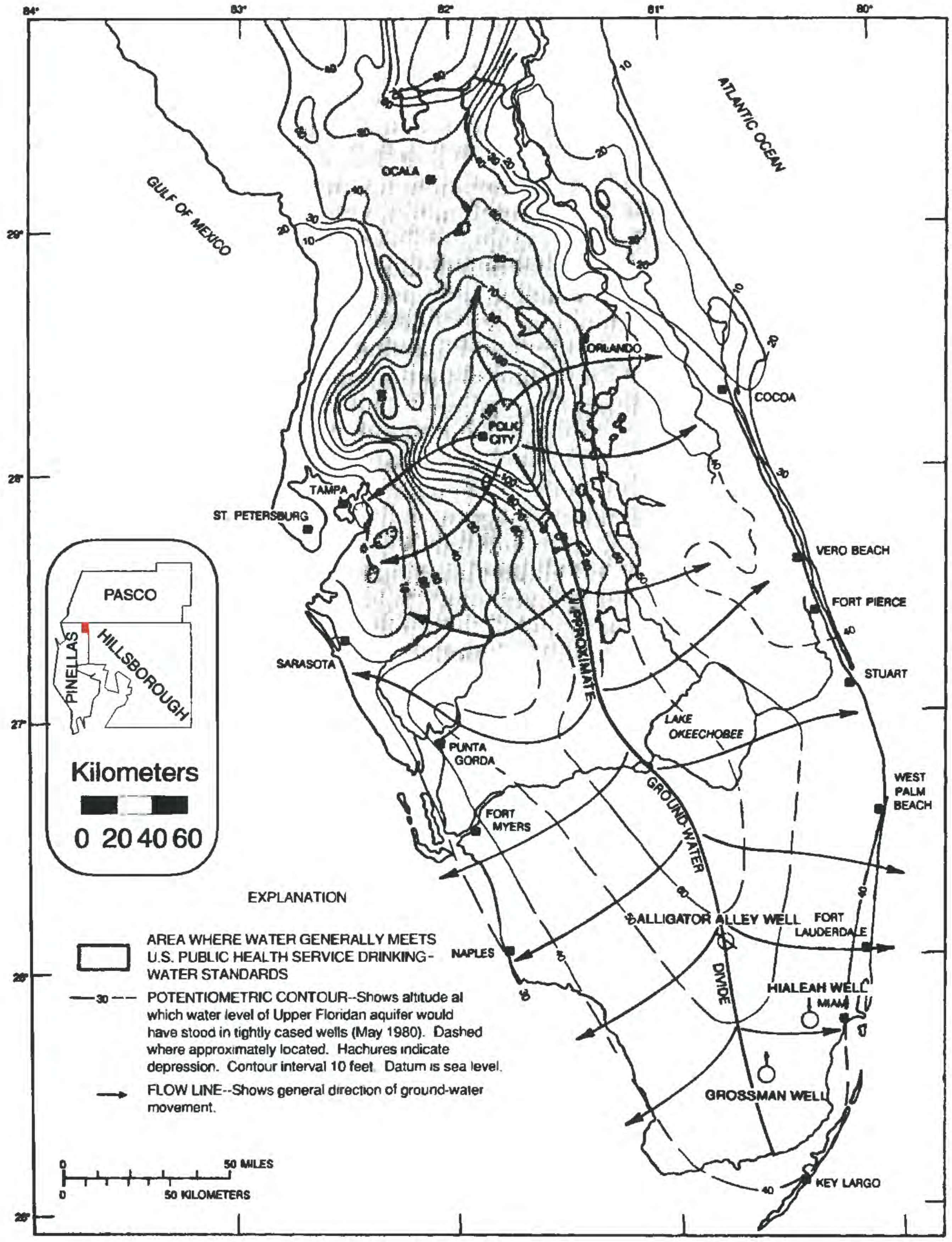

Figure 2. Map showing approximate potentiometric surface of the Upper Florida Aquifer in May 1980 (Meyer, 1989). Inset: Location of the study area at the intersection of Pinellas, Hillsborough, and Pasco counties near Tampa Bay is shown in red.

trace is the surface expression of the vertical zone of fracture concentration, Parizek has suggested that *"fracture zone trace"* might be a more appropriate descriptive term (Parizek and Diodato, 1995).

The potential geologic origins of lineaments and fracture traces are discussed in Lattman (1958) and Lattman and Parizek (1964). Lineaments and fracture traces can be evidence of zones of permeability contrast relative to the neighboring rock mass. In the case in which they are zones of enhanced permeability, they may preferentially conduct groundwater. Alternatively, where weathering in zones of fracture concentration in relatively permeable parent rocks leads to formation of clays *in situ*, reduced permeability may result. In that case, zones of fracture concentration create impediments to groundwater flow. Zones of fracture concentration in soluble rocks such as carbonates and evaporites can lead to enhanced dissolution of these rocks due to accelerated chemical and physical weathering. In the case of rocks prone to karstification, White (1999) has determined that the development of karst conduits begins when fracture apertures reach about 1 centimeter.

Because of the narrowness of fracture traces, application of fracture-trace mapping to siting of ground-water wells requires substantial care and accuracy (Lattman and Parizek, 1964; Parizek and Diodato, 1995). In some geologic settings, errors in well siting as small as a meter can result in well yields far below their potential maximum. Accordingly, great care is required in the transfer of mapped photolinears from aerial photographs to base maps or orthorectified photographs. Where field orientation is ambiguous or difficult, the use of the global positioning system satellites to locate digitally-orthorectified fracture traces may prove to be of great benefit to the field hydrogeologist.

The detection of lineaments and fracture traces is based on a variety of criteria including, but not limited to, soil tonal variation, tree height-alignment, topographic relief or offset, and stream-segment alignment. In well-drained areas, fractures can result in a lightening of soil tones as a result of enhanced water movement and leaching of organic materials and minerals. In poorly-drained areas, relatively dark fracture traces may be the result of increased soil moisture content. In carbonate rocks where karstification occurs, the alignment of sinkholes can be diagnostic. In the Eldridge-Wilde well field, sinkholes are so ubiquitous that they cannot be used as diagnostic indicators. However, the occurrence of sinkholes along mapped fracture traces and at fracture trace intersections is taken as supplemental independent evidence of the occurrence of a zone of enhanced permeability.

PHOTOLINEAR MAPPING METHODOLOGY

The photolinear analysis described here was based on the photographs identified in Table 2. The photographs are at a scale of 1:20697 (Aerial Photography Summary Record System, 1996).

Following a site inspection, the analysis was conducted as follows.

1. First, large photolinears clearly observable without stereoscopic views or magnification were delimited on the photos with pairs of symbols ">" and "<" marking their termini. In some cases, a 7x magnifying lupe was used to check that

Table 2: Photographs used in the photolinear analysis at Eldridge-Wilde well field, Pinellas County, Florida

Series	Number	Date
GS-SWFM	4-54	12 December 1971
GS-SWFM	4-55	12 December 1971
GS-SWFM	4-56	12 December 1971
GS-SWFM	4-57	12 December 1971

the features were not remnants of old roads or other non-geologic activity, or to search more closely for termini.

2. Second, photolinears observable using oblique views were marked with "—" at their termini. The oblique analysis was accomplished by placing the photographs on a stiff board and rotating through 360 degrees at close viewing range and high viewing angle
3. Third, photolinears observable with the aid of a mirror stereoscope at either 1x or 3x magnification were marked with "I" at their termini.

Because relief in the study area is negligible, viewing the photographs under a mirror stereoscope did not significantly aid in the detection of fracture traces.

When the photolinear mapping was completed, the mapped features were transferred to the USGS Elfers topographic quadrangle 1:24000-scale base map using a Bausch & Lomb zoom transfer scope. The zoom-transfer scope optically corrects for flight-line parallax, allowing rectification of small areas of the images to the base maps. Confidence in the exact placement of the photolinears on basemaps was reduced because the entire photograph could not be rectified simultaneously. Furthermore, it was not always possible to rectify the entire extent of regions containing long photolinears simultaneously.

Potentially misleading linear features -- those not related to fractures or fracture zones -- clearly observable on aerial photographs in the study area included jeep trails, animal paths, drainage ditches, areas of citrus tree and other agricultural cultivation, and recent and historical fence lines. In addition, it was reported that paleohurricane tracks have been documented to leave long-lasting linear scars on the landscape in this region (R. Evans, Southwest Florida Water Management District, oral comm., 1999), although none of these were recognized in this analysis.

MAPPED FRACTURE TRACES AND PHOTOLINEARS

A total of forty-three unique photolinears were mapped on the four photographs listed in Table 2. (Those photographs are included in Appendix A.) Figure three shows those fracture traces and photolineears mapped within the study area, as projected using the Bausch & Lomb zoom transfer scope onto the USGS Elfers topographic quadrangle. Two of the photolinears were mapped in whole or in part on two photographs. Four of the forty-three

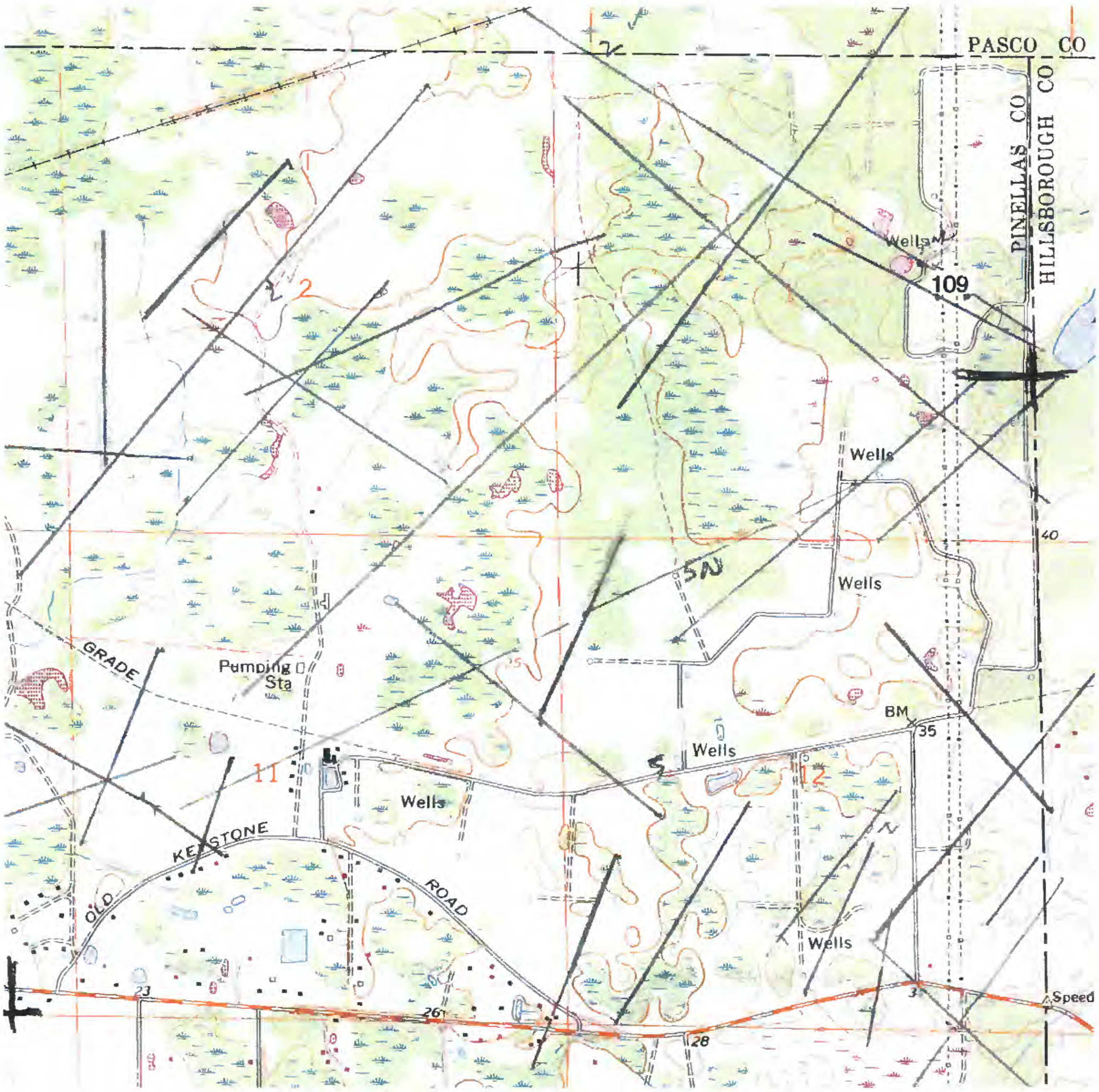

Figure 3. Map showing projected locations of the mapped photolinears at the Eldridge-Wilde well field. Only the photolinear near well 109 has been verified in the field to be a fracture trace.

photolinears were outside of the study area.

The length of the forty-three photolinears ranged from 269 m to 2.53 km, with an average length of 1.09 km. The dominant azimuthal orientation of the photolinears is in the range of 041° to 050° (fig. 5). A secondary orthogonal peak in the range of 331° to 340° is most likely a structural conjugate set of fractures.

More confidence is placed on linears detected on more than one photograph and/or mapped by more than one method. In two cases, photolinears were mapped

Figure 4. Sinkhole near well 109 which developed recently before the March 1999 field visit. This well is on the edge of a mapped fracture trace. Note the break in topographic slope in front of the cluster of tall trees to the right of the well house.

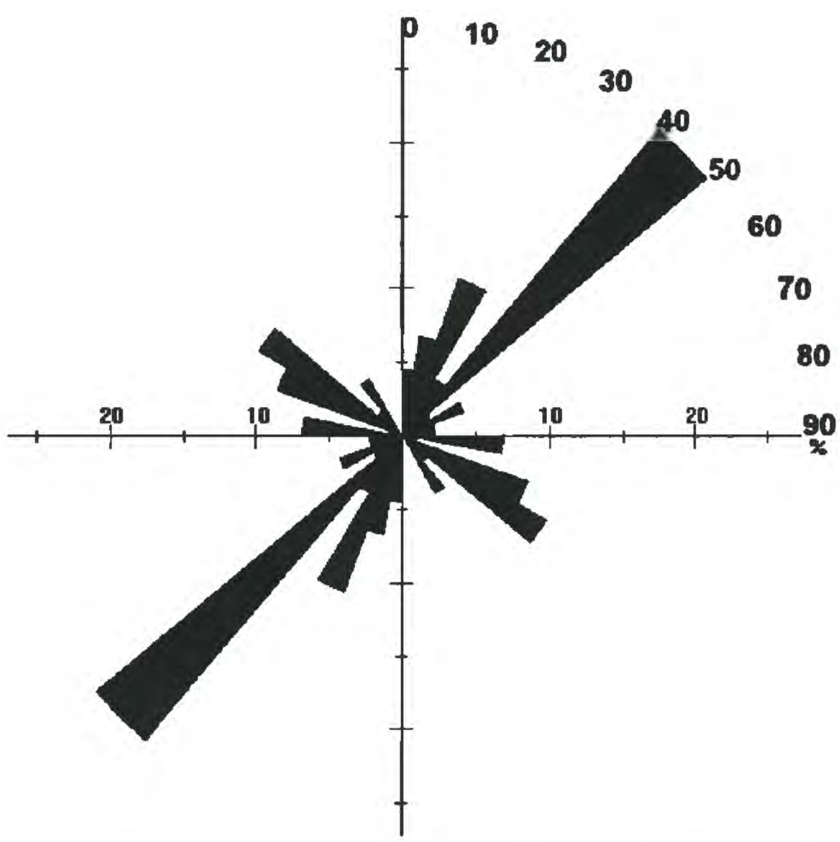

Figure 5. Rose diagram showing frequency (percent) of mapped photolinear orientations. Azimuthal orientation is shown from zero to 90 degrees.

on two photographs. However, the extent of those mapped photolinears was not identical.

The angle of the sun, both at the time of photography and at the time of analysis, can influence which linears are discernible on which photograph. Further inspection of the photographs in different light revealed one fracture trace extending substantially beyond the originally mapped length. This extension, nearly doubling the length of the mapped photolinear, extended outside of the study area and was not included in this analysis. More fracture traces and lineaments can be identified on these photographs by inspecting them under different lighting conditions.

Although field verification is a critical component of fracture trace analysis, the location of only one of the fracture traces mapped in this study has been field-verified. Wells 102, 103, 113, 116, 117, 5N, and N1S lie on mapped but not field-verified fracture traces. In fig. 6, a new sinkhole in alignment with older sinkholes was observed in the field near well 109. This is independent evidence of the existence of the mapped fracture trace at this location. Well 109 is adjacent to a field-verified fracture trace. Wells 101 and 122 lie on visible fracture traces that were not mapped.

INFLUENCE OF FRACTURE TRACE LOCATION ON WELL YIELD

None of the wells in the Eldridge-Wilde well field were represented to the author as having been located on the basis of fracture-trace mapping. Despite this, some wells appear to have been located on fracture traces purely by chance. For the purpose of analysis, wells were classified as either "off" a fracture trace or "on" a fracture trace. A well was defined as being "on" a fracture trace if it was within ±1 millimeter of that trace on the aerial photograph (approximately 20 m on the ground). A total of seven wells were found to have been drilled on fracture traces, forty-one other wells were classified as "off."

Acknowledging that (1) not all fracture traces that exist were mapped, and (2) only one of the fracture traces was field verified, it is nonetheless of interest to test for the significance of zones of fracture concentration on ground-water well yield in the Upper Floridan Aquifer at the Eldridge-Wilde well field. To this end, exploratory and non-parametric statistical analysis of well yield versus fracture trace location were conducted.

Specific yield data for forty-eight production wells in the Eldridge-Wilde well field were available from five different engineering studies (Black, Crow and Eidness, 1970; Gee and Jenson Engineers-Architects-Planners, 1981a, 1981b, 1983; Nettles and Vandor, 1985). For many wells, the multiple values reported in the studies often differed owing to well development, redrilling, and other unknown factors. Because of that variability, the largest reported specific yield was arbitrarily used for all wells. Furthermore, no correction was made for well bore diameter, which ranged from 12 to 16 inches, or for length of open well interval. Because of the small number of samples (wells in the data set), further subsetting by those factors or by production interval or horizon was not pursued.

Figure six is a boxplot comparing yields from wells not located on fracture traces with those of wells that are located on fracture traces. The whiskers extend to the

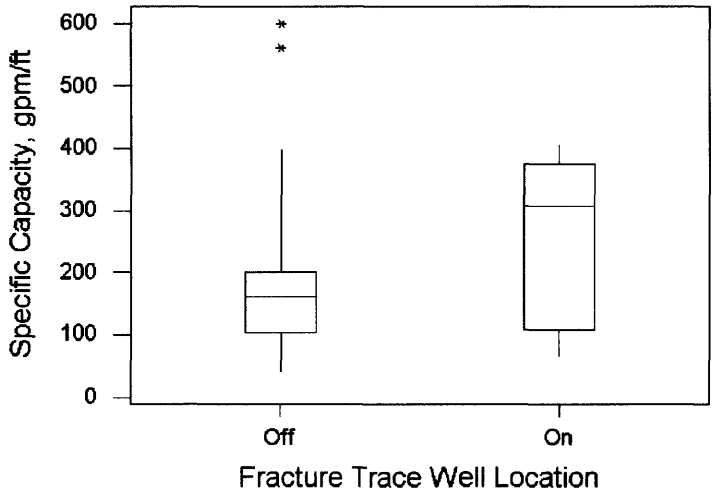

Figure 6. Boxplot of well yields from non-fracture trace and fracture trace wells. Specific capacity is in units of gallons per minute per foot of drawdown. Central lines are median values, asterisks are outliers.

limits of the quartiles of the data sets, the box limits indicate the 95th-percentile confidence interval, and the lines in the boxes show the median values of the sample population. The median specific yield of wells on fracture traces (308 gallons per minute per foot of drawdown (gpm/ft)) was nearly twice that of wells not located on fracture traces (160 gpm/ft). The outliers, shown in the plot as asterisks, represent wells 101 and 122. Although no fracture traces were initially mapped in the vicinity of these wells, further examination of the photographs in different lighting conditions reveals proximal photolinears that are most likely the surface expressions of zones of fracture concentration. Productivity data for well N1S was not available, and it was not included in the "on" data set.

The Kruskal-Wallis test is a nonparametric test that can indicate whether multiple samples come from populations having the same statistical distribution and central value (Davis, 1986). Nonparametric tests are preferred in this case because they do not assume an underlying statistical distribution of the data. The null hypothesis posed to the Kruskal-Wallis test was that the samples came from the same population. The Kruskal-Wallis test statistic, H, was 1.54 for the one degree of freedom test, so that the null hypothesis could not be rejected.

APPLICATION TO FIELD HYDROGEOLOGIC INVESTIGATIONS

Successful application of the mapped photolinears to hydrogeologic investigations at the Eldrige-Wilde well field will require awareness on the part of the investigator of the issues outlined in this paper. Because of likely inaccuracies introduced in the rectification of photolinears onto the topographic base map, because the locations of features on USGS topographic quadrangles may be in error by as much as 13 m (G. Desmond, USGS, oral comm., 1999), and because of other subsequent distortions in scanning and printing, no well siting should be based on fig. 3. Instead, wells can be reliably located by field-verification of fracture traces mapped on the photographs included in Appendix A, along with all relevant supplemental information available to the field hydrogeologist.

Parizek (1978, 1985, 1988a, 1988b) has identified several dozen natural geologic and hydrogeologic factors as variables that can influence the development of porosity and permeability, the dynamics of ground-water flow, and the stability of engineering projects in carbonate, gypsum, and evaporite rock settings. Heterogeneity in the distribution of permeability and porosity can influence the flow of ground water and the transport of solutes. In this study, sixteen variables of that type that are confirmed or are likely to exist in the Floridan Aquifer at the Eldridge-Wilde well field were identified. Those variables, listed in Table 3, are based on field observations and background information pertaining to the hydrogeology of the region. The controls in Table 3 are variables that have different spatial extents; furthermore not all of them may have surficial expression. Any hydrogeological investigations at the site should include the consideration of the factors listed in Table 3.

To take full advantage of photolinear analysis of fracture traces, further supplemental information and interpretation is required. First, the locations of fracture traces identified on photographs must be field checked and verified. Other desirable supplemental information includes, in part: detailed lithologic and hydrologic stratigraphy at the site scale, aquifer stress test data with drawdowns from two or more monitoring wells, and local- and site-scale potentiometric surface data. Aquifer stress tests with drawdown data at multiple, orthogonally-positioned monitoring wells can be used to measure anisotropy of the permeability tensor. The average permeability tensor in the field may be found to be aligned with the orientation of the fracture traces shown in fig. 4. Further, multivariate nonparametric statistical analysis of all wells in the field with classification according to: (a) productivity, (b) proximity to fracture trace or lineament, (c) proximity to intersection of two or more fracture traces or lineaments, and possibly (d) solute concentration may be fruitful. Multivariate analysis can be used to determine the relative influence of a large number of hydrogeologic parameters on well production (Siddiqui and Parizek, 1971), and potentially the relation of well water chemistry to zones of fracture concentration. Other statistical methods, such as principal components analysis, may also prove fruitful.

In addition to those activities, it is worthwhile to seek correlation with fracture traces mapped by other investigators. The delineation of fracture traces by multiple investigators gives greater confidence in the existence of the mapped features.

Finally, correlation of the results of fracture-trace mapping with geophysical investigations may prove fruitful. Previous researchers have investigated the relation between photolinear analysis and geophysical survey results with regard to identification of hydrogeologic features. Spratt (1996) found that some geophysical methods were able to image mapped fracture traces and others were not. Successful detection of fracture zones by geophysical methods requires experimental design consideration of the likely scales and

Table 3: Factors that may influence the distribution of porosity and permeability at the Eldridge-Wilde well field

Zones of fracture concentration
Zones of biogenic limestone
Sandy zones
Shelly zones
Bedding planes
Location of karst conduits
Location of karst sinkholes
Location of paleowater tables
Location of paleokarst conduits
Location of paleofluvial channels
Location of paleodune deposits
Zones of chalky chemical limestone
Zones of dolomite
Clay-rich zones - will reduce permeability
Zones of paleolacustrine deposits - will reduce permeability
Coincidence of two or more of the above factors

extents at which they will be detectable for the various methods of geophysical investigation.

SUMMARY AND CONCLUSIONS

Forty-three unique photolinears were mapped in the vicinity of the Eldridge-Wilde well field, Pinellas County, Florida. One photolinear was positively identified in the field to be a fracture trace. More photolinears can be mapped in the study area by examination of the photographs under different lighting conditions.

Specific yield data were available for forty-eight wells in the study area. The median specific yield of wells located on fracture traces was 308 gpm/ft, compared with 160 gpm/ft for wells not located on fracture traces. The higher median specific yield of the "on" group as compared to the "off" group suggests that the yield of new production wells in the Upper Floridan can be increased by locating the wells directly on fracture traces, optimally at fracture trace intersections.

In the course of the investigation, a list of sixteen hydrogeologic variables that can influence porosity and permeability at the Eldridge-Wilde well field was developed. Water supply development can be optimized by considering each of the elements in the list and identifying spatial zones where one or more of them may contribute to enhanced porosity and permeability in the Eldridge-Wilde well field.

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APPENDIX A. PHOTOGRAPHS WITH MAPPED PHOTOLINEARS IN THE VICINITY OF THE ELDRIDGE-WILDE WELL FIELD

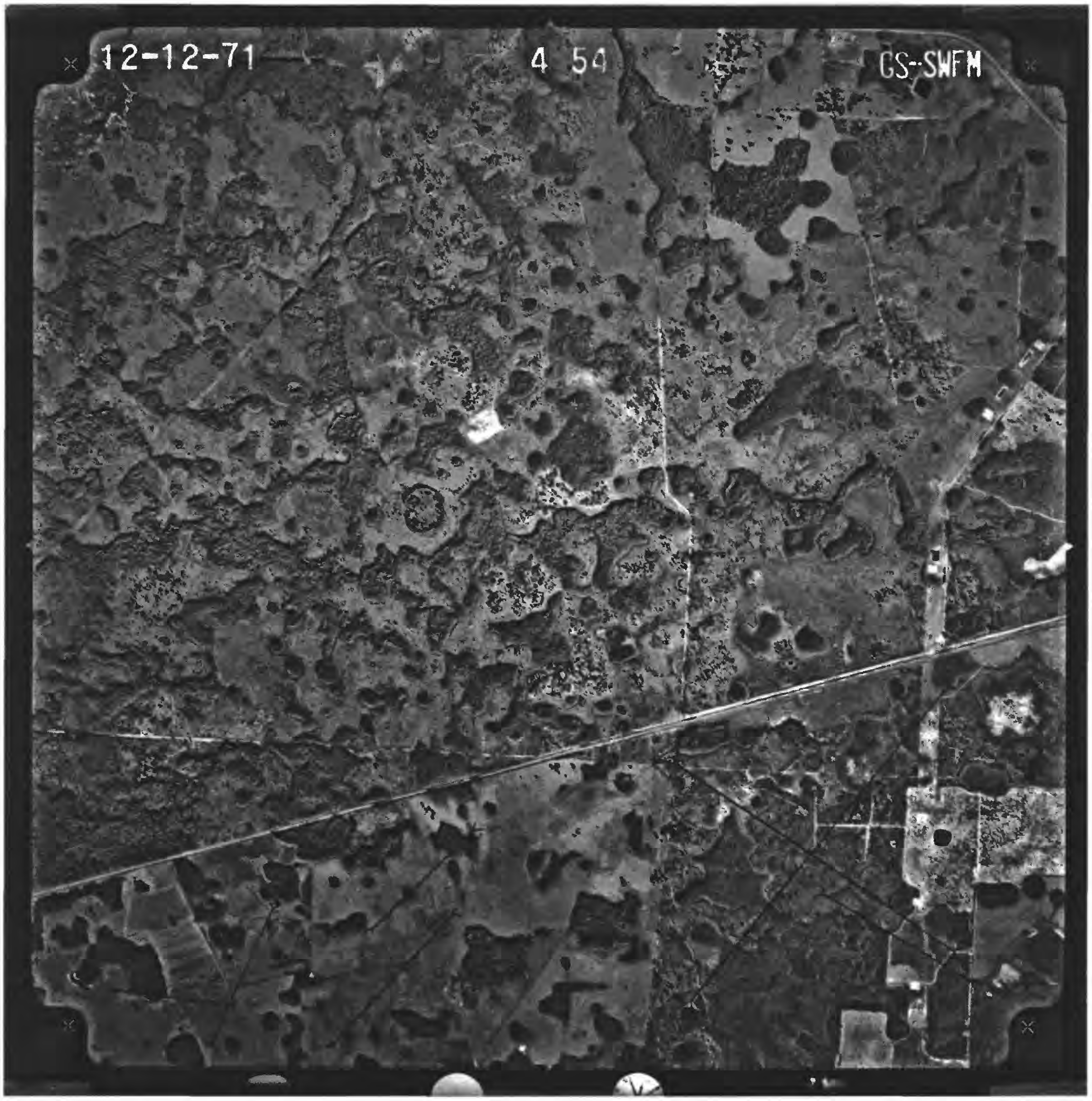

Figure 7. Photograph GS-SWFM 4-54. Image has been scanned at 500 dpi optical and scaled to 0.66 of original size.

Figure 8. Photograph GS-SWFM 4-55. Image has been scanned at 500 dpi optical and scaled to 0.66 of original size.

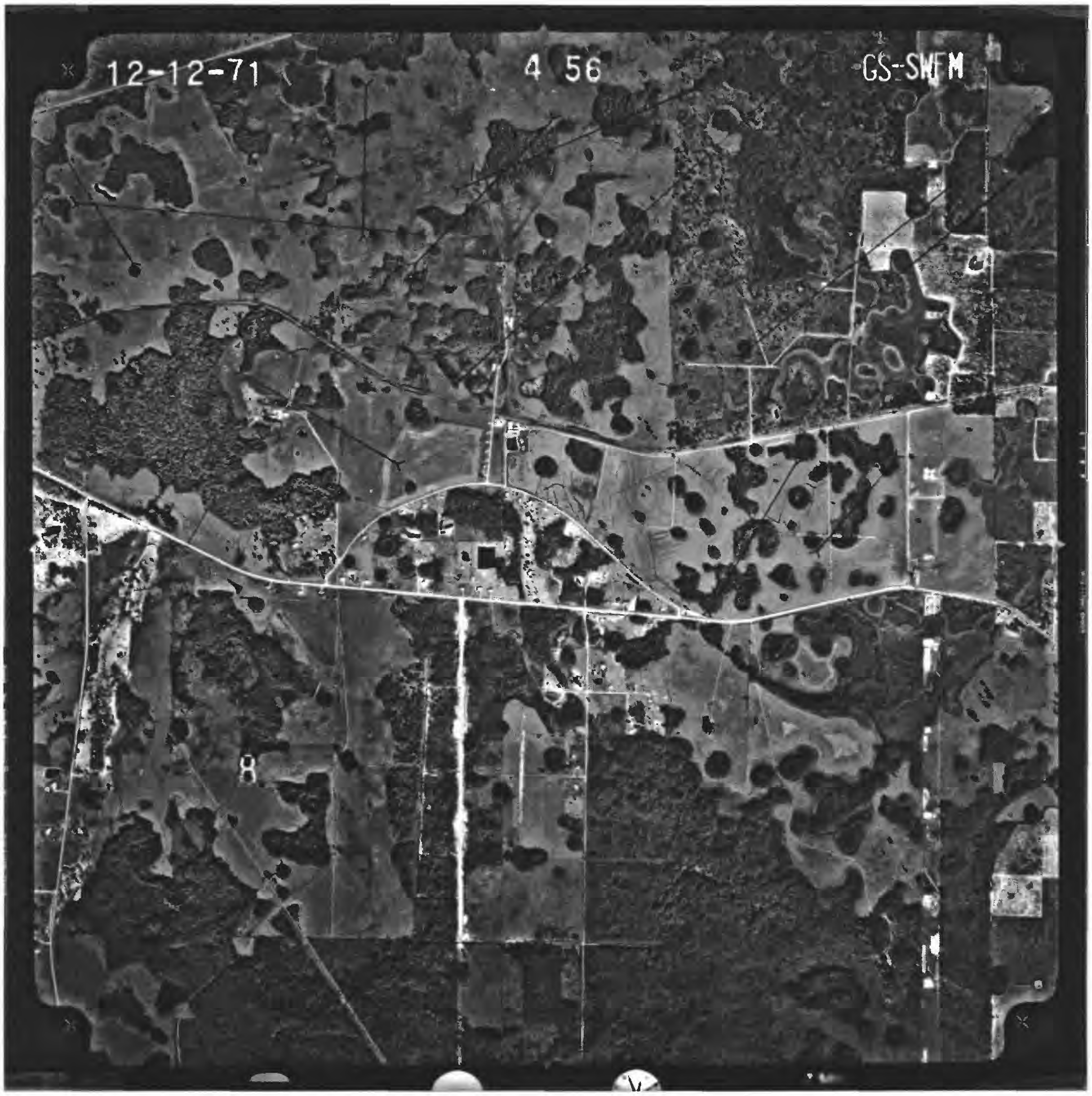

Figure 9. Photograph GS-SWFM 4-56. Image has been scanned at 500 dpi optical and scaled to 0.66 of original size.

Figure 10. Photograph GS-SWFM 4-57. Image has been scanned at 500 dpi optical and scaled to 0.66 of original size.