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Induced polarization and magnetic response of titanium-bearing
placer deposits in the southeastern United States

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INDUCED POLARIZATION AND MAGNETIC RESPONSE OF TITANIUM-BEARING
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ABSTRACT

The induced polarization (IP) response of economically valuable placer deposits of altered ilmenite and other heavy minerals in fossil beach-complex sediments of northeastern Florida is unusually strong. This suggests that mineral-resource exploration and evaluation could be made much more efficient by use of the IP method. Field and laboratory studies conducted on detrital heavy-mineral deposits and on commercial concentrate stockpiles in Florida indicate that of the two main titanium ore minerals, altered ilmenite has a strong IP response while that of rutile is weak.

Induced polarization spectra for altered ilmenite were acquired by a unique laboratory sampling method and are distinctly different from those of pyrite. Placer ilmenite consistently shows a phase-angle maximum at about 10 Hz, whereas pyrite has a phase-angle maximum that varies with grain size but generally centers at around approximately 0.1 Hz. This difference, along with the unusually strong amplitude and phase variations observed in the IP response of altered ilmenite, should permit separation of this altered ilmenite from pyrite in the field under typical northeastern Florida survey conditions. In northern Florida, our experiments suggest that one volume percent of ilmenite corresponds to about 5-6 millivolt-seconds/volt inherent chargeability (or about 6-7 milliradians phase shift at 1.0 Hz). This permits quantification of ilmenite reserves by use of surface IP measurements.

The magnetic susceptibility of altered placer ilmenite concentrates was significant (ranging from 0.0025 to 0.0045 SI units), yet substantially below that reported in the literature for stoichiometric ilmenite. Field magnetic measurements have not been diagnostic of the presence of ilmenite, due in part to the surprisingly low susceptibilities as well as to the low concentrations found in southeastern U.S. economic deposits. High-resolution aeromagnetic surveys, however, have been successfully used regionally in outlining target areas for drilling.

Other geophysical exploration techniques for ilmenite-bearing placers, such as gamma-ray spectrometry and Side-Looking Airborne Radar (SLAR), are dependent on geophysical signatures of associated minerals, and/or geomorphologic associations, and detect only surface characteristics. Consequently quantification of resources with field measurements is not possible with these methods.

The studies carried out so far encourage us to think that IP might be the most efficient means to locate and delineate analogous ilmenite concentrations in submerged U.S. Continental Shelf sediments. If on-going research proves this to be the case, IP will become a major marine exploration tool in the evaluation and exploration for placer mineral resources within the U.S. Exclusive Economic Zone.

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INTRODUCTION

Titanium is abundant in the earth's crust, but the metal can be extracted economically only from a limited group of titanium-bearing minerals, principally rutile (TiO_2), ilmenite (FeTiO_3), and ilmenite altered by surficial processes (including leucoxene), the last-named being chemically somewhere between the first two (Lynd and others, 1954; Garnar, 1980; Patyk-Kara, 1980). Most southeastern U.S. titanium minerals originate in igneous and metamorphic source rocks in the Appalachians and Piedmont; their TiO_2 content is upgraded by a chemical weathering or leaching process that begins with transport from source rocks through fluvial systems to Atlantic Coast beaches. This enrichment process, along with later post-depositional (in-situ) weathering (iron depletion), is indicated by the arrows in Figure 1 (from Garnar, 1978). This figure shows the range in compositions of the titanium minerals usually encountered in nature. This weathering process selectively removes iron and thus increases the percentage of TiO_2 in ilmenite, thereby upgrading the TiO_2 content from the stoichiometric value (52.7 percent) to as much as 95 percent and results in leucoxene (essentially microcrystalline, porous rutile). The expression "altered ilmenite" used throughout this paper refers to the form of ilmenite most commonly found on the earth's surface (stoichiometric ilmenite has only been found naturally in certain metamorphic rocks and in lunar samples), which contains 60-65 percent TiO_2 and consists in part of disordered rutile (Temple, 1966; Force and Lynd, 1984).

Figure 1. Ternary diagram of titanium minerals, adapted from Garnar, 1978. Stoichiometric ilmenite, FeTiO_3 , on the right edge of the diagram, is found naturally in lunar samples and metamorphic rocks but not in placer deposits.

Placer deposits of heavy minerals in beach-complex sediments yield about half of the world's production of titanium minerals, including nearly all the world's rutile, zircon, and monazite (U.S. Bureau of Mines, 1982). These

minerals are mined in many parts of the world, including Australia, India, Sri Lanka, and the southeastern United States. U.S. heavy-mineral requirements, including many strategic and critical minerals, exceed the domestic supply. In 1981, the U.S. net import reliance was 43 percent of the total U.S. requirements for ilmenite and approximately 100 percent of the requirements for rutile (U.S. Bureau of Mines, 1982). Imports for these minerals come largely from Australia, South Africa, Canada, and Sierra Leone.

In the U.S., heavy minerals including ilmenite, leucoxene, rutile, zircon, monazite, and other weathering-resistant minerals have concentrated along fossil beaches, alluvial floodplains, and recent shorelines. Major deposits are located in the Coastal Plain sediments of New Jersey, the Carolinas, Georgia, and Florida (Garnar, 1980). Other deposits of ilmenite, chromite, gold, tin, platinum, and a number of other placer minerals are found in Pacific and Alaskan coast sediments (U.S. Department of the Interior, 1979). Similar concentrations have been inferred for former shoreline-complex sands now submerged on the U.S. Continental Shelves.

Physical properties of the titanium mineral group are summarized in Table 1.

Table 1. Near Here.

PREVIOUS GEOPHYSICAL WORK ON TITANIUM MINERALS

Most of the economic titanium-bearing deposits so far discovered in the southeastern U.S. are in former or present beach-complex deposits (beach-berm, dune, inlet, and washover fan deposits) of low topographic relief. Historically, the only geophysical techniques that have been used in their exploration and mapping have been total-count and spectral gamma-ray methods, though airborne methods have been used in after-the-fact individual research efforts.

A. Non-IP Methods:

Conventional exploration methods for onshore deposits include ground and airborne (total count and spectral) gamma-ray radiometric surveys on geomorphologically defined targets, followed by drilling and detailed mineralogic and geochemical studies. The Trail Ridge deposit described below, for example, is an ancient dune shoreline that forms a ridge about 5 kilometers wide and 200 kilometers long, stretching from central peninsular Florida to the Altama River in Georgia (Force and Garnar, in press). Low-angle SLAR data could be a useful adjunct to a regional exploration program in defining similar morphological features, especially in southern Georgia, where relief is too subtle to be easily represented on conventional topographic maps.

Force et al. (1982), and Grosz (1983) have in fact shown that both airborne total-count and ground spectral gamma-ray radiation surveys in the southeastern U.S. are useful adjuncts to placer-heavy mineral exploration, depending on the monazite content (and its thorium content) of surficially exposed concentrations. Their experiments indicated that a sand cover 3-5 cm thick will effectively mask the radiometric signature of such concentrations, precluding their detection by airborne surveys. Ground surveys can often detect the radioactive species to depths of tens of centimeters, depending upon local factors such as moisture content of soils and atmospheric pressure.

B. IP Methods:

IP measurements by Robson and Sampath (1977) on mill concentrate stockpiles in Australia gave strong responses for the magnetic (ilmenite) fraction of the concentrates but very weak responses for other concentrates (presumably including rutile and zircon; monazite was not specifically identified in the paper). Field IP surveys on economic ore deposits proved inconclusive, but they did note that magnetic induced polarization (MIP) data gave good correlation with heavy-mineral concentrations. This was due, they

felt, to the higher resolution obtained with MIP on very shallow (less than 5 meters) and thin ilmenite-rich layers.

Other IP work on related titanium minerals includes that of Elliot and Guilbert (1975), who reported unusually strong IP responses (over 100 millivolt-seconds/volt (hereafter this unit will be referred to as milliseconds for simplicity) chargeability, or significantly stronger than responses to sulfides for similar volume percents) in certain southern California ilmenite-rich igneous rocks. They attributed this response to elongated and extremely fine hematite plates in exsolution intergrowth lamellae in ilmenite.

Lawton and Hochstein (1980), in laboratory and field studies of different concentrations of titanomagnetite with feldspathic quartz sands in Australia, observed that both density and magnetic susceptibility of titanomagnetite ($Fe TiO$) sands increased monotonically with volume concentration. They concluded, however, that "no significant induced-polarization (IP) response could be observed even for mixtures of almost pure titanomagnetite". Robson and Sampath (1977) found that field magnetic surveys in the Jerusalem Creek area of New South Wales gave no significant responses from heavy-mineral deposits.

Results of these and other IP studies are summarized in Table 2.

Table 2. Near Here.

Our values for magnetic susceptibility of altered placer ilmenite concentrates in northeastern Florida range from 0.0025 to 0.0045 SI units. Carmichael, 1982, vol. 2, p. 268, however, gave much higher values for stoichiometric ilmenite, ranging from 0.31 to 3.77, with an average of 1.88 SI units. The discrepancy is probably due to the fact that commercial concentrates from Florida are not stoichiometric ilmenite but are altered and

contain significant amounts of microcrystalline rutile and/or pseudorutile (Temple, 1966). In addition, ilmenite concentrations in southeastern U.S. economic deposits are low (on the order of 2 to 3 percent TiO_2 -bearing minerals). As a result, field magnetic measurements in Florida have not been diagnostic of the presence of ilmenite. Industry experience has shown, nevertheless, that high-resolution aeromagnetic surveys have been successfully used regionally in outlining target areas for drilling and in fact outline one major orebody now being considered for exploitation (the Altama deposit in southeastern Georgia).

Other placer heavy minerals, including monazite (a thorium- and rare-earth-rich mineral produced as an economic by-product during mill concentration), tend to be associated with ilmenite by the transport and winnowing process because of their similar high specific gravities. Spectral gamma-ray surveys in northeastern Florida gave a strong thorium-dominated response only for concentrations very close to the surface.

LABORATORY STUDIES

Initial laboratory studies were conducted to test the inherent IP effects and magnetic susceptibilities of a group of ore samples and concentrates. The resistivity of pure altered ilmenite is quite low, ranging from 0.001 to 4 ohm-meters, and that of rutile 29 to 910 ohm-meters (Carmichael, 1982, vol. 1, p. 231). Due to the very low percentages of both minerals in typical economic deposits (a few percent total TiO_2 -bearing minerals down to a depth of 20 meters maximum), field resistivity measurements over sand deposits normally will reflect only variations in the sand compaction (porosity) and the electrolyte content of the local groundwater.

Laboratory measurements of the IP effect show a response ranging from 16 to nearly 100 milliradians [for conversion from phase angles to chargeability, use $0.8 * \text{phase} \approx \text{chargeability}$ (Zonge, Sauck, and Sumner, 1972)]. Figure 2 summarizes the results of these laboratory studies.

Measurements were also made with 1-meter dipole spacings on concentrate stockpiles (Table 3), providing equivalent values of polarization as high as 200 milliradians phase shift. The non-negligible responses in the tailings, zircon, and staurolite concentrates are almost certainly due to incomplete separation of ilmenite from these samples. An exceptional feature of figure 2 is the unexpectedly strong response of monazite, a thorium- and heavy-rare-earths-rich phosphate mineral. Only one other measurement of the IP effect from monazite is known to the authors, from a vein deposit in metamorphic rocks in Tennessee, which gave very large values when measured by an IP tool in a drillhole (C. J. Zablocki, personal communication).

Figure 2. Bar Chart of the IP response of various concentrates and ores.
Table 3. Near Here.

Laboratory experiments also suggest that there is a monotonically increasing value of chargeability or phase with increasing volume percent of ilmenite. This effect, however, appears to saturate at about 20 percent ilmenite in our experiments; correlation of chargeability or phase to ilmenite percent is precluded beyond this point. Most of the economic deposits contain ilmenite in concentrations of less than 7 percent by weight on the average, so this 20 percent limitation is not expected to be significant to exploration.

Measurements of the IP spectra were also conducted with a unique measuring system we call the "Sandbox". This system is similar to laboratory rock-sampling systems mentioned in Zonge and Wynn (1975) and Ostrander and Zonge (1978), except that unconsolidated sands were sampled in an acrylic

container instead of as conventional solid rock cores (Figure 3). These measurements were carried out with a two-channel, 12-bit microprocessor system (Zonge Engineering GDP-12.)A constant-current source driven by the microprocessor is modulated to provide 8, 1, and 0.125 Hz square waves across the sampling electrodes. A variable resistor, in series with and adjusted to the low-frequency resistance of the sample, is used to balance the measuring circuit and to provide an accurate current monitor. Channel 1 is used to trace the measured signal (voltage) across the sample while Channel 2 is used to trace the voltage across the variable resistor and therefore the energizing current. Both channels are monitored for signal linearity using a dual-channel oscilloscope.

Figure 3. Diagram of a laboratory placer-sampling Spectral IP (complex resistivity) system, showing the container used to hold the placer sample and a schematic of the sampling electronics (not to scale).

When a square wave signal is introduced at one of these frequencies, the magnitude and phase of the voltage across the sample and variable resistor are measured and converted to real and imaginary (i.e. 90 degrees out-of-phase) components using a Fast Fourier Transform. The Channel 1 (received waveform) signal is then deconvolved in the transform domain with the Channel 2 (current monitor) signal to remove peculiarities of the signal spectrum introduced by the system.

Each fundamental waveform therefore provides system-independent magnitude and phase information at the odd harmonics (1st, 3rd, 5th, 7th, 9th, 11th) of the fundamental waveform. Each component 7th and 9th harmonics of the fundamental waveform are checked to ensure that they bracket the magnitude and phase of the fundamental of the next higher frequency square wave. Apparent resistivity, phase, and percent frequency effect are calculated from the fundamental response at 0.125 Hz. The accumulated

results for each frequency of each fundamental waveform are compiled into a spectral plot of real vs. imaginary components called an Argand diagram or a Cole-Cole plot (Zonge and Wynn, 1975).

Special electrodes and a sample holder were designed (K.L. Zonge, personal communication, 1973) to accommodate placer samples. The electrodes were housed in an acrylic rectangular container open at the top and having dimensions of 15 x 7 x 7 cm. The transmit- and received-signal electrodes were screens of bronze mesh having dimensions of 5 x 6 cm, buried in the placer sample equally spaced along the long axis of the container. A system calibration was made using these electrodes and a decade resistance box and removed from the deconvolved voltage/current signal in the transform domain. The volume of dry sand sample used in our measurements was 400 ml. Current density during the measurements was restricted to the range 0.2 - 2.0 microamps per square centimeter.

Samples were actually measured wet with distilled, deionized water. An attempt to run the samples damp but without significant pore fluid was unsuccessful because the mixture was too resistive. Saturating the samples with 150 ml water (about a 2.5:1 sample-to-water ratio) gave rise to a massive electrode effect, indicating current-channeling and subsequent saturation of the received signal by the bronze-mesh electrode-electrolyte reaction. Adequate conduction for all samples (an acceptable signal-to-noise ratio) was achieved with 50 ml of water (an 8:1 ratio).

The spectral IP measurements on southeastern U.S. (Green Cove Springs) altered ilmenite show a distinctive spectral signature that has very large amplitude variations with a phase maximum between 10 and 100 Hz. For conventional IP equipment, these large-amplitude variations would correspond to unusually high Percent Frequency Effects (PFE's). Figure 4 shows three typical spectra giving a sense of the relative amplitude variations we

encountered. For reference, an "IP inert" rock or non-mineralized sand sample would give spectra of equal size or smaller in both magnitude and phase (or real and imaginary) variation to the zircon spectrum shown in Figure 4. Figure 5 shows typical spectra from the same deposit for ilmenite, rutile, and tailings (which can be regarded as an example of non-mineralized sand) on an Argand plot. Rutile, as used here, is industry standard with typically 95 percent TiO_2 .

Figure 5 is typical in that the amplitude and phase variations that we measured appear to vary smoothly, decreasing with the drop in iron content in the mineral. Note however that the maximum phase peaks at about 10-20 Hz for all titanium-bearing mineral concentrates, and this peak frequency does NOT vary with concentration of TiO_2 or the depletion of Fe^{++} . Figure 6 shows the altered ilmenite spectrum in an amplitude/phase plot, for readers more familiar with this representation. This maximum phase characteristic is very different from that of pyrite, which varies considerably with grain-size but typically reaches a maximum in the vicinity of 0.01 to 0.1 Hz (Pelton and others, 1978, Figure 14). It should be possible, therefore, to distinguish ilmenite from pyrite under typical survey conditions encountered in the southeastern U.S. (10-meter dipole spacing, and resistivities of 200-1000 ohm-meters) where electromagnetic coupling will not be a serious problem even in the 10 Hz range. In actual field practice with a conventional IP (phase-measuring) system, this separation could be made successfully by measuring phase at the highest possible frequency, preferably 10 Hz. Note, however, that because rutile has very little if any inherent IP response, this technique will underestimate total titanium content in areas where rutile predominates.

Figure 4. IP spectra of three typical placer minerals (note that monazite, though typical, is normally found in much smaller concentrations than the other minerals). These spectra are drawn in the form of Argand, or Cole-Cole, diagrams with the real (in-phase) component being horizontal, and the imaginary (90 degrees out-of-phase) component being vertical, all values being normalized to the 0.125 Hz real component for each spectral shape shown. Squares represent the real/imaginary location of the fundamental frequency, and circles represent the locations of the odd harmonics. The 0.1 Hz phase angle and the 0.1-1.0 Hz PFE for each sample are also given for reference.

Figure 5. Heavy mineral spectra of Green Cove Springs altered ilmenite, of rutile, and of wet-mill tailings. See explanation for figure 4.

Figure 6. Amplitude/phase diagram of Green Cove Springs Ilmenite.

Magnetic susceptibility measurements in the laboratory showed that nearly pure altered ilmenite samples had values of 0.0025 to 0.0045 SI units, whereas a typical ore sample had susceptibilities in the range 0.000025 to 0.00025 SI units. These results are shown in Figure 7. In this figure zircon, rutile, staurolite, monazite, leucoxene, Green Cove Springs ilmenite, and Folkston (Georgia) ilmenite are commercial concentrates, while humate refers to a humate-rich non-mineralized sand, and Green Cove Springs ore is a typical northeastern Florida heavy-mineral ore sample. These low susceptibilities would not normally produce a discernible response in a typical field environment where there are other uncontrolled variables.

Figure 7. Magnetic susceptibility of various concentrates and ores. Humate ore refers to humate-cemented, non-mineralized sands, and GSC refers to Green Cove Springs.

NORTHEASTERN FLORIDA FIELD STUDIES

Field studies were conducted on orebodies and on mineral concentrate stockpiles at several operating mines in northeastern Florida (Figure 8). Initial field studies were conducted by using IP, magnetic, and ground spectral gamma-ray radiometric survey methods.

Figure 8. Location map of Florida titanium deposits (marked by circles). Not all deposits are currently being mined.

Laboratory-derived phase-angle data for a number of placer sand samples, including monomineralic concentrates and mixes, in conjunction with stockpile-derived data (converted to phase angles) enabled us to assemble a so-called "calibration curve" (Figures 9 and 10) for the expected IP response vs. volume percent ilmenite that is valid for northeastern Florida and very likely for all southeastern U.S. ilmenites. There is a smooth monotonic relation between ilmenite and phase angle until ilmenite reaches approximately 20 percent. At this point, the IP effect of ilmenite saturates and the linear correlation no longer holds.

Figure 9. "Calibration Curve" showing the relationship between phase angle measurements in milliradians (and chargeability for convenience) and percent altered ilmenite. This curve was assembled using laboratory and stockpile measurements; the single square represents the only measurement made on a monazite concentrate.

Figure 10. "Calibration Curve" showing detail of the left side of figure 9 to 20 percent altered ilmenite.

Trail Ridge Deposit

The first IP field pseudosection reported here is from the Trail Ridge deposit, in northeastern Florida east of Starke. This ore deposit is thought to be no older than early Pleistocene; it is a compound beach berm-aeolian dune deposit having a fairly sharply defined eastern edge (where this pseudosection was acquired) and a variable thickness ranging from 8 to 21 meters. The heavy minerals constitute about 4 percent of the deposit and are disseminated in sediments that are thought to be beach-berm deposits and overlying aeolian dune deposits with high-angle crossbeds, which in turn are overlain by variable thicknesses of non-mineralized sands of Holocene age. In the area of the field test, ore minerals ranged in depth from 3 to 14 meters. The Trail Ridge and adjacent heavy-mineral deposits have been extensively described, and further details are available in Calver (1957), Pirkle and others (1977), Garnar (1978, 1980), and Force and Garnar (in press).

The dipole spacing used for the IP survey (dipole-dipole array) was 30 m. The apparent resistivity pseudosection (Figure 11) indicates nothing more than a water table being encountered at about 15-20 meters as dipole spacing increases. The chargeability pseudosection indicates a truncated polarizable body at about 30 meters depth (Figure 12). The inherent chargeability of this body ("M" values in Figure 12) reaches as high as 90 milliseconds, which corresponds according to laboratory results in Figure 10 to about 18 percent ilmenite. For the modelling results of Figure 12, we used a 2-D finite difference modelling program first described by Dey and Morrison (1976).

Available borehole data along this profile (Figure 13), however, do not extend to the depth of the strongly polarizable body; at this locality it stops at a 2-meter-thick deposit of lower Pleistocene brown coal at the bottom of the ore (T.E. Garnar, personal communication). Relatively thin overburden cover and the wide dipole spacing used preclude quantitative resolution of the ilmenite content (here about 2 to 3 percent of the sand), and the effectiveness of the IP method was not adequately tested. Dredging followed closely after the IP survey, and as a consequence a resurvey with a smaller dipole spacing could not be carried out.

Analysis of cores from nearby drillholes (Spackman, oral communication) shows that a 2-meter thick layer of lignite, buried 20 to 30 meters deep, contains from negligible amounts to as much as one percent pyrite. This amount of pyrite could account for some of the unusually high inherent chargeability, but by no means all of it, even for extremely fine pyrite grain sizes (Pelton, 1978, Figure 6). If pyrite contamination does turn out to be a serious problem in titanium placer deposits elsewhere, the very different spectral characteristics of the two minerals could be used to

distinguish and separate them. Conventional IP measurements probably would be unable to distinguish the two minerals unless measurements were made at 10 Hz.

This particular field example, although not entirely a success story, was included here because it suggests one possible problem-- pyrite contamination-- with exploration for titanium minerals with IP and also indicates how easily the economic minerals can be missed with an overly large dipole spacing. Without geologic control, or knowledge of the IP spectral characteristics of ilmenite and pyrite, this anomaly could easily have been misinterpreted as being due to another body of unknown type beneath the one already being mined.

Figure 11. Trail Ridge deposit IP field data. Dipole-dipole survey, with A-spacing of 30 meters. Top: apparent resistivity pseudosection with values in ohm-meters; bottom: chargeability pseudosection with values in millivolt-seconds/volt. West is left.

Figure 12. Trail Ridge deposit IP model. Top: model used to generate the attached pseudosections, vertical exaggeration times two. Unless otherwise indicated, resistivities (ρ) are given on the right for layers indicated, including blocks of more highly polarizable material (indicated by M =). Middle: modelled apparent resistivity pseudosection, in ohm-meters; bottom: modelled chargeability pseudosection, in millivolt-seconds/volt.

Figure 13. Trail Ridge deposit geologic section for comparison. Numbers are percentages of TiO_2 -equivalent provided by mine geologists. The "Clay Bottom" is a local drillers' term referring to more consolidated sands below which drilling is judged to be uneconomic. Often this level is defined by a thin layer of woody lignite that causes havoc with the dredge used to mine, thereby defining the economic bottom.

Green Cove Springs Deposit

The second field pseudosection is constructed with data collected on the Green Cove Springs orebody due east of Trail Ridge and south of Orange Grove, Florida. The heavy-mineral orebody is significantly different from Trail Ridge in that the mineral assemblage contains significantly more monazite (though still only on the order of 0.001 percent), garnet, and epidote, and the ore zone is considerably shallower (less than 6 meters). The deposit is

also more thickly bedded (a beach-berm deposit) and higher in grade (although less extensive volumetrically) than the Trail Ridge deposit.

The pseudosections at Green Cove Springs shown in Figure 14 were chosen as an example because they are characteristic of a typical southeastern U.S. near-surface economic orebody. The dipole spacing used was 10 meters, and it required a 5-meter spacing to achieve closure on the near-surface anomaly in the center of the chargeability pseudosection. The apparent resistivity pseudosection in Figure 14 is unremarkable except for a slight decrease in resistivity in the vicinity of the orebody. The cause of this decrease is not known to the authors. The chargeability pseudosection shows an anomaly from stations 5 through 9 that in fact continues west (left) beyond stations 2 and 3 after a partial pinch-out at station 4.

The model in Figure 15 shows a body with inherent chargeability ("M" in the figure) of about 75 milliseconds, which would translate to about 14 percent ilmenite using the calibration curve of Figure 8. The orebody ranges in depth from about 3 to 6 meters over the entire range of the pseudosection, thinning somewhat and becoming shallower to the left (west). The negative chargeabilities seen beneath the orebody are a so-called shadow effect and are geometric in origin, unrelated to any mineral-caused phenomenon beneath the orebody.

The available geologic information for this deposit (Figure 16) is based on three drill cores at the IP stations 2, 7, and 12. The "Clay Bottom" is a local drillers' term that does not necessarily refer to clays per se but rather to sediments finer grained than the ore, with significantly more clay, and as a consequence more indurated than the overlying medium- to fine-grained sand and more resistant to drill penetration. Percent ilmenite in the ore zone was indicated to the authors to have reached values in excess of 10 percent for several meters beneath IP station 7. This agrees extremely

well with the IP model derived directly from the field data and converted to percent ilmenite using the calibration curve. The mineral distribution is not as homogeneous as the figure might seem to imply; in fact only three drill cores are available, and the mineralogy has been averaged over 1.5-m lengths of the core sample.

The magnetic profile, shown on figure 16 for completeness only, shows moderate variations that are difficult to correlate with ilmenite content. While these data are not encouraging, high-resolution aeromagnetic surveys have nevertheless been used to guide regional exploration programs. One deposit (Altama) was initially found with a high resolution aeromagnetic surveys.

Figure 14. Green Cove Springs orebody IP field data. Dipole-dipole survey, with A-spacing of 10 meters. Top: apparent resistivity pseudosection with values in ohm-meters; bottom: chargeability pseudosection with values in millivolt-seconds/volt. West is left.

Figure 15. Green Cove Springs IP model. Top: model used to generate the attached pseudosections. Unless otherwise indicated, resistivities () are given on the right for layers indicated, including blocks of more highly polarizable material (indicated by M =). Middle: modelled apparent resistivity pseudosection, in ohm-meters; bottom: modelled chargeability pseudosection, in millivolt-seconds/volt. There is no vertical exaggeration.

Figure 16. Geologic section for the Green Cove Springs deposit derived from three drill cores, taken at IP stations 2, 7, and 12 as indicated. A magnetic field profile acquired over it is shown for reference. Numbers are percentages of TiO₂-equivalent provided by company geologists. The "Clay Bottom" is a local drillers' term referring to more consolidated sands below which drilling is judged to be uneconomic. Often this level is defined by a thin layer of woody lignite that causes havoc with mine dredges, thereby defining the economic bottom. There is no known lignite at this site.

OTHER GEOPHYSICAL METHODS USED AT THESE SITES

Field experiments using a 0.25-nT sensitivity proton precession magnetometer failed to distinguish the ore from the host sediments at both Trail Ridge and Green Cove Springs. This failure is due in part to the relatively low susceptibilities reported in the laboratory section above and

in part to the low concentrations of ferromagnetic minerals in the ore. Changing concentrations of ferromagnetic minerals in the sediments immediately underlying the very shallow ore-grade zones constitute another complicating factor.

The ground total-count and spectral gamma-ray radiometric data also revealed no discernible contrast between orebody and host sediments, although background values are higher than in surrounding areas. Airborne total-count and spectral radiation survey maps, however, show that the entire north-eastern Florida area is radiometrically anomalous, with coast-parallel medium- to low- intensity anomalies (thorium-dominated) that correlate exceptionally well with modern and ancient shoreline-complex deposits including the Trail Ridge system (Grosz and others, unpublished data).

CONCLUSIONS

Our experiments with induced polarization document that altered ilmenite and monazite give a strong IP signature; that of altered ilmenite can be quantified and used in the field for estimating volumes and percentages. Note that monazite occurs in much lower concentrations than ilmenite and would not normally contribute to the IP response in field data over placer deposits. The IP method, with appropriate fine tuning, has the potential for being a much more powerful and significantly cheaper method of exploring for such deposits than wildcat drilling guided by geomorphologic criteria. Rutile, the high-titanium mineral related to ilmenite, has a much weaker IP effect almost certainly caused by small amounts of residual ilmenite-leucoxene remaining in the commercial separates that we examined.

Due to the potential variability of the weathering process, the calibration curves for percent altered ilmenite vs. chargeability given in figures 9 and 10 can be considered rigorously applicable only for north-

eastern Florida. However, because the sediments we studied have been transported over considerable distances and have been through several cycles of deposition and erosion, it is reasonable to expect some degree of homogeneity in the alteration state of ilmenite in northeastern Florida, and in fact the scatter in Figure 10 is remarkably low. The observed homogeneity suggests that our calibration results may be applicable over larger areas, perhaps including the entire southeastern Atlantic Coastal Plain and parts of the adjacent Atlantic Continental Shelf.

A potential problem with using IP to map titanium sands is the possibility of encountering pyrite in areas of humate ores and other sediments containing much organic matter. The distinctive IP spectral shape of titanium-bearing minerals, however, suggests that it should be relatively easy to separate ilmenite from pyrite in the field (their maximum-phase frequencies differ by two orders of magnitude). Additionally, the large-amplitude ilmenite response should usually drown out any background pyrite signature if pyrite is present in quantities of less than about 2 percent. Measuring phase-shifts in the 10-Hz range should remove pyrite interference as a significant problem for conventional IP systems; this relatively high frequency should not cause serious problems with electromagnetic coupling because the typical resistivities are large and the dipole spacing used there is unusually small.

Resistivity of ilmenite and rutile has not been examined in detail since all known deposits in the southeastern U.S. are hosted by beach-complex sediments in areas where the water table is commonly within a meter or two of the surface. Any variations in resistivity measured in the field, therefore, are expected to reflect only changes in the electrolyte content of the local water and have nothing to do with relative ilmenite content. This is

certainly true for the percentages found in economic deposits to date.

Other physical properties of the titanium-bearing minerals show variations dependent on ilmenite percentage similar to the IP effect. Magnetic susceptibility in concentrates varies directly with ilmenite percentage, with virtually no susceptibility observed in pure rutile. Magnetic susceptibilities of ilmenite-bearing heavy-mineral placers are lower than those reported in the literature for stoichiometric ilmenites. Ilmenite percentages are low in economic deposits of the southeastern U.S., and probably for these reasons ground magnetics have been ineffective so far in field experiments conducted in northeastern Florida.

Vast resources of ilmenite may exist in beach-complex sand deposits of the Atlantic Coastal Plain and adjacent Atlantic Continental Shelf. Radioactive heavy minerals, principally monazite, are commonly found associated with titanium-bearing minerals; they impart a characteristic gamma-ray signature to such orebodies that makes them suitable for exploration by airborne and ground radiometric techniques.

Preliminary investigations of grab and vibracore samples from the Atlantic Continental Shelf have shown the presence of extensive areas with probable fossil beach deposits submerged since the last episode of glaciation (Grosz and Escowitz, 1983). Some of these offshore samples have yielded as much as 3 percent ilmenite. As grid vibracoring in 100-meter depths is not very efficient, we propose to develop a marine IP dragged-streamer to survey large areas prior to vibracoring.

ACKNOWLEDGEMENTS

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Table 1 PHYSICAL PROPERTIES OF TITANIUM-BEARING MINERALS.

Mineral Name	Density (gm/cc)	Magnetic Property	Electrostatic Response	IP Response
ALTERED ILMENITE	4.7	paramag.	conductive	strong
LEUCOXENE	3.6-4.3	para->non	conductive	decreasing
RUTILE	4.3	non	conducts	very weak
Altered Ilmenite	: (Fe,Mg,Mn)TiO ₂	dominantly Fe		46-53% TiO ₂
Leucoxene	: FeTiO ₃ -> TiO ₂			76-90% TiO ₂
Rutile	: TiO ₂			97-99% TiO ₂

* _____ *

Table 2 IP RESPONSE OF TITANIUM-BEARING MINERALS

MINERAL	IP RESPONSE	REFERENCE
Hemo-Ilmenite (Hematite exsolutions)	Very Strong	Elliot & Guilbert (1975)
Titanomagnetite ("Ironsands")	Null	Lawton & Hochstein (1980)
Ilmenite	Very Strong	Robson & Sampath (1977)
Altered Ilmenite	Very Strong	This paper.
Leucoxene	Moderate to Strong	This paper.
Rutile	Weak	This paper.

Table 3 RESULTS FROM STOCKPILE EXPERIMENTS

IP Parameters: A-Spacing = 1 meter Current = 0.06 - 0.2 amps
 N-Spacing = 1 Receiver: Scintrex IPR-10
 Array = Dipole-Dipole Transmitter: Scintrex TSQ-2E

STOCKPILE	Decay Curve broken into 6 components.	Decay Curve broken into 3 components./+/ M31 = 118 mv-sec/v M32 = 118 " M33 = 94 "
Ilmenite: Dupont Highland Mine	M61 = 121 mv-sec/v M63 = 96 " M66 = 88 "	M31 = 118 mv-sec/v M32 = 118 " M33 = 94 "
Ilmenite: Dupont Trail Ridge Mine		M31 = 165 mv-sec/v M32 = 165 " M33 = 151 "
Ilmenite: Green Cove Springs Deposit	M61 = 89 mv-sec/v M63 = 82 " M66 = 77 "	M31 = 87 mv-sec/v M32 = 87 " M33 = 81 "
Staurolite: Green Cove Springs Deposit (a mill separate used for sandblasting)		M31 = 5.7 mv-sec/v M32 = 5.7 " M33 = 5.5 "

/+/
 M61, M32 etc. are Scintrex designations for the area under the IP decay curve sampled; these are given as the following for a 2-second-on time-domain waveform (50% transmitter duty cycle):

M31 samples from	.130 to .650 msec, with mean at	.390 mv-sec/v	
# M32 samples from	.650 to 1.170 msec, with mean at	.910 "	#
M33 " "	1.170 to 1.690 " " " "	1.430 "	
M61 " "	.130 to .390 " " " "	.260 "	
M62 " "	.390 to .650 " " " "	.520 "	
M63 " "	.650 to .910 " " " "	.780 "	
M64 " "	.910 to 1.170 " " " "	1.040 "	
M65 " "	1.170 to 1.430 " " " "	1.300 "	
M66 samples from	1.430 to 1.690 msec, with mean at	1.560 "	

M32 is indicated to be equivalent to the so-called "Newmont Standard" chargeability for a 2-second-on time-domain transmitter duty cycle.

/+/
 Taken from the "IPR-10 Digital Time-domain induced polarization receiver manual", Scintrex part # 726702, printed July 1978

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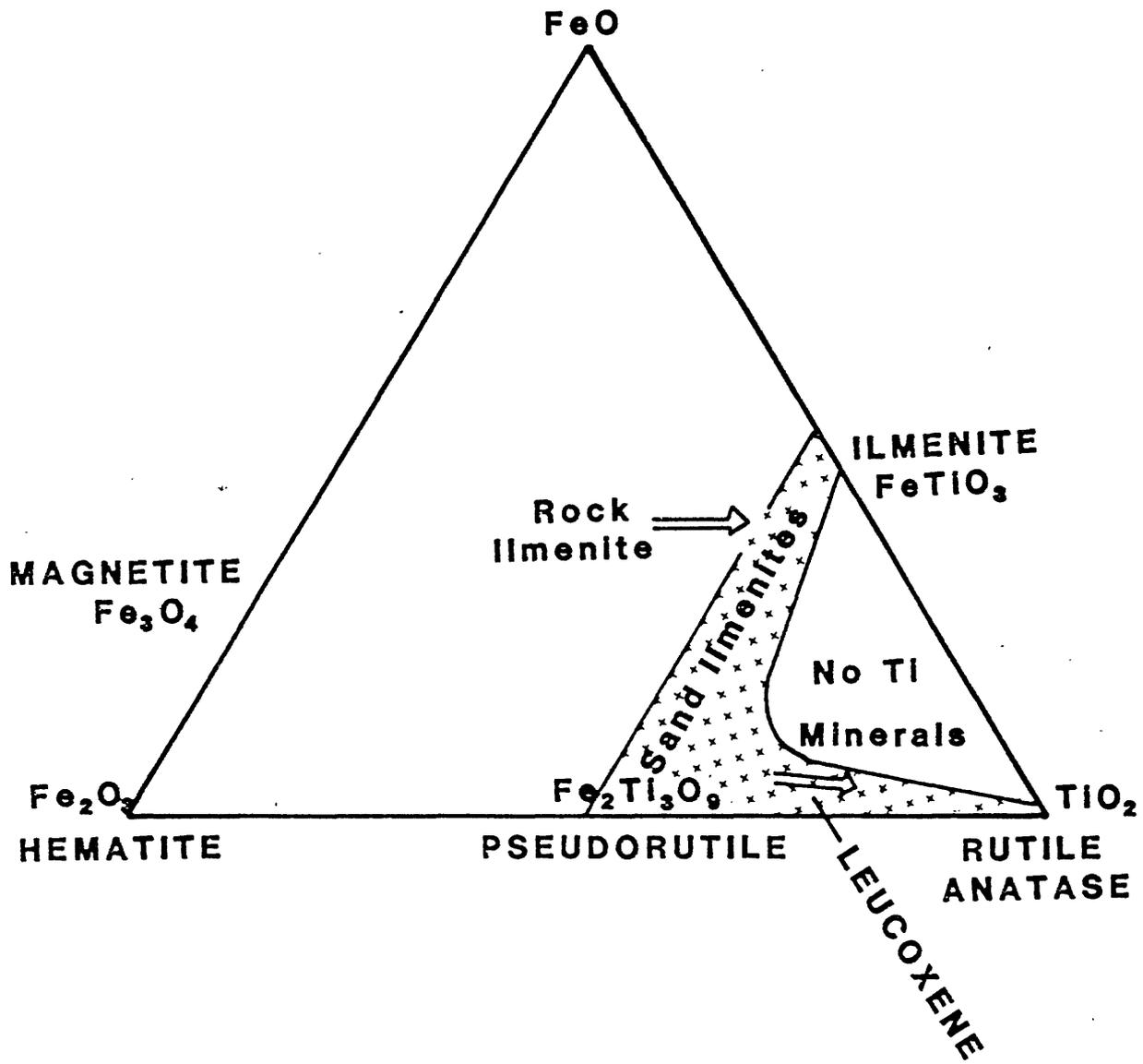


FIGURE 1

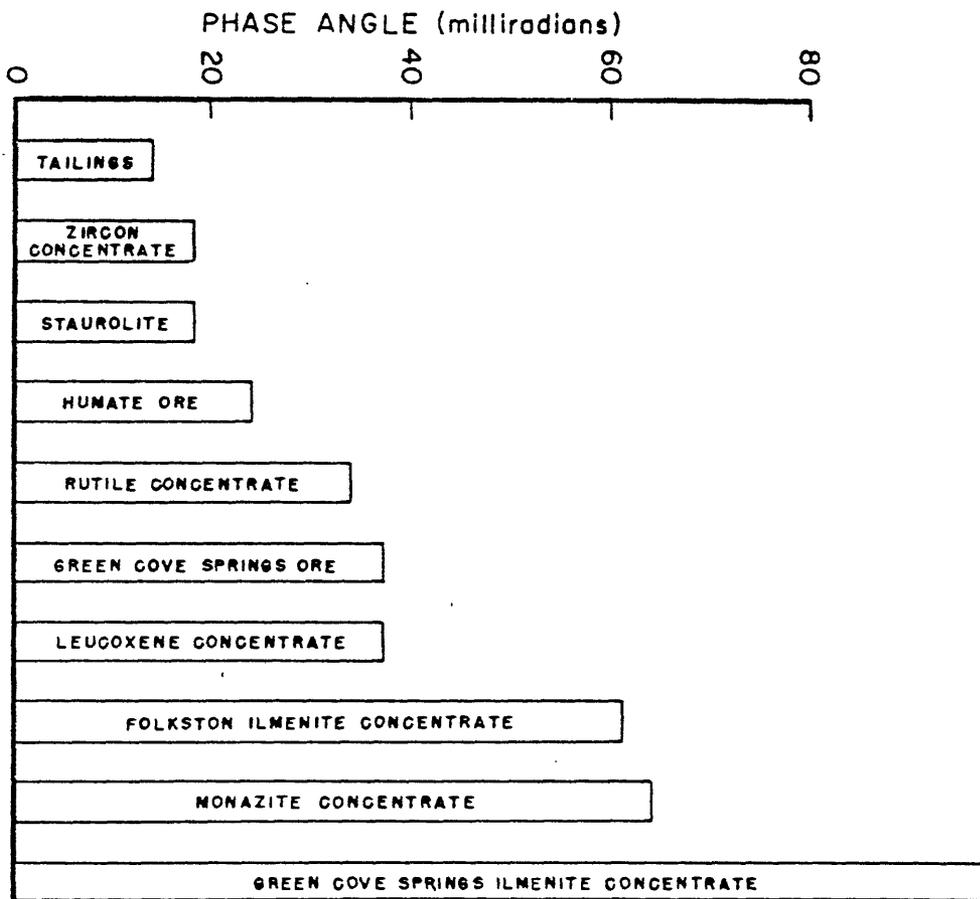


FIGURE 2

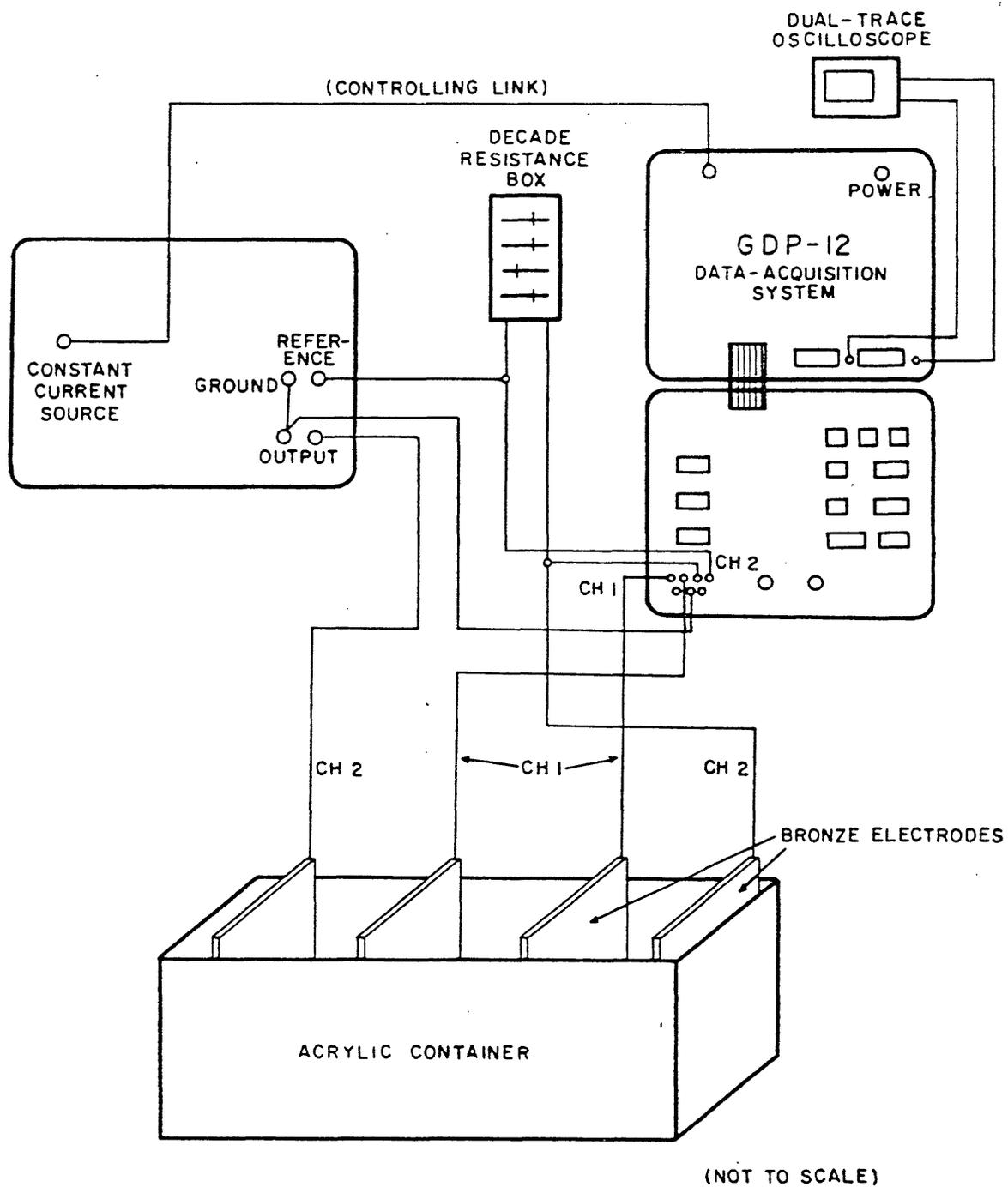


FIGURE 3.

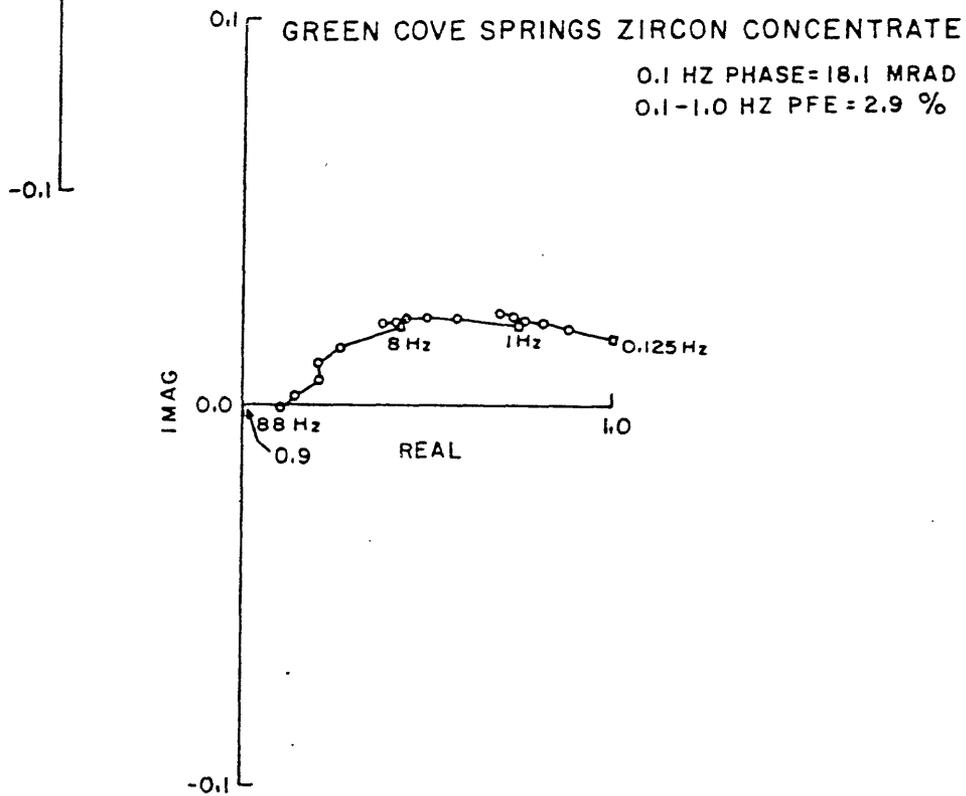
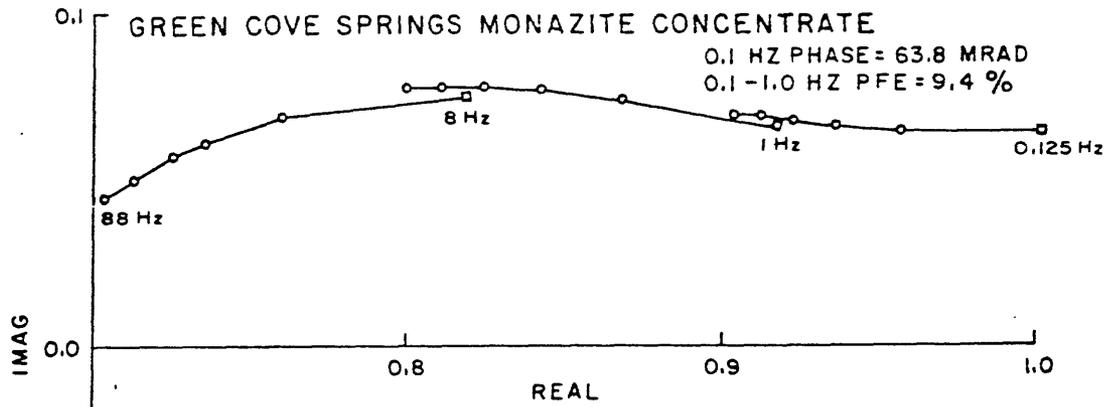
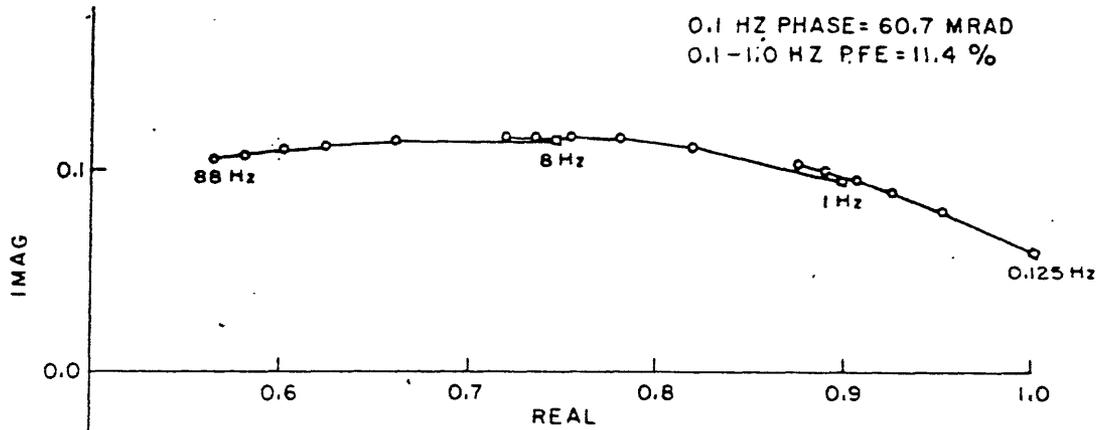


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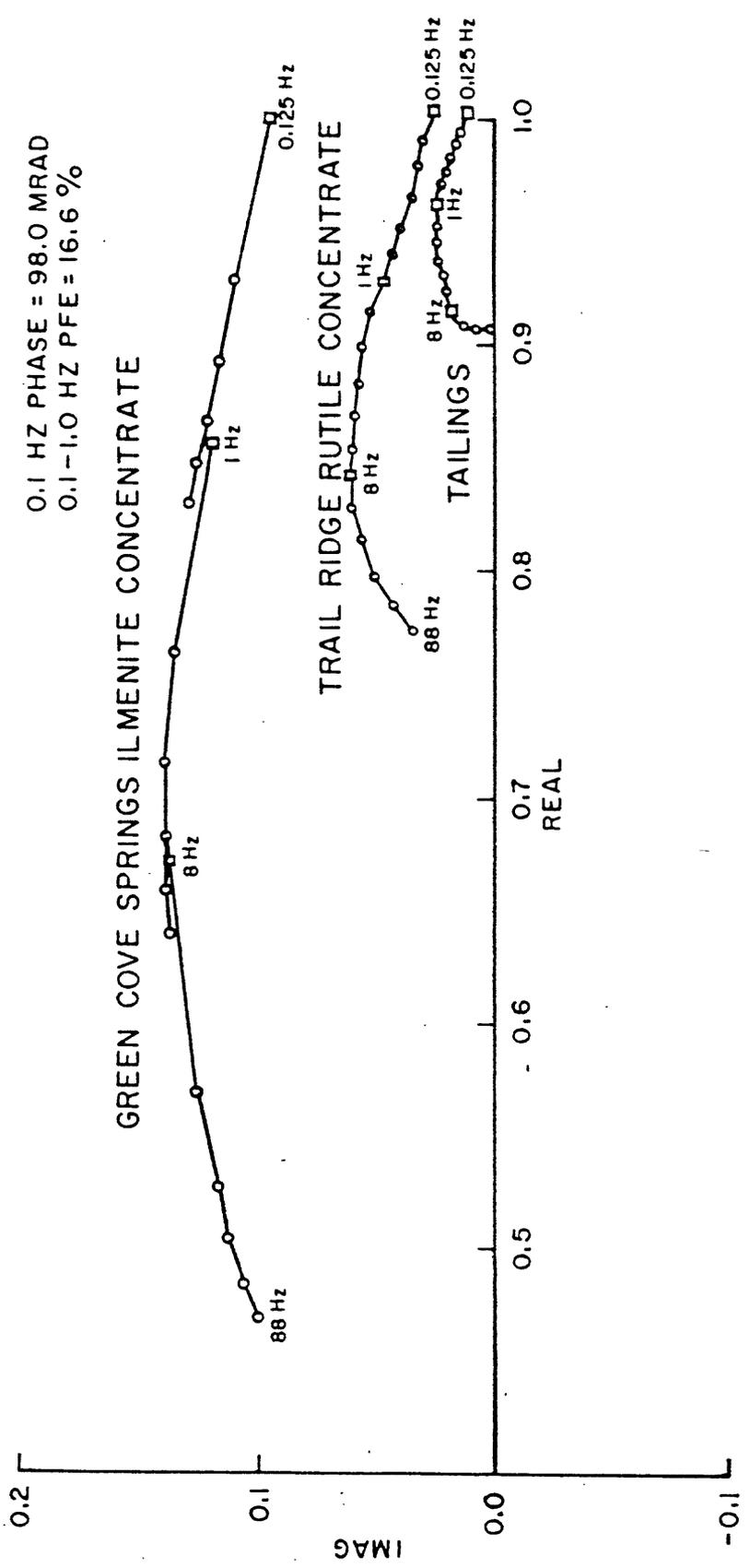


FIGURE 5

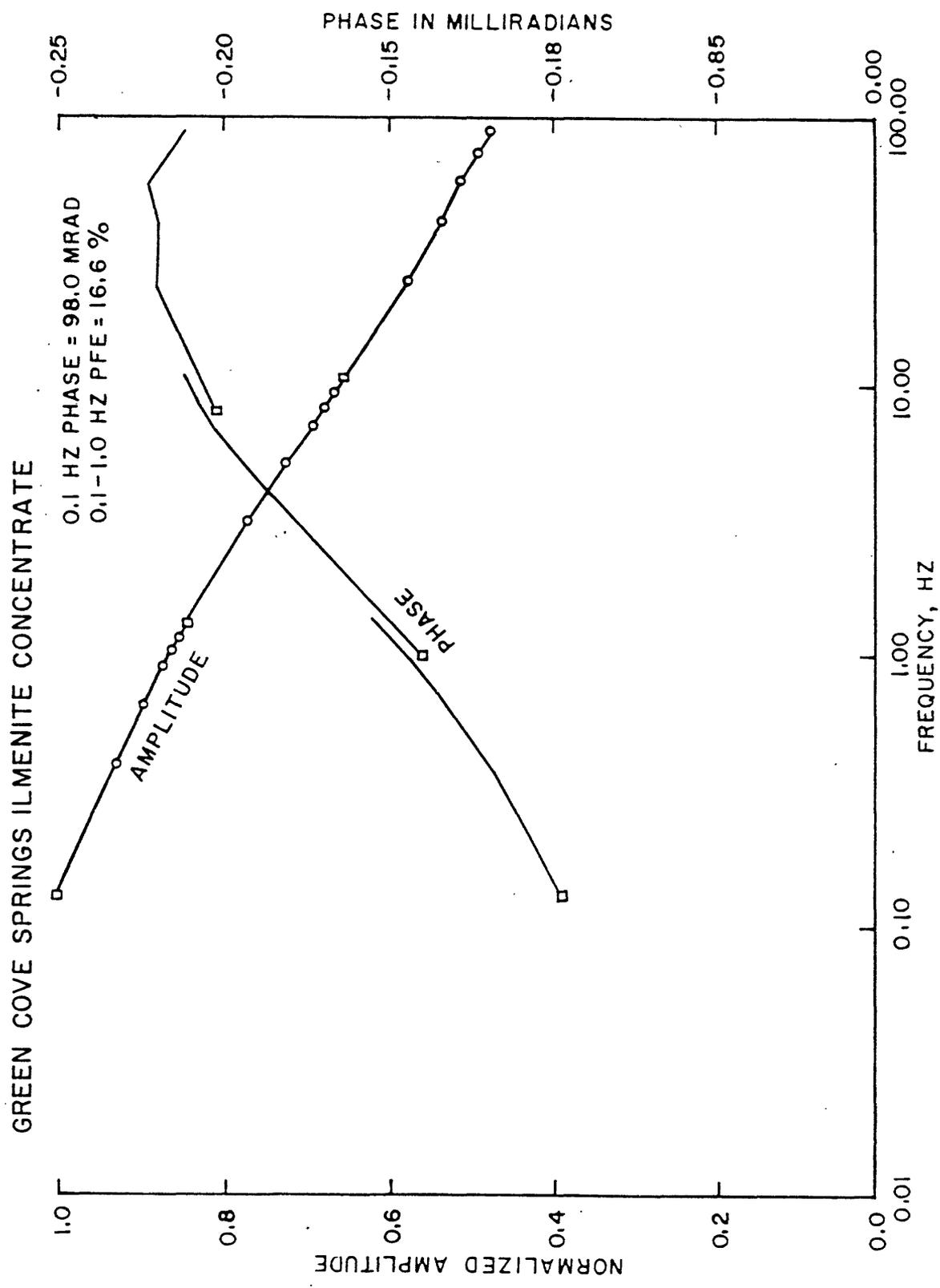


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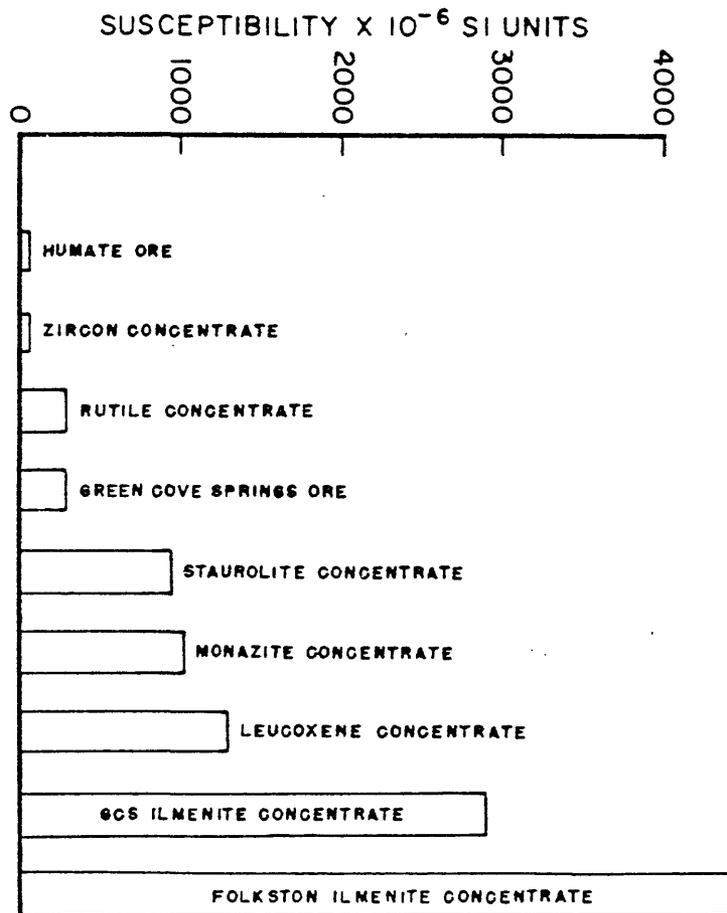


FIGURE 7

FLORIDA TITANIUM DEPOSITS

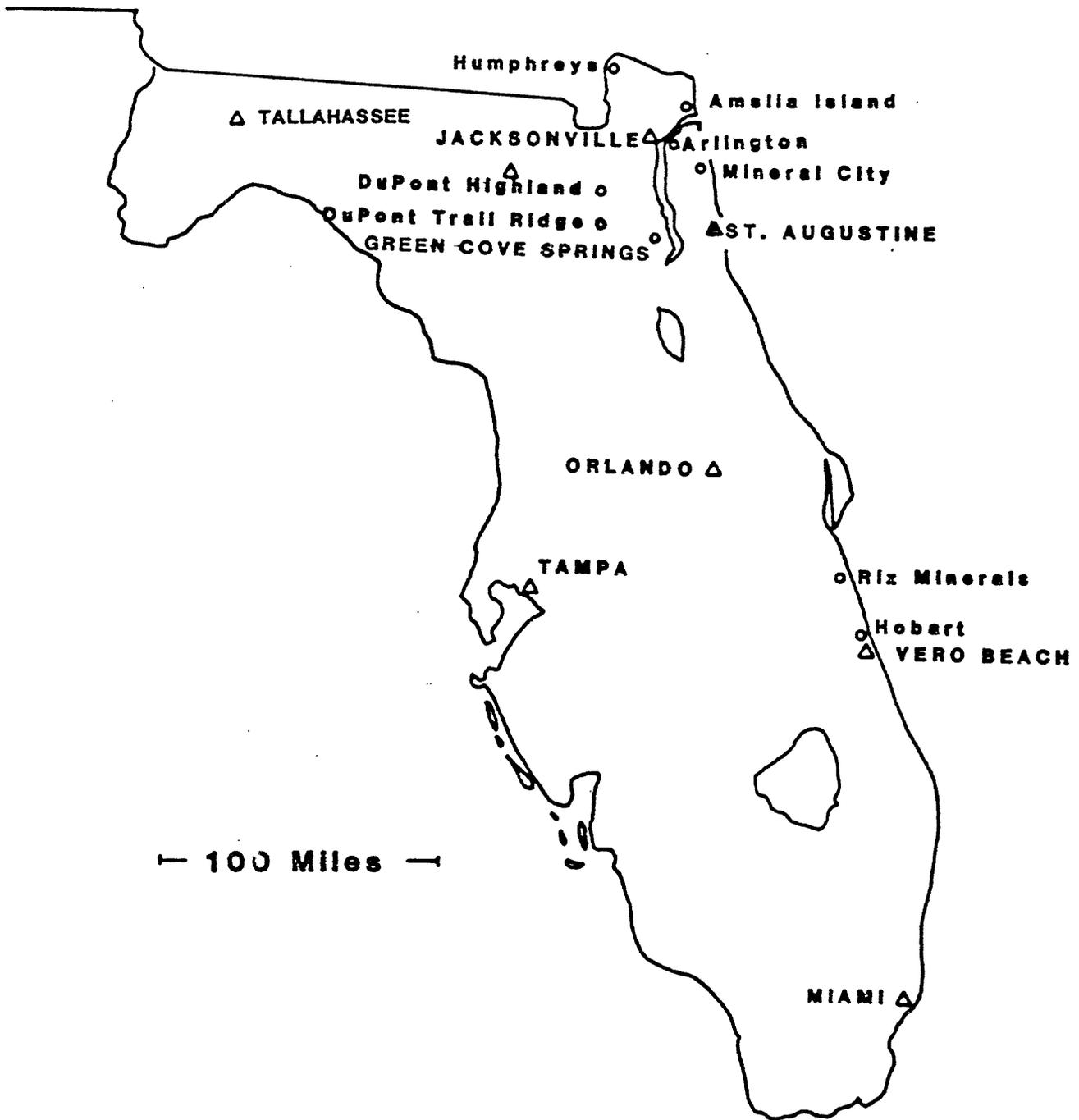


FIGURE 8

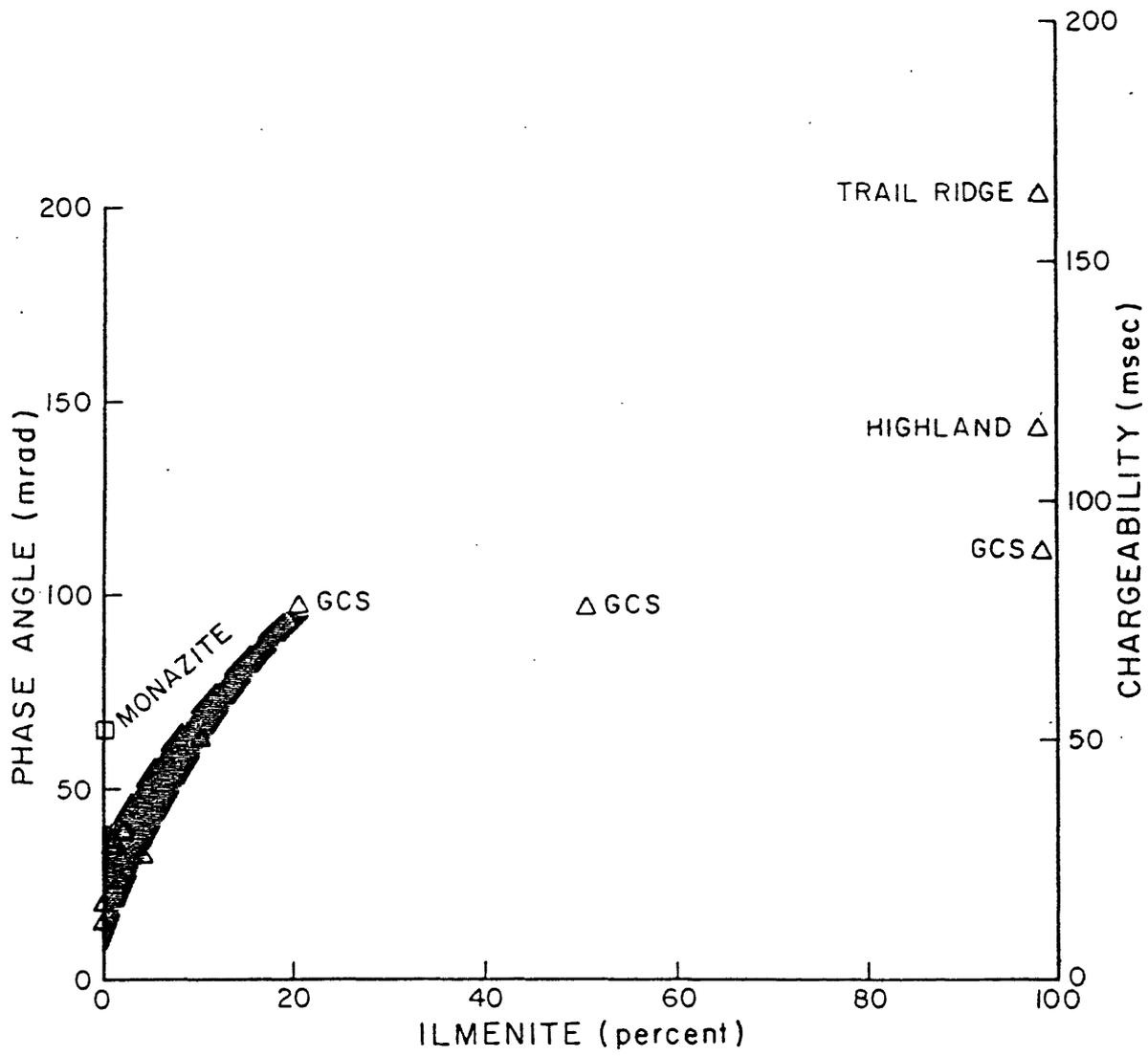


FIGURE 9

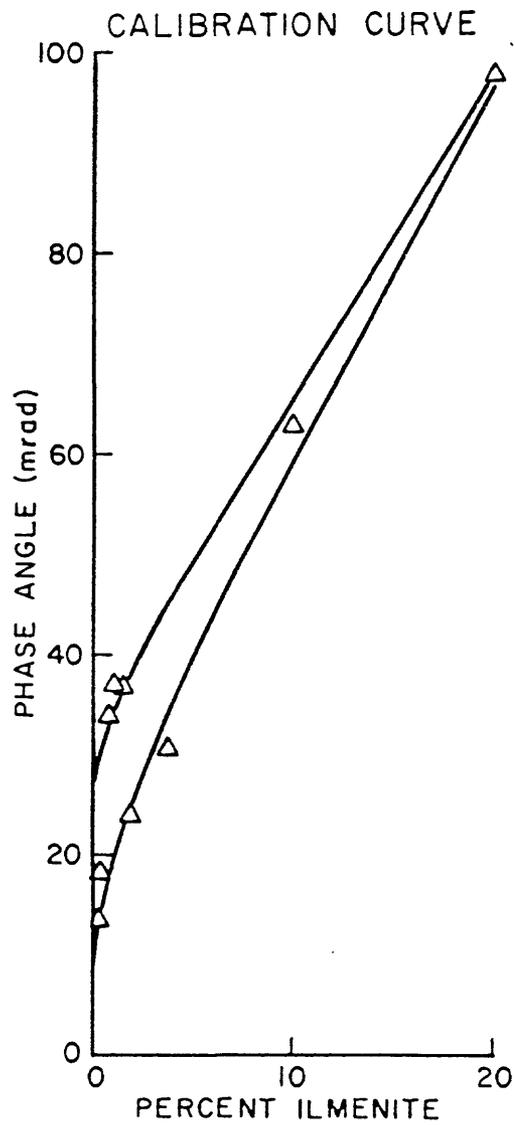
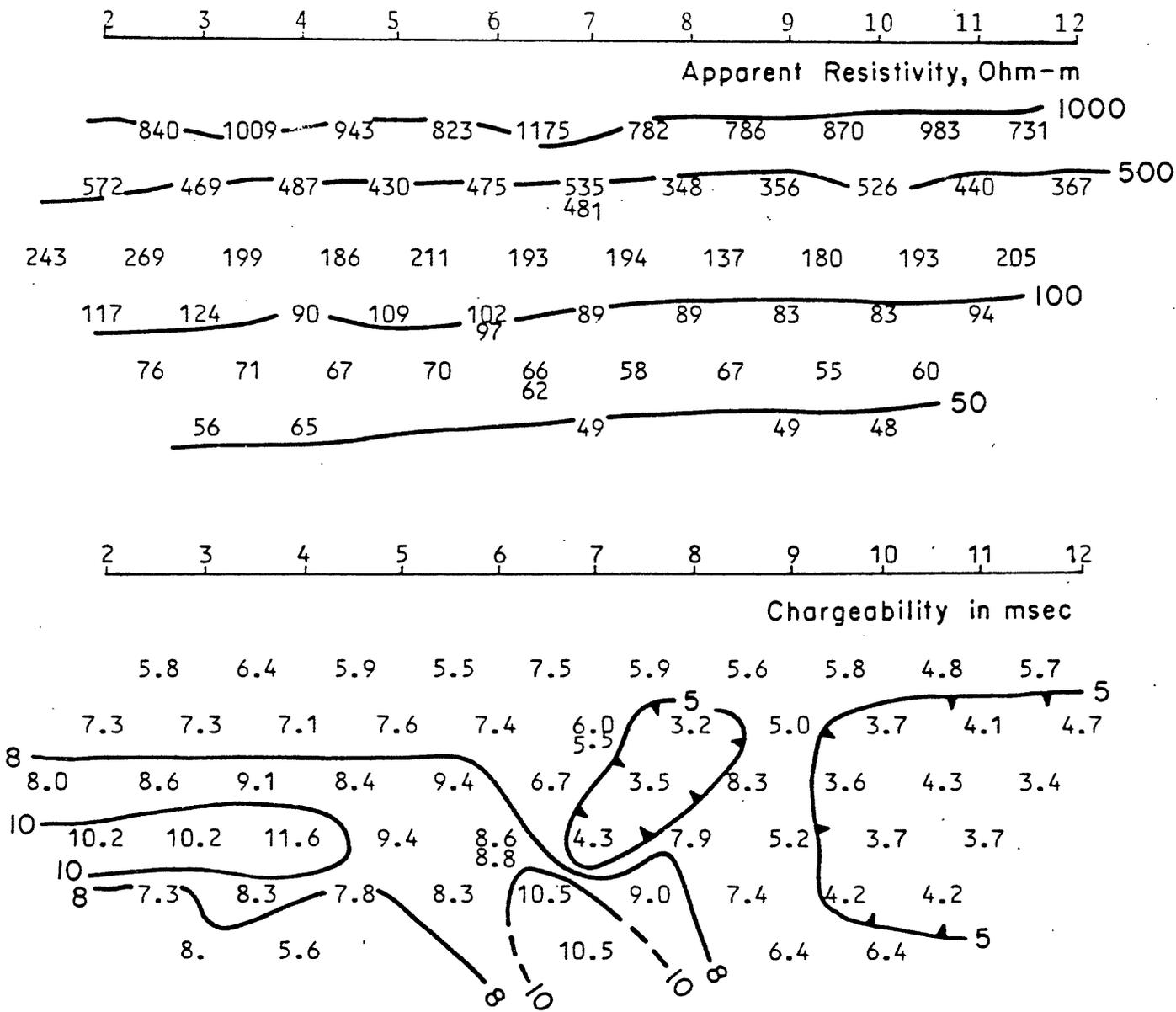


FIGURE 10



DIPOLE SPACING = 30 m

FIGURE 11

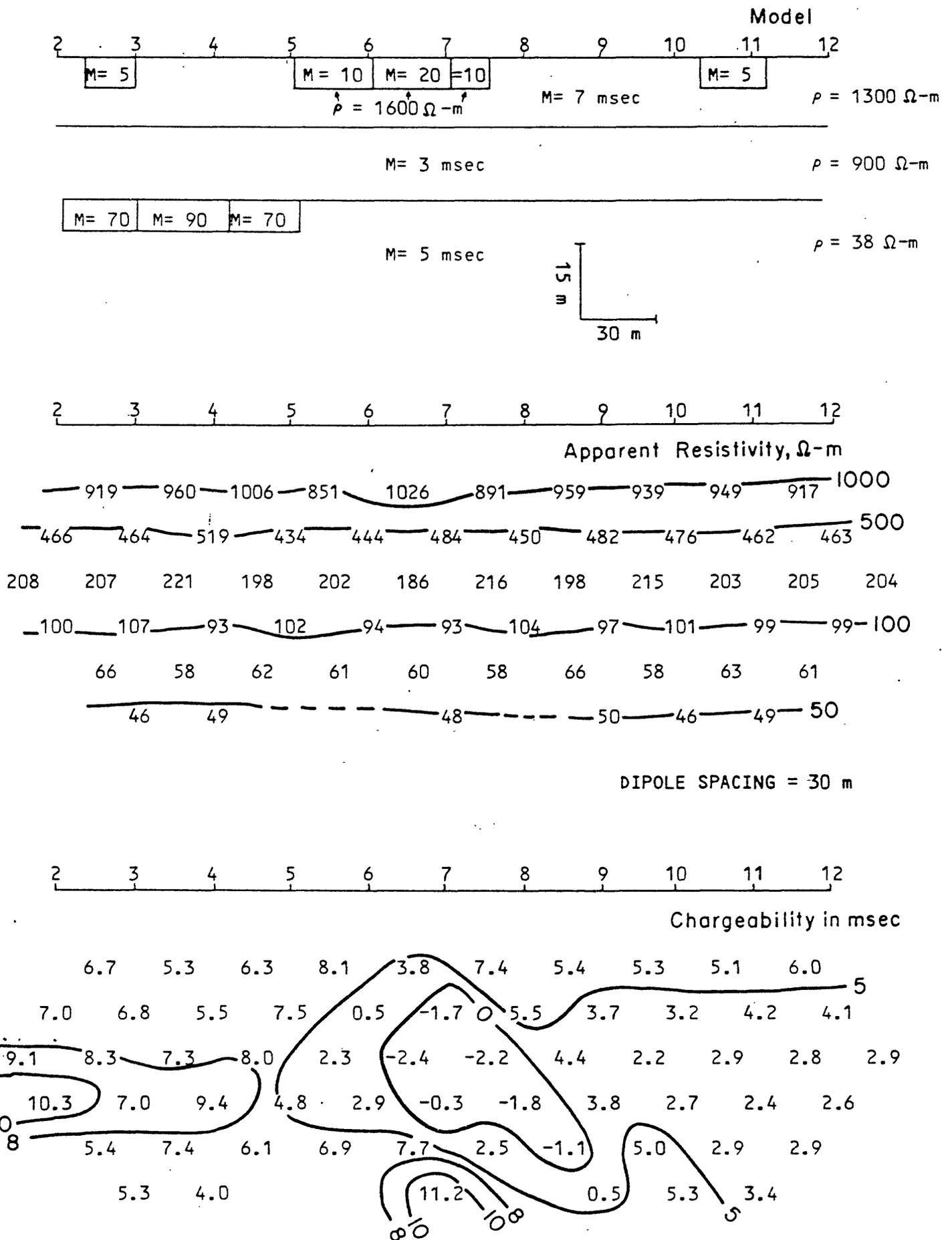


FIGURE 12

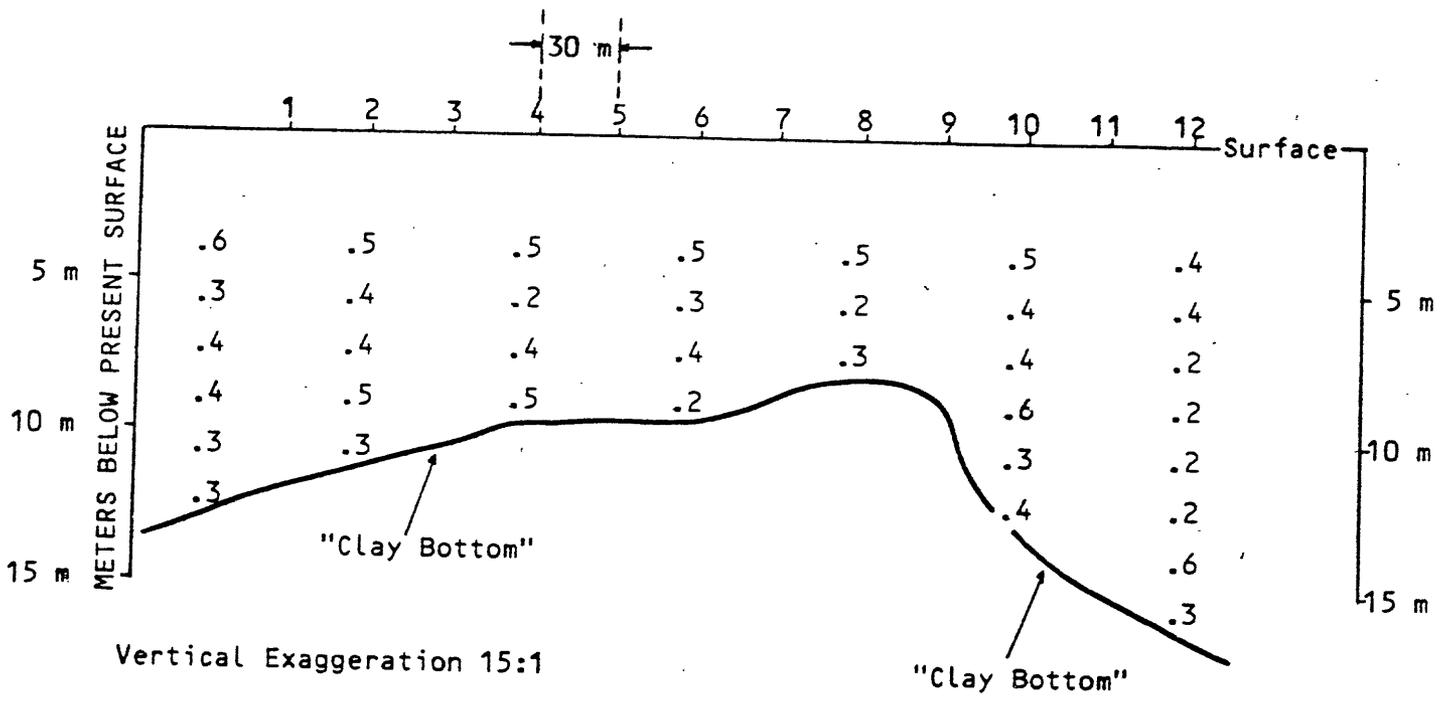
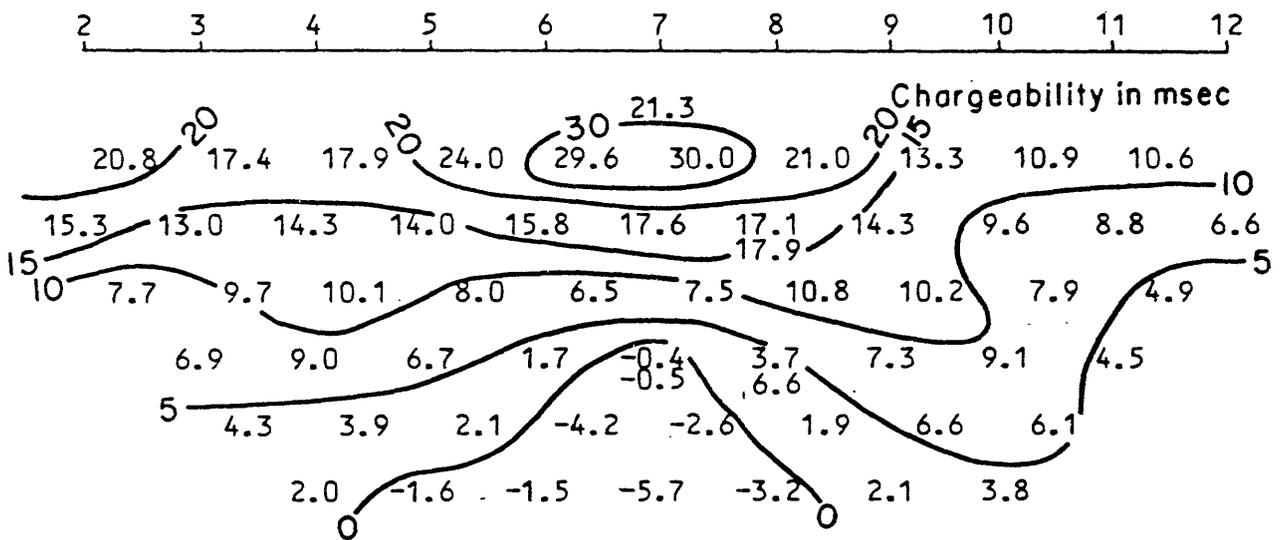
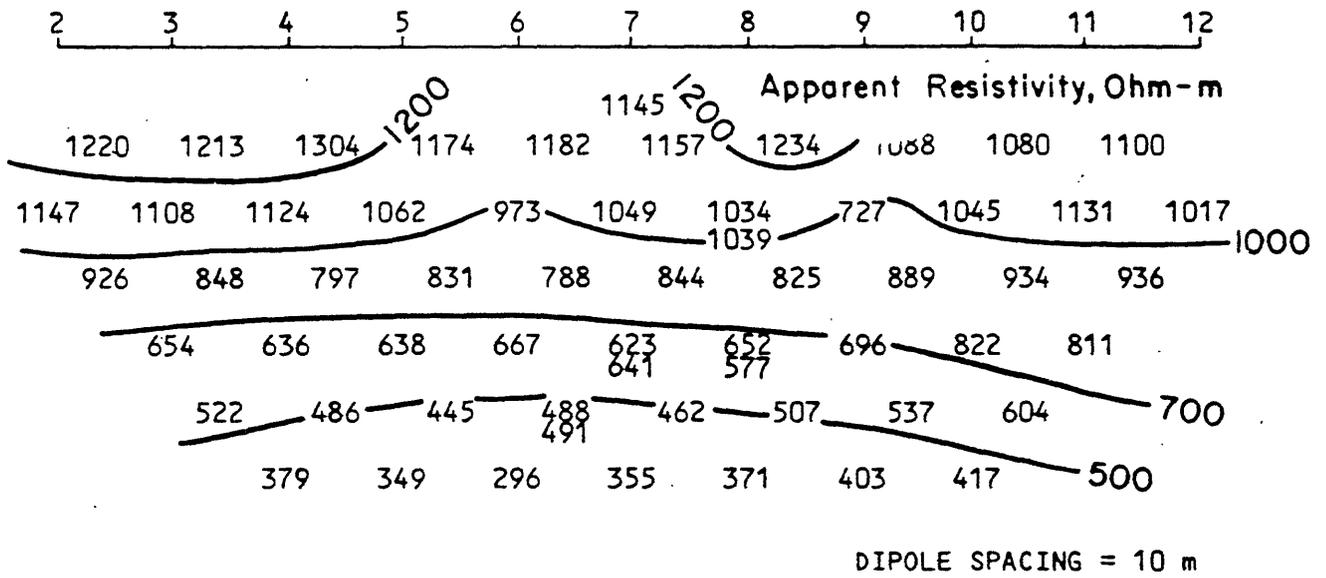


FIGURE 13



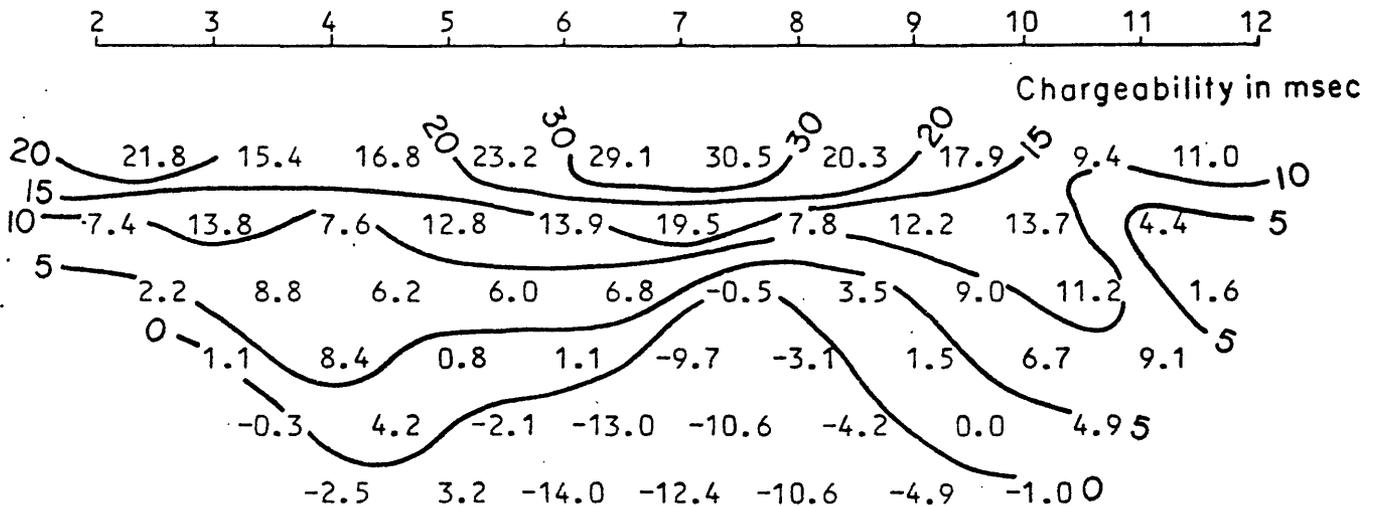
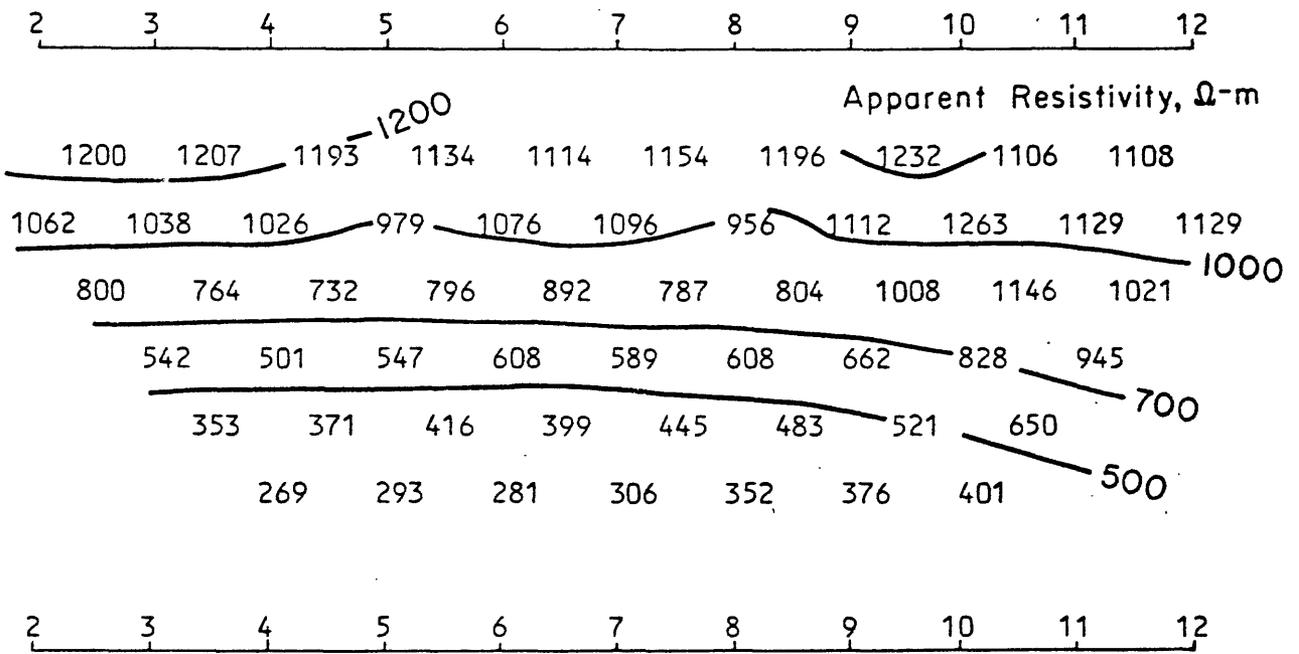
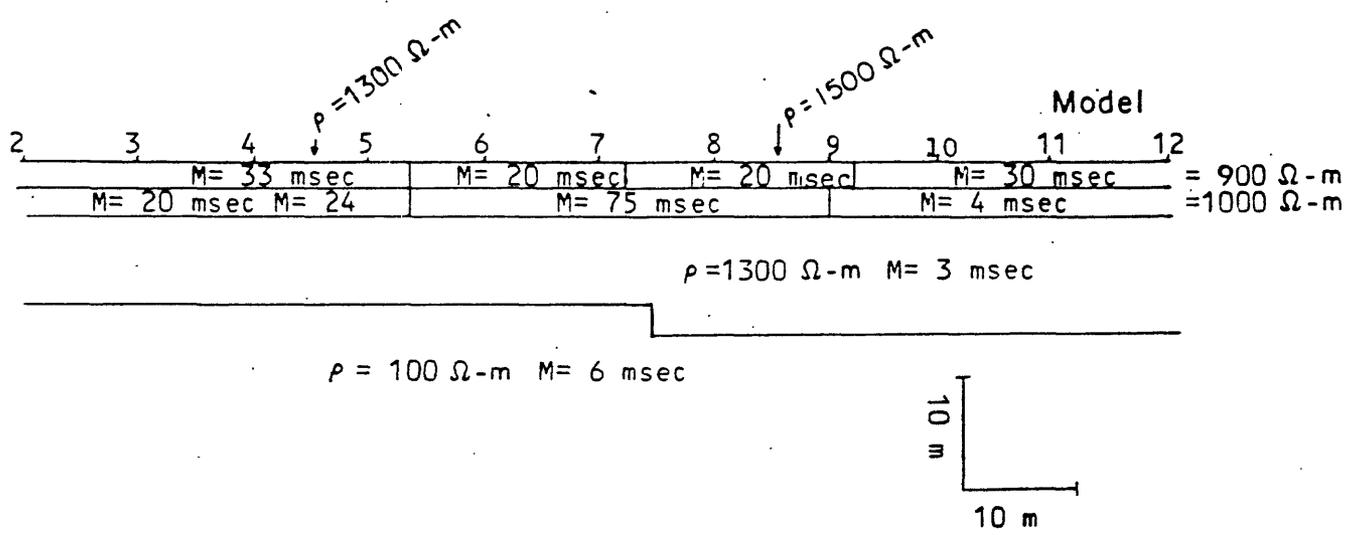


FIGURE 15

DIPOLE SPACING = 10 m

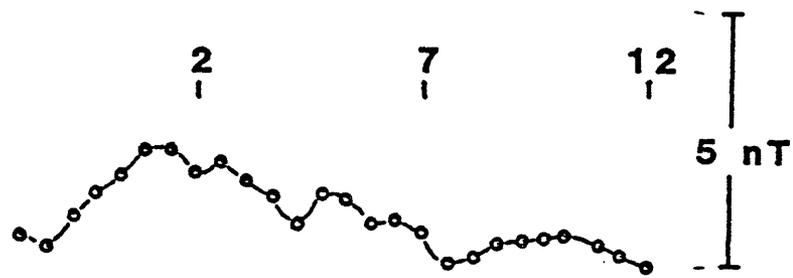
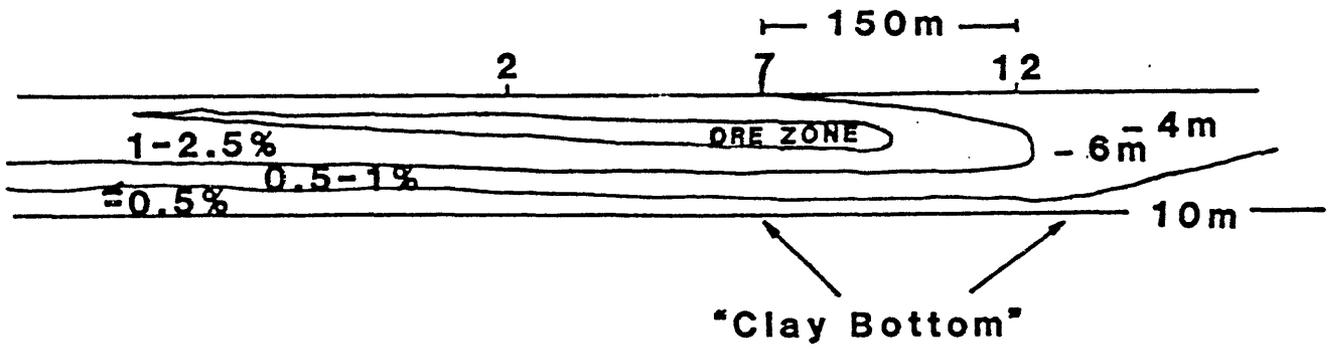


FIGURE 16