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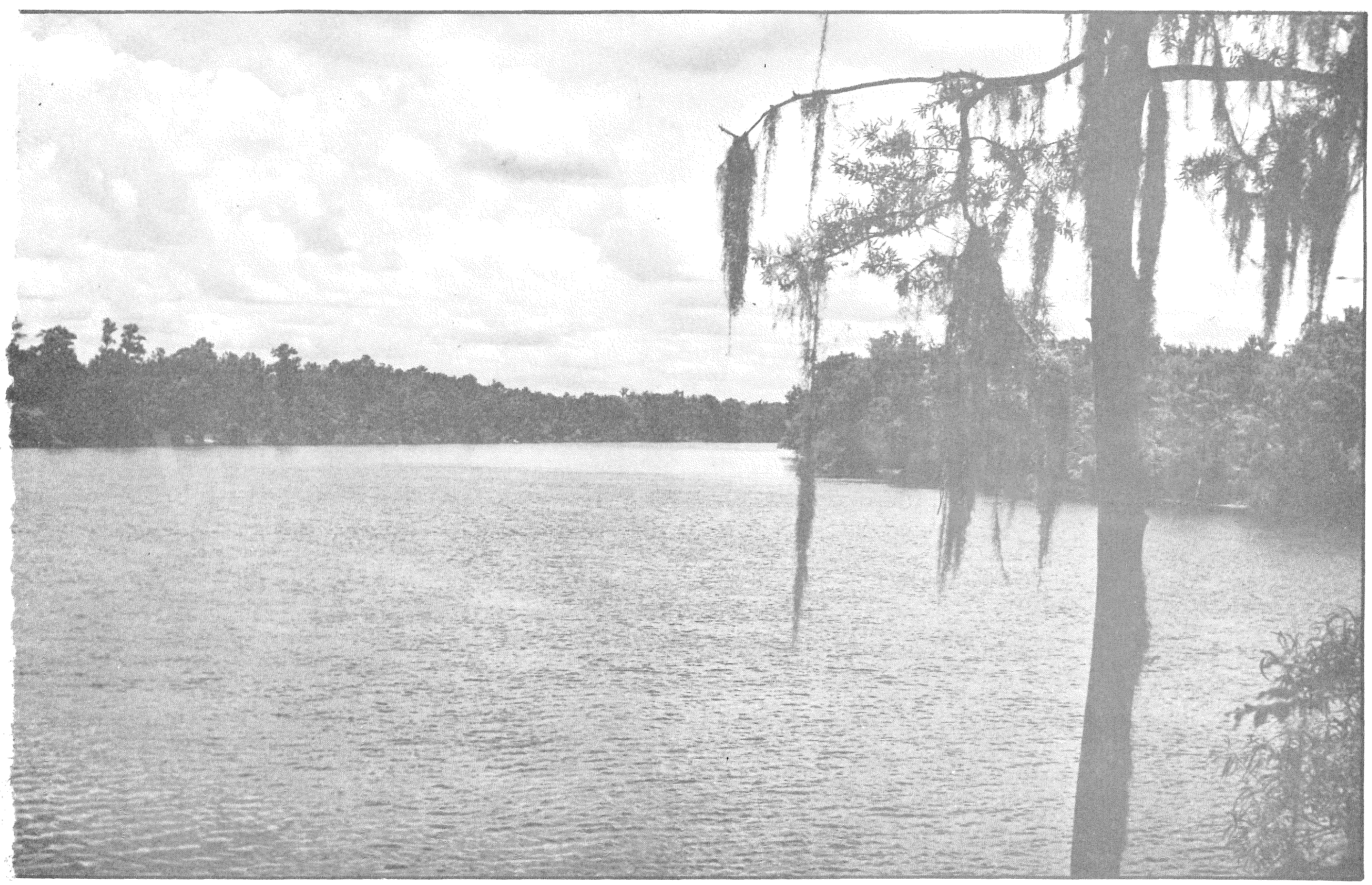
EVALUATION OF A GROUND TRANSIENT ELECTROMAGNETIC REMOTE SENSING METHOD FOR THE DEEP DETECTION AND MONITORING OF SALT WATER INTERFACES

By

Mark T. Stewart
Michael C. Gay

Geology Department
University of South Florida
Tampa



UNIVERSITY OF FLORIDA

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ABSTRACT

A ground transient electromagnetic sounding method was evaluated for the detection of salt water-fresh water interfaces along the Gulf Coast of Florida. Seventy-nine soundings were completed utilizing either 80 x 80 meter or 160 x 160 meter horizontal transmitter coils. A 30 Hertz step function transmitter frequency was used. The decay of the vertical magnetic field was monitored over a period of 8 msecs during transmitter off-time. Measurements of the rate of decay of the magnetic field were converted to produce an apparent resistivity curve for each sounding. Computer produced theoretical curves were matched to the apparent resistivity curves.

The results of this study are encouraging. The soundings compare favorably with chloride ion concentrations in area wells and with data from previous geophysical studies. An 80 x 80 meter coil is sufficient for sounding to depths of 250 meters. Depths and resistivities accurate to within plus-or-minus 10 percent of actual field values are possible. The transient electromagnetic method is safe, efficient, and economically attractive.

INTRODUCTION

Ground water continues to be the primary source of potable water for many of Florida's coastal communities. Rapid population growth in recent years has caused concern for the quality of this abundant, but vital resource. Salt water intrusion poses a serious threat to the quality of the groundwater in coastal aquifers. Intrusion has already occurred in many areas along the Gulf coast of Florida (Causseaux and Fretwell, 1982; Mills and Ryder, 1977; and Sherwood and Klein, 1973). Fresh water injection (Bruington, 1969) and pumping of brackish waters (Gregg, 1971) have brought limited success in controlling salt water intrusion, but these methods are expensive. Efficient management of ground water in coastal aquifers is dependent upon inexpensive and reliable methods of detecting and monitoring changes in the position of the salt water - fresh water interface.

The sampling of well water for chloride content is the standard method of monitoring interface movement. Construction of minitor wells is costly, however, and this method cannot provide sufficient data density for adequate delineation of the interface. Wells of opportunity are often sampled as a means of supplementing this data, but depth control on such wells may not be reliable. Certain geophysical methods appear to be suitable for monitoring the salt water - fresh water interface. This study evaluates transient electromagnetic soundings for locating the interface.

Objectives

The objectives of this study are:

1. Mapping of the deeper portion of the salt water interface in the Coastal Rivers Basin, Florida.

2. Comparison of the results of the transient electromagnetic survey with data obtained by other geophysical and geochemical methods.
3. Determination of the most efficient field and interpretation techniques applicable to this problem.
4. Assessment of the potential of the transient electromagnetic method for ground water quality investigations.
5. Preparation of a cost/benefit analysis of the transient electromagnetic method as compared to other methods.

Scope

This study was conducted in Pasco, Hernando, Citrus, and Levy Counties, between latitudes 28°25'10"N and 29°03'10"N, and longitudes 82°28'10"W and 82°41'35"W. The study area is indicated by the shaded area in Figure 1. Seventy-nine soundings were made during 18 field days during May and June of 1982. Figure 2 is a map showing the locations of all sounding sites. Results from these soundings were compared to available chloride data and data from previous geophysical investigations conducted in the area.

Previous Investigations

Direct current resistivity techniques have been widely used to detect ground water contamination. Cartright and McComas (1968); Kelly (1976); and Stollar and Roux (1975) detected contamination derived from landfills and industrial sites. Swartz (1937, and 1939) pioneered the use of direct current (DC) methods as a means of locating salt water interfaces, by delineating fresh water lens boundaries in the Hawaiian Islands. Bisdorf and Zohdy (1979) and Fretwell (1978); used DC methods to map the interface in Citrus County, Florida.

Ryu and others (1972) were the first to suggest the possibility of using electromagnetic (EM) sounding as a means of locating and monitoring coastal

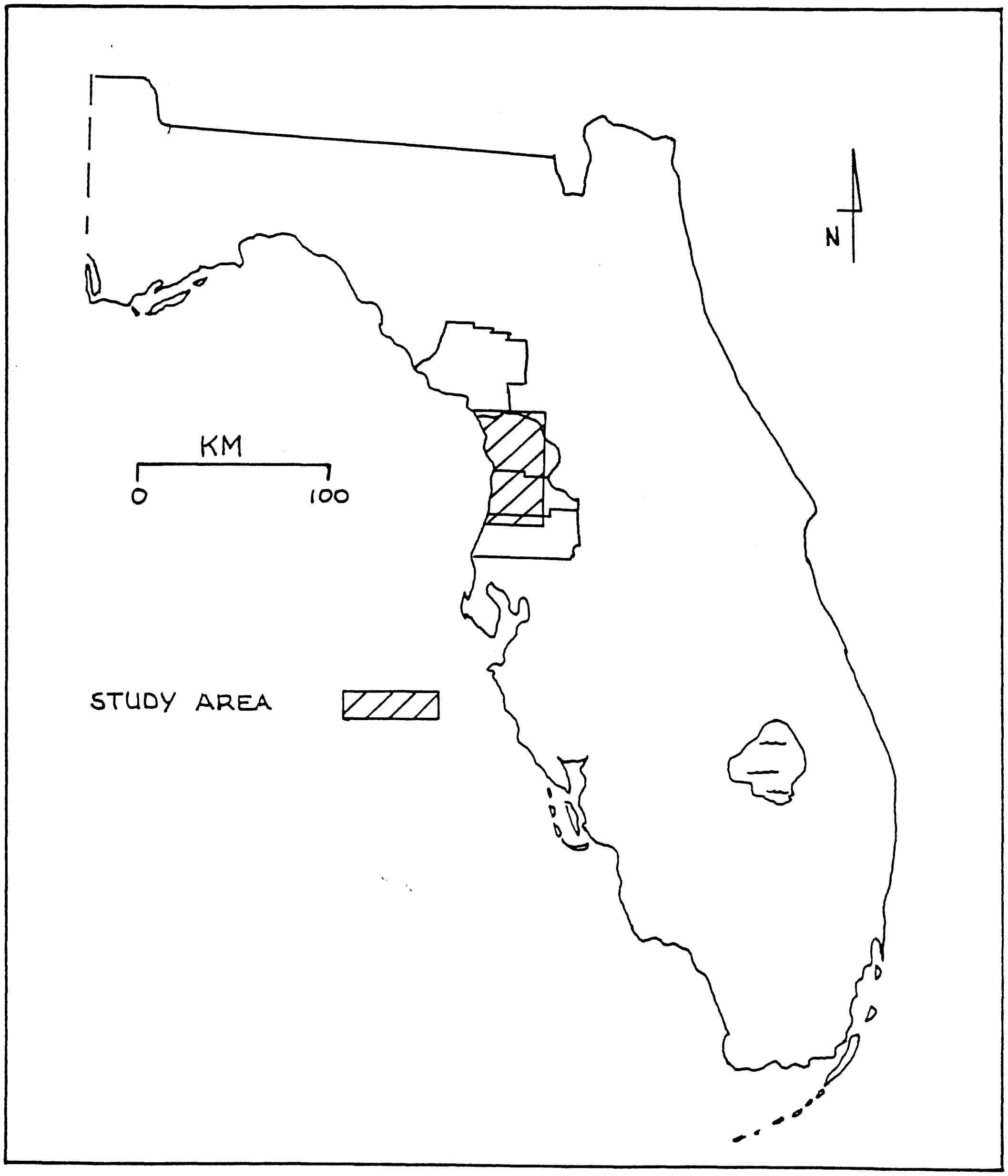

Figure 1. Map of Florida showing the location of the transient electromagnetic study area.

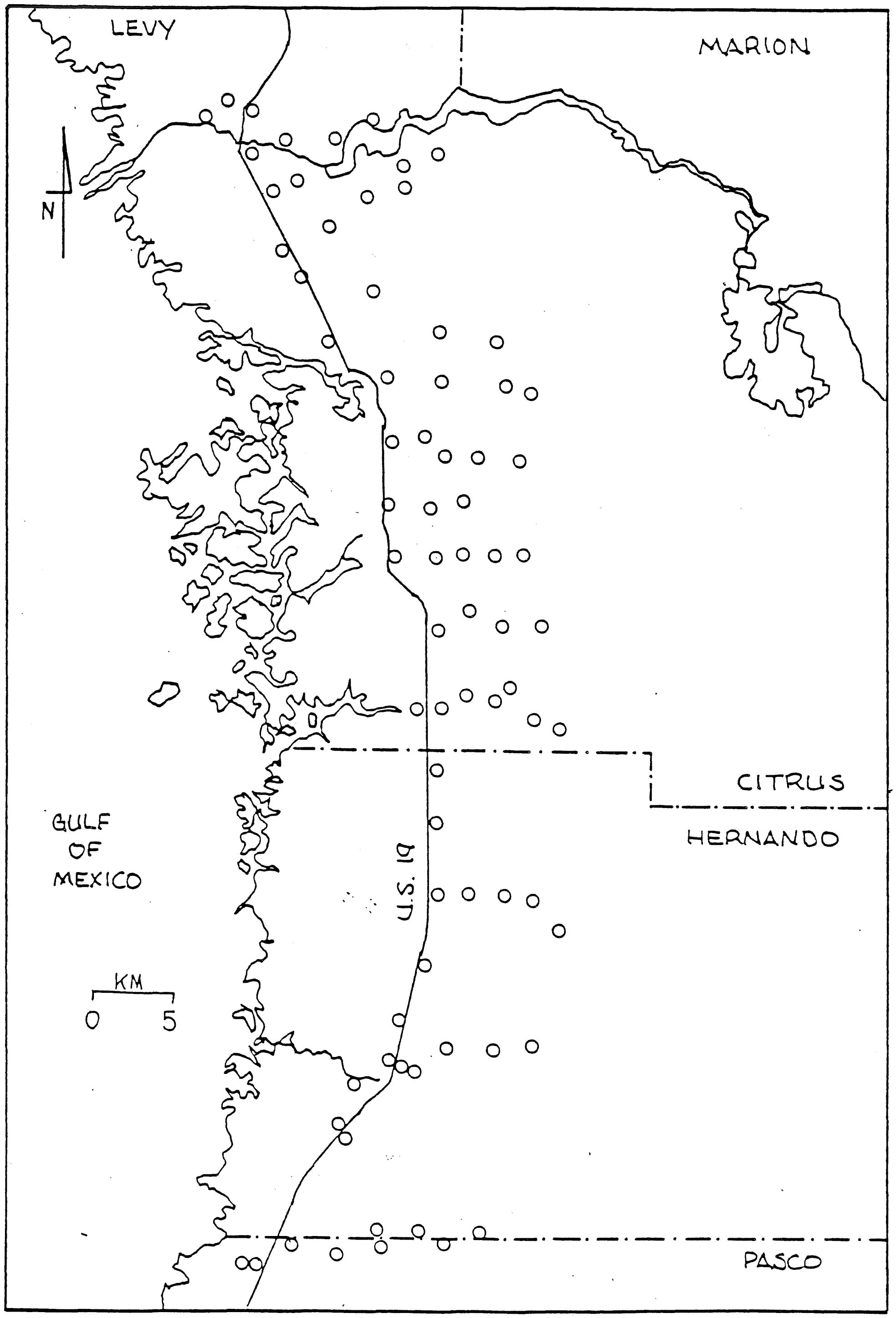

Figure 2. Map of the transient electromagnetic sounding site locations.

salt water - fresh water interfaces. They used frequency domain electromagnetics to search for potential aquifers in the Santa Clara Valley, California. Frequency domain electromagnetic methods have been used to locate the interface in Citrus and Collier Counties, Florida (Stewart, 1981). Both DC and frequency EM methods have been used and compared in the Belle Meade area of Collier County, Florida (Layton, 1981; and Stewart, 1981).

The transient EM method was used to search for potential geothermal energy sources in Hawaii (Kauahikaua, 1981). A computer-aided literature search conducted in May, 1982 yielded no reference to the use of transient EM methods for the purpose of locating salt water - fresh water interfaces.

Geology

Several hundred meters of Tertiary limestone units comprise the subsurface geology in the study area. These units exhibit very gentle dips toward the south and southwest (Wetterhall, 1965). Exposed rock units became progressively younger toward the south. Figure 3 shows the surficial geology of the study area. The entire area is underlain by Lake City Limestone (Fig. 4). The Lake City Formation has been completely dolomitized and later impregnated with gypsum and anhydrite (Vernon, 1951). It forms an effective lower confining unit for the Floridan Aquifer. The Lake City Limestone is overlain by the Avon Park Formation, the Ocala Group, and Suwannee Limestone. The Alachua Formation is exposed just outside the eastern edge of the study area.

Carbonic acid, formed by the saturation of water with carbon dioxide, is instrumental in dissolving large quantities of subsurface limestone (Krauskopf, 1979). Surface expression of this is evident in the number of small lakes and sinks in the area. Dissolution of limestone is most intense just below the water table (Smith and Randazzo, 1975). Sea level changes associated with Pleistocene glaciation have caused significant vertical

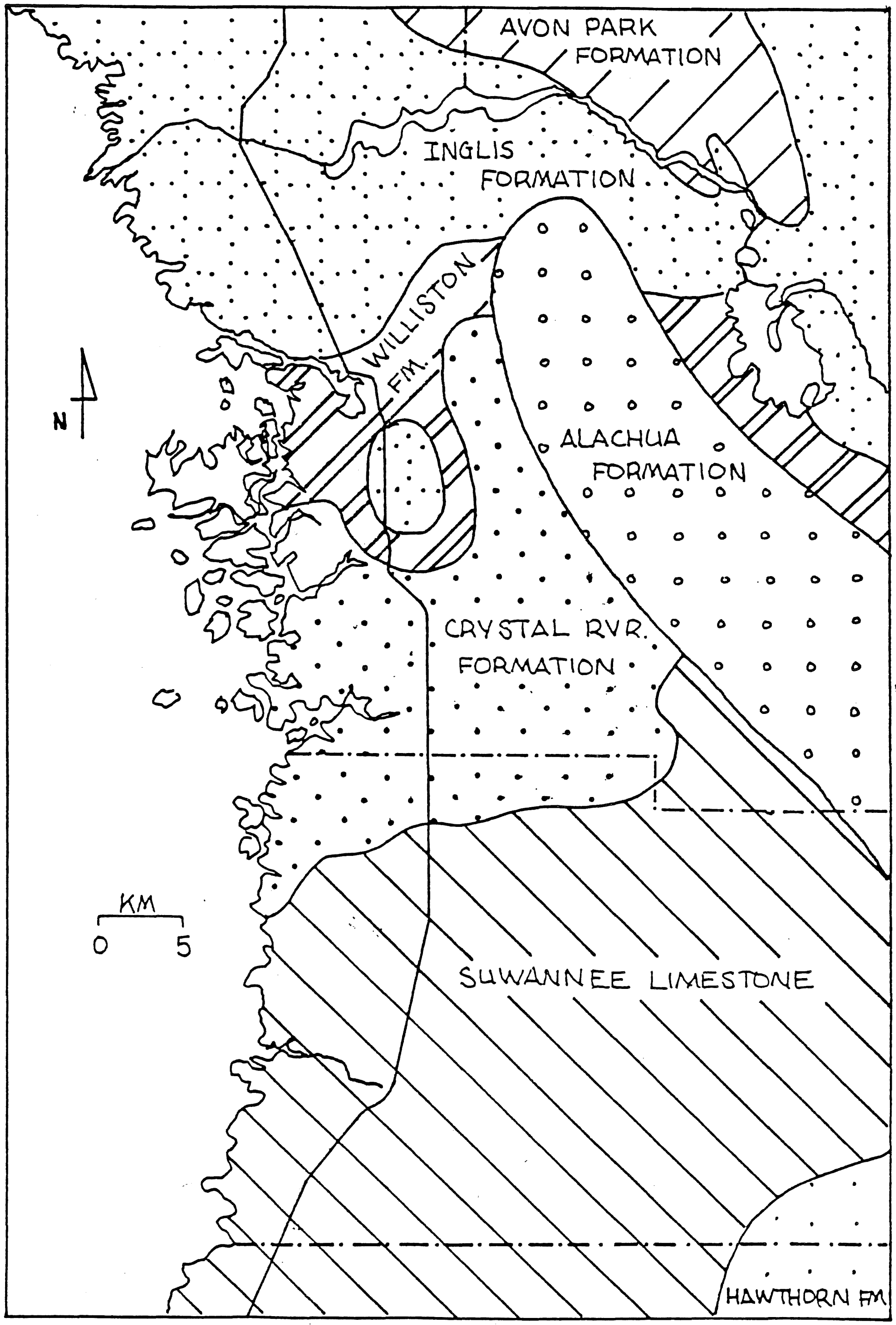

Figure 3. Geologic map of the transient electromagnetic study area. After Vernon and Puri, 1965.

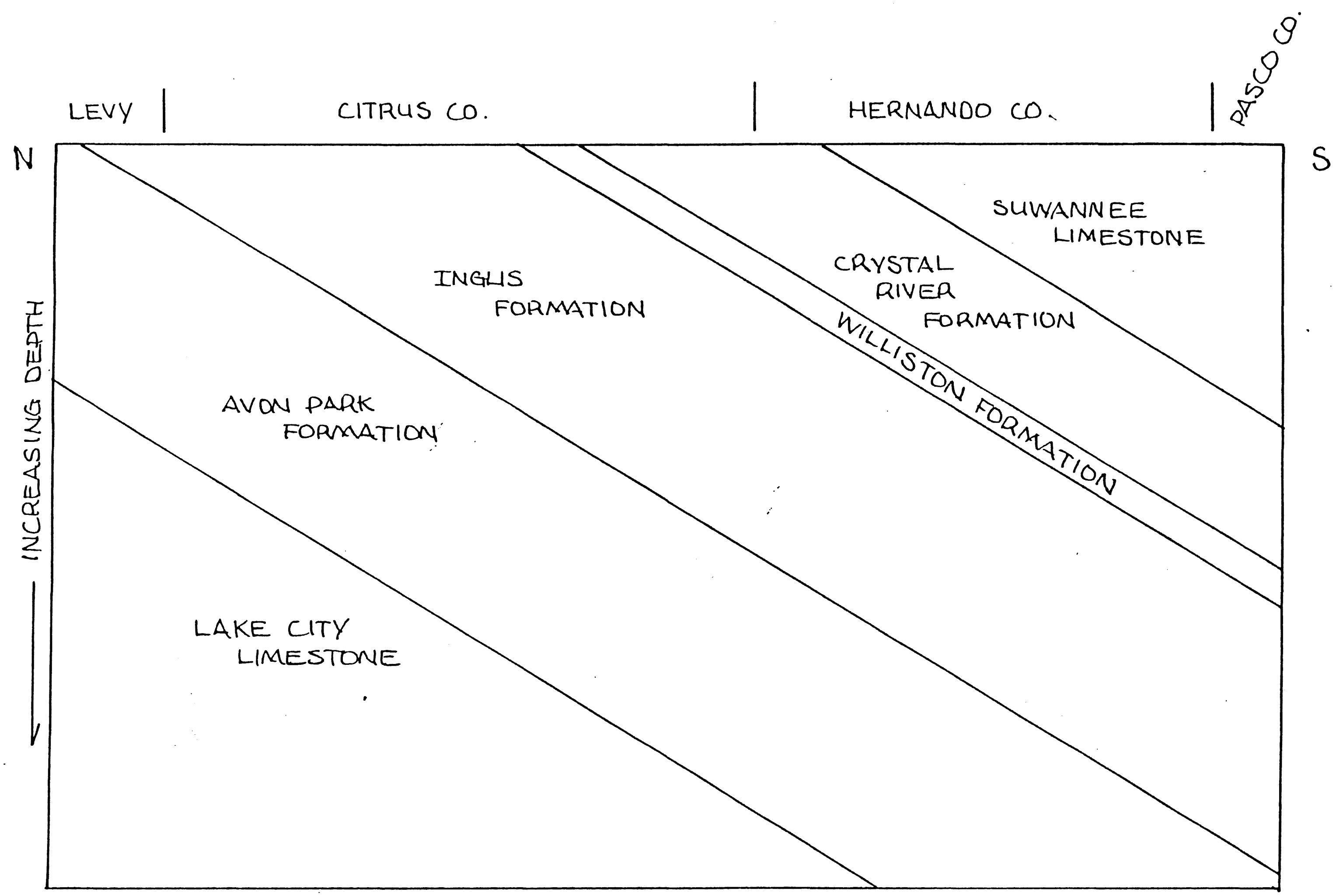

Figure 4. Generalized geologic cross section of the transient electromagnetic study area.

movements of the water table and thereby insured the formation of a highly complex, interconnected porosity system within the limestone (Smith and Randazzo, 1975). This system is capable of storing and transporting very large volumes of water. Because of the predominance of subsurface flow, there is little surface runoff. Several small streams originate as springs, and receive little direct runoff (Cherry, et al., 1970). Relief varies from 20 to 30 meters in the eastern part of the study are to less than 2 meters toward the west.

The dominant structural feature is the post-Oligocene Ocala uplift (Vernon and Puri, 1965). Associated with the uplift are several minor, NW-SE trending faults and grabens. The best known of these within the study area is the Inverness Fault which cuts across the northeast corner of Citrus County (Vernon, 1951).

THEORY

Nature of the Salt Water - Fresh Water Interface

Under ideal hydrostatic conditions, fresh water and salt water behave as immiscible liquids with the fresh water floating horizontally over the more dense salt water (Freeze and Cherry, 1979). The depth to the interface can be calculated by the well known Ghyben - Herzberg equation (Freeze and Cherr, 1979):

$$Z_s = \frac{d_f}{d_s - d_f} h_f \qquad (1)$$

where: Z_s = depth to the interface below sea level,

d_f = density of fresh water,

d_s = density of salt water, and

h_f = height of the water table above sea level.

Substituting values of 1.0 and 1.025 for d_f and d_s, respectively, equation (1) becomes:

$$Z_s = 40\ h_f \qquad (2)$$

Ideal hydrostatic conditions do not exist in nature. Mixing of fresh and salt water creates density gradients which cause a continuous landward flow of salt water at the base of the aquifer. At the salt water - fresh water interface salt water is diluted, becomes less dense, and rises (Cooper, et al., 1964). At higher levels it is carried seaward by flowing fresh water. The result of the opposing flows of salt and fresh waters is the establishment of a dynamic equilibrium at the interface.

The interface is a landward - dipping transition zone of varying thickness. Dip direction may be locally reversed as described in the discussion section of this paper. During periods of reduced fresh water flow, the interface migrates landward, and contamination of wells may result. Normal sea water contains 35,000 milligrams per liter salt or 19,000 milligrams per liter chloride. Chloride levels of only 250 milligrams per liter are considered non-potable.

Electrical Properties of Earth Materials

Electrical resistivity is an intrinsic physical property of soils and rocks. It is measured in ohm-meters. Conductivity (the reciprocal of resistivity) is measured in mhos/meter, and is a measure of the ability of a substance to conduct an electric current. Resistivity should not be confused with resistance. Resistance is a function of both resistivity and the specific size and shape of an object. Resistance is related to current and potential by Ohm's law which states:

$$I = E/R \qquad (3)$$

where:

I = current measured in amperes,

E = potential measured in volts, and

R = resistance measured in ohms.

Bulk electrical resistivity of porous earth materials is a complex property dependent upon several factors. Conductivity of the solid matrix, electrolytic conductivity of fluids contained within the matrix, and the dielectric constants of both solid and fluid materials influence the overall conductivity and resistivity of porous materials (Telford, et al., 1981). Most rocks are poor conductors. Current flow in porous rocks is concentrated within the pore spaces. The geometric arrangement of pore spaces and the electrical conductivity of fluids in these spaces are therefore the predominant factors affecting bulk resistivity of porous rock (Telford, et al., 1981). Rocks saturated with saline waters exhibit higher conductivities (lower resistivities) than fresh-water saturated rocks of equivalent porosity because fluid conductivity increases with an increase in electrolyte concentration. Rocks with lower porosities exhibit higher resistivities (lower conductivities) than more porous rocks.

Transient Electromagnetic Theory

All electromagnetic methods depend on the electromagnetic induction of secondary eddy currents in the ground by a primary alternating electric current. A primary transmitted current generates a magnetic field, the direction and strength of which are directly related to the direction and strength of the current. If the current and attendant magnetic field vary with time, an electromotive force is induced in the ground. The magnitude of this force is proportional to the time rate-of-change of the magnetic field, (Sears and Zemansky, 1970). The electromotive force causes secondary currents to flow in the ground.

In transient EM, a low frequency alternating current is caused to flow in a large, horizontal, wire transmitter loop. The wave form of this current is shown by Figure 5a. Current turn-on induces small unwanted transients in nearby conductors. A steady current level is maintained for a short period of time to allow these transients to dissipate. Current turn-off is a steep, linear ramp function. It is desirable to terminate the primary current and magnetic field rapidly so as to produce a large electromotive force of short duration (Fig. 5a, 5b). Primary current remains off during secondary current and magnetic field decay (Fig. 5a, 5c).

Decay of the secondary magnetic field creates an electromotive force of its own. This force produces a small but measurable voltage in a small receiver coil. It is important to note that the receiver senses the electromotive force or time rate-of-change of the magnetic field, and not the field itself.

The secondary current and magnetic field decay over time as a function of the conductivity and geometric configuration of the subsurface. The variation of the secondary magnetic field over time should yield information about the electrical properties and goemetry of the ground. The current and magnetic field in a conductive earth decay slowly. The resultant induced electromotive force, or voltage measured in the receiver coil, is initially small, but decays slowly (McNeill, 1980a). The rate of decay of a field in a resistive earth is greater. The induced voltage is initially high, but decays rapidly (McNeill, 1980a).

In transient or time domain electromagnetic sounding, a series of

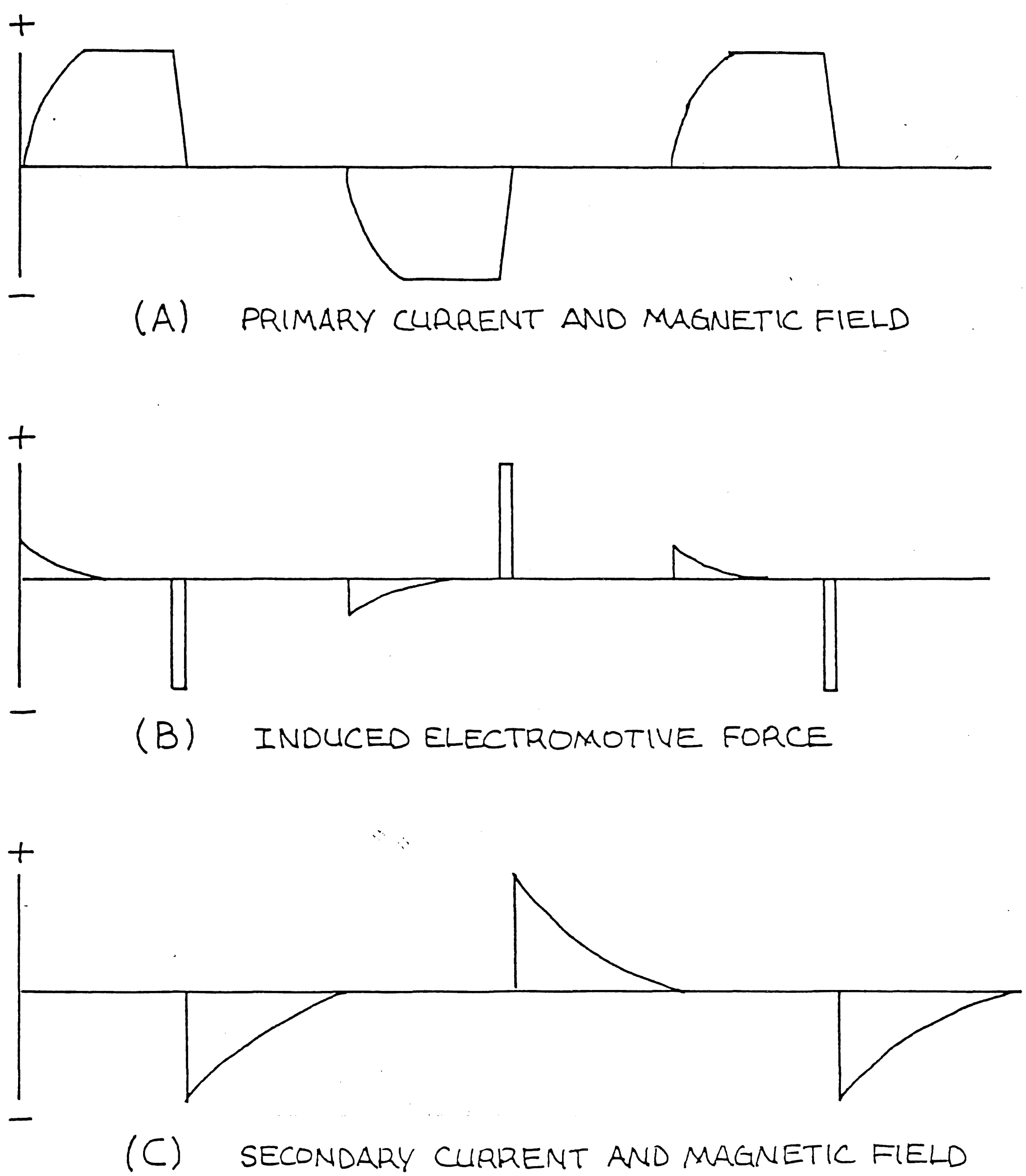

Figure 5. General configurations of the transient electromagnetic system waveforms. After McNeill, 1980a.

electronic gates or channels is used to sample the output voltage or rate of decay of the secondary magnetic field in the ground (Fig. 6). Receiver output voltage varies less rapidly during later stages of decay. A logarithmic distribution of sampling gates over time is therefore more efficient than a simple linear distribution. For a 30 Hertz transmitter frequency, 20 narrow gates are spaced over two decades of time (80 usec to 8 msec) after termination of the primary current and field (McNeill, 1980b).

Secondary current induction is a continuous process. Immediately upon termination of the primary current, a surface current flows such that the current maximum is located just below the transmitter loop. This current begins to diffuse into the ground as induction continues. Figure 7 is a vertical cross section through the transmitter loop. The figure depicts the movement of a decreasing current maximum downward and away from the transmitter loop. The current maximum moves in this manner because current decay occurs later at depth and at a distance than in the immediate vicinity of the transmitter loop. Actual current flow occurs in horizontal concentric rings and does not possess any vertical or radial component. The apparent vertical and radial flow is the result of induction.

Movement of the current maximum is a function of subsurface conductivity. The movement is more rapid for materials of low conductivity. The lateral distance to the current maximum is proportional to:

$$d = 2\pi \left(\frac{2t}{\mu \sigma} \right)^{\frac{1}{2}} \qquad (4)$$

where d = distance to current maximum,

t = time,

μ = permeability of free space, and

σ = subsurface conductivity.

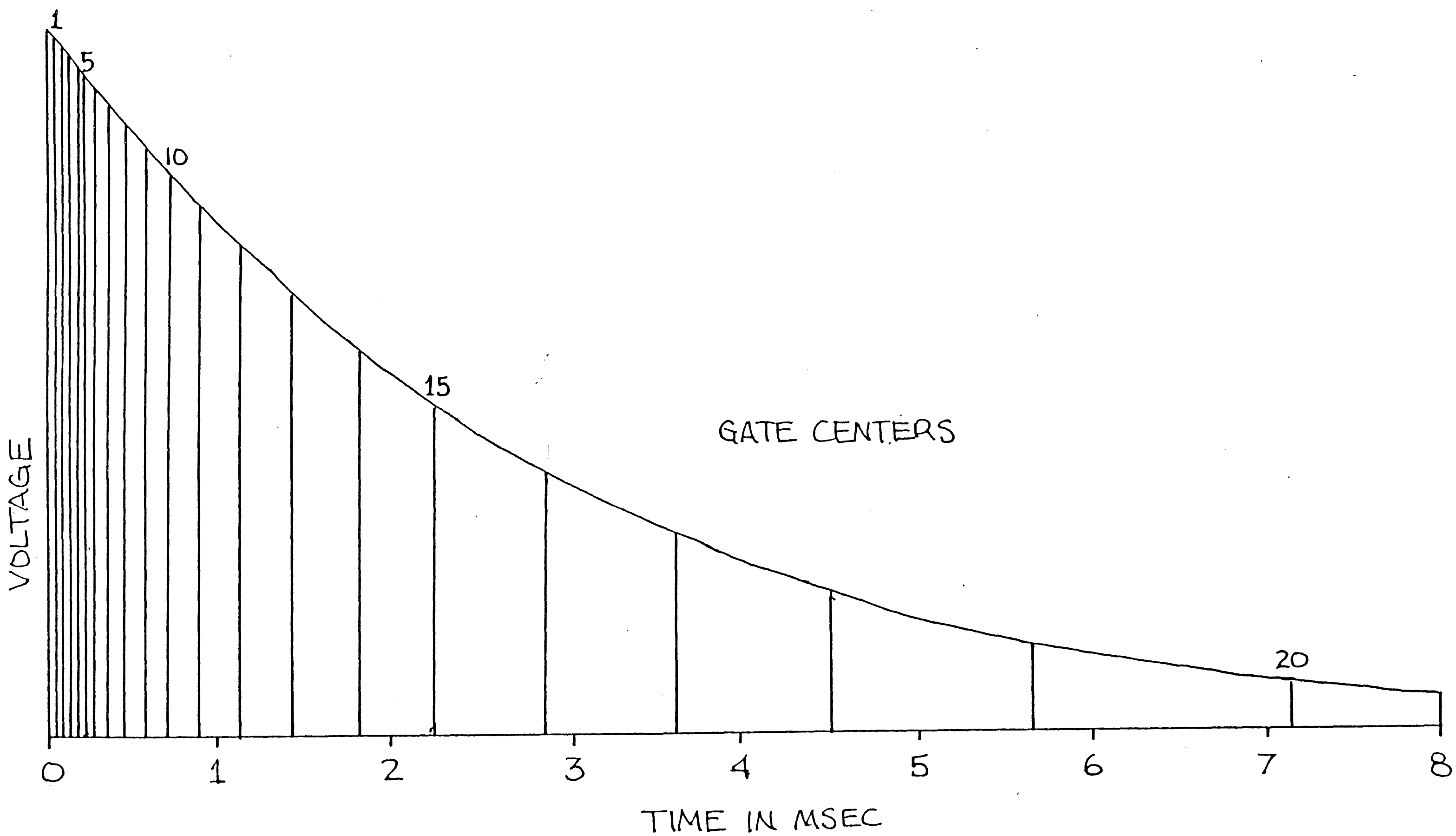

Figure 6. A typical output voltage curve showing the distribution of the sampling gates over time.

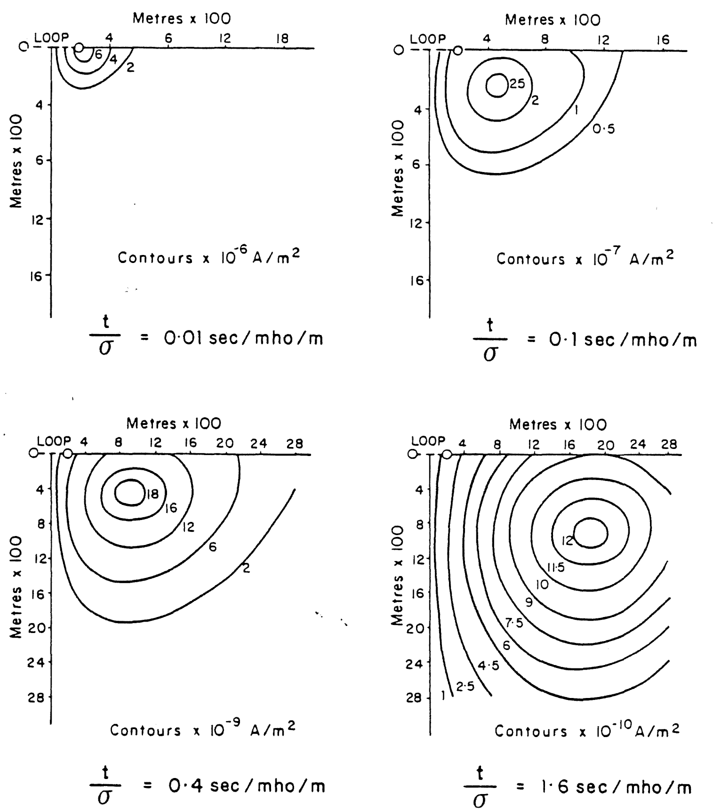

Figure 7. Cross section through the transmitter loop depicting a hypothetical set of current density contours. From McNeill, 1980a.

McNeill (1980a) recognizes three phases of current decay. Immediately upon termination of the primary magnetic field, secondary currents flow so as to maintain the original field strength and distribution. This phase is called "early - time". Current decay begins quickly, however, and current distribution changes with time. The time characterized by changes in the current distribution is called "imtermediate - time". After the current maximum has moved away from the transmitter and an appreciable distance out beyond the receiver, the current distribution between the transmitter and receiver remains uniform. The period of time characterized by uniform current distribution is called "late - time".

The salt water - fresh water interface is best treated as a layered earth model in which a layer of resistivity $_1$ and thickness h_1 (fresh water saturated zone) overlies a layer of resistivity $_2$ (salt water saturated zone). The channels or gates sample the field decay during "late time". Decay during "late time" is exponential at a rate dependent upon the resistivities and thicknesses of the layers. Response in the early channels is characteristic of upper layer resistivity; while middle channel response is diagnostic of upper layer thickness; and response in the later channels is a function of lower layer resistivity.

METHODS

Field Methods

Potential sounding site locations were selected from 1:24,000 scale separate air photographs. Site selection in the field was based on access, vegetative cover, and the location of potential noise sources, such as power lines, fences, buried pipelines, etc. Site locations and elevations are given in Gay, 1983. Seventy-nine soundings were completed during the instrument rental period. An 80 meter square transmitter loop was used for 70 sites. A larger, 160 meter square loop was used for 9 sites.

The instrument used was a Geonics EM 37 Ground Transient Electromagnetic System (available from Geonics Limited, Mississauga, Ontario, Canada). Four modes of transmitter-receiver synchronization are available: reference cable, crystal controlled, primary pulse, and radio. The reference cable mode of synchronization was used exclusively. A one meter diameter receiver coil was positioned at the center of the transmitter loop. Transmitter frequencies of 30 Hertz and 3 Hertz were used. Signal strength was integrated over a period of approximately 30 seconds as a means of increasing the signal-to-noise ratio. Three readings (in millivolts) were taken for both positive and negative current polarities for each gate.

Data Interpretation

Average readings for each gate were entered into a simple computer program which calculates apparent resistivities. Apparent resistivity as a function of time is

$$\rho_a = \frac{\mu}{4\pi t} \; \frac{2\mu M}{5tB_z}^{2/3} \qquad (5)$$

where ρ_a = apparent resistivity,

μ = permeability of free space,

t = time,

M = dipole moment, and

B_z = output voltage.

Standard two layer master curves (Fig. 8) are available for interpretation of apparent resistivity values (Kaufman, et al., 1969). The logarithms of apparent resistivity values are plotted against the logarithm of the square root of time. Figure 9 is an example of one of these plots. Listings of the field data and apparent resistivity curves are given in Gay (1983). The master curves are matched to each plotted apparent resistivity curve until the best two layer solution for that site is found. Each master curve represents a specific combination of depth and resistivity. Data obtained from the 3 Hertz soundings were highly irregular and were not used. These data are the responses from depths far below the salt water-fresh water interface.

Two layer solutions were not adequate for most soundings. Interpretation of data from these sites required 3 or 4 layer solutions. The number of resistivity-thickness combinations, and hence the number of required master curves, increases rapidly with an increase in the number of layers. Master curves are available for three layer hand solutions, but computer solutions are more efficient for multi-layer (3 or more) interpretations.

Multi-layer interpretation was accomplished with the aid of a computer program (ALEX.FOR) available from Geonics Ltd. This program does not invert the data or produce its own iterative solution. The program produces a theoretical sounding curve for a given set of thickness and resistivity parameters. The theoretical curves were compared to the plotted apparent resistivity curves in the same manner as the two layer master curves. The two layer hand-fitted solutions served as guidelines for the selection of

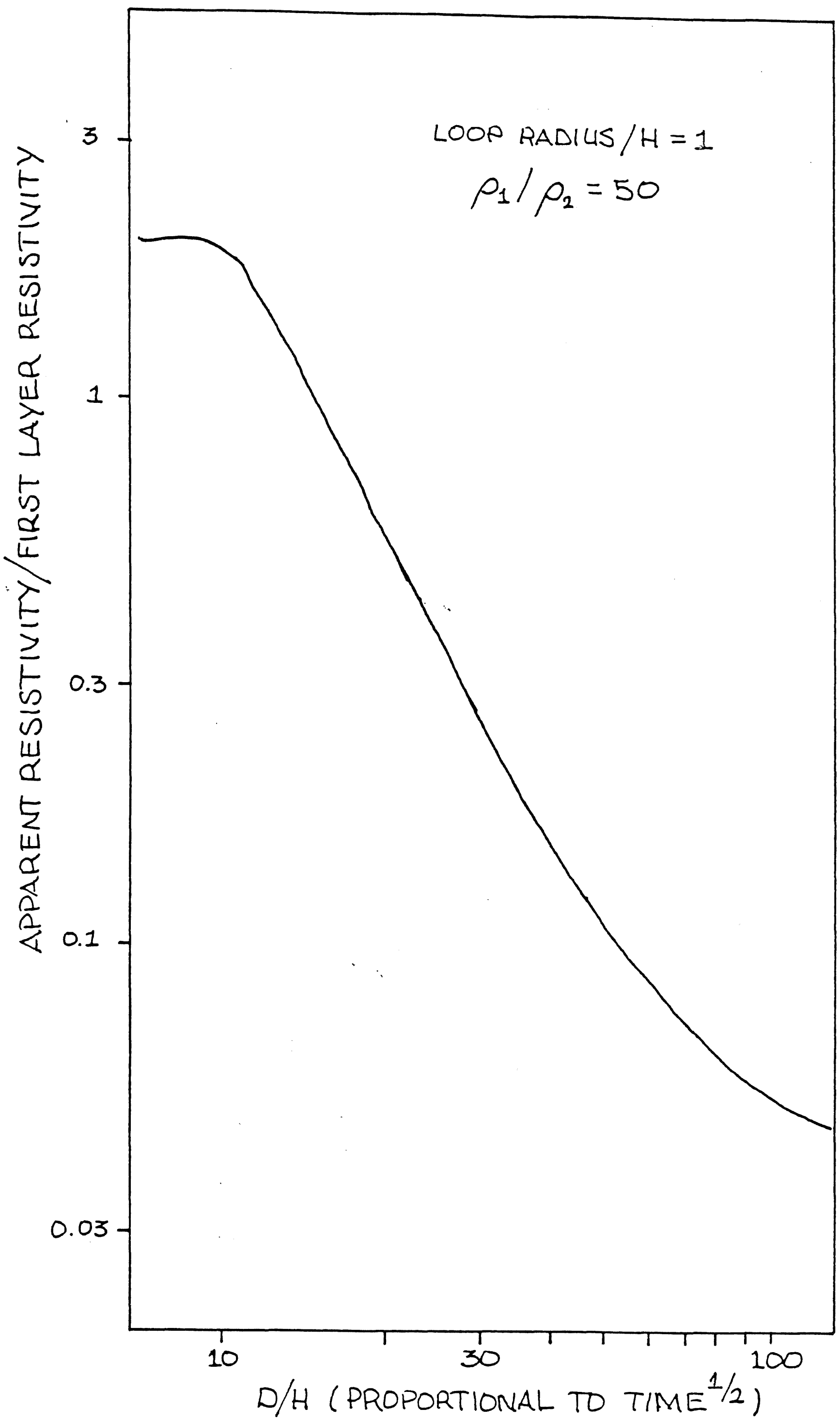

Figure 8. An example of a standard two layer master curve. After Kaufman et. al., 1969.

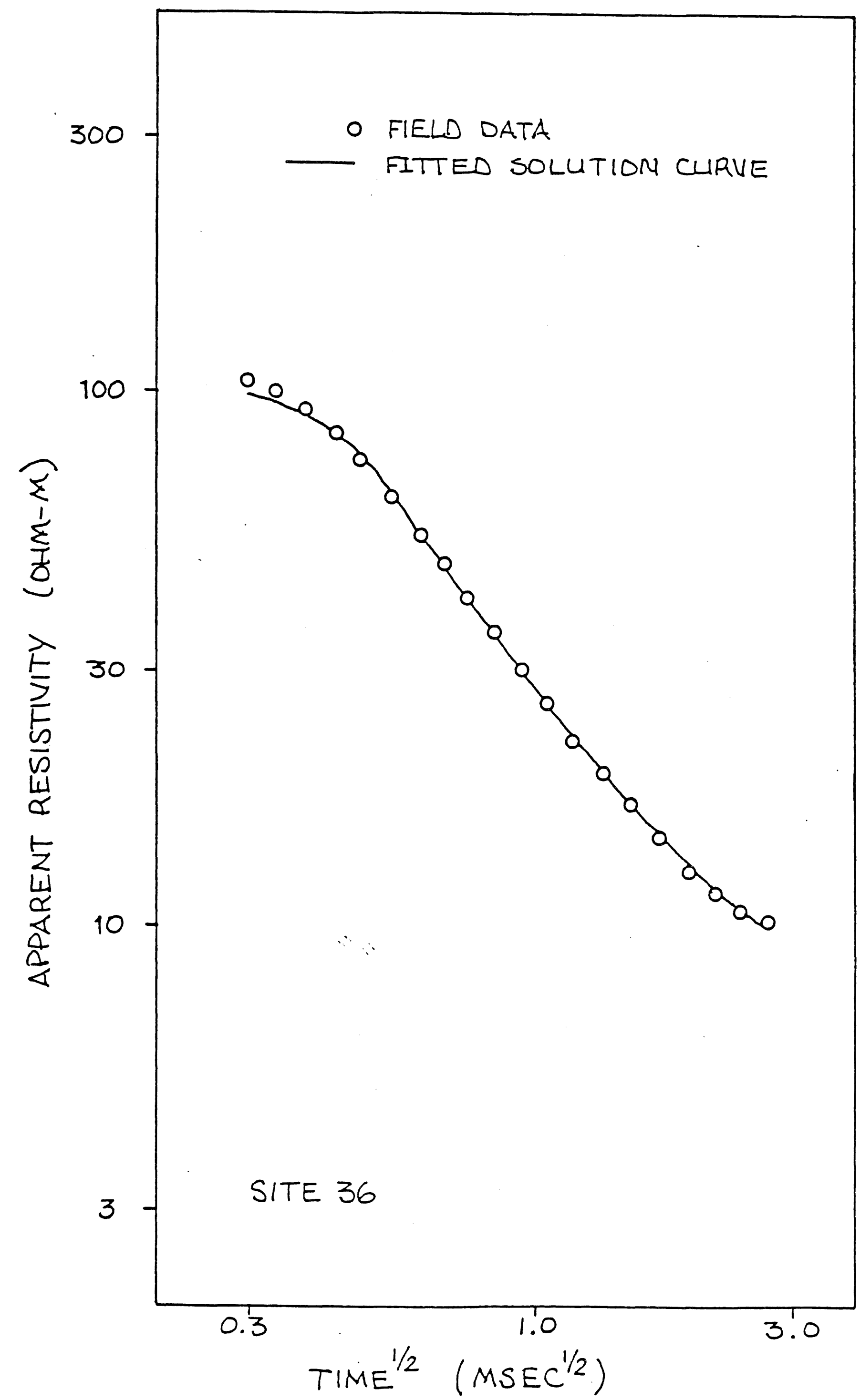

Figure 9. An example of a plot of apparent resistivity values and a fitted solution curve.

parameters for the initial curve matching attempt. The parameters were adjusted with each successive matching attempt until a satisfactory solution was obtained.

The decision to accept a given solution is largely subjective. Figure 9 shows that for most cases, the actual and theoretical sounding curves match one another quite well. In many cases they are almost indistinguishable. The differences are less than those obtained by intentional 10 percent alterations of thickness or resistivity values.

Several other models are available for the multi-layer solution of transient EM sounding data (Koefoed et al., 1972; Lee and Lewis, 1974; Mallick and Verma, 1978; Mallick and Verma, 1979; Morrison et al., 1969; Mundry, 1967; and Raiche and Spies, 1981).

RESULTS

Interface Map

Figure 10 depicts a sounding solution as a vertical section. The resistivity contrast between the first and second layers is quite pronounced, the upper layer being the more resistive of the two. The upper layer is interpreted as the fresh water saturated zone. The second layer is interpreted as a zone of salt water saturation. All site solutions are listed in tabular form in Appendix Table A3.

The salt water-fresh water interface map is a contour map of the depths to the boundary between the two upper layers. It should be emphasized, however, that the actual interface is a zone of varying salinity, not a

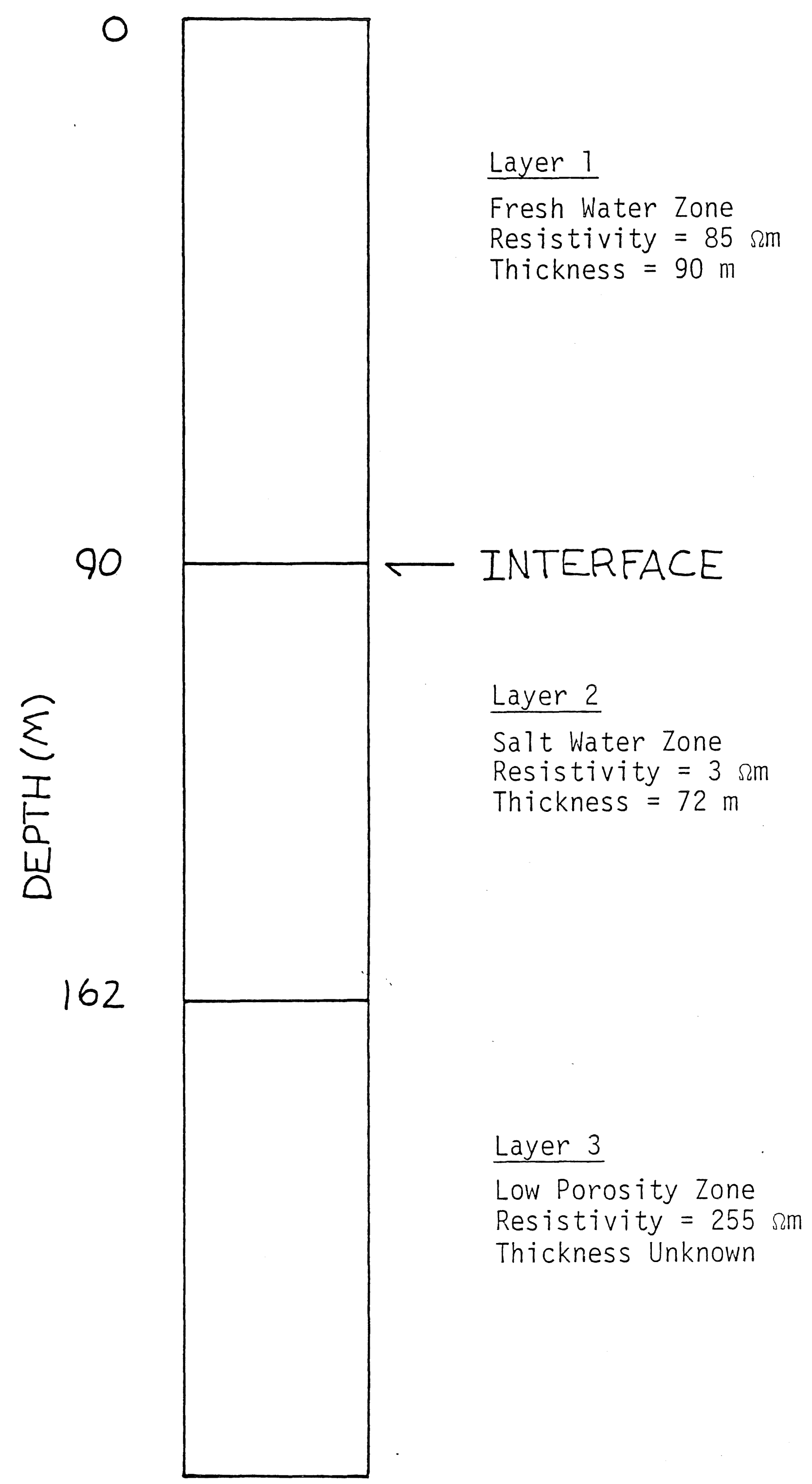

Figure 10. A vertical section illustrating a typical sounding solution.

sharp, two-dimensional surface. Figure 11 is a map of the position of the salt water-fresh water interface relative to the land surface. Figure 12 is a map of the interface relative to mean sea level. Dashed contours on Figures 11 and 12 indicate uncertainty in the data.

A lower layer of very high resistivity was detected under most sounding sites (Fig. 10). The upper surface of this layer is located within the Avon Park Formation and above the presumed first occurrence of anhydrite. Figure 13 is a contour map of depths to this surface relative to mean sea level. The high resistivity of this layer is a consequence of the lack of effective porosity and permeability of both the Avon Park Formation and the underlying Lake City Formation.

Reentrants

Examination of Figures 11 and 12 reveals the presence of three major interface reentrants in Citrus County. These are located near Hall's River and Homosassa Springs, near Crystal River, and in the area just to the south of Lake Rousseau and the Cross Florida Barge Canal. The salt water-fresh water interface map, based on transient EM sounding data, compares favorably with data from previous geophysical and geochemical surveys. The reentrants are convenient areas for data comparison.

Chloride Data

Chloride data taken from monitor wells and wells of opportunity were compiled from four sources (Causseaux and Fretwell, 1982; Southwest Florida Water Management District, 1982a; Southwest Florida Water Management District,

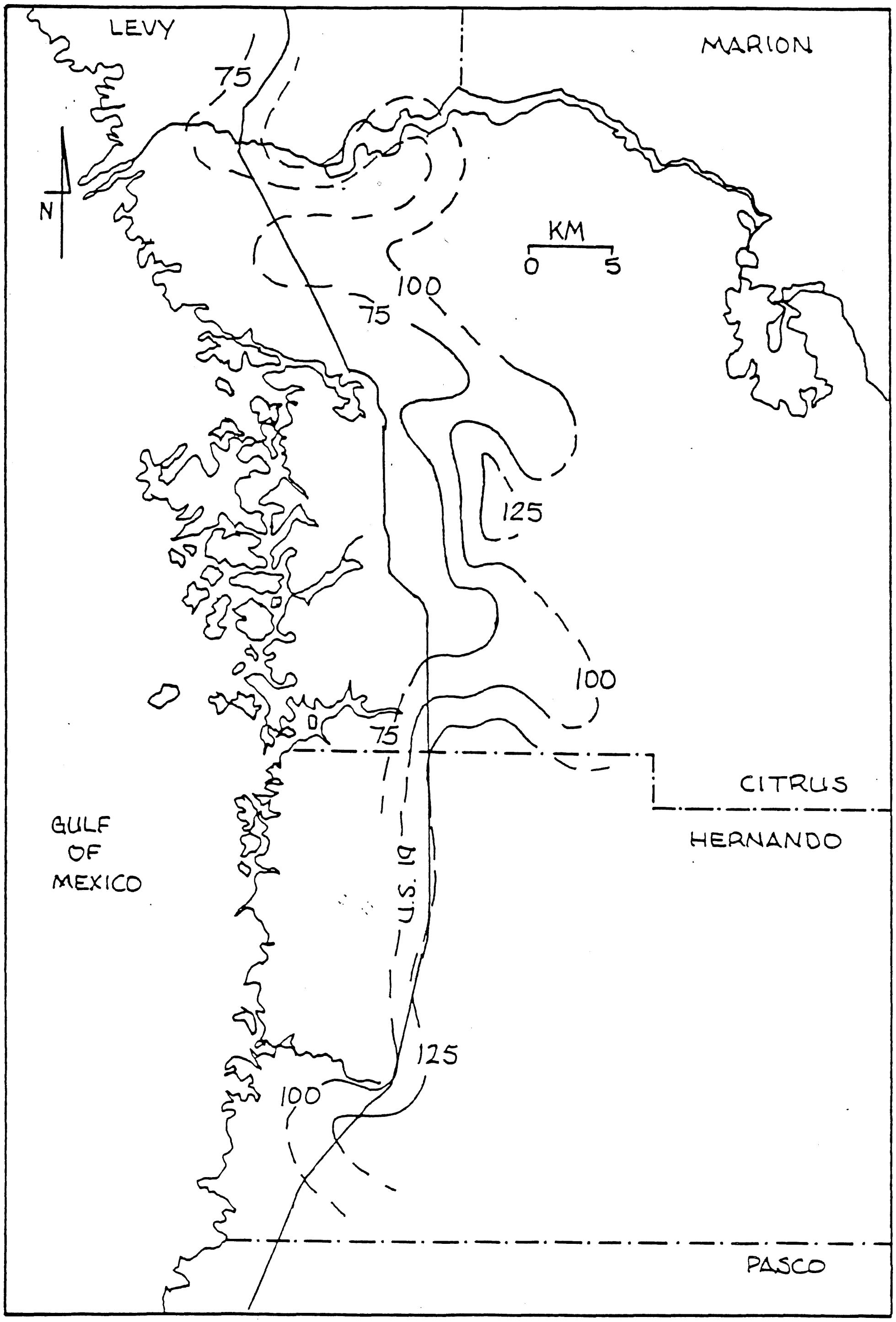

Figure 11. Depth to the salt water-fresh water interface relative to land surface.

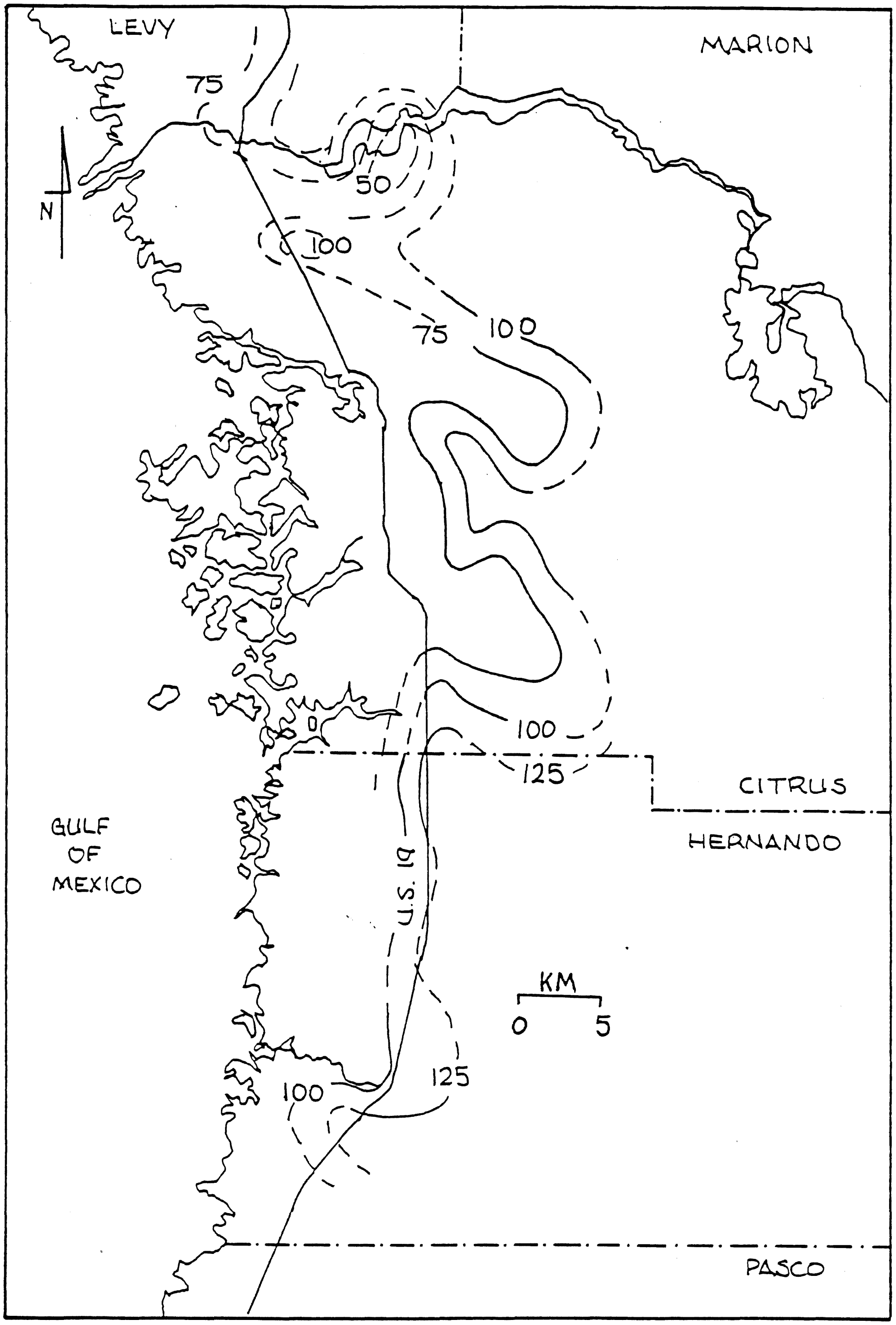

Figure 12. Depth to the salt water-fresh water interface relative to mean sea level.

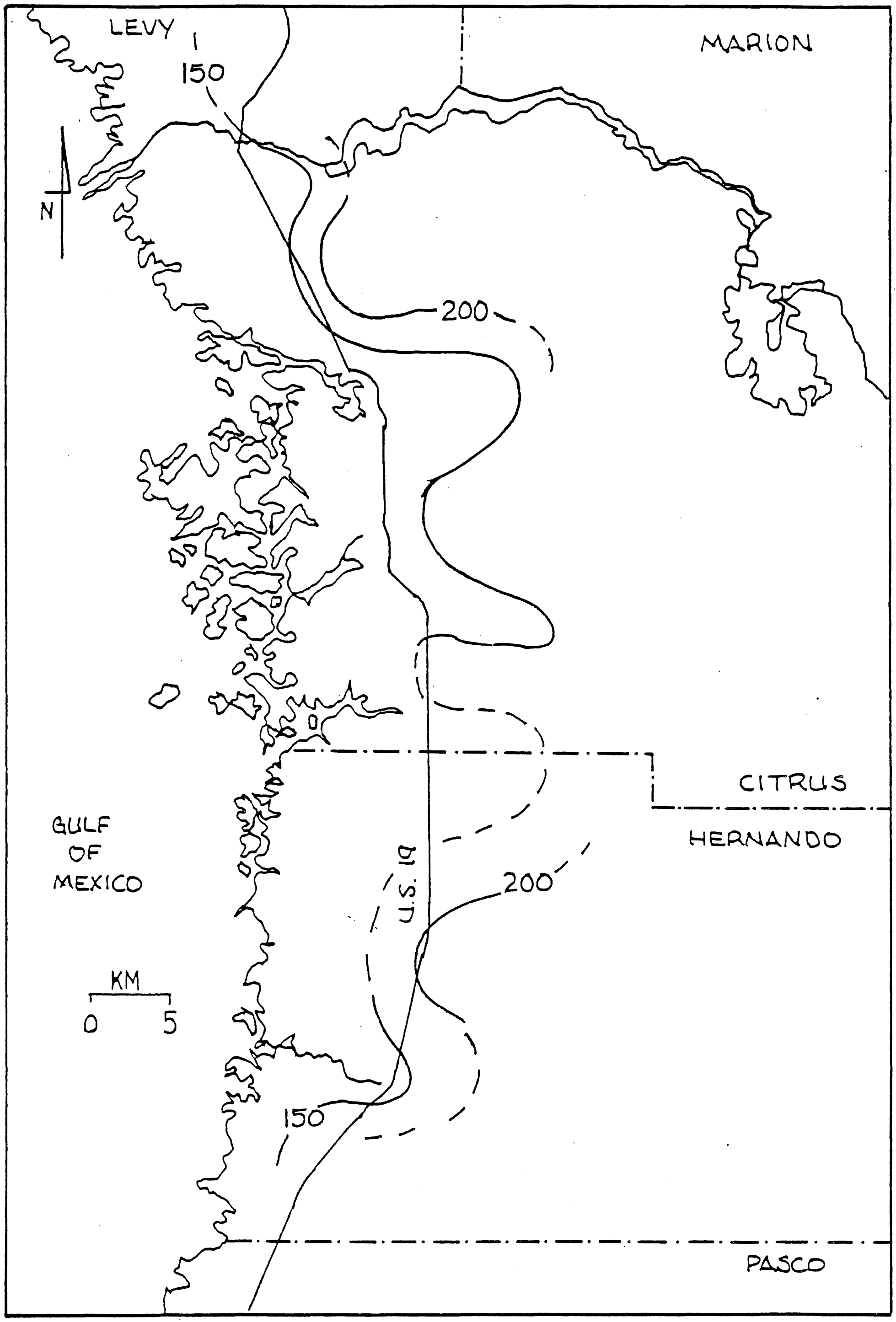

Figure 13. Depth to the top of the high resistivity layer relative to mean sea level.

1982b; and U. S. Geological Survey, 1980). Complete chloride, location, and depth information was available for 68 wells in the study area. These data are listed in Gay (1983). Well locations and the locations of two cross sections based on chloride data are given in Figure 14. The general configuration of the interface, normal to its strike, is reflected by the isochlors on the Crystal River - Homosassa Airport cross section (Fig. 15).

A general inverse relationship exists between chloride levels in area wells and resistivity values at equivalent depths from nearby electromagnetic sounding sites (Fig. 16). It is difficult to establish a precise relationship between resistivity and chloride content, however, because porosity is extremely variable and exercises a profound effect on resistivity. Chloride concentrations at the transient EM interface are generally about 200 to 300 milligrams per liter.

DISCUSSION

Homosassa Springs Reentrant

The US-19 cross section (Fig. 17) demonstrates a reversal of the usual isochlor configuration in the Hall's River and Homosassa Springs area. This reversal is based on the high chloride concentration in well 28 and is coincident with the reentrant defined by transient electromagnetic data. The reentrant is confirmed by Fretwell (1978); Bisdorf and Zohdy (1979); and Stewart (1981).

Figure 18 is a map of the potentiometric surface of Citrus County. The Ghyben-Hertzberg equation is significant even in the absence of ideal

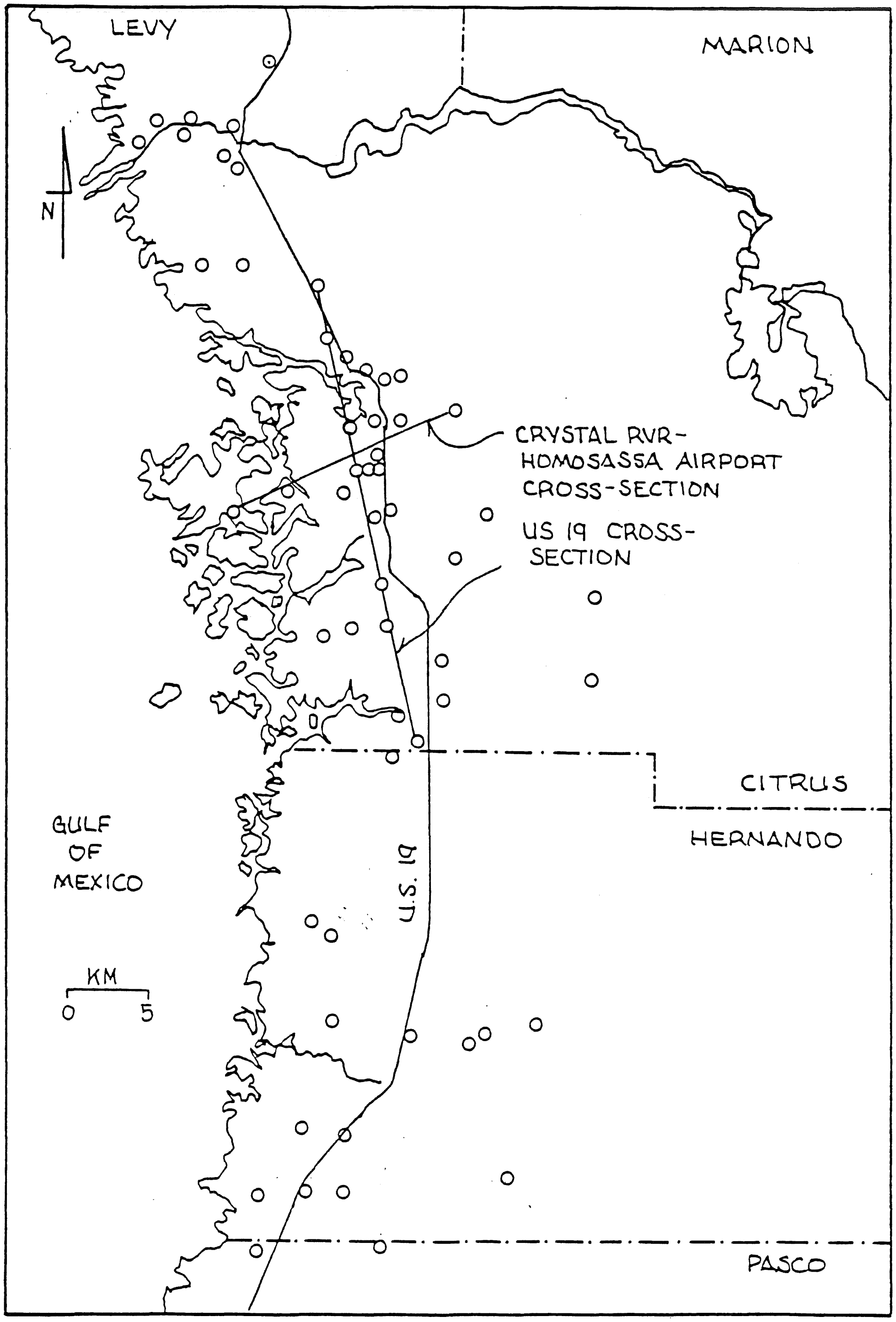

Figure 14. Map of the chloride monitor well sites.

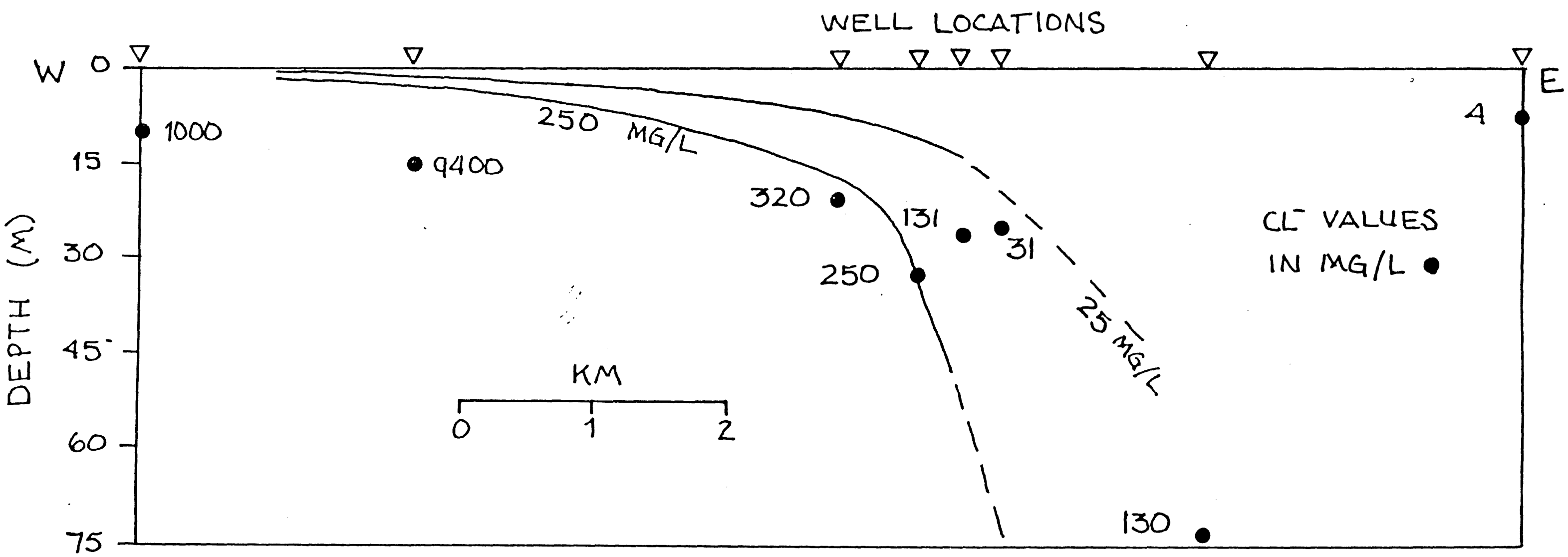

Figure 15. Crystal River-Homosassa Airport cross section showing the general configurations of isochlors.

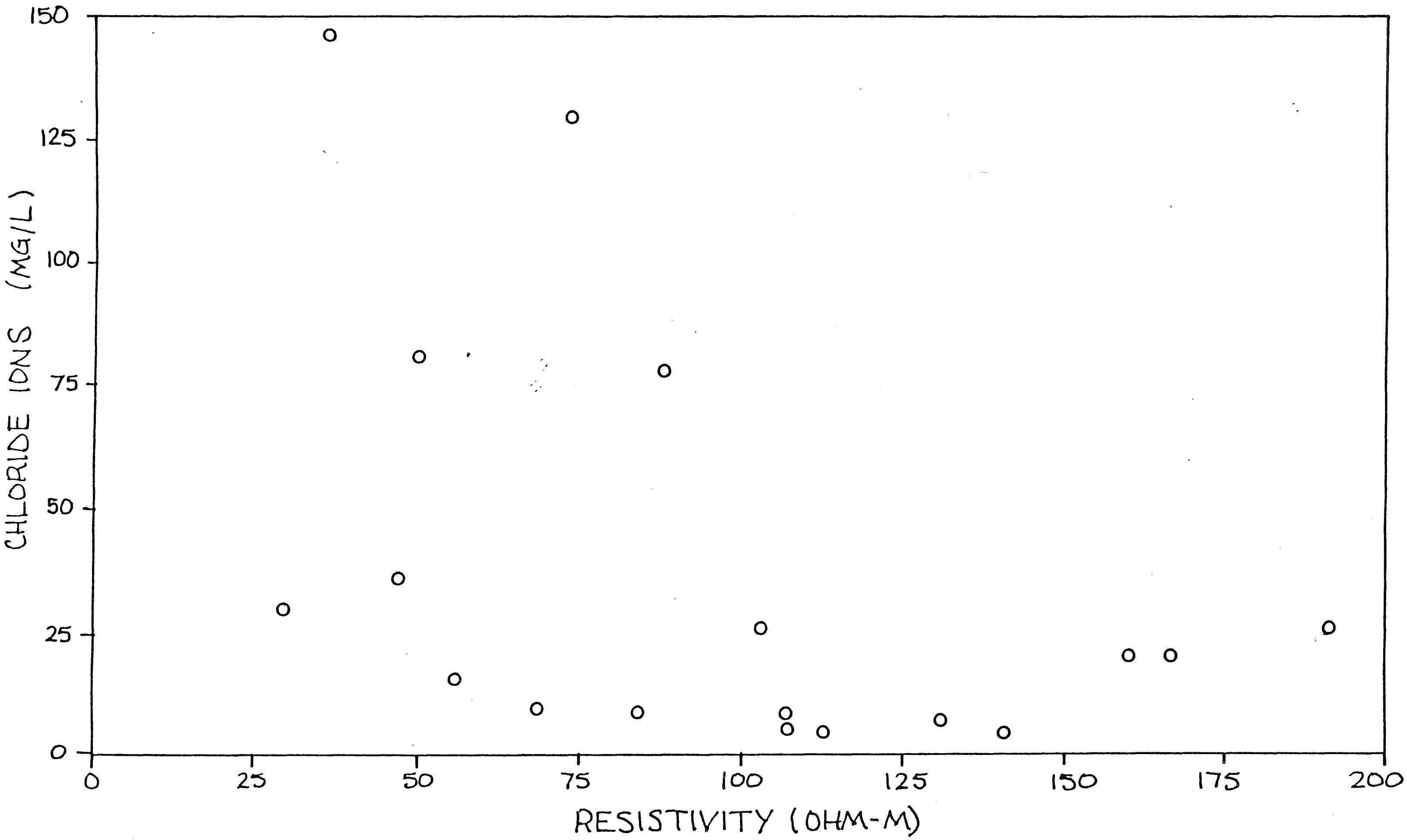

Figure 16. Graph depicting the general inverse relationship between subsurface resistivities at transient electromagnetic sites and chloride ion concentrations from nearby wells.

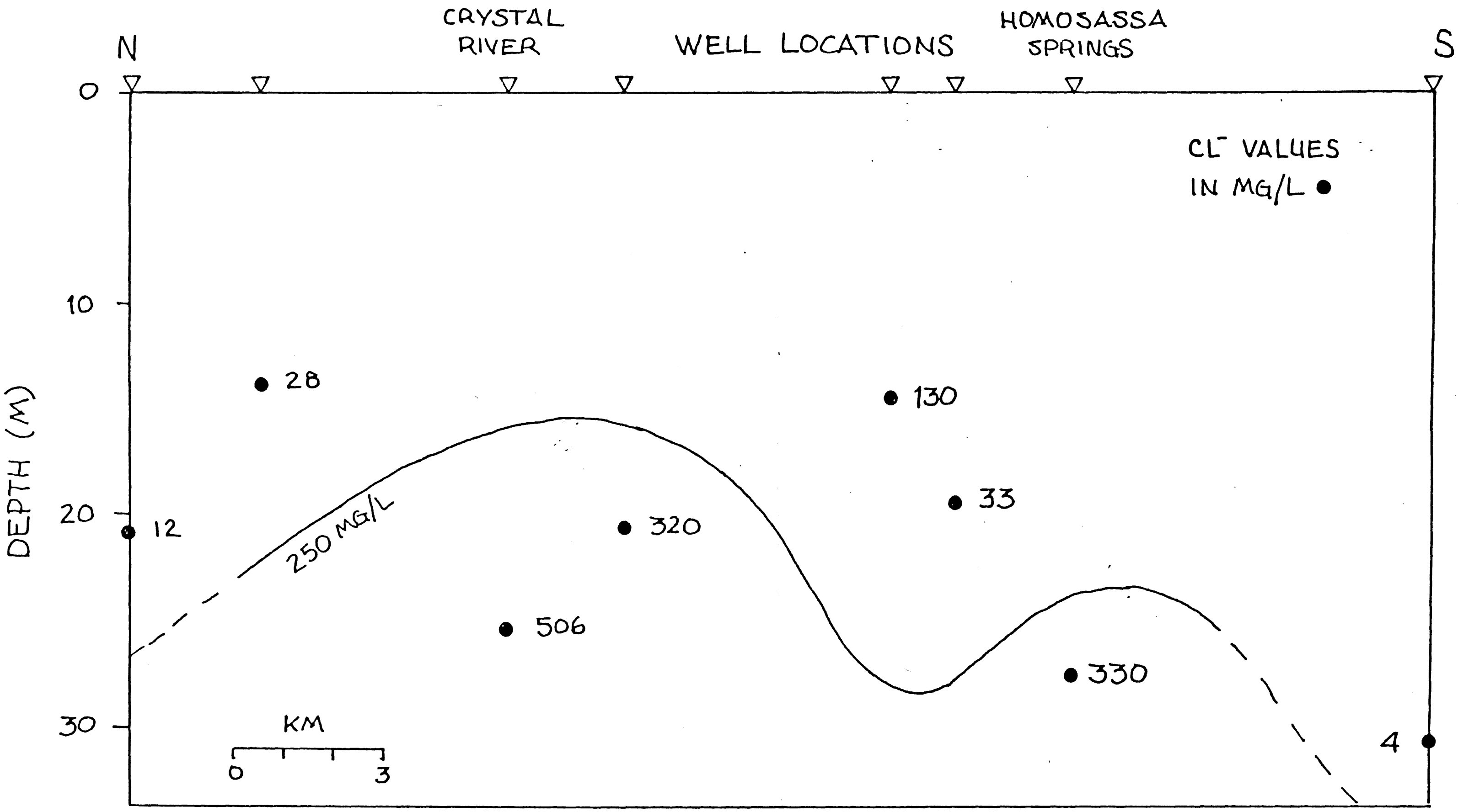

Figure 17. Cross section parallel to U.S. Hwy. 19 showing elevated isochlors at Homosassa Springs and Crystal River.

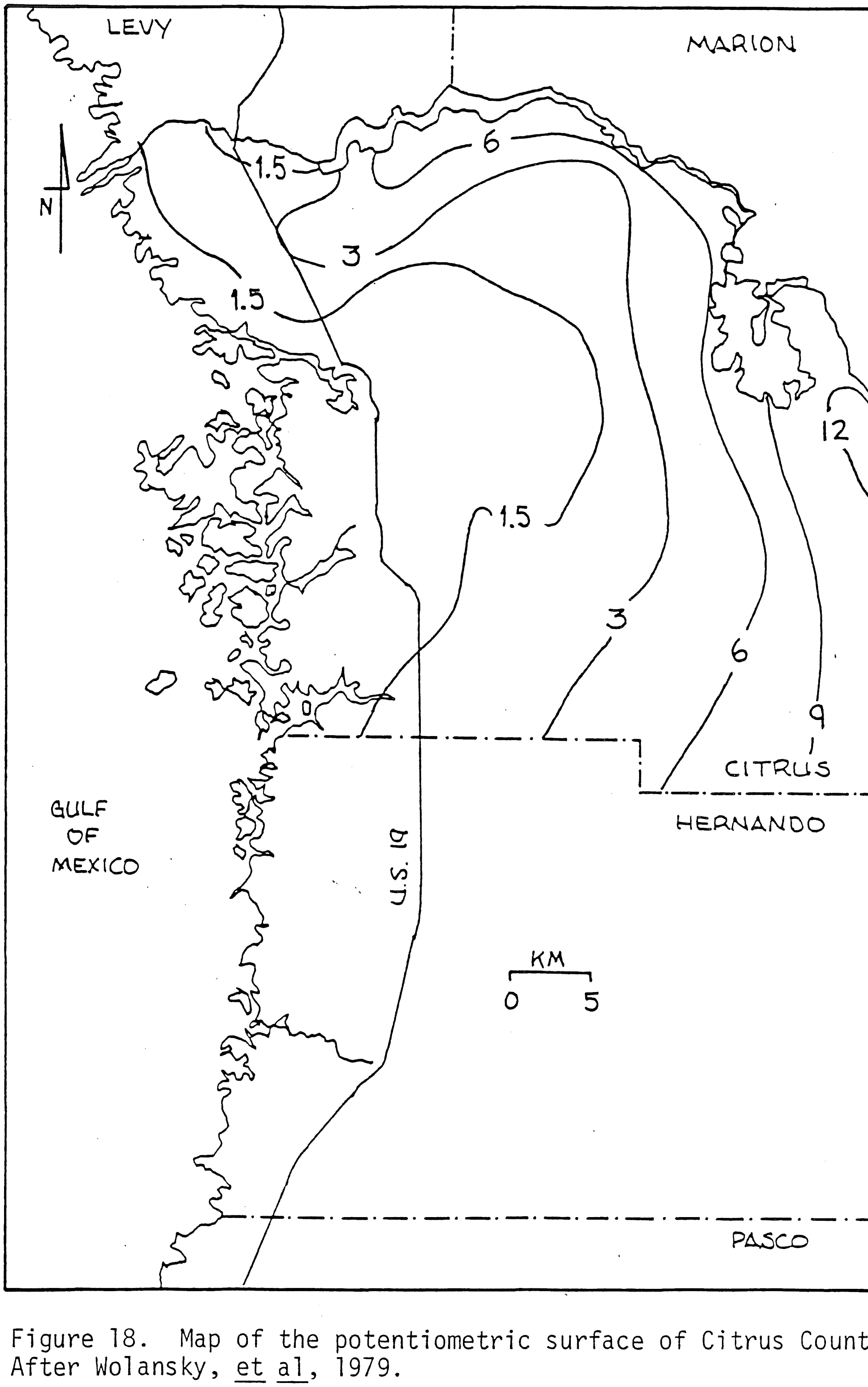

Figure 18. Map of the potentiometric surface of Citrus County. After Wolansky, et al, 1979.

hydrostatic equilibrium, and potentiometric data should reflect the position of an interface reentrant. Equipotential lines are locally concentric about points of discharge and are generally parallel to depth contours on the salt water-fresh water interface map. Ground water follows flow lines normal to equipotential lines and convergent on the discharge points. These discharge points are the many springs in the area.

Hall's River and the main springs at Homosassa discharge brackish water (Cherry, et al., 1970). The isochlor reversal in this area implies an up-coning of saline water which may be the source of brackish discharge in these springs. This shallower saline water zone is also evident from the interface map based on transient electromagnetic data (Figs. 11 and 12). Encroachment of sea water by means of conduit flow within the karstic limestone aquifer may account for the interface reentrant in this area. The reentrant extends about five to eight miles inland along a SE trend.

Crystal River Reentrant

Transient EM data indicate a major reentrant near Crystal River (Figs. 11 and 12). High chlorides in well 47 (Fig. 17) support this interpretation. The Crystal Springs are first and second magnitude springs which discharge large quantities of fresh water into the Crystal River. The river is dominated by tidal influx, however, and brackish conditions exist far upriver. Net flow is often upstream, especially during spring high tides and high energy events such as storm surges (Cherry, et al., 1970). Salt water is able to infiltrate the aquifer far inland to contribute to the maintenance of the interface reentrant. The low ground water potential results in a shallow interface seaward of Crystal Springs. The interface depth contours are consistent with the observed concentration of discharge at the springs. The interface reentrant has been observed by Fretwell (1978) and Stewart (1981). It extends about five to six km inland along a roughly SE trend.

Barge Canal Reentrant

A major interface reentrant is indicated at or just south of the Cross Florida Barge Canal and Lake Rousseau (Figs. 11 and 12). The exact location of the reentrant is uncertain, however, because data density is low in this area. Also, no additional geophysical or geochemical support for the reentrant is available. It is expected that the Barge Canal and Lake Rousseau would influence the position of the reentrant. If the reentrant is south of the canal, however, some additional influence must be sought as well. Conduit flow may allow the infiltration of sea water in this area. Further research is needed to interpret the reentrant satisfactorily.

Noise

Good solutions for apparent resistivities in the first 4 or 5 channels were unobtainable for about one-third of the soundings. Figure 19 is an example of this problem. The problem is the result of nearby, non-geologic conductors. Induction in these conductors results in the extension of "intermediate-time". The use of an aliminum lawn chair during the first week of field work contributed to a number of poor solutions in Hernando County.

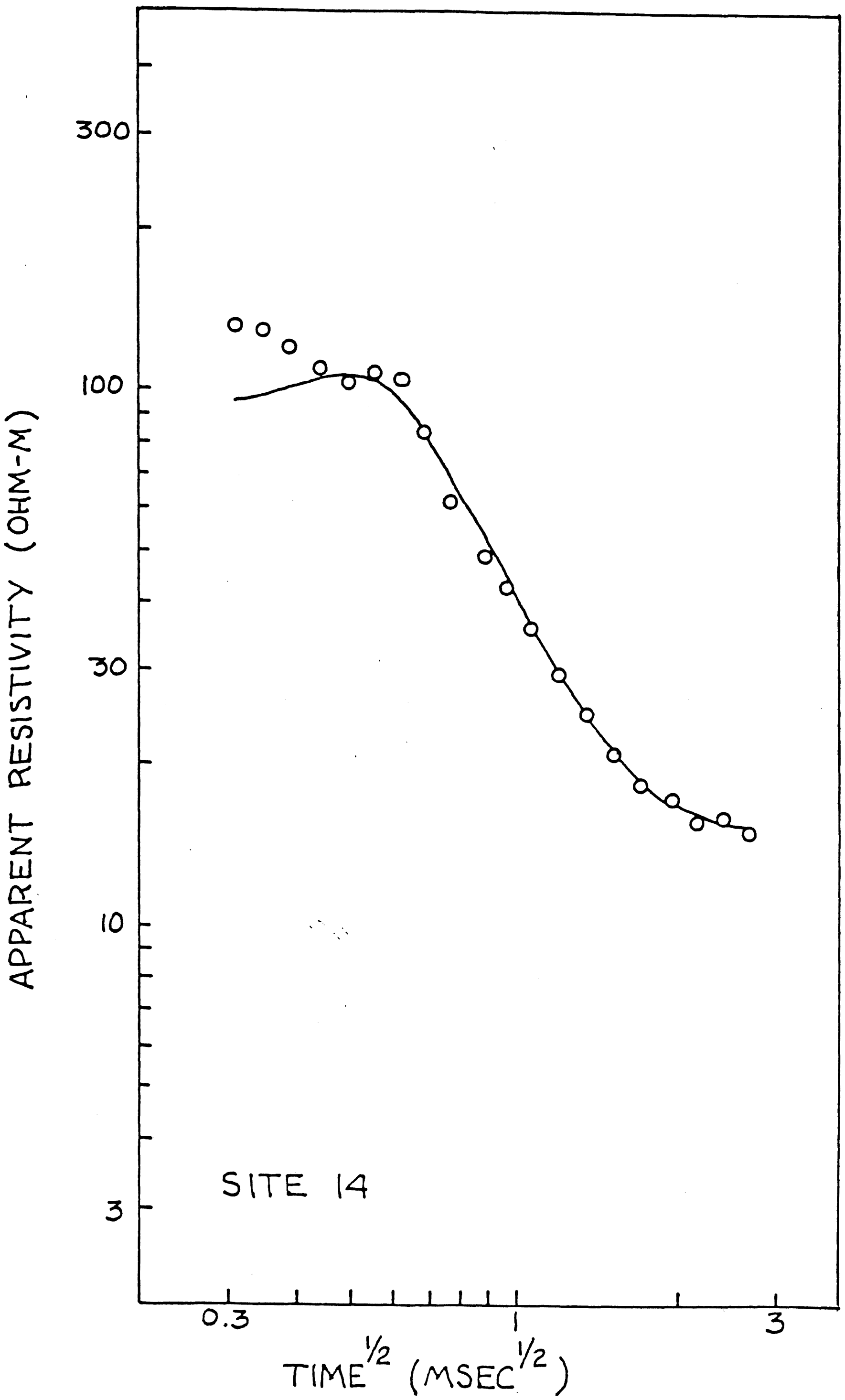

Figure 19. An example of a set of apparent resistivitity data and a fitted solution curve providing poor early channel match.

Other sites were affected by metal fences and power lines. Although the EM 37 is synchronized to standard 60 Hertz power line circuits, the wires act as conductors and produce noise by extending "intermediate-time".

Reliability of Sounding Solutions

Ideally, the theoretical apparent resistivity curve should exactly match the actual field curve. It is useful to know the degree by which the curve parameters must differ in order to distinguish the curves visually. Figure 20 illustrates the effects on curve shape of a plus-or-minus 10 percent variation in upper layer thickness. Figures 21 and 22 illustrate the effects of 10 percent variations in second layer resistivity and second layer thickness, respectively. In each case, the curves are easily distinguished. Second layer resistivity and thickness have a greater effect on curve shape, however, than does first layer thickness. Interpretation of second layer parameters appears to be more reliable.

Most of the field curves and theoretical curves produced in this study exhibit much better agreement than do the curves in Figures 20, 21, and 22. Solutions for these soundings are considered to be well within the 10 percent of actual field values.

The problem of equivalence arises with the simultaneous variation of two parameters. This is illustrated in Figure 23 where the simultaneous increase of both second layer thickness and resistivity can produce a nearly identical curve. Mallick and Verma (1979) show that the root mean square difference between alternate solutions reaches a minimum not equal to zero, however. Theoretically, all soundings should be resolvable, but practical

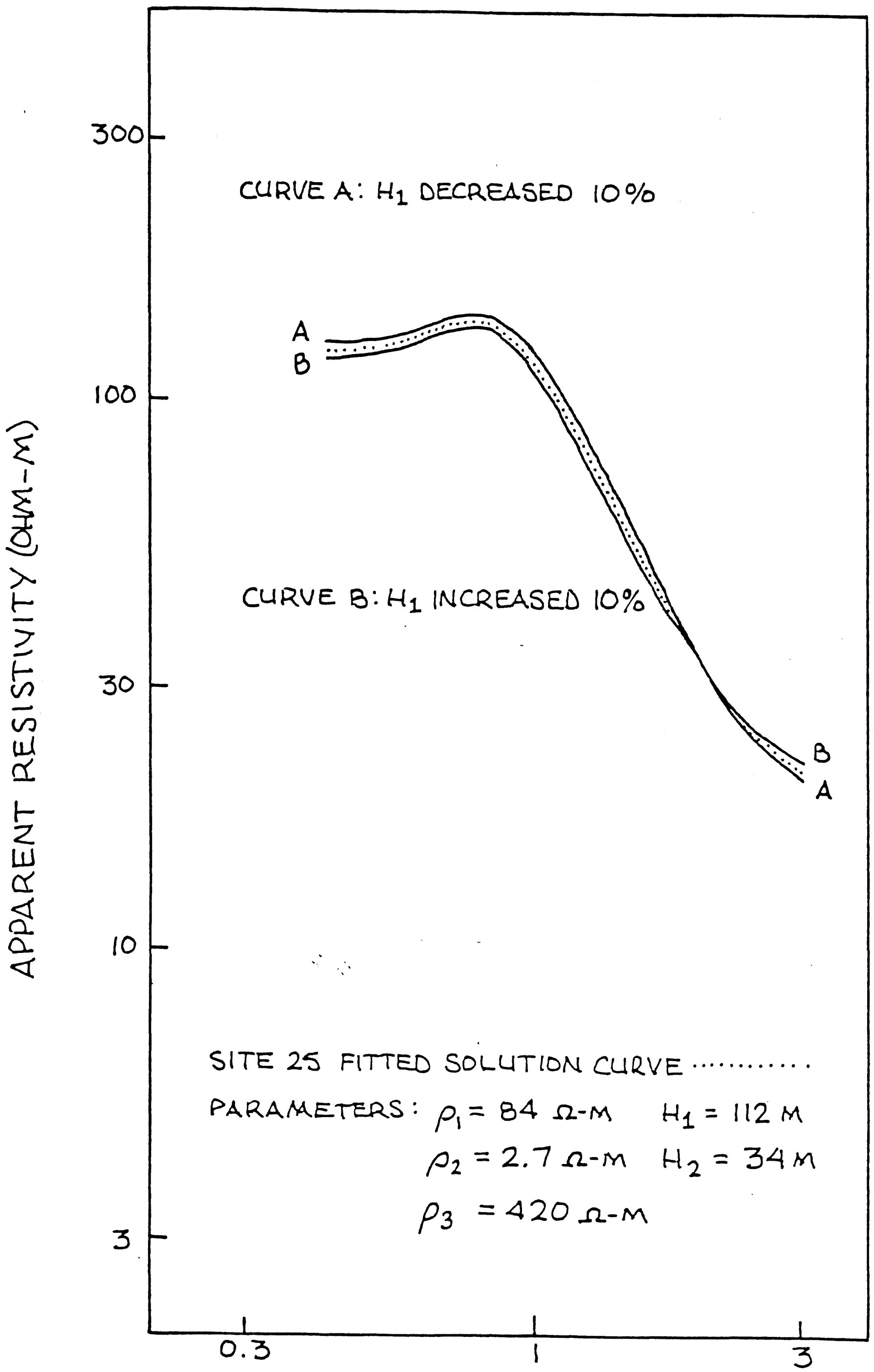

Figure 20. Curves illustrating the effects on apparent resistivity of 10 percent alterations of first layer thickness.

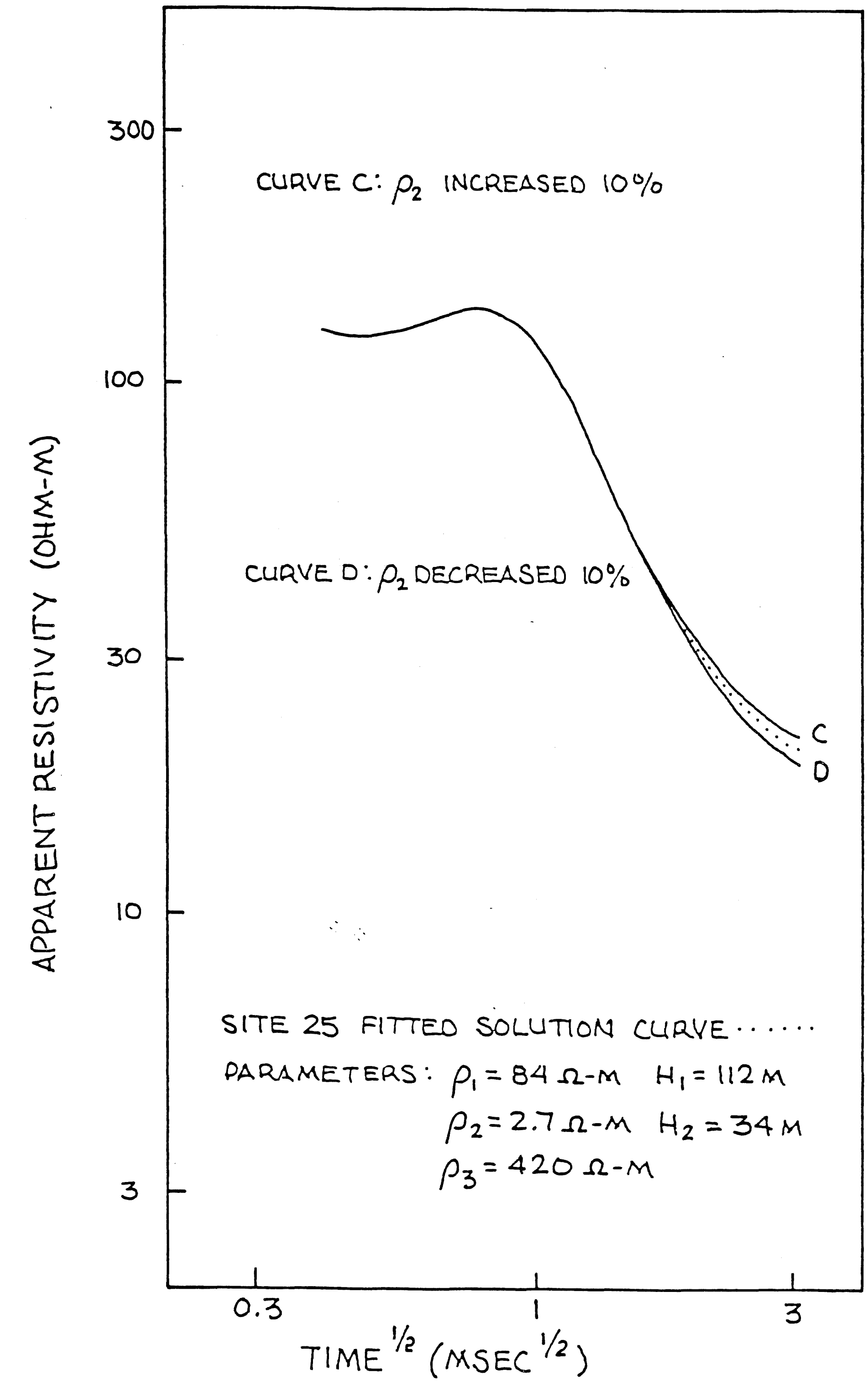

Figure 21. Curves illustrating the effects on apparent resistivity of 10 percent alterations of second layer resistivity.

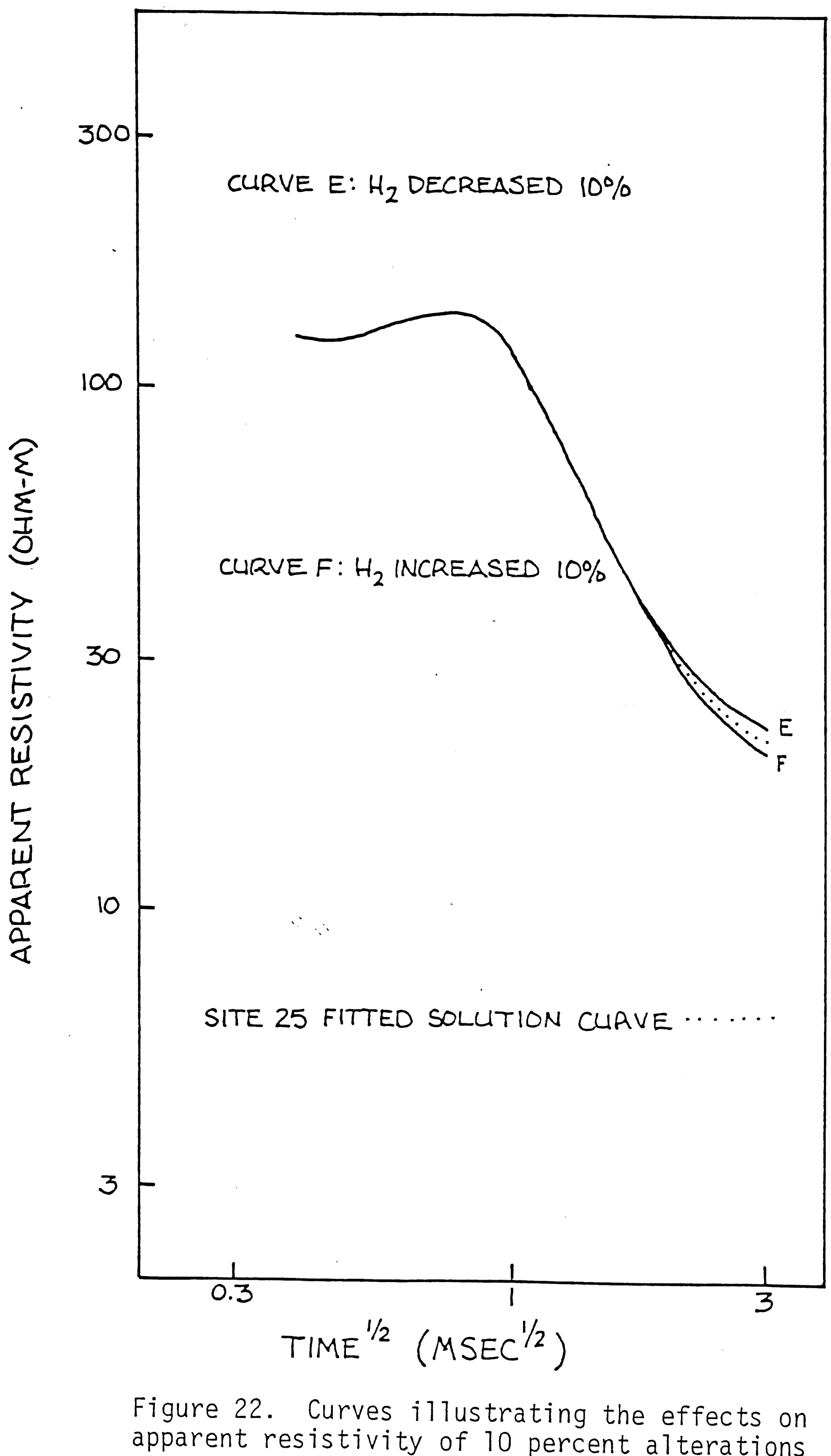

Figure 22. Curves illustrating the effects on apparent resistivity of 10 percent alterations of second layer thickness.

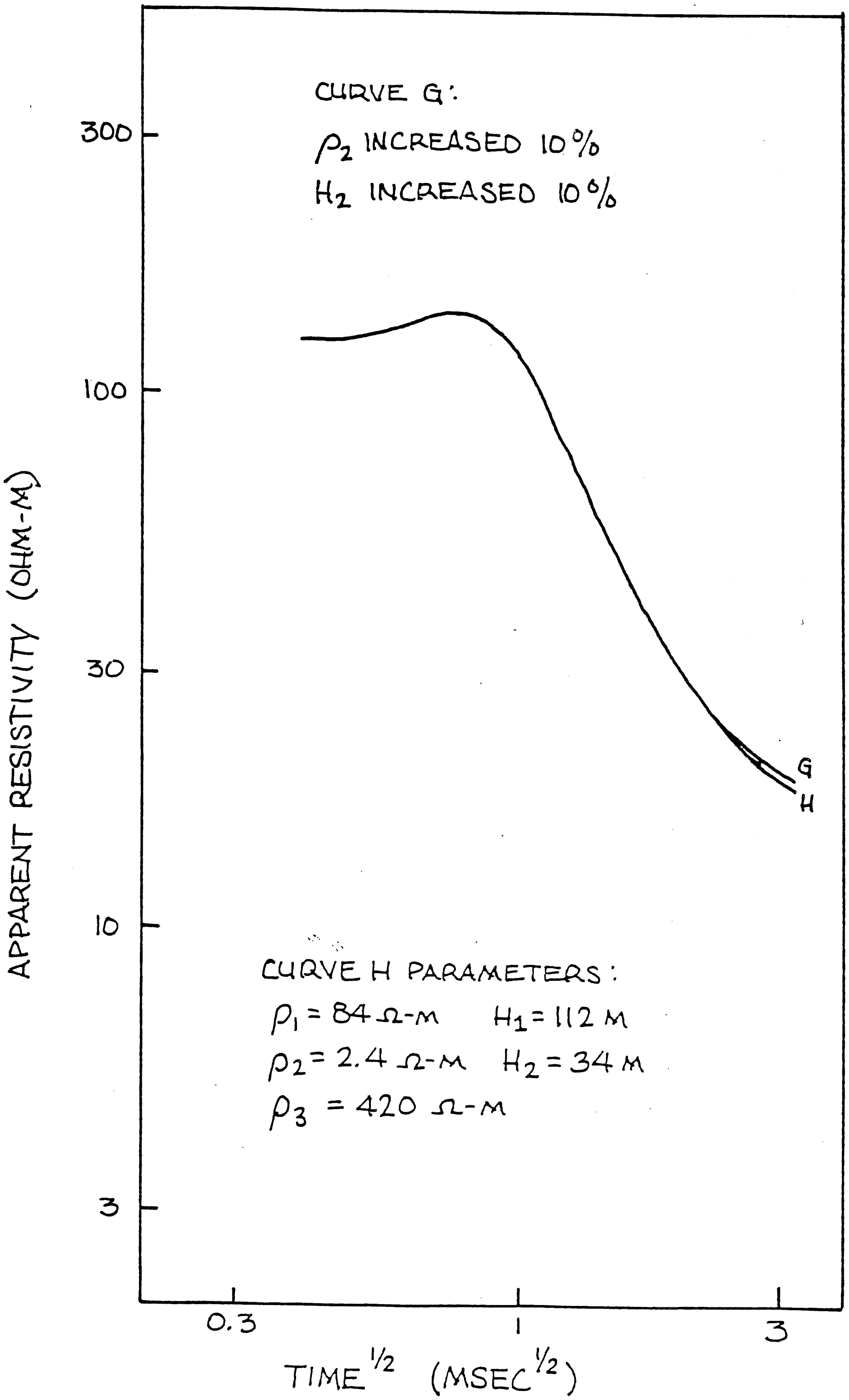

Figure 23. An example of equivalence resulting from a simultaneous increase of both second layer resistivity and thickness.

considerations limit the ability to distinguish between similar curves. Partial knowledge of the subsurface geology may aid interpretation.

CONCLUSIONS

Method Evaluation

The transient electromagnetic method enjoys several advantages over other methods currently used to monitor the salt water-fresh water interface. Penetration to depths up to 500 meters is possible without reliance on the excessively long electrode spacings and wires characteristic of direct current surveys. Electrodes are unnecessary as current is introduced into the ground by induction. This fact makes electromagnetic methods especially attractive in areas where surface conductivity is low, and introduction of current by electrodes is inefficient. Low frequency transient EM also provides better resolution than DC (Kaufman, 1978). Anisotropy is not a problem in horizontal strata, because current flow is always horizontal (McNeill, 1980a).

A few disadvantages are inherent to transient EM methods. Interpretation is more involved, and some technical training is required. The method is ineffective for shallow studies (depths less than 50 meters). Other EM methods and the DC method are complementary in this respect, as their practical use is limited to shallow surveys.

Transient EM survey costs are only slighly higher than DC costs. The EM 37 instrument rental cost is $2400 per week. A two-person field crew can complete 6 soundings per day (30 per week) for a cost of $80 for the instrument plus labor costs of $40 per sounding. Interpretation averages 2 hours ($30 for labor) plus $35 for computer time per sounding. Total personnel, instrument, and computer cost is $185 (1982 dollars) per sounding. Fretwell and Stewart (1981) completed a direct current survey involving 28 soundings at a cost of $3150 or $112 (1978 dollars) per sounding. The EM 27 purchase price is $85000 (1982, Canadian). Ignoring maintenance and shipping costs, the instrument will pay for itself over rental costs after 35 weeks of field use (assuming an even rate of exchange).

Recommendations

Efficient field work is facilitated by advance site selection and adherence to the following simple guidelines. All potential sites should be thoroughly reconnoitered and potential noise sources noted. The field crew should insure against the introduction of additional noise sources such as metal chairs, radios, vehicles, etc. An 80 meter square transmitter loop is adequate for detection of the interface in the Coastal Rivers and Withlacoochee Basins, Florida. The 3 Hertz transmitter frequency does not contribute any significant additional information, and the signal to noise ratio is unacceptable for reasonable integration times. The use of this frequency is not recommended. The ideal field crew consists of two persons. One person lays out the transmitter loop while the other prepares the transmitter and receiver units. Triplicate readings should be taken for each channel at each sounding site.

The transient electromagnetic method is ideally suited to the location of deeper portions of the salt water-fresh water interface. Additional research is indicated in Hernando County and in the vicinity of the

Cross Florida Barge Canal and Lake Rousseau. The position and shape of the interface are poorly understood in these areas. Smaller transmitter loop sizes may be adequate seaward of US Highway 19 where the interface is closer to the surface. The results from such studies would be more directly comparable to DC data. Seasonal variation of the interface position should be monitored. Increased data density would better define the interface reentrants and assist in the selection of future chloride monitor well sites.

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