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MILITARY HYDROLOGY

Report 6

ASSESSMENT OF TWO CURRENTLY "FIELDABLE" GEOPHYSICAL METHODS FOR MILITARY GROUND-WATER DETECTION

by

Dwain K. Butler and Jose L. Llopis

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October 1984

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Ground-Water Detection Workshop were: (a) there are two currently ^Afieldable' geophysical methods, electrical resistivity and seismic refraction, that are applicable to the ground-water detection problem and may offer a near-term solution to the identified detection technology shortfall, and (b) there are several state-of-the-art and emerging geophysical techniques that may have potential in the far term for application to the ground-water detection problem.

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This report is the result of a study to (a) assess the feasibility of using two currently fieldable geophysical methods for military ground-water detection applications, (b) determine the limitations of the complementary use of the methods for the detection application, and (c) determine the level of expertise required for acquiring, processing, and interpreting the geophysical data if the methodology is feasible and the limitations are acceptable. The report presents the results of geophysical surveys at two sites, White Sands Missile Range, New Mexico, and Fort Carson, Colorado.

Locations surveyed at the two sites presented varied geological complexity and ground-water conditions. Results of the surveys demonstrated success, marginal success, and failure in the ground-water detection application.

Study conclusions can be summarized as follows: complementary seismic refraction and electrical resistivity surveys (a) can generally be used successfully for ground-water detection when the water table occurs in unconsolidated sediments and (b) generally cannot be used successfully for detection of ground water in confined rock aquifers. For the case of rock aquifers, a ground-water exploration program is required. The differences between the exploration and detection applications of geophysics are explained in the report.

The study determined that:

- a. Rugged, reliable seismic refraction and electrical resistivity instrumentation equipment that is commercially available would require very little adaptation for military ground-water detection application.
- **b**. Rugged field microcomputer systems that are commercially available are suitable for processing and aiding in the interpretation of survey data, and interactive, "user-friendly" computer programs are available for survey data interpretation.
- c. Military personnel can be trained to conduct seismic refraction and electrical resistivity surveys; minimum recommended training time is 3 months.
- d. Professional expertise is required for final data interpretation.

Feasible deployment options are also considered in the report.

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PREFACE

This work was performed during the period 1 May 1982 to 30 April 1983 by personnel of the Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES). The effort was sponsored by the US Army Belvoir Research and Development Center (formerly the US Army Mobility Equipment Research and Development Command), Fort Belvoir, Virginia, under Project Order No. A2253, dated 13 April 1982, and by the Office, Chief of Engineers (OCE), US Army, Washington, DC, under Department of the Army Project No. 4A762719AT40, "Mobility, Soils, and Weapons Effects Technology," Task Area CO, "TO Construction," Work Unit 017, "Remote Procedures for Locating Water Supplies."

Dr. Dwain K. Butler, Messrs. José L. Llopis, Donald E. Yule, and Charlie B. Whitten, and 1LT Stephen G. Sanders were responsible for conducting the study, under the general supervision of Dr. Arley G. Franklin, Chief, EEGD, and Dr. William F. Marcuson III, Chief, GL. This report was prepared by Dr. Butler and Mr. Llopis.

The Environmental Laboratory, WES, Dr. John Harrison, Chief, funded publication under the AT40 task as a contribution to the Military Hydrology series. Dr. Clemens A. Meyer was the OCE Technical Monitor.

The overall project was a cooperative effort with the Colorado School of Mines (CSM), Golden, Colorado. Principal investigators for CSM were Mr. Brian Rodriguez and Dr. James Applegate. Information was freely exchanged between WES and CSM during the course of this investigation. Dr. Adel A. R. Zohdy and Mr. Robert J. Bisdorf, US Geological Survey (USGS), Denver, Colorado, served as consultants during the course of this investigation. Appendix A is a letter report prepared by Mr. Bisdorf.

Mr. Robert G. Meyers, USGS, Las Cruces, New Mexico, served as geological consultant during this work and provided valuable assistance during the early phases of site selection and site access. The cooperation and assistance of Messrs. Louis Buescher and John Hyndman, Directorate of Facilities Engineering, White Sands Missile Range, is gratefully acknowledged.

COL Tilford C. Creel, CE, was Commander and Director of WES during the conduct of this study. Mr. F. R. Brown was Technical Director.

This report should be cited as follows:

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
feet per second	0.3048	metres per second
miles (U. S. statute)	1.609347	kilometres
ohm-feet	0.3048	ohm-metres
pounds (mass)	0.4535924	kilograms

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ASSESSMENT OF TWO CURRENTLY "FIELDABLE" GEOPHYSICAL METHODS FOR MILITARY GROUND-WATER DETECTION

PART I: INTRODUCTION

Background

1. Military hydrology is a specialized field of study that deals with the effects of surface and subsurface water on the planning and conduct of military operations. In 1977, the Office, Chief of Engineers, approved a military hydrology research program; management responsibility was subsequently assigned to the Environmental Laboratory, US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

2. The objective of military hydrology research is to develop an improved hydrologic capability for the Armed Forces with emphasis on applications in the tactical environment. To meet this overall objective, research is being conducted in four thrust areas: (a) weather-hydrology interactions; (b) state of the ground; (c) streamflow; and (d) water supply.

3. Previously published Military Hydrology reports are listed on the inside of the front cover. This report is the third that contributes to the water-supply thrust area, which is oriented toward the development of an integrated methodology for rapidly locating and evaluating ground-water supplies, particularly in arid regions. Specific work efforts include: (a) the compilation of guidelines for the expedient location of water for human survival; (b) the development of remote imagery interpretation procedures for detecting and evaluating groundwater sources; (c) the adaptation of suitable geophysical methods for detecting and evaluating ground-water sources; and (d) the development of water-supply analysis and display concepts.

4. A Defense Science Board (DSB) Water Support Task Force concluded that technology shortfalls exist in surface techniques for detection of ground water.* These shortfalls in technology were also

* Classified reference. Bibliographic material for the classified reference will be furnished to qualified agencies upon request.



recognized in a Draft Letter of Agreement (DLOA) for a Subsurface Water Detector (SSWD) (U. S. Army Engineer School 1981), which called for the development of a "black box" water detector. The consensus of those who reviewed the DLOA was that the concept was premature. In recognition of the ground-water detection technology shortfalls and in response to the questions raised by the DLOA, a Ground-Water Detection Workshop was held at Vicksburg, Mississippi, 12-14 January 1982. The workshop was sponsored jointly by WES and the U. S. Army Mobility Equipment Research and Development Command (MERADCOM).*

5. The conclusions of the Geophysics Working Group at the Ground-Water Detection Workshop were: (a) there are two currently "fieldable" geophysical methods, electrical resistivity and seismic refraction, that are applicable to the ground-water detection problem and may offer a near-term solution to the technology shortfall and (b) there are several state-of-the-art and emerging geophysical techniques that may have potential in the far term for application to the ground-water detection problem. The near-term solution, i.e., the use of currently fieldable methods, has the potential of significantly reducing the risk of dry holes during water well drilling operations, but the field operations are somewhat cumbersome and time-consuming for possible deployment in support of forward area operations. Development of one or more of the emerging geophysical techniques offers the possibility of delivering the desired SSWD or at least something closer to it than the near-term methodology.

6. The present investigation was initiated in May 1982 to determine the feasibility of implementing the near-term solution.

Objectives

7. Objectives of this investigation were (a) to assess the feasibility of using two currently fieldable geophysical methods for military

* In October 1983, MERADCOM became the US Army Belvoir Research and Development Center.

ground-water detection applications, (b) to determine the limitations of the complementary use of the methods for the detection application, and (c) to determine the level of expertise required for acquiring, processing, and interpreting the geophysical data if the methodology is feasible and the limitations are acceptable.

Scope

8. The investigation reported here includes the following phases or considerations:

- <u>a</u>. Review of geophysical ground-water detection and exploration concepts.
- b. Evaluation and selection of geophysical equipment.
- c. Selection of two field test sites for demonstration of the geophysical methods for ground-water detection.
- d. Evaluation of data interpretation methods in processing data from the field test sites.
- e. Assessment of the electrical resistivity and seismic refraction methods for military ground-water detection applications and the minimum levels of expertise required for all phases of the operation.

PART II: GEOPHYSICAL GROUND-WATER DETECTION CONCEPTS

Detection Versus Exploration

9. Geophysical methods are used throughout the world in exploration programs for the assessment and development of ground-water resources. The geophysical methods predominantly used in these exploration programs are gravity, electrical resistivity, and seismic refraction methods. Although occasionally only one of these methods will be used in an exploration program, generally at least two are used in a complementary approach. A geophysical ground-water exploration program normally will use all available borehole and other geological data in order to produce the best possible assessment of the ground-water potential and conditions in an area.

10. The primary objective of geophysical ground-water exploration is the mapping of subsurface structural and stratigraphic indicators of the possible occurrence of ground water, such as buried river channels, fracture zones in bedrock, confining layers (aquacludes), etc. Actual detection of the ground-water table with any of the geophysical surveys may be noted but may not be of primary importance in the overall groundwater exploration assessment.

11. Use of the seismic refraction method to delineate a buried channel in an arid region in western Kansas is illustrated in Figure 1.* Identification of material type was made by correlation with exploratory borings near each end of the profile. In this example, the water table was detected by the occurrence of a characteristic seismic velocity (to be discussed later in this part) in the central part of the survey profile. However, even if the ground-water table had not been detected in this example, the stratigraphic indicators would dictate the greatest ground-water potential for a well placed in the center of the subsurface channel.

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.



12. The expression "ground-water detection" as used in this report, in contrast to ground-water exploration, applies to the concept of detecting the presence (or absence) of ground water and the depth to the water table beneath a given "point" on the surface by conducting one or more types of geophysical tests at that point. In the ideal case, the aquifer thickness and water quality would also be determined. For some cases, information regarding ground-water occurrence and other geological factors might be available, but in general, the assessment of the presence of ground water must rely solely on the geophysical results at the given surface location in the detection scenario. In many cases, geophysical ground-water surveys will probably be required to select a site from among those alternate sites already identified by other methods as having good ground-water potential. Of the three geophysical methods most commonly used in ground-water exploration programs, only two (electrical resistivity and seismic refraction) are applicable to the groundwater detection problem; these two methods and applicable detection principles are considered in the following paragraphs.

Detection Principles

13. A thorough discussion of the physical principles involved in the electrical resistivity and seismic refraction methods is beyond the scope of this report. Useful general references for more detailed information on these methods are Engineer Manual 1110-1-1802 (Department of the Army 1979), Griffiths and King (1969), Parasnis (1979), and Telford et al. (1976). References that particularly address applications of geophysics to ground-water exploration and detection are Zohdy, Eaton, and Mabey (1974) and Geological Survey of Canada (1967). Electrical resistivity method

14. The electrical resistivity method most often applicable to the ground-water detection problem is vertical resistivity sounding, where the objective is to make electrical measurements at the surface from which the vertical variation of electrical resistivity with depth can be interpreted. The resistivity of a material is numerically equal

to the resistance of a specimen of the material with unit dimensions and is a fundamental or characteristic geophysical parameter of the material. Although the range of resistivities of geological materials is of the order of 10^{20} ohm-ft, the range commonly encountered in groundwater exploration and detection is 10^5 ohm-ft (0.1 to 10,000 ohm-ft).

15. Most soils and rocks conduct current primarily electrolytically, i.e., through interstitial pore fluid. Thus, porosity, water content, and dissolved electrolytes in the water are the controlling factors in determining resistivity rather than the soil or rock type. A major exception to this generalization are clays, which can conduct current both electrolytically and electronically. The general relation between bulk resistivity ρ_b of a soil or rock and the porosity ϕ (volume fraction), pore fluid saturation S_w (volume fraction of ϕ), and pore fluid resistivity ρ_w can be expressed by the empirical equation

$$\rho_{b} = c \rho_{w} \phi^{-m} S_{w}^{-n}$$
(1)

where c , m , and n are constants that depend on the soil or rock type. Below the water table $S_w = 1$ (100 percent saturation). Qualitatively, Equation 1 indicates: (a) as porosity increases, bulk resistivity decreases; (b) as pore fluid saturation increases, bulk resistivity decreases; and (c) as pore fluid resistivity increases, bulk resistivity increases.

16. The most common and successful use of resistivity sounding is for detecting the freshwater-saltwater interface, which will always be detected by the occurrence of a prominent resistivity decrease. Detection of the water table itself is a more difficult problem. Under favorable conditions, the water table will be detected as the top of a conductive or less resistive layer since, except for unusual conditions, even fresh potable ground water is much lower in resistivity than the dry aquifer material. The most favorable conditions will be when the water table occurs in unconsolidated sediments with little clay content. Dry silts, sands, and gravels will have resistivities of 1000 ohm-ft and greater; for fresh water, the resistivity at the water table will

decrease to a range of 50 to 200 ohm-ft in areas such as the southwestern United States. In sediments with considerable clay content, the resistivity contrast will be much smaller and may be undetectable. At a freshwater-saltwater interface, the resistivity of the aquifer will decrease considerably, perhaps to $\tilde{<}1$ ohm-ft. Zohdy et al. (1969) and Zohdy, Eaton, and Mabey (1974) adopt a qualitative criterion of $\rho_b \sim$ 30 ohm-ft to differentiate freshwater from saline ground-water conditions in a large ground-water assessment program at White Sands, New Mexico. Clays can have resistivities intermediate to the resistivities of highly saline and fresh aquifer conditions.

Seismic refraction method

17. The seismic method applicable to the ground-water detection problem (in the near term) is the refraction method. From a seismic refraction survey at a given location, it is possible in principle to determine depths to interfaces between materials with contrasting bulk density and seismic velocity and to determine the seismic velocities of the different materials. Generally, only compression- or P-wave velocities are easily determined from seismic refraction surveys.

18. The physical principle involved in detection of the water table by seismic methods is that the compression-wave velocity of saturated sediments is considerably greater than the same sediments in dry or only partially saturated conditions. Typically, the compression-wave velocity will increase from 1000-2000 ft/sec to 4500-5500 ft/sec at the water table, where the water table occurs at shallow depths (\leq 100 ft) in unconsolidated sediments (silts, sands, and gravels). The occurrence of a characteristic 5000 ft/sec-velocity at shallow depths at a site generally is strongly indicative of a ground-water table, although some weathered rocks and massive clay deposits also exhibit this velocity.

19. If the water table occurs at greater depths (>100 ft, for example), the seismic velocity of the saturated sediments can be as high as 7500 ft/sec; in these cases, the velocity of the unsaturated sediments just above the water table can be as high as 4000 ft/sec. The smallest velocity contrast at the water table will occur in very finegrained sediments, where the velocity contrast can be as small as

500 ft/sec. When the water table occurs as an unconfined surface in rock, there will always be a velocity increase at the water table, although it may be small. Where the ground water occurs in a confined rock aquifer, there will be little in the seismic data to suggest the presence of ground water without independent or complementary information. Whether the water table in an unconfined aquifer is detected depends on the thickness of the saturated zone above high-velocity rock. In some cases, where the contrast in seismic velocity between rock and saturated sediments is large and the saturated zone is thin relative to its depth, the water table refraction will not be detected in an "ordinary" seismic refraction interpretation due to a blind zone problem (see Redpath 1973 and Zohdy, Eaton, and Mabey 1974).

Complementary methods

20. The resistivity and refraction methods are complementary in the sense that they respond to or detect different physical properties of geologic materials. Both methods can detect the water table, and hence, the presence of ground water under certain conditions. In cases where both methods detect the water table, one method serves to confirm the results of the other or to resolve ambiguities. Also, certain conditions, such as the presence of a freshwater-saltwater interface, can be detected by one method but not the other. The conclusions portion of this report presents examples from the field demonstration tests of cases in which the complementary method approach probably would be successful, possibly would be successful, or would not be successful.

21. Generally, when depths to interfaces determined by geophysical methods are compared to "ground truth" data from nearby boreholes, the agreement is within ±10 percent for the seismic refraction and ±20 percent for the electrical resistivity method. Of course, the difference between the actual interface depth and geophysical interface depth can occasionally be greater due to the effects of blind zones and velocity inversions (departures from the normally assumed case where seismic velocity increases with depth) in seismic refraction interpretation and highly equivalent layers in electrical resistivity interpretation (Department of the Army 1979; Telford et al. 1976; Zohdy, Eaton, and Mabey

1974). The problem of geophysical determination of the water table depth is complicated by the physical nature of the "interface." The geophysical interface often may be within the capillary zone. The velocity and resistivity interfaces may be different, and neither may agree with the standing water depth in a borehole (and the standing water depth itself may be different from the actual water table). The difference in geophysical and borehole water table depth determinations should be greatest in fine-grained sediments and least in coarse-grained sediments.

فتستخدد

PART III: FIELD PROCEDURES AND EQUIPMENT SELECTION

Electrical Resistivity Method

Field procedures

22. The surface electrical resistivity methods considered in this study involve linear four-electrode geometries (arrays). Two of the most common electrode arrays are illustrated in Figure 2. In each of the



WENNER ELECTRODE ARRAY



SCHLUMBERGER ELECTRODE ARRAY



arrays, an electrical current I is input to the ground at electrodes C_1 and C_2 . Electrodes P_1 and P_2 are used to measure a potential difference ΔV . The following equation can be used to calculate an apparent resistivity ρ_A :

$$\rho_{\mathbf{A}} = \mathbf{K}_{\mathbf{G}} \left(\frac{\Delta \mathbf{V}}{\mathbf{I}} \right) \tag{2}$$

where K_{G} is a geometric factor that depends on the array type and electrode spacings within the array. For the Wenner array, $K_{G} = 2\pi a$; for the Schlumberger array $K_{G} = \pi s \left[(L/s)^{2} - 1/4 \right]$, where $L = \overline{C_{1}C_{2}}/2$ and $s = \overline{P_{1}P_{2}}$ (generally L > 5s).

23. The resistivity given by Equation 2 is called an apparent resistivity since it may not actually be the true resistivity of any of the subsurface materials. This fact can be illustrated by a conceptual example: consider a layer of soil over rock that is very thick. If a

Schlumberger or Wenner electrode array is used to study the example just presented, the following facts can be stated: (a) for electrode spacings a or L much smaller than the soil layer thickness, the measured apparent resistivity (ρ_A) approaches the true resistivity of the soil (ρ_1); (b) for electrode spacings a or L much greater than the soil layer thickness, the apparent resistivity approaches the true resistivity of the rock (ρ_2); and (c) for a or L values between these two extremes, the apparent resistivity will be intermediate in value (i.e., the measured apparent resistivity will be some type of volume average of ρ_1 and ρ_2 , with the volume included in the measurements increasing with a and L).

24. In vertical resistivity sounding, the electrode array is expanded symmetrically about a center point, and variations in apparent resistivity as the electrode spacing increases are assumed to reflect changes in true resistivity as a function of depth beneath the surface point of symmetry of the array. The objective in vertical sounding interpretation is to determine the variation in true resistivity versus depth from the apparent resistivity versus electrode spacing data. The result will generally be a layered model consisting of layer thickness and associated true resistivities. Interpretation is usually accomplished by curve matching (i.e., matching field data curves with standard curves) or by the use of a resistivity inversion computer program. Useful discussions of resistivity theory, field methods, interpretation procedures, and case histories can be found in Telford et al. (1976), Department of the Army (1979), and Zohdy, Eaton, and Mabey (1974).

25. For the Wenner array, all four electrodes must be moved for each measurement; for the Schlumberger array, only the two current electrodes are moved for each measurement (except as described below). Thus, there are advantages in terms of field effort in using the Schlumberger array. The resistivity soundings presented in this report were accomplished using the Schlumberger array. Generally, a minimum of six measurements per decade of electrode spacing (L ranging from 10 to 100 ft, for example) are required. If the minimum number is used, the measurements should be made at electrode spacings that are approximately

equally spaced on a logarithmic scale (e.g., 10, 14, 20, 30, 50, 70, 100, 140, etc.). During the course of conducting a Schlumberger sounding, the potential difference between P_1 and P_2 may become too small to measure with the resistivity instrument, and the spacing P_1P_2 must be increased before continuing. As a rule of thumb, the sounding should be carried out to an L-spacing equal to at least four times the desired depth of investigation.

26. Field measurements, which may be ΔV and I individually or the ratio $\Delta V/I$, are converted to apparent resistivities ρ_A using Equation 2. The ρ_A are then plotted versus L on log graph paper. The data are then ready for interpretation. Equipment

27. The equipment required for the resistivity method consists of (a) a power supply, (b) instruments for measuring current and potential difference, (c) four stainless steel electrodes, (d) cable reels and cable, (e) nonconducting tapes for distance measurements (or other method for determining distances such as precision odometers), and (f) two-way portable communications equipment (up to 1-mile range). For the present investigation, cable reels equipped with cable sufficient for a maximum L-spacing of 2000 ft were used. Figure 3 shows the resistivity instrument



Figure 3. Resistivity instrument selected for fieldwork

selected for the fieldwork. The instrument is a microprocessor-controlled signal-averaging system capable of depths of investigation of 1000 ft or greater under most field conditions. A system of "beeps" and error codes communicates with the operator, making the instrument very easy to use with minimal training. Power for the instrument is supplied by rechargeable 12-V batteries, and the entire system (including all accessory equipment) is easily portable in a single "jeep-size" vehicle. Total equipment weight for the resistivity field system in about 110 lb. Personnel requirements

28. A minimum of three field personnel are required for conducting a Schlumberger resistivity sounding. Nonprofessional personnel can be trained to conduct the field surveys. A minimum training period of 6 weeks in field procedures, equipment operation, data processing, elementary geological principles, and elementary resistivity surveying principles is recommended.

Seismic Refraction Method

Field procedures

29. The seismic refraction method involves the generation, propagation, and detection of seismic waves. Seismic waves are generated in two ways in surveys for ground-water detection applications: impact sources (e.g., weight drop or hammer blow) and explosive sources (e.g., dynamite, exploding bridge-wire detonators, and air guns*). Detection of the seismic waves is generally by velocity transducers called geophones, which are connected to a seismograph that amplifies and displays the geophone output. The objective of the seismic methods is to deduce properties of the media through which the seismic waves pass from properties of the detected wave forms (primarily the arrival times of various events or types of waves at the geophones).

30. The seismic refraction method is a survey technique in which the source locations and geophones are along a common line. Figure 4 illustrates the concept of the seismic refraction method, where the

* Air guns generate seismic waves by a sudden release of compressed gas.





Figure 4. The seismic refraction method, illustrated by a simple two-layer case with plane, parallel boundaries, and the corresponding time-distance plot (after Redpath 1973)

time-distance plot represents the arrival times of the first event at each geophone location. The first event at a given geophone will be due to a wave that propagates directly from the source or to a wave that is refracted along an interface with a higher velocity material. The arrival time-distance data generally will define a straight line segment for each subsurface layer. The first-arrival time-distance plot can be interpreted to give the velocities of subsurface soil/rock layers and depths to interfaces. Figure 4 illustrates the analysis for the simple case of two horizontal layers (Department of the Army 1979).

31. For the case of three horizontal layers, the analysis of the time-distance plot to yield lager velocities and interface depths is

still tractable by manual methods. Also, the case of two layers where the interface dips relative to the surface can be similarly analyzed using manual methods (Department of the Army 1979, Telford et al. 1976). However, for the cases of greater than three horizontal layers and greater than one dipping interface, a programmable calculator or a microcomputer is desirable for the interpretation. The presence of dipping layers is indicated by an examination of the time-distance plots from forward and reverse "shooting" along a seismic survey line, i.e., from data obtained by using a source at each end of the geophone line. Figure 5 illustrates the appearance of the time-distance plot for a twolayer case with dipping interface, where the apparent velocity of the second layer is always greater when "shooting" in the up-dip direction. 32. In the past, seismic refraction data processing has involved



Distance



Figure 5. Example of dipping interface and concepts of "reverse shooting" and "apparent velocity" (after Redpath 1973)

manual "picking" of first-arrival events and scaling arrival times from analog records. The time-distance data were then manually plotted, and straight-line segments were fit to the data if possible. Velocities were calculated as the inverse of the slopes of the line segments. Interface depths and dips were then determined manually. This procedure is still common, particularly when refraction survey data are processed and interpreted in the field. However, the availability of digital seismographs (such as the one shown in Figure 6) and powerful microcomputers (such as the one shown in Figure 7) now makes it possible to automate much of the seismic data-processing and interpretation procedure and to accomplish it expeditiously in the field.



Figure 6. Digital seismograph selected for fieldwork

Equipment

33. The equipment required for the seismic refraction method consists of (a) a multichannel seismograph, (b) seismic sources, (c) geophones, and (d) seismic cables. For the present investigation, two 12channel seismographs such as the one pictured in Figure 6 were coupled together, although 24-channel seismographs are available with similar features. The seismograph displays output from all 12 (or 24) channels



Figure 7. Completely self-contained field microcomputer

on a CRT display and a built-in printer can produce a hard copy. Also, the seismograph stores the data in digital form and can record the data on a companion cassette recorder.

34. For depths of investigation of approximately 50 ft or less, a sledgehammer blow can be used as a seismic source; for greater depths of interest, an explosive source is required (1- to 3-1b TNT-equivalent is sufficient for depths of investigation to approximately 600 ft).

35. Geophones are readily available in several acceptable types. Typically, 30 geophones are required (24 for each test plus 6 spares). Seismic cables are multiconductor, with geophone takeouts at constantspacing intervals along its length. The commonly available geophone takeout intervals of cable for seismic refraction work are 10, 25, 50, and 100 ft. Typically, two 12-takeout seismic cables are utilized to form a 24-geophone refraction spread, and one or more spreads are used for each seismic survey line, with the required length of the seismic line determined by the desired depth of investigation (the seismic refraction line length should be at least four times the desired depth of investigation). The total weight of the equipment required for seismic refraction surveying is about 350 lb and the equipment is easily transportable in a jeep-size vehicle.

Personnel requirements

36. Three field personnel are required for conducting seismic refraction surveys. Nonprofessional personnel can be trained to conduct the field surveys. A minimum training period of 6 weeks in field procedures, equipment operation, elementary seismic surveying principles, seismic event recognition, data quality assessment, data processing, and elementary geological principles is recommended.

Data Processing and Interpretation

Techniques and computer programs

37. Some aspects of the data-processing and interpretation requirements for seismic refraction and electrical resistivity survey data have been discussed in the preceding paragraphs. A detailed discussion of the techniques involved in data processing and interpretation is beyond the scope of this report, although the concepts are illustrated in Part IV with the data acquired in the present study. Butler et al. (1982) discuss in detail the data-processing and interpretation techniques used in this study. The seismic refraction data were processed on a WES inhouse microcomputer facility, while the resistivity data were processed in an interactive time-sharing mode on the WES mainframe computer. The seismic refraction computer programs are in BASIC language and can be easily converted to run on the field microcomputer discussed in paragraph 39. The resistivity interpretation computer programs are in FORTRAN language and would require more effort to convert to BASIC language for use on a field microcomputer.

38. Two additional resistivity computer programs, both in BASIC language, were evaluated in the present study. Selected resistivity sounding data from the field study were interpreted using a U. S. Geological Survey (USGS) computer program on a USGS in-house microcomputer (Zohdy 1975, Bisdorf 1983*). The second additional resistivity interpretation program (ABEM program) is written especially for the field

* The letter report by Bisdorf (1983) is included as Appendix A to this report.

microcomputer discussed in paragraph 39 (Atlas Copco 1980). The ABEM program is very similar in concept and operation to the WES interpretation program; the USGS program is different in that it does not require the input of an initial (first approximation) model* for the subsurface. <u>Computer requirements</u>

39. Figure 7 shows a microcomputer suitable for field use for processing resistivity and refraction data. The field microcomputer is completely self-contained with integrated CRT display, printer, and data cassette reader/recorder. Generally, a microcomputer with 32K bytes RAM (random-access memory) or greater is required; an integral or peripheral disk drive for long-term mass data storage is desirable but is not essential.

Personnel requirements

40. Nonprofessional personnel can be trained to process electrical resistivity and seismic refraction data using existing, userfriendly computer programs. Minimum recommended training time is 2 weeks, which is included in the 6-week training periods estimated for both the seismic refraction and electrical resistivity methods. Generally, however, individuals processing the data have ready access to professional geophysicists or more experienced processors who can assist with difficult or nonroutine data sets; examples of difficult data sets are the resistivity data from test site locations HTA-1 and B-30, which are discussed in Part V. The results of the data processing and interpretation are geophysical models (see Part V).

* The term "model" as used in this report refers to a representation of the subsurface in terms of layers described by geophysical parameters: thickness, resistivity, seismic velocity. This geophysical model is deduced by interpretation of field survey data.

PART IV: FIELD STUDIES

Selection of Field Sites

41. Two field sites were selected as representative of two common aquifers: an unconfined alluvial aquifer and a confined (artesian) rock aquifer. White Sands Missile Range, New Mexico, was selected as the alluvial aquifer site, and Fort Carson, Colorado, as the confined rock aquifer site.

42. Five locations (MAR, B-30, HTA-1, SW-19, and T-14) were selected at the White Sands site, as shown in Figure 8. Each location is near a water supply well, test well, or borehole, so that water table depths are known and some boring log information is available. The five locations have water table depths ranging from approximately 60 to 450 ft and water resistivity varying from fresh (\geq 85 ohm-ft) to brackish (\leq 1 ohm-ft) (Cruz 1981). Plate 1 is a general site map showing topographic features and the five survey areas.

43. The shallowest depth to water at the five locations occurs at HTA-1, where a thin layer of sediments covers a weathered granite rock surface in the northwestern part of the Headquarters area reentrant. At the other four locations, which are in the Tularoosa Basin, the depth to rock is much greater. Stratigraphic test well T-14 was drilled to a depth of 6000 ft without penetrating rock. Bolson (valley fill) sediments at the MAR, B-30, and T-14 locations consist of clay, silt, sand, and gravel, with the amount of fine sediments decreasing toward the west side of the Tularoosa Basin until, in the vicinity of supply wells SW-19 and SW-20, the material is predominantly sand and gravel. Boring log information and other available data are summarized in Part V.

44. One location near White Butte at the Fort Carson, Colorado, site was selected (see Figure 9). A well at this location produces good quality water from the Dakota Sandstone (Lower Cretaceous) aquifer; depth to the top of the aquifer is approximately 270 ft and the thickness is approximately 100 ft (see Part V, Figure 36, for boring log information). The aquifer is confined on both top and bottom by shale layers. The







Dakota Sandstone outcrops approximately 0.7 mile to the west of the White Butte location and has a regional dip to the east of about 330 ft/ mile. Plate 2 shows the geologic structure and stratigraphy of the Fort Carson area (Dardeau and Zappi 1977). Due to the rugged topography and complex near-surface geology at the well site, geophysical surveys were conducted about 0.5 mile to the west and about 0.5 mile to the

south, in addition to near the well site itself. Surveys were conducted parallel to the strike of the Dakota Sandstone (north-south) and perpendicular to the strike (i.e., east-west or parallel to the dip), as shown in Figure 9.

Geophysical Field Programs

45. Fieldwork at the two sites was conducted by WES and the Colorado School of Mines (CSM). In addition, resistivity data from recent fieldwork conducted by the USGS at one of the White Sands locations was provided for use in this study. Details of the field programs at the two sites are summarized in the following paragraphs.

White Sands geophysical program

46. Table 1 summarizes the geophysical surveys performed at the White Sands site. Location numbers correspond to the well or borehole designations, as shown in Figure 8. For the seismic refraction surveys, the survey line length refers to the total shotpoint-geophone spread length; for the resistivity surveys, the survey line length refers to the maximum electrode spacing (L-spacing shown in Figure 2) for the sounding.

Location	Survey Type	Performing Agency	Survey Line Length, ft	Comments
HTA-1	Refraction	WES	240	
		CSM	330	
	Resistivity	WES	600	
B-30	Refraction	WES	360	
	Resistivity	WES	800	Both Schlumberger and Wenner electrode arrays used at this location
T-14	Refraction	WES	540	
		CSM	600	Perpendicular to WES refraction and resis- tivity lines
		(Co	ntinued)	•

White Sands, N. Mex., Geophysical Program

Table 1

Table 1 (Concluded)

Location	Survey Type	Performing Agency	Survey Line Length, ft	Comments
	Resistivity	WES	1000	
MAR	Refraction	CSM	825	
	Resistivity	USGS	4000	USGS sounding location does not coincide with CSM survey location
SW-19	Refraction	WES CSM	1800 1650	
	Resistivity	WES	1800	Approximately perpen- dicular to WES and CSM refraction lines and centered about 500 ft west of Well 19

Fort Carson geophysical program

47. At Fort Carson, the resistivity surveys were conducted by WES, and the refraction surveys were conducted by CSM. The resistivity and refraction surveys were not conducted in identical locations or orientations, as shown in Figure 9. Table 2 summarizes the surveys conducted at Fort Carson.

Table 2

Fort Carson, Colo., Geophysical Program

Survey Type	Performing Agency	Survey No.	Survey Line Length, ft	Comments
Refraction	CSM	1	1650	Significant topographic variation along line
		2	825	At same location as WES-4
		3	1100	Approximately perpen- dicular to WES-3
Resistivity	WES	1	1000	WES-1 and WES-2 are per- pendicular, crossing at midpoints
		2	900	-
		3	1000	
		4	1000	
		5	700	Line length limited by topography

Geophysical Survey Results

48. Seismic refraction data were processed using a computer graphics tablet to pick first-arrival events from the analog records at each geophone location. Arrival time-distance plots for each survey were automatically produced by a microcomputer-plotter system, straight-line segments were fit manually to the data, and then seismic velocities and interface depths were determined using techniques and computer programs described by Butler et al. (1982). Electrical resistivity field data were converted to apparent resistivity using Equation 1 and $K_{\rm G}$ for the Schlumberger array and sounding curves prepared for each survey ($\rho_{\rm A}$ versus L-spacing). The resistivity sounding curves were smoothed and corrected for lateral effects, and interpreted using the techniques described by Butler et al. (1982).

49. Figures 10-19 are the results of the seismic refraction and electrical resistivity surveys at the five locations at the White Sands, New Mexico, site. Results of surveys at the Fort Carson, Colorado, site are shown in Figures 20-27. Seismic velocities are shown by each line segment (inverse slope of the line segment) in the seismic refraction time-distance plots. The refraction plots also contain the calculated interface depths, indicated at the intersection points of two line segments. Except for the field data and smoothed, corrected sounding curves, no additional information is shown on the electrical resistivity plots. Interpretation of these data is discussed in Part V.










Figure 15. Electrical resistivity data, T-14, White Sands











e

Figure 18. Seismic refraction results, SW-19, White Sands











Figure 25. Seismic refraction data, CSM-1, Fort Carson



Figure 26. Seismic refraction data, CSM-2, Fort Carson



Figure 27. Seismic refraction data, CSM-3, Fort Carson

PART V: GEOPHYSICAL INTERPRETATION AND GEOLOGICAL CORRELATION

Geophysical Interpretation

50. For the ground-water detection application of geophysics for military use, the assessment of the presence of ground water must rely primarily on the geophysical test results at a given surface location (i.e., geological information is assumed to be either unavailable or, if available, there is no one capable of interpreting it and integrating it into the ground-water assessment) (see Part II). Thus, the interpretations developed in this section are determined directly from the survey data using standard procedures. This type of interpretation can proceed without any prior knowledge of subsurface conditions, although judgment based on experience is desirable. All of the interpreters were geoscience professionals,* all had cursory knowledge of the geologic conditions prior to the field surveys and the interpretation, but all were careful not to make use of the prior knowledge in the standard interpretation procedure. In the geophysical ground-water assessments that follow, a qualitative rating using the terms "poor," "fair," or "good" is given indicating the confidence in the assessment for the site.

51. Results of interpretation of the seismic refraction timedistance plots were introduced in Part IV. As an example of the procedures by which the electrical resistivity survey data are interpreted, the resistivity sounding at SW-19 at the White Sands site is examined. Based on the sounding curve characteristics (Figure 19), a "first guess" or trial model of the subsurface is deduced. The minimum number of layers in the trial model is indicated by the number of relative maxima and minima in the sounding curve, but well-defined changes in slope of the curve may suggest a model with more than the minimum number of layers.

^{*} Two of the interpreters have degrees in geophysics and one has a degree in geology. The interpreters have practical experience in geophysical data processing and interpretation ranging from 1 year to more than 10 years.

52. The trial model is input, along with the field sounding data, to a resistivity interpretation computer program. The program adjusts the parameters of the trial model until a model sounding curve is produced which closely matches the field sounding curve. Interpretation of the sounding at SW-19 using the trial model, final model, and field sounding curves is illustrated in Figure 28. The final model curve fits the field curve within experimental accuracy. The initial and final resistivity models are compared in Figure 29.



Figure 28. Example of resistivity interpretation procedure, SW-19, White Sands

Geophysical interpretation of White Sands survey data

53. <u>HTA-1</u>. Refraction and electrical resistivity data for the geophysical surveys at HTA-1 are shown in Figures 10 and 11, respectively. The refraction data indicate three subsurface layers. The resistivity data, however, are somewhat ambiguous. The sounding curve, Figure 11, indicates a minimum of three layers but suggests as many as five layers. Thus, the resistivity data were interpreted in terms of

Initial Model	Final Model
$P_{1} = 1500 \text{ ohm-ft}$ $h_{1} = 5 \text{ ft}$	
$P_2 = 400$ h ₂ = 50	$P_2 = 534$ $h_2 = 45.2$
P ₃ = 800 h ₃ = 200	$P_3 = 643$ h ₃ = 350.2
₽4 = 100	P ₄ = 167

NOTE: $\boldsymbol{\rho}_i$ and h_i are the resistivity and thickness, respectively, of the ith layer of the model.

Figure 29. Comparison of the initial and final models for the resistivity interpretation, SW-19 (see Figure 28)

three-, four-, and five-layer models. The three resistivity models and the refraction model are compared in Figure 30, along with the interpreted results of the CSM refraction line.

54. The four- and five-layer resistivity models in Figure 30 for HTA-1 agree closely in the top three resistivities and first two interface depths. Also, the WES and CSM seismic refraction models agree closely, although the somewhat longer CSM refraction line detects a third interface at an interpreted depth of 105 ft. The first interface depth in both the resistivity and refraction models agrees, and the third interface location in the five-layer resistivity model and the CSM refraction model agrees. However, the second interface in the refraction models is considerably shallower than the second interface in the resistivity models.

55. Based on the complementary geophysical models in Figure 30 and the detection concepts of Part II, the following ground-water assessment is made for location HTA-1:



Figure 30. Geophysical models, HTA-1, White Sands

- a. If ground water is present in usable quantities, it will be shallower than 105 ft, since the material below this depth has a seismic velocity characteristic of dense, low-porosity rock.
- b. There are indications of a possible water table at the approximate 8-ft depth, due to lower resistivity (305 ohm-ft) and a seismic velocity (4250 ft/sec) close to the characteristic 5000 ft/sec velocity below the first interface.
- c. If ground water is present at a depth of 8 ft, it must be fresh since the bulk resistivity is high for an aquifer.
- d. Since the seismic velocity is somewhat low and the resistivity is high, the qualitative rating of the ground-water assessment is "poor."

56. <u>B-30.</u> Refraction and resistivity data for the geophysical surveys at this location are shown in Figures 12 and 13, respectively. The seismic refraction results indicate a three-layer model, and the material below the interface at 65-ft depth has a seismic velocity of 5300 ft/sec, very close to the characteristic 5000 ft/sec velocity of shallow saturated sediments. Qualitatively, the resistivity sounding

curve indicates apparently a five-layer model, with the lowest layer detected having an extremely low resistivity (conductive basement for the survey). Generally, such a conductive basement indicates a thick zone of very saline ground water or a thick, conductive, clay layer. Quantitatively, it is difficult to fit a model to the sounding curve (see also comments in Appendix A). Also, the final resistivity sounding curve is sensitive to the choice of trial models. The resistivity model shown in Figure 31, with the refraction model, is an "average" model based on eight final models (including some deduced from the Wenner sounding); the vertical bars on the interface depths indicate the range of depths predicted by all the models. The depth range is ±20 percent of the average model depths in all cases.



Figure 31. Geophysical models, B-30, White Sands

57. Based on the complementary geophysical models shown in Figure 31, the following groundwater assessment is made for location B-30:

- <u>a</u>. There is a possible ground-water table at 65-ft depth, as indicated by the characteristic seismic velocity below this depth.
- **b**. The ground water becomes very saline at 125-ft (+25 ft) depth.
- <u>c</u>. Qualitative rating of this ground-water assessment is "good."

270H

58. <u>T-14.</u> Refraction and resistivity data for the geophysical surveys at location T-14 are shown in Figures 14 and 15, respectively. The refraction data indicate a three-layer model. A large velocity increase occurs at a depth of 95 ft (from 1725 to 6550 ft/sec); this type of velocity increase is characteristic of the increase that occurs at a water table, although the 6550 ft/sec velocity for the material below 95 ft is larger than normally anticipated for this depth. Interpretation of the resistivity data is complicated by the apparent occurrence of a thin, very low-resistivity layer at a depth of ~16 ft. Known as a highly equivalent layer, this very low-resistivity layer makes it difficult to interpret depths to interfaces below it. Figure 32 presents resistivity and refraction models for T-14.

59. Based on the complementary geophysical models in Figure 32, the following ground-water assessment is made for location T-14:

- a. There is a possible ground-water table at 95-ft depth, as indicated by a large seismic velocity contrast at an interface at that depth.
- b. Below a depth of ~150 ft, the ground water becomes saline.
- c. Qualitative rating of this ground-water assessment is "fair."

60. MAR. Refraction and resistivity data for the geophysical surveys at location MAR are shown in Figures 16 and 17, respectively. The resistivity sounding location was about 0.5 mile east of the refraction survey location, so resistivity and refraction models cannot be compared directly. Figure 33 presents the refraction model and the resistivity model for the displaced resistivity sounding location. Using the resistivity data shown in Figure 17 as well as data from a sounding 0.5 mile west of the refraction location, the resistivity interface at 245 ft in Figure 33 projects to a depth of ~300 ft beneath the refraction



survey location. The large velocity contrast at 160-ft depth (increase from 3110 to 7500 ft/sec) is characteristic of the occurrence of a water table, although a velocity of 7500 ft/sec could also be indicative of a poorly cemented or weathered rock. There is, however, no indication of a major resistivity change at this depth.

61. Based on the geophysical models in Figure 33, the following ground-water assessment is made for location MAR:

- a. If ground water is present in usable quantities, it will be shallower than ~1000 ft, since the resistivity interpretation indicates a resistive basement at that depth, i.e., a dense, low-porosity rock (not shown in Figure 33).
- <u>b</u>. The seismic data indicate a possible water table at 160-ft depth.
- c. Groundwater between ~300 ft and the resistance basement is very saline, or a very thick clay layer exists.
- d. Qualitative rating of this ground-water assessment and the ground-water potential is "fair."

62. <u>SW-19.</u> Refraction and resistivity data for the geophysical surveys at SW-19 are shown in Figures 18 and 19; the interpretation procedure for the resistivity data is illustrated in Figures 28 and 29. Both the refraction and resistivity data indicate a four-layer model, as shown in Figure 34 (a model based on the CSM data for this location is also shown).

63. The geophysical data for this location are straightforward to interpret and follow a familiar pattern for sites where a water table occurs in coarse-grained sediments. A geological interpretation of the geophysical models is also shown in Figure 34. The following groundwater assessment for SW-19 can be made:

- a. A ground-water table occurs at a depth of 400 ft.
- b. Based on the interpreted resistivity beneath 400 ft, the ground water is fresh.
- <u>c</u>. Qualitative rating of this groundwater assessment is "very good."

Geophysical interpretation of Fort Carson survey data

a.

64. Geological and topographical complexities at the Fort Carson site combined to make a straightforward geophysical interpretation of



Figure 34. Geophysical models and interpretation, SW-19, White Sands

all the data impossible (see also comments in Appendix A). Also, except for WES-4 and CSM-2, the refraction and resistivity surveys were not conducted at the same locations. Thus, the geophysical interpretation will concentrate on WES-4 and CSM-2.

65. Figure 35 presents geophysical models for WES-4 and CSM-2 (same location). Interfaces at depths of approximately 35 and 100 ft are predicted in both models. Based on the geophysical models in Figure 35, the following ground-water assessment can be made:

- a. There is a possible water table at a depth of ~35 ft, indicated by a velocity increase from 2600 to 6050 ft/sec, although this could be an interface between soil and rock since the resistivity increases at this depth.
- <u>b</u>. If there is ground water present below 35 ft, it becomes somewhat brackish at ~60 ft, since there is a significant resistivity decrease at that depth.
- c. There is somewhat less ground-water potential below 100 ft, since the velocity and resistivity indicate a lower porosity rock below that depth.
- d. Qualitative rating of this ground-water assessment is "poor."



Figure 35. Geophysical models, Fort Carson

Conceivably, the procedures used to make the preceding ground-water assessments can be cast in the form of a flowchart and computer algorithm for use by nonprofessionals.

<u>Geological Correlation and Constraint</u> of Geophysical Interpretations

66. The preceding discussion and ground-water assessments have not involved any considerations of specifics of the sites* or existing knowledge of geological and ground-water conditions at the sites. Generally, all available knowledge about a site is used to constrain or guide the geophysical interpretation. In an effort to evaluate the effectiveness of the preceding ground-water assessments made under the detection application constraint, all available ground-water and other geologic information will now be compared to the geophysical models interpreted from the survey data. The extent of information available at each location varies considerably. Available information could include such elements as (a) water table depth at nearby borehole only, (b) regional geologic information plus specific information at a borehole, which must be extrapolated to actual survey location, (c) water table depth plus general information on material type at nearby borehole, or (d) detailed borehole log information at the survey location.

Geological verification of White Sands geophysical ground-water assessments

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67. Results of the five geophysical ground-water assessments made for the White Sands locations are summarized in Table 3. The available ground-water and geologic information for the five locations is summarized in Table 4. Comparison of Tables 3 and 4 indicates general qualitative agreement between the geophysical ground-water assessments and known ground-water data for all of the locations except HTA-1. The predicted water table depths are consistently too shallow, however, compared to the borehold water depth measurements, by amounts ranging from

^{*} An exception to this is the Fort Carson site, where topographic variations and lateral complexities of the geology apparently make a straightforward interpretation of some of the geophysical data impossible.

Location	Predicted Water Table Depth, ft	Water Quality Statement	Predicted Aquifer Thickness	Confidence in Ground-Water Assessment
HTA-1	8	Fresh	100 ft	Poor
B-30	65	Fresh from 65-125 ft, becoming very saline below 125 ft	?	Fair to good
T-14	95	Fresh from 95-150 ft, becoming saline below 150 ft	?	Poor to fair
MAR	160	Fresh from 160-300 ft; very saline from 300- 1000 ft	Base of aquifer, 1000 ft	Fair
SW-19	400	Fresh	?	Very good

Table 3

Summary of White Sands Geophysical Ground-water Assessments

12 percent at SW-19 to 28 percent at B-30 and T-14 (not considering HTA-1).* The water table depth comparisons are given in Table 5. The water quality assessments in Table 3 are generally consistent with the water quality measurements reported in Table 4.

68. <u>HTA-1.</u> No explanation for underpredicting actual water table depth suffices for HTA-1. An alternate explanation for the interface at 8 ft, which appears on both refraction and resistivity interpretations, is not apparent. The interface at 62 ft in the resistivity model (Figure 30) is at the right depth to correspond to the water table, but the resistivity actually increases from 305 to 825 ohm-ft at this interface. Neither geophysical model indicates an interface at the 82-ft depth where weathered granite was reported. The borehole geophysical logs (neutron and natural gamma) do not show prominent water table indications at 65 ft, although both logs exhibit dramatic changes at ~84 ft. The

* Conversely, the predicted water table depths would have to be increased by amounts ranging from 14 percent for SW-19 to 39 percent for T-14 to agree with the measured depths.

Table 4

E

Summary of Geologic/Ground-Water Information

For White Sands Test Locations

	Measured Wat	ter Table	Water Quality*		
Location	Depth, ft/ Date	Variation ft	(Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
HTA-1	64 (2/15/83)	vo	50 fresh	Limited borehole lith- ology info. Sand and gravel to 82 ft. Weathered granite encountered at 82 ft.	Natural gamma and neutron borehole geophysical logs
B-30	89.5 (2/15/83)	1	<4 (@185 ft) saline	None	Natural gamma and neutron borehole geophysical logs
T-14	132 (2/16/83)	-	21 (@200 ft) 22 (@300 ft) marginal	Borehole lithology log for entire 6000-ft depth. Sand with silt and clay, 0-105 ft; clay with sand and silty, 105-220 ft; sand with clay, 120-180 ft; clay with sand and silt, 180-430 ft.	Complete set of borehole geophysi- cal logs from 400- 6000 ft

This criterion converts approximately to a "specific conductance" <1560 µmhos/cm or a resistivity >21 ohm-ft. Generally fresh water is considered to have <1000 mg/ ℓ total dissolved solids. *

(Continued)

	Comments	Electric logs available	Nonpumping water level: 409 ft (7/22/64) (402 ft, SW-18; 462 ft, SW-20) SW-20)	
uded)	Type Geologic Information Available and Summary	Borehole lithology log. Gravel, 0-112 ft; clay, 112-160 ft; gravel, 160-165; clay, 165-200; gravel, 200-210; clay, 210-225; etc., predomi- nantly clay below 630 ft.	Limited material descrip- tions. Poorly sorted sands and gravels to >900 ft.	
Table 4 (Concl	Water Quality* (Resistivity) ohm-ft	32 (~300 ft) 0.6 (@750 ft in MAR-2 and MAR-3) fresh (@300 ft)	85 (>400 ft) fresh	
	er Table Variation ft		Υ	
	Measured Wate Depth, ft/ Date	214 (MAR-2; 2/14/83) 220 (MAR-2; 1981)	454 (2/25/83) (427 for SW-18) (514 for SW-20)	
	Location	MAR	SW-19	

Table 5	Ta	b	le	5	
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		mparison of	Predicted and	neasured	
Water Table Depths					
	Predicted	Measured	% Error	Required % Increase	
	Denth ft	Denth ft	$D_m - D_n$	$\operatorname{in} D_{n} - D_{n} - D_{m} $	
	Depen, 10	DCPCA, 10	$\frac{1}{D} \times 100$	$P \left[\frac{P}{D} \right] \times 100$	
Location	<u>p</u>	<u>m</u>	<u> </u>		
HTA-1*	8*	64.0	88*	700*	
B-30	65	89.5	27	38	
T-14	95	132.0	28	39	
MAR	160	214.0	25	34	
SW-19	400	454.0	12	14	

Discussion of error for the HTA-1 case is not meaningful since the water table was not detected by the complementary geophysical methods.

natural gamma log shows a decrease in activity at 110 ft, which would correlate with an interpretation of the velocity interface at 110 ft being the approximate boundary between weathered and unweathered granite.

69. SW-19. Geologic conditions at SW-19, primarily coarsegrained sediments, are the most favorable for successful application of the ground-water detection techniques. As a consequence, geophysical ground-water assessment at SW-19 was the most successful of the five conducted at White Sands.

70. B-30, T-14, and MAR. Geophysical models for these locations are similar in that, apparently, saline water exists beneath the fresh water. The resistivity method is successful at detecting the freshwatersaltwater interface or transition zone. Also, there are considerable amounts of clay at these three locations, which complicates the groundwater assessments. Although the ground water is interpreted to be saline at depth at T-14 and MAR, the large resistivity decrease at large electrode spacings may be due to thick clay sequences at these locations.

Geological verification of Fort Carson geophysical ground-water assessment

71. Figure 36 presents a simplified lithology log for the well at



White Butte. Also, the surface topography and top of the Dakota Sandstone are projected to the location of WES-4 and CSM-2. The surface topography is estimated from a 20-ft contour interval topographic map, and surface elevations are probably accurate to ± 5 ft. The top of the Dakota Sandstone is projected based on the known depth at the White Butte well and a regional value of dip for the Dakota Sandstone. The depth to the top of the Dakota Sandstone at the location of WES-4 and CSM-2 is probably accurate to only ± 15 ft.

72. The interface at 35 ft in the geophysical models (Figure 35) correlates with the top of the Dakota Sandstone, and the interface at 100 ft could correspond to the base of the sandstone unit. Two possibilities can be suggested for the resistivity interface at ~60-ft depth: (a) since the resistivity decreases, a change in ground-water salinity could occur at this depth; (b) since this location is very near the Dakota Sandstone outcrop, hence the area of recharge, this interface could be an unconfined water surface in the dipping aquifer.

73. In the geophysical ground-water assessment, the water table was interpreted based solely on the large velocity contrast; the velocity 6050 ft/sec occurring at such a shallow depth (35 ft) suggests the possibility of rock below 35 ft. The low resistivities (190 and 55 ohm-ft) between 35 and 100 ft suggest that if the unit is rock, then it is saturated, particularly the lower part. However, based solely on the geophysical data at one location, it is not possible to predict whether the interface is rock, saturated rock, or an unconfined water table.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

74. This report presents the results of geophysical surveys at two sites. The surveys, consisting of complementary seismic refraction and electrical resistivity surveys, were conducted to assess the feasibility of using two currently fieldable methods for military groundwater detection applications (see Part II). Locations surveyed at the two sites presented varied geological complexity and ground-water conditions. Results of the surveys demonstrated success, marginal success, and failure in the ground-water detection application.

Conclusions

75. Based on the results of this work, the following conclusions are made regarding the applicability of the two complementary geophysical methods for ground-water detection:

- <u>a</u>. For cases in which the water table occurs in coarsegrained sediments (sands and gravels), the geophysical methods can be used very successfully for ground-water detection.
- b. For cases in which the water table occurs in finegrained sediments (clayey sands, silts, silty clays, sandy clays, etc.), the geophysical methods can be used for ground-water detection; however, the interpretation will sometimes not be as straightforward as for case a, and the difference between predicted and actual water table depth can sometimes be much greater than for case a.
- c. A freshwater-saltwater interface is easily detected by the resistivity method, but will not show as an interface in seismic refraction results; detection of this interface is useful in that any fresh water present will be shallower than the interface depth.
- d. Rock aquifers can be detected by the geophysical methods, but there may be nothing in the survey results to differentiate a rock aquifer from an unsaturated rock unit (except for the case where the rock unit has high resistivity, in which case the unit is not an aquifer).
- e. For some field situations, such as at the Fort Carson site, topographic variations and complex, lateral geologic changes make a straightforward data interpretation impossible.

- \underline{f} . In some cases, such as the HTA-1 location at White Sands, the straightforward interpretation method can lead to false identification of the water table.
- <u>g</u>. In order to be conservative, geophysical water table depth estimates should be increased by ~40 percent.
- h. It is envisioned that the desired depth of investigation will probably be dictated by considerations such as maximum desired drilling depth or maximum probable depth to water in an area; geophysical ground-water assessment productivity is strongly dependent on depth of investigation, as shown below:

Maximum Depth of Investigation ft	Estimated Number of Complete Geophysical Ground-Water Assessments per Day, 3-Man Crew
30	5-6
100	3-4
600	1-2
>600	1

76. The conclusions of the study can be summarized as follows: complementary seismic refraction and electrical resistivity surveys (a) can generally be used successfully for ground-water detection when the water table occurs in unconsolidated sediments, and (b) can generally not be used successfully for detection of ground water in confined rock aquifers. For the case of rock aquifers, a ground-water exploration program is required.

Recommendations

Equipment

77. Kingged, reliable seismic refraction and electrical resistivity instrumentation equipment that is commercially available would require very few modifications for military ground-water detection applications. The primary equipment development needs are for improved, more efficient cable and reel systems coupled with procedures for "putting out" and "taking up" cable from moving vehicles. The improved cable and reel systems could reduce the time required for conducting resistivity and refraction surveys by 25 to 50 percent.

Data processing and interpretation

78. Rugged field microcomputer systems that are commercially available would be suitable for processing and aiding in the interpretation of survey data. Also, interactive, user-friendly computer programs are available for survey data interpretation. The work required to convert computer programs to run on a specific microcomputer would be minimal.

Field personnel

79. Military personnel can be trained to conduct seismic refraction and electrical resistivity surveys. Minimum recommended training time is 3 months. While troops could be trained to make ground-water interpretations using a flowchart approach (or computer program based on the flowchart) incorporating the logic stated in this report and used for the ground-water assessments, this is not considered the most feasible approach. Feasible options for deployment are considered below.

Feasible deployment options

80. If the decision is made to develop a geophysical ground-water detection/exploration capability in field military forces, the following options are considered feasible:

- a. Recruit or assign junior officers with degrees in geology, geophysics, or other science/engineering fields with strong geoscience backgrounds to teams trained as specified in paragraph 79.
- b. Utilize teams trained as specified in paragraph 79 to conduct surveys and then relay data to a rear area interpretation unit or data analysis contractor that could handle data from several survey units and be better able to incorporate information from ground-water maps and databases into the ground-water assessments.
- <u>c</u>. Develop geophysical survey expertise in National Guard or Reserve units which already have identified professional geoscience expertise.
- d. Establish arrangements with Government agencies and/or geophysical firms for on-call geophysical testing and interpretation services for areas that are reasonably secure; these personnel should have full access to ground-water maps and databases.

Future work

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- 81. The following requirements for future work are identified:
 - <u>a</u>. Develop improved cable and reel systems for fieldwork as identified above.
 - **b.** Adapt computer interpretation programs to run on selected field microcomputer systems.
 - <u>c</u>. Develop a geological and geophysical database for world areas of interest.
 - d. Proceed with research and development on state-of-the-art and emerging geophysical techniques for ground-water detection, such as frequency-domain and time-domain electromagnetic methods and the concept of determining the ratio of compression wave to shear wave seismic velocities as a function of depth.
 - e. Develop training manuals and programs for geophysical survey operators and for geophysical ground-water interpretation procedures; examine feasibility of developing geophysical ground-water interpretation "flowcharts," and ultimately an automated system for assessing groundwater potential.
 - f. Develop a totally integrated system for ground-water assessment that would incorporate (1) existing water resources-related information, (2) remote imagery analysis and interpretation capabilities, and (3) geophysical expertise.

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PLATE 1



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APPENDIX A: LETTER REPORT, SCHLUMBERGER SOUNDINGS, by R. J. BISDORF, USGS

Introduction

1. In an effort to evaluate different resistivity interpretation techniques and computer programs, selected data from the White Sands, New Mexico, and Fort Carson, Colorado, sites were sent to Mr. Robert Bisdorf and Dr. Adel Zohdy of the U. S. Geological Survey for assessment and comment. The cooperation and assistance provided by Mr. Bisdorf and Dr. Zohdy prior to and during the course of this investigation are greatly appreciated.

2. Information provided in this appendix includes output from the automatic inversion program and documentation for soundings conducted at locations HTA-1, B-30, SW-19, and T-14 at the White Sands, New Mexico, site.

3. The data indicated that soundings S-2 and S-3 at the Fort Carson, Colorado, site are approaching a resistivity layer from one side (Figure A1). The cusps appear to be due to more than just faulting, although the capability to model these interesting two-dimensional problems is not yet available. The rest of the soundings do not appear to be affected by lateral effects; however, since they are probably oriented parallel to strike, the effects would be subtle.

<u>←×→</u>		
	150 ohm-ft	
80 ohm-ft	500 ohm-ft	80 ohm-ft

110 ohm-ft

Figure A1. Possible explanation for fat cusps, Fort Carson data

A1

Inversion of Schlumberger Sounding Data

4. The sounding curves and their automatic inversions are given in Figures A2-A17. All the sounding data were automatically processed and interpreted (Zohdy 1973, 1975) as shown in the graphs. The curves were interpreted on a Hewlett-Packard (HP) 9845B desktop computer using a program based on the program of Zohdy (1973). The HP program was modified to use O'Neill coefficients (O'Neill 1975) in place of Ghosh coefficients (Ghosh 1971).

- 5. For each sounding, the data include:
 - <u>a</u>. A log-log plot of the field data points, in which the "O"'s represent the individual data points. The AB/2 electrode spacings have been converted to metres. Each set of data points that was made with the same potential electrode spacing (MN) is connected with a solid line. Measurements were made at the fixed MN/2 spacings of 2, 6, 20, 60, 200, and 600 ft.
 - **b**. A tabulation of the AB/2 electrode spacings in metres and the corresponding apparent resistivities in ohm-m.
 - c. A log-log plot of the output of the automatic inversion program in which:
 - (1) The continuous curve represents the shifted-digitized field curve (Bisdorf and Zohdy 1979).
 - (2) The step-function curve represents the distribution of interpreted-true resistivity with depth.
 - (3) The "S"'s represent points on the theoretical sounding curve for the given distribution of resistivity with depth. These points are given to show how well the interpreted model fits the shifteddigitized curve.
 - d. A tabulation of the interpreted depths in metres and the interpreted resistivities in ohm-m.

6. For some soundings the original inversion did not fit the digitized data very well. These soundings were smoothed in a fashion that would help automatic inversion to fit parts of the data better. These soundings have "-S" appended to their names (Figures A6-A9 and A14-A17).

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BIGITIZED CALCULATED LAYERING HTA-1

DEPTH In	RESISTIVITY IN	DEPTH In	RESISTIVITY In
FEET	CHM-FEET	FEET	OHM-FEET
.97	1231.66	19.89	331.92
1.42	1229.65	28.13	188.09
2.09	1238.22	42.39	314.52
3.07	1252.60	60.01	748.01
4.50	1219.85	90.35	561.33
6.59	1035.17	135.70	479.68
9.60	756.63	197.71	757.64
13.90	539.87	257.15	1921.70
		3281093.77	3181.60

Figure A3. Data inversion for	HTA-1
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Figure A	15.	Data	inversion	for	B-30
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Figure All.	Data	inversion	for	SW-19
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Figure A13. Data invo	ersion for T-14
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Figure A14. Smoothed data (1) for sounding T-14





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Figure A16. Smoothed data (2) for sounding T-14



. 4 4	148.61	12.18	991.02
.65	114.87	18.61	381.85
.95	180.12	24.92	79.42
1.38	199.73	30.24	13.96
2.02	107.82	49.15	38.36
2.97	104.48	62.43	344.87
3.88	413.82	107.39	234.88
5.73	599.86	157.95	336.41
8.54	867.24	252.92	127.84
		3281089.53	22.15

Figure A17. Data inversion for smoothed T-14 data in Figure A16

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