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TECHNICAL REPORT GL-90-23

WATER DETECTION RESPONSE TEAM
GEOPHYSICS ELEMENT CASE HISTORIES

by

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and

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The US Army Water Detection Response Team is a rapid response team designed to offer assistance to the military in securing water supplies in support of military operations. Currently, the team is staffed by volunteer civilians. However, plans are to transition field operations functions of the team to active or reserve military units. The Geophysics Element of the team develops and maintains capability to apply surface geophysical methods for location well drilling sites in the areas of interest. The Geophysics Element will only be deployed if existing data are insufficient to support assistance requests. Currently, the Geophysics Element is equipped to conduct and interpret seismic refraction, electrical resistivity, and very low frequency electromagnetic surveys for water well siting. The Water Detection Response Team has assisted requesting major commands in Southwest Asia, Northeast Africa, Central America, and Korea. The Geophysics Element has been deployed to participate in several major military exercises. Case histories of the Geophysics Element involvement in these exercises are presented in this report.

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US Army Engineer Topographic Laboratory and Terrain Analysis Center

PREFACE

This report documents work of the Geophysics Element of the US Army Water Detection Response Team (WDRT) that was performed at various times during the period 1984 to present. The Geophysics Element is permanently staffed by personnel of the Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), and augmented as required by personnel of other WES offices and government agencies. The WDRT Team Leader is stationed at the US Army Engineer Topographic Laboratory and Terrain Analysis Center (ETL/TAC). The case histories described herein were conducted under a variety of funding sources (Direct Allotted RDT&E, Operations and Maintenance, Army, and reimbursible). Most of the Operations and Maintenance and reimbursible funds were channeled through the ETL/TAC. This report was funded under MIPR No. E8790K129, 25 April 1990, from the ETL/TAC.

This work was accomplished by the following members of the Geophysics Element, WDRT: Dr. Dwain K. Butler, Element Leader, EEGD, Messrs. Jose L. Llopis, Donald E. Yule, and Michael K. Sharp, EEGD, and Elba A. Dardeau, Environmental Systems Division, Environmental Laboratory. Other personnel from WES, ETL/TAC, and the US Geological Survey (USGS) participated in WDRT deployments and provided assistance to the Geophysics Element: John G. Collins, James H. May, and Regina Bochicchio, WES; Laura Dwyer, Dennis Bowser, Stanton Wilhelm, and Claudia M. Newbury, ETL/TAC; David V. Fitterman, Glenn A. Brooks, Joel Frisch, and Jerry Stevens, USGS. Mr. Allan E. DeWall, ETL/TAC, was WDRT Leader during the performance of this work. Current WDRT Leader is Mr. Charles H. Lopez, ETL/TAC. This report was prepared by Dr. Butler under the general supervision of Mr. Joseph R. Curro, Chief, Engineering Geophysics Branch, EEGD, Dr. Arley·G. Franklin, Chief, EEGD, and Dr. William F. Marcuson, Chief, GL.

COL Larry B. Fulton, EN, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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WATER DETECTION RESPONSE TEAM
GEOPHYSICS ELEMENT CASE HISTORIES

PART I: OVERVIEW OF THE WATER DETECTION RESPONSE TEAM (WDRT)

Background

1. Adequate water supply is a critical requirement for support of military operations in arid and semi-arid areas and for fixed military bases. Water supply has been identified as a high priority problem for the military. Surface water supplies are inadequate, unreliable, and unpredictable in many arid regions of strategic importance; thus, the capability of rapidly detecting producible ground-water resources in such areas is critically important. However, technology shortfalls exist in surface techniques for detection of ground water. There is no device or black box that can be placed on the ground surface at a given location to determine depth, quantity and quality of ground water with a high confidence level. Even in the foreseeable future, there is little likelihood that such a device will be available. There are, however, geophysical methods that can be utilized to significantly enhance the likelihood of selecting locations for wells which tap producible, potable ground water.

2. The WDRT was formed in response to the high-priority military requirement and the identified ground-water detection technology shortfall (Defense Science Board Water Support Task Force, 1981[1]). The WDRT consists of volunteer civilian scientists and engineers with specialties in the areas of remote sensing, geology, hydrogeology, geophysics, and well drilling and completion. Figure 1 is a chronology of events leading to the formation of the WDRT and its subsequent activities.

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

1977   MILITARY HYDROLOGY PROGRAM INITIATED

1981   DEFENSE SCIENCE BOARD/JOINT CHIEFS OF STAFF IDENTIFY
          GROUND-WATER DETECTION AS MAJOR TECHNOLOGY SHORTFALL

1982   WES HOLDS GROUND-WATER DETECTION WORKSHOP

1982   WATER RESOURCES MANAGEMENT ACTION GROUP CHARTERED
          (JOINT SERVICES)

1983   BRDEC FUNDS WES TO INVESTIGATE FIELDABLE GEOPHYSICAL METHODS

1985   HQ USACE APPROVES CONCEPT OF WDRT

1985   HQ USACE HOLDS WATER DETECTION SYMPOSIUM

1985   US ARMY ENGINEER SCHOOL PREPARES DRAFT ORGANIZATIONAL AND
          OPERATIONAL PLAN FOR WDRT

1985   WDRT PARTICIPATES IN BIG PINE/BLAZING TRAILS EXERCISES
          (HONDURAS)

1985   WDRT PARTICIPATES IN BRIGHT STAR 85 (EGYPT, JORDAN)

1986   WDRT PARTICIPATES IN GALLANT EAGLE 86 (FORT IRWIN, CA)

1987   WDRT PARTICIPATES IN BRIGHT STAR 87 (SOMALIA)

1988   WDRT PARTICIPATES IN WELL DRILLING (SOMALIA)

1988   WDRT PARTICIPATES IN WELL DRILLING EXERCISES (WHITE SANDS, NM)

1988   WDRT PROVIDES GEOSCIENCE TRAINING FOR MILITARY WELL DRILLERS

Figure 1. Chronology of events leading to WDRT formation and activities
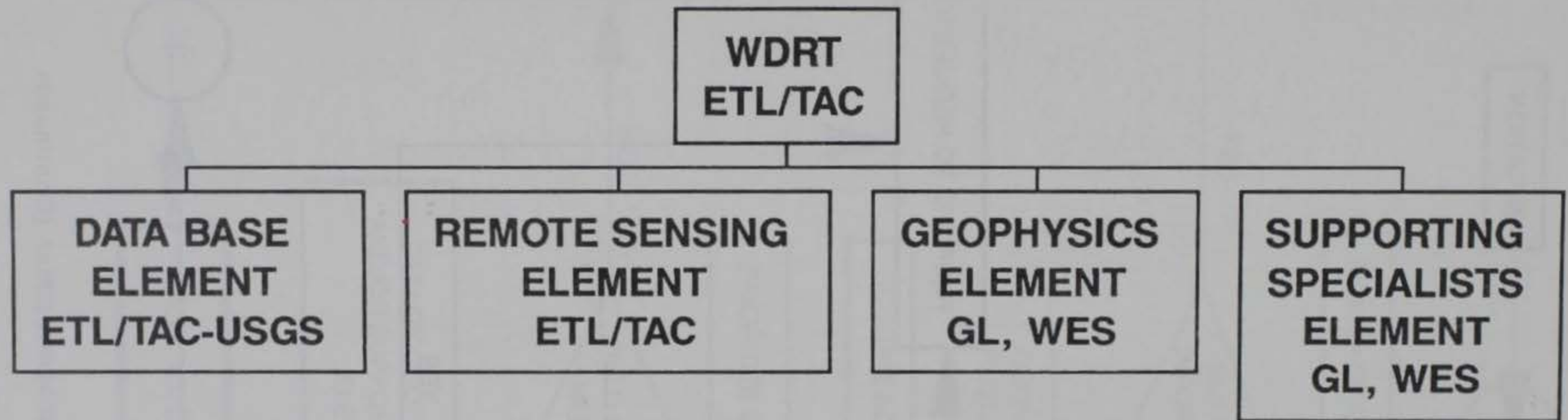
Organization and Operation

3. The Team consists of four elements as shown in Figure 2. Overall management of the WDRT and management of the Data Base and Remote Sensing Elements are at the US Army Engineer Engineer Topographic Laboratories-Terrain Analysis Center (ETL/TAC). Management of the Geophysics and Supporting Specialists Elements is at the US Army Engineer Waterways Experiment Station (WES). Figure 3 is an idealized flow chart illustrating the Military Major Command (MACOM) request for assistance leading to activation of WDRT and possible deployment of WDRT Elements to the area of operations.

4. WDRT is envisioned as a rapid response team, on call for deployment to support the military in locating potable ground water supplies. The primary scenario for WDRT activation is to assist rapid deployment, joint services military forces in a Southwest Asia setting. As illustrated in Figure 3, three operational stages are possible following WDRT activation:

> Stage 1 -- examine all available data on water supply
> for area of operations; if sufficient data
> is available, prioritize drilling sites;

> Stage 2 -- if necessary, initiate acquisition of addi-
> tional data by military and civilian satel-
> lite remote sensing, intelligence sources,
> civilian experts, etc.; if additional data
> are available and sufficient, prioritize
> drilling sites;

> Stage 3 -- if necessary, deploy teams from the
> Geophysics Element and/or the Supporting
> Specialists Element to the area of opera-
> tions to conduct geophysical surveys,
> geological reconnaissance, and assist
> military well drillers.

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┌─────────────┐
│    WDRT     │
│   ETL/TAC   │
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DATA BASE ELEMENT ETL/TAC-USGS	REMOTE SENSING ELEMENT ETL/TAC	GEOPHYSICS ELEMENT GL, WES	SUPPORTING SPECIALISTS ELEMENT GL, WES

AGENCIES

○ COE LABS & FOA'S   ○ DIA
○ BRDEC   ○ USGS
○ DMA

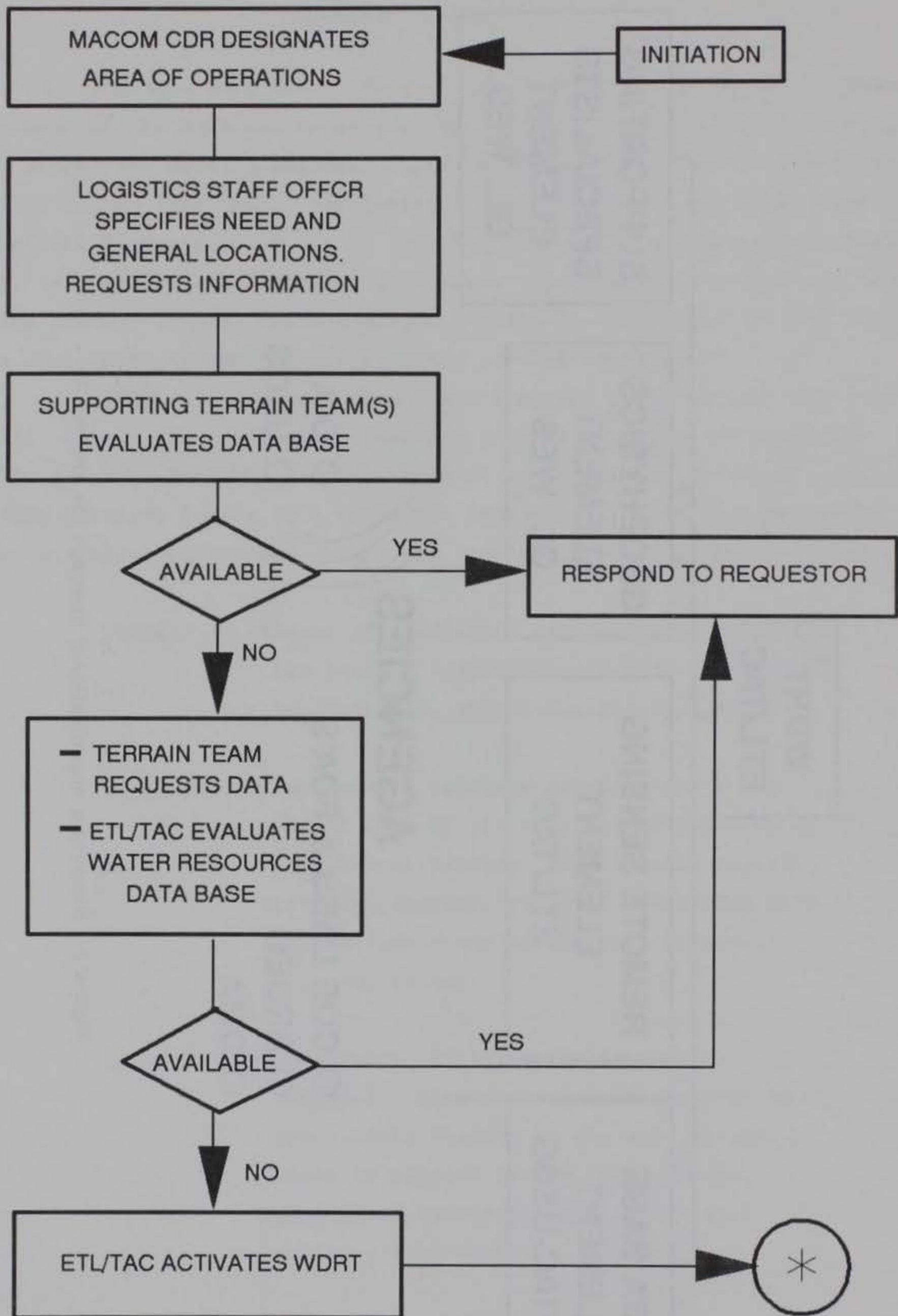Figure 2. Simplified organizational concept for the WDRT

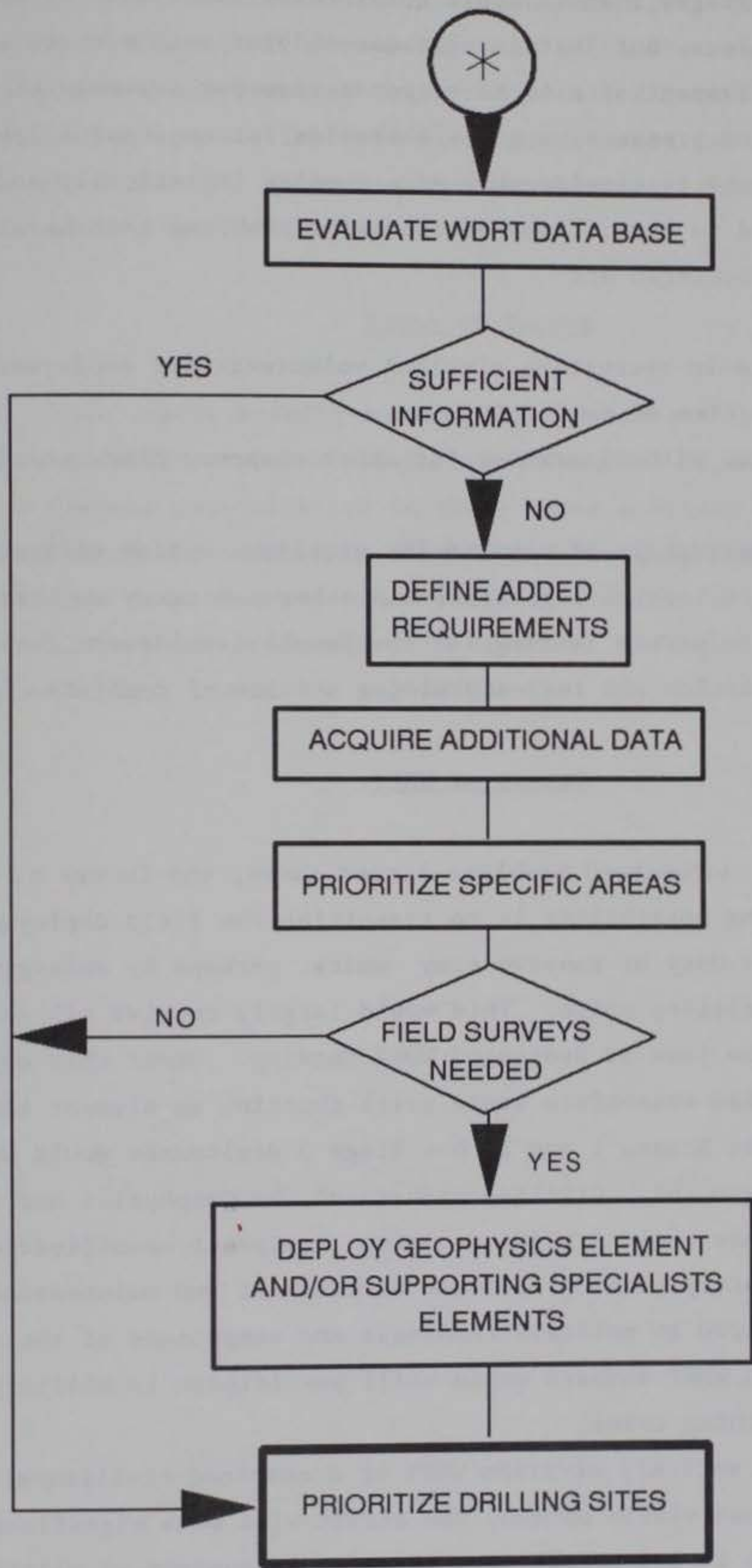Figure 3. WDRT activation/deployment plan (Continued)

8

Figure 3. (Concluded)

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5. Operating Stages 1 and 2 would not involve deployment of civilians to the area of operations, but just involve assembly of team members at ETL/TAC or WES. Achievement of a 48-hr response time for assembly of team members is possible and presents no major obstacles for successful implementation. Operating Stage 3 is considerably more complex logistically and has not been fully implemented to date. Some of the major problems that have been identified and/or encountered are:

a. Difficulties in recruiting civilian volunteers for deployment to area of operations in time of conflict;

b. Difficulties with clearances for short response time out-of-country deployment;

c. Lack of clear chain of command for civilians during military operations resulting in lack of logistical and other necessary support;

d. Inability to secure funding for the Geophysics Element for dedicated equipment acquisition and for maintaining a state of readiness.

Future of WDRT

6. Due to the unresolved problems listed above, the future of WDRT is uncertain. A promising possibility is to transition the field deployment mission of WDRT to active-duty or reserve Army units, perhaps by enlarging the mission of the well drilling units. This would largely resolve all the problems except for the lack of dedicated WDRT funding. Under this modified WDRT structure, civilian scientists would still function as element leaders and perform operational Stages 1 and 2, but Stage 3 deployment would be performed by military personnel. Civilian members of the Geophysics and Supporting Specialists Elements would provide training, equipment specification and selection, computer interpretation software development and maintenance, and other support as required to maintain readiness and competence of the military field teams. Civilian WDRT members would still participate in military exercises in teaching/coaching roles.

7. Whether an entirely civilian WDRT or a combined civilian/military WDRT emerges as the most viable option, the result will be a significantly improved capability to locate potable ground water in support of military

operations. A key function of the civilian scientists under either option will be to keep abreast of new developments in remote sensing data acquisition, new ground water resource data from areas of interest, new geophysical techniques and equipment, improved field procedures, new and improved interpretation techniques for geophysical survey results, and drilling and well completion innovations.

Scope of Report

8. This report briefly surveys the concept and operation of WDRT. The primary emphasis, however, is on case histories of the results of Geophysics Element participation in three major military exercises. Part II is an overview of the Geophysics Element and the geophysical methods, field procedures, and data interpretation methods used for field surveys. Parts III - V cover Geophysics Element participation in Bright Star 85, Egypt, Gallant Eagle 86, Fort Irwin, CA, and Bright Star 87, Somalia, respectively.

Geophysics Element Organization

9. The Geophysics Element, WDRT, is staffed by personnel of the Geotechnical Laboratory, WES. The Element Leader is a Senior Research Geophysicist, and team members are geophysicists, geologists and civil engineers with specialized experience in engineering and ground water geophysics and hydrogeology. Deployments to date have consisted of two or three Geophysics Element personnel and have relied on other WDRT personnel or military personnel for assistance in conducting geophysical surveys. A deployment relying totally on Geophysics Element personnel will likely consist of four Element members. In addition to the Element Leader, two other Element members are fully capable of leading deployments of the Geophysics Element.

Concepts and Procedures

10. The operating scenario for the Geophysics Element is to conduct surface geophysical surveys at selected locations in the area of operations which are judged to have high ground water potential at reasonable depths and/or are determined to be logistically desirable. It is necessary not only to minimize the time spent at each location but also the total time in the area of operations. After analysis of the survey results, the locations are ranked in terms of ground water potential for military well drilling units. At this point, the Geophysics Element will depart, except perhaps for one member who will advise the well drillers and reinterpret the geophysical survey results on the basis of drilling results, if necessary. This operating scenario is summarized by the flow chart in Figure 4.

11. The above operation scenario is a nonstandard application of geophysics. Typically, geophysics is applied in an exploration mode, where the objective is to define the subsurface over an area (three dimensions) in terms of geologic structure and stratigraphy. For the WDRT application, the ideal situation is to be able to determine the depth to ground water beneath a given surface location by conducting one or more geophysical surveys at the

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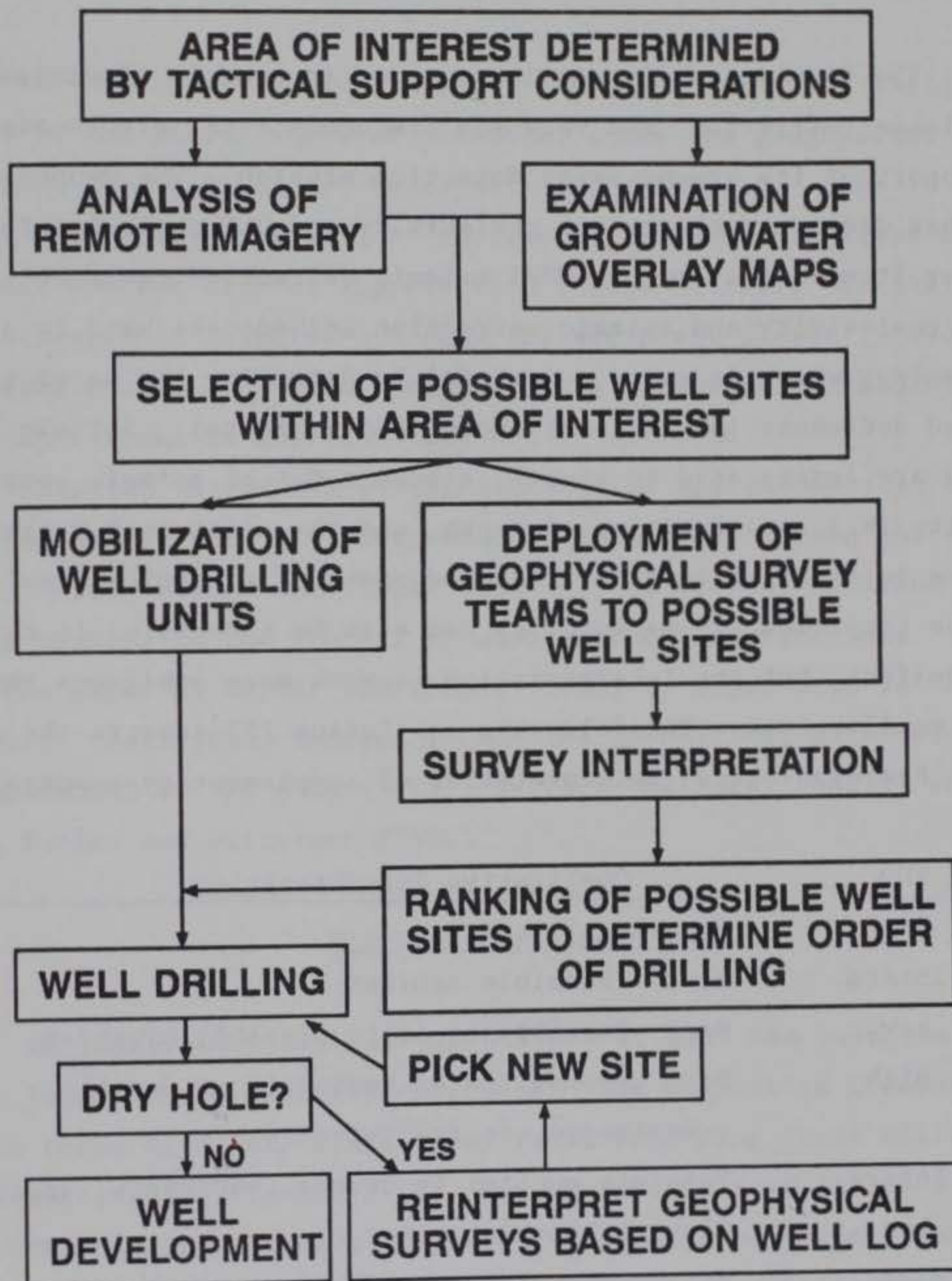
Figure 4. Rationale for deployment of the WDRT Geophysics Element

surface location. This procedure is called ground water detection, contrasted to the more typical ground water exploration. The concept of detection and exploration is discussed in detail by Butler and Llopis (1984, 1985).

Geophysical Methods

12. The Geophysics Element is prepared to conduct electrical resistivity, seismic refraction, and very low frequency (VLF) electromagnetic surveys in support of its ground water detection mission. The Geophysics Element currently has dedicated electrical resistivity and VLF equipment for the WDRT mission, but it must rely on non-WDRT seismic refraction equipment. The electrical resistivity and seismic refraction methods are used in a complementary methodology which is quite successful in detecting the water table in unconsolidated sediments (phreatic or unconfined aquifers). Seismic refraction survey data are interpreted to give a layered model of seismic compression wave velocity (V_p) as a function of depth, and the electrical resistivity survey data are interpreted to give a layered model of electrical resistivity (RHO_b). The complementary methodology can also be successful in detecting confined aquifers, but the interpretation is much more ambiguous than for the unconfined aquifer case. The following tabulation illustrates the concept of qualitative hydrogeological interpretation of complementary geophysical data:

V_p	RHO_b	Qualitative Interpretation
High	High	Impermeable rock.
High	Interm.	Rock. Possible aquifer.
High	Low	Rock. Possible aquifer; probably brackish.
Interm.	High	Dry, unconsolidated sediments at depth; weathered, or fractured rock;
Interm.	Interm.	Possible aquifer in uncons. sediments; weathered rock.
Interm.	Low	Clay or brackish water.
Low	High	Dry unconsolidated sediments; no clay.
Low	Interm.	Unconsolidated, wet sediments.
Low	Low	Wet, clayey sediments.

V_p--High (>3,000 m/s); Low (<1,000 m/s);

RHO_b--High (>300 ohm-m); Low (<10 ohm-m)

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The VLF electromagnetic method is primarily used for detection of fractured rock aquifers, where the objective is the location of fractures and fracture intersections in hard, otherwise impermeable rock. Although the VLF method requires surveying over an area or along lengthy survey lines, the method is so rapid and logistically simple that it is feasible in a WDRT operational scenario.

13. The Geophysics Element operational plans call for taking two sets of equipment to the field, whenever possible, since the geophysical electronic instrumentation generally cannot be repaired in the field. Also it must be assumed that the deployments will be to remote, inaccessible areas and that the teams must operate without support with regard to their specialized equipment ("non-mil-spec"). Figures 5-7 show the equipment presently used by the WDRT Geophysics Element. Nominal weight of the equipment to be deployed to the area of operations is approximately 635 kg (1400 lb).

14. Detailed discussion of the concepts of the geophysical methods, the field procedures, and the interpretation methods is beyond the scope of this report. Also, Butler and Llopis (1984, 1985) present detailed discussions of the methods in the context of military/WDRT applications. For completeness, the paper by Butler and Llopis (1985) is reproduced in the Appendix to this report. Additional information on the geophysical methodology can be found in Department of the Army (1979), Telford, Geldart, Sheriff and Keys (1976), and Butler and Fitterman (1986).

Military Exercises

15. An important aspect of the history of WDRT has been the participation in joint forces military exercises. The Geophysics Element has participated in three major exercises. Key facts regarding these military exercises are summarized in Figures 8-10. For the Bright Star 85 and 87 Exercises, the WDRT contingents were completely dependent on the military for transportation and other support. In the Gallant Eagle 86 Exercise, the WDRT functioned independently of the military command structure, and secured and arranged its own transportation, lodging and other support. These exercises are extremely important in identifying problems encountered by civilian units

operating in a military environment. Identification of these problems will lead to changes and refinement of the WDRT organizational and operational plan.

a. Electrical resistivity equipment

b. Electrical resistivity survey during Bright Star 85

Figure 5. Electrical resistivity equipment used by the Geophysics Element

a. WDRT seismograph

b. Seismic refraction survey in progress

Figure 6. WDRT seismic refraction equipment

Figure 7. Very low frequency (VLF) electromagnetic equipment and survey in progress

BRIGHT STAR 85
DESERT EXERCISE
EGYPT

★ 10-MEMBER WDRT PARTICIPATES IN EXERCISE

★ WDRT STUDIES TWO AREAS AND LOCATES TWO WELL SITES

★ AIR FORCE RED HORSE AND ARMY WELL DRILLING UNITS DEPLOYED

★ AIR FORCE WELL SUCCESSFULLY COMPLETED AND PRODUCTION
    ESTIMATED AT 8-10 GPM FROM SHALLOW, PERCHED AQUIFER

★ WDRT FUNCTIONS COMPLETELY IN A MILITARY ENVIRONMENT,
    DEPENDENT ON MILITARY UNITS FOR ALL SUPPORT

Figure 8. Brief fact sheet for WDRT participation in Bright Star 85

GALLANT EAGLE 86
DESERT EXERCISE
FORT IRWIN, CA

★ 17-MEMBER WDRT PARTICIPATES IN EXERCISE

★ WDRT STUDIES FOUR SITES AND PRIORITIZES TWO SITES FOR DRILLING

★ AIR FORCE AND ARMY DRILLING UNITS DRILL TWO WELLS AT WDRT SITES

★ AIR FORCE WELL SUCCESSFULLY COMPLETED AND TESTED AT 80-100 GPM

Figure 9. Brief fact sheet for WDRT participation in Gallant Eagle 86

BRIGHT STAR 87
SOMALIA

★ 8-MEMBER WDRT PARTICIPATES IN EXERCISE

★ WDRT STUDIES AREA NEAR SPECIAL FORCES ENCAMPMENT

★ ARMY WELL DRILLING UNIT DEPLOYED

★ FOLLOW-ON WELL DRILLING AND WDRT DEPLOYMENT IN 1988

★ WELL SUCCESSFULLY COMPLETED AND TESTED AT 6 GPM

Figure 10. Brief fact sheet for WDRT participation in Bright Star 87

Background

16. Bright Star 85 was a U.S. Central Command joint exercise with the Egyptian Armed Forces, conducted in Egypt between mid-July and late August 1985. The Third U.S. Army (TUSA) was the Army command. U.S. troop strength peaked at approximately 12,000 in late July. The majority of the exercise contingent was bivouaced at Cairo West, an Egyptian Air Force Base, with additional personnel at Gebel Hamza, an abandoned World War II British air field, approximately 12 km northwest of Cairo West. Cairo West and Gebel Hamza are shown on the excerpt from a Joint Operations Graphic (NH 36-5) in Figure 11.

17. A WDRT was deployed by military charter flight to participate in the exercise. The WDRT mission was to locate potential water well sites for Air Force and Army well drilling units. The WDRT contingent consisted of four WES personnel and five ETL/TAC personnel. The WDRT was attached to the TUSA for food, shelter and logistics support. Two FORSCOM personnel and personnel of the Air Force Red Horse Drilling Team provided significant assistance to the WDRT. Initially, bottled drinking water was was brought to the site by military transport. By the end of the first week of the WDRT deployment, a Tactical Water Distribution System (TWDS) was installed, which brought water from the Berkash Well (also known as Anwar's Well) to Cairo West. The Berkash Well is located about 9 km from Cairo West, near the edge of the Nile flood plain, and is the normal water supply for Cairo West.

Geophysics Element Activities

18. The Geophysics Element for this exercise consisted of the three WES personnel, with assistance from other personnel as required. Electrical resistivity equipment, a magnetometer, portable field microcomputer, and other miscellaneous field supplies were transported to Egypt for use by the Geophysics Element in conducting surveys. Magnetometer surveys were planned solely for detection of faults which might exist and exert structural control

Figure 11. Vicinity map of Cairo, Egypt, showing the Cairo West and Gebel Hamza sites in lower left (Defense Mapping Agency, Joint Operations Graphic, Series 1502, Sheet NH 36-5, January 1981)

on ground water in the Cairo West vicinity. Seismic refraction surveys were
not planned or conducted due to difficulties with transporting or arranging
in-country supplies of explosives necessary for conducting the surveys. Lack
of the complementary information provided by seismic refraction surveys was
definitely a handicap in the groundwater detection efforts.

19. In the vicinity of the Cairo West site, the Geophysics Element
conducted four electrical resistivity soundings and a magnetic survey along an
8.2 km (27,000 ft) line. The survey locations are shown in Figure 12. The
magnetic survey line began close to Anwar's Well and followed a road to the
junction of an access road to Cairo West. Resistivity sounding 1 was near
Anwar's Well, and sounding 2 was near the site finally selected for the Air
Force Well. Following the geophysical surveys and selection of the well site
near Cairo West, the Geophysics Element shifted operations to the Gebel Hamza
site. Unfortunately, the resistivity equipment malfunctioned during a resis-
tivity sounding at the location shown in Figure 13. Since the equipment could
not be repaired in the field, geophysical surveys were terminated.

20. The productivity of the Geophysics Element was hindered by the
lack of dedicated vehicles, lack of communication capability during conduct of
surveys, and various site access problems. Transportation problems prevented
the team from beginning work until after 0900 each day, and lack of radios
complicated and slowed the field work. The late starts each day limited the
productive work which could be accomplished, since the extreme heat neces-
sitated termination of field work in the mid-afternoon.

Survey Results, Hydrogeological Interpretations
and Drilling Results

Electrical resistivity results

21. The electrical resistivity sounding data were processed and in-
terpreted in the late afternoon each day using a field microcomputer and pro-
cedures discussed by Butler et al (1982) and Butler and Llopis (1984).
Briefly, the data acquisition and interpretation sequence is as follows:

       a. Field measurements acquired at a sounding site

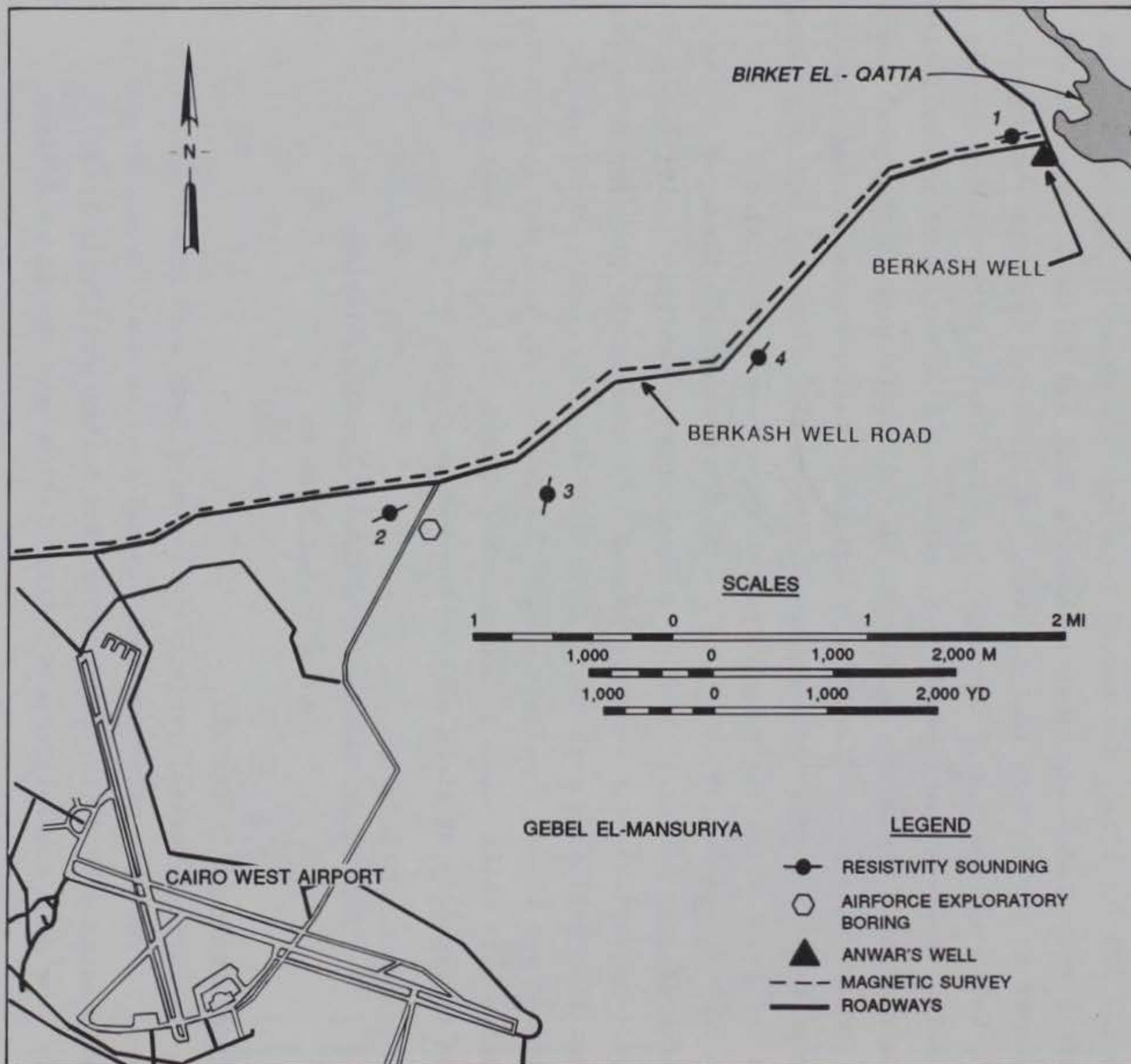   (electrode spacings in ft or m and resistance in ohms);

Figure 12. Locations of geophysical surveys and the Air Force well at the Cairo West site
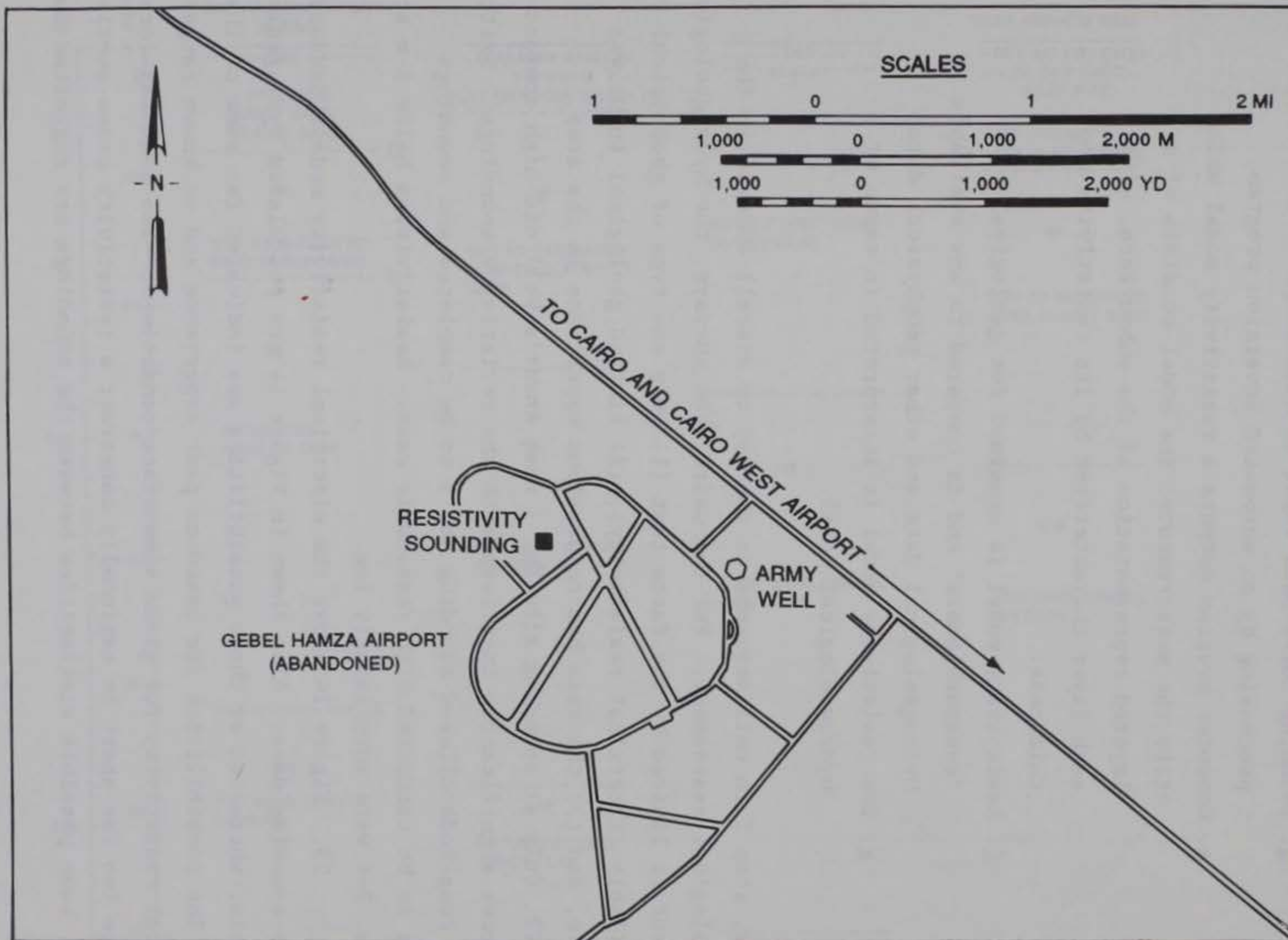
Figure 13. Geophysical survey and Army well locations at the Gebel Hamza site

b. Measurements converted to apparent resistivities
in ohm-ft or ohm-m;

c. Apparent resistivity plotted versus electrode
spacing to form a sounding curve;

d. Sounding curve data input to microcomputer for
processing by an automated inversion program;

e. Computer program outputs a resistivity model which
fits the measurements; the model consists of a
layered representation of the subsurface, with
each layer characterized by its resistivity and
thickness;

f. Resistivity model is examined for geological
"reasonableness" and is compared to any available
hydrogeological data and other geophysical data;

g. The resistivity model is interpreted in terms of a
hydrogeological model.

Normally, step f in this sequence is the key to overall success in the
hydrogeological assessment. For the Cairo West surveys, the hydrogeological
assessment is limited by the facts that (1) only one type of geophysical data
was available (electrical resistivity), (2) limited geological input was
available, and (3) the team had no previous experience in the area.

22. Only at sounding site No. 1 near Anwar's Well did high contact
resistances significantly interfere with the resistivity soundings. Switching
to 4-ft-long rods allowed sounding No. 1 to be completed and soundings
nos. 2-4 to be conducted with reasonable ease. Resistivities below 1 m at
site nos. 2-4 were surprisingly low.

23. Figure 14 shows the electrical resistivity models deduced
from the sounding data. Also shown in Figure 14 are postulated hydrogeologi-
cal models, where two or three possibilities are indicated for some of the
cases. The possibilities are based on past experience and on known ranges of
electrical resistivity for given subsurface conditions. The sounding loca-
tions are too far apart to rationally construct a resistivity cross-section.
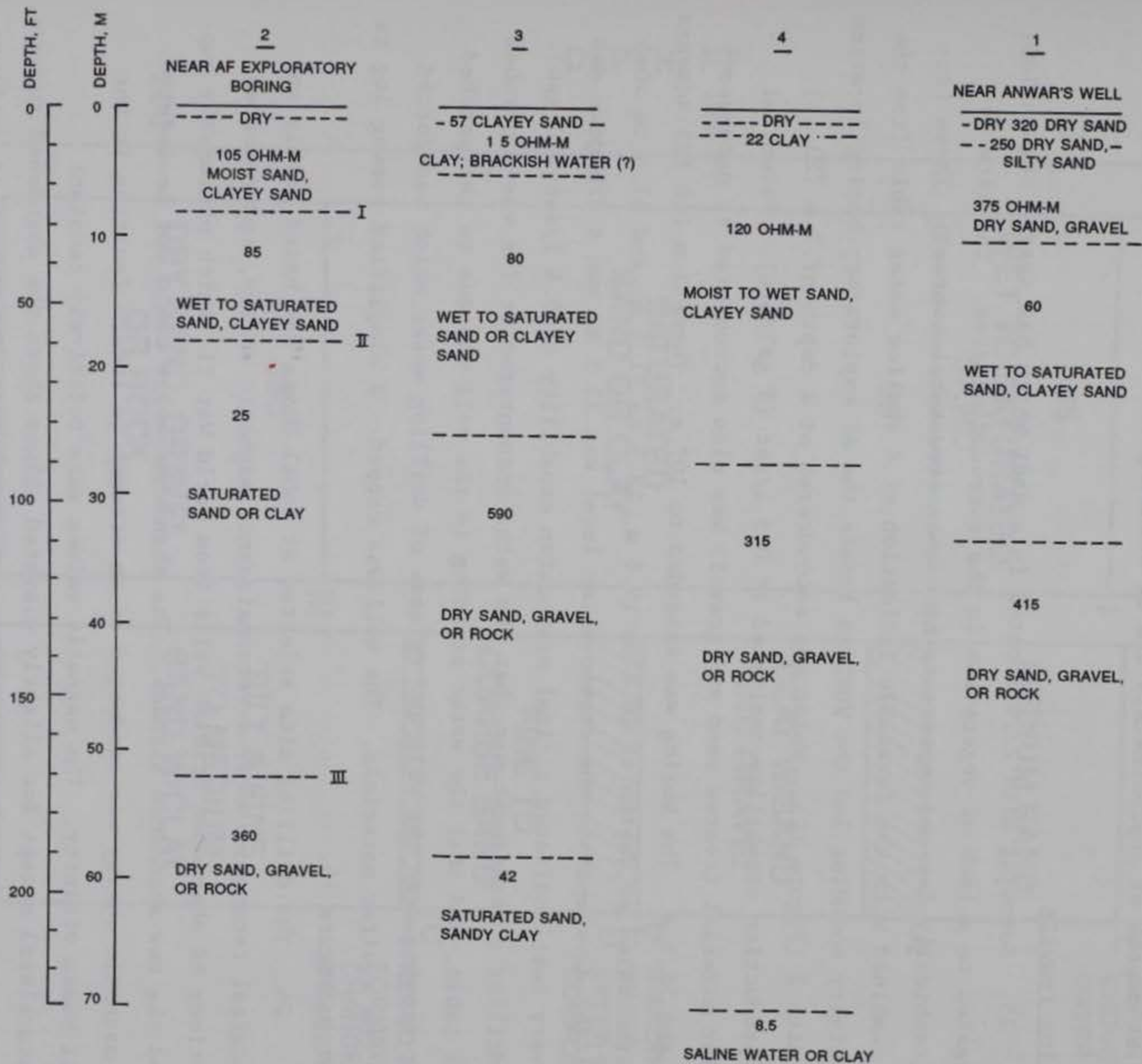However, some possible similarities between the soundings are suggested in

DEPTH, FT — DEPTH, M

2

NEAR AF EXPLORATORY
BORING

---- DRY -----

105 OHM-M
MOIST SAND,
CLAYEY SAND
----------- I

85

WET TO SATURATED
SAND, CLAYEY SAND
----------- II

25

SATURATED
SAND OR CLAY

----------- III

360

DRY SAND, GRAVEL,
OR ROCK

3

- 57 CLAYEY SAND —
1 5 OHM-M
CLAY; BRACKISH WATER (?)

80

WET TO SATURATED
SAND OR CLAYEY
SAND

590

DRY SAND, GRAVEL,
OR ROCK

42

SATURATED SAND,
SANDY CLAY

4

---- DRY ----
--- 22 CLAY · --

120 OHM-M

MOIST TO WET SAND,
CLAYEY SAND

--- --- ---

315

DRY SAND, GRAVEL,
OR ROCK

--- -- --- -
8.5

SALINE WATER OR CLAY

1

NEAR ANWAR'S WELL

- DRY 320 DRY SAND
- - 250 DRY SAND,—
SILTY SAND

375 OHM-M
DRY SAND, GRAVEL
--- -- ---

60

WET TO SATURATED
SAND, CLAYEY SAND

415

DRY SAND, GRAVEL,
OR ROCK

27

Figure 14. Electrical resistivity results (models) for the Cairo West site (see Figure 12)

Figure 14. All of the resistivity models and postulated hydrogeological models were made in the field prior to any drilling activity.

24. The interpreted interface at 10 m depth at the sounding site 1 correlates well with the recorded water table depths at the nearby Anwar's Well cluster (static water level--6.7 to 8.1 m depth; pumping water level--10.7 to 11.7 m depth). Sounding site 1 is 1 to 2 m higher in elevation than Anwar's Well. Based on the resistivity results, shallow ground water is possible at depths of approximately 8 m at sounding site 2 and 5 m at sounding site 3.

Drilling results

25. Sounding site 2 is located in a wadi which has sparse vegetation, contrasted to a lack of vegetation in the surrounding area. The site is topographically low and appears to have some structural control. These factors combined with the favorable indication of a shallow water table from the resistivity sounding led the WDRT to locate the AF exploratory boring location near site 2 (Figure 12). Water was encountered at a depth of 7 m (23 ft), with production capability estimated at 0.5 l/sec (8 gal/min). Potential aquifer material (coarse sand and gravel) was also encountered at depths of 27.5 and 36.5 m. The boring was extended to 107 m. Three 3 m (10 ft) screens were installed at depths of 16.8 to 19.8 m, 28.3 to 31.3 m, and 37.5 to 40.5 m. After development, the static water level was 33.5 m, and a drawdown and recovery test indicated a final production capability of 0.6 l/sec (10 gpm). The driller's assessment was that the water encountered at 7 m was a perched water table, and that the water standing in the well was due to the perched water flowing down the well and release of drilling water which was forced into the aquifer materials. The well was capped. A simplified boring log is shown in Figure 15.

26. The drilling site selected at Gebel Hamza was based solely on geological reconnaissance, a reconnaissance magnetic survey, and reported locations of abandoned British wells from World War II, which presumably supplied the now abandoned airbase. The abandoned wells could not be located. The magnetic survey was conducted in an attempt to locate faulting in the Gebel Hamza vicinity. The magnetic values were relatively constant (featureless) except for slightly elevated values above the abandoned runways. Figure 13 shows the site selected for the Army well. The Army well drillers
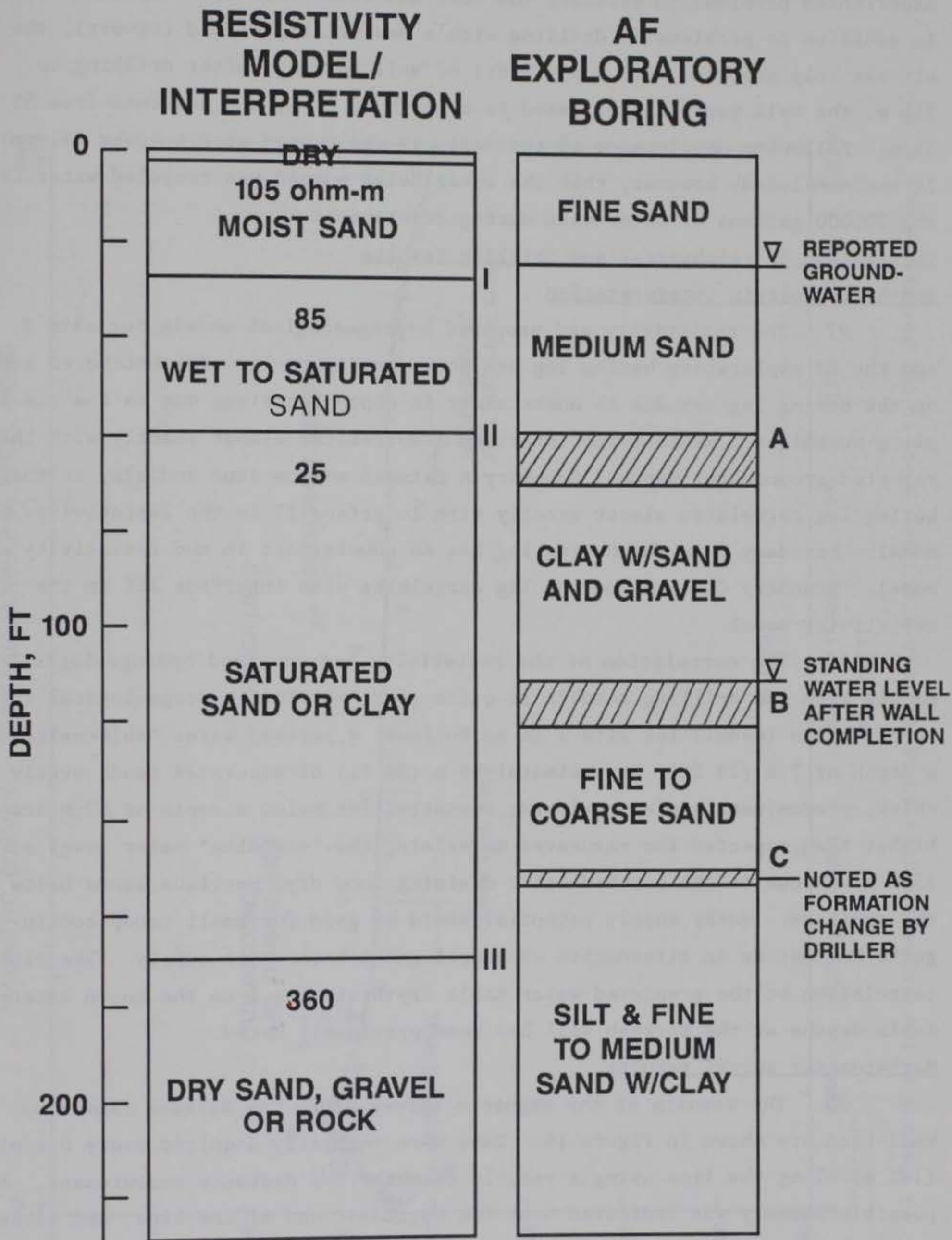
28

RESISTIVITY MODEL/ INTERPRETATION

AF EXPLORATORY BORING

Figure 15. Comparision of the in-field interpretation of the resistivity sounding at location 2 with the Air Force driller's log: the hatchured zones represent depth uncertainty on material type change

experienced problems in drilling the well and with the well completion kit. In addition to problems in drilling with a new drilling fluid (revert), the kit was only supplied with 6 m (20 ft) of well screen. After drilling to 315 m, the well was plugged, cased to a depth of 67 m, and screened from 55 to 61 m. Following development of the well, it was pumped at 0.4 l/sec (7 gpm). It was concluded, however, that the water being pumped was recycled water from the 30,000 gallons of water used during development.

Correlation of geophysical and drilling results and hydrogeologic interpretation

27. The resistivity and proposed hydrogeological models for site 2 and the AF exploratory boring log are shown in Figure 15. The hatchured zones on the boring log are due to uncertainty in depth locations due to the sampling technique. Resistivity interface I correlates almost exactly with the reported groundwater depth. Boundary A between medium sand and clay in the boring log correlates almost exactly with interface II in the resistivity model. Boundary B in the boring log has no counterpart in the resistivity model. Boundary C in the boring log correlates with interface III in the resistivity model.

28. The correlation of the resistivity and proposed hydrogeological models with the drilling results is quite good. A final hydrogeological interpretation (model) for site 2 is as follows: a perched water table exists at a depth of 7 m (23 ft); approximately 9 m (30 ft) of saturated sands overly a thick, predominantly clay aquitard; resistivities below a depth of 52 m are higher than expected for saturated materials; the "standing" water level at 33.5 m was due to the perched water draining into dry, pervious sands below the aquitard. Water supply potential would be good for small troop contingents but not as an alternative or supplemental base water supply. The close correlation of the predicted water table depth at site 1 to the known water table depths at the Berkash Well has been previously noted.

Magnetometer survey results

29. The results of the magnetic survey along the Berkash (Anwar's) Well road are shown in Figure 16. Data were initially acquired every 0.1 mi (161 m) along the line using a vehicle odometer for distance measurement. A possible anomaly was indicated near the northeast end of the line, and subsequently measurements were acquired at 30.5 m (100 ft) intervals for the first
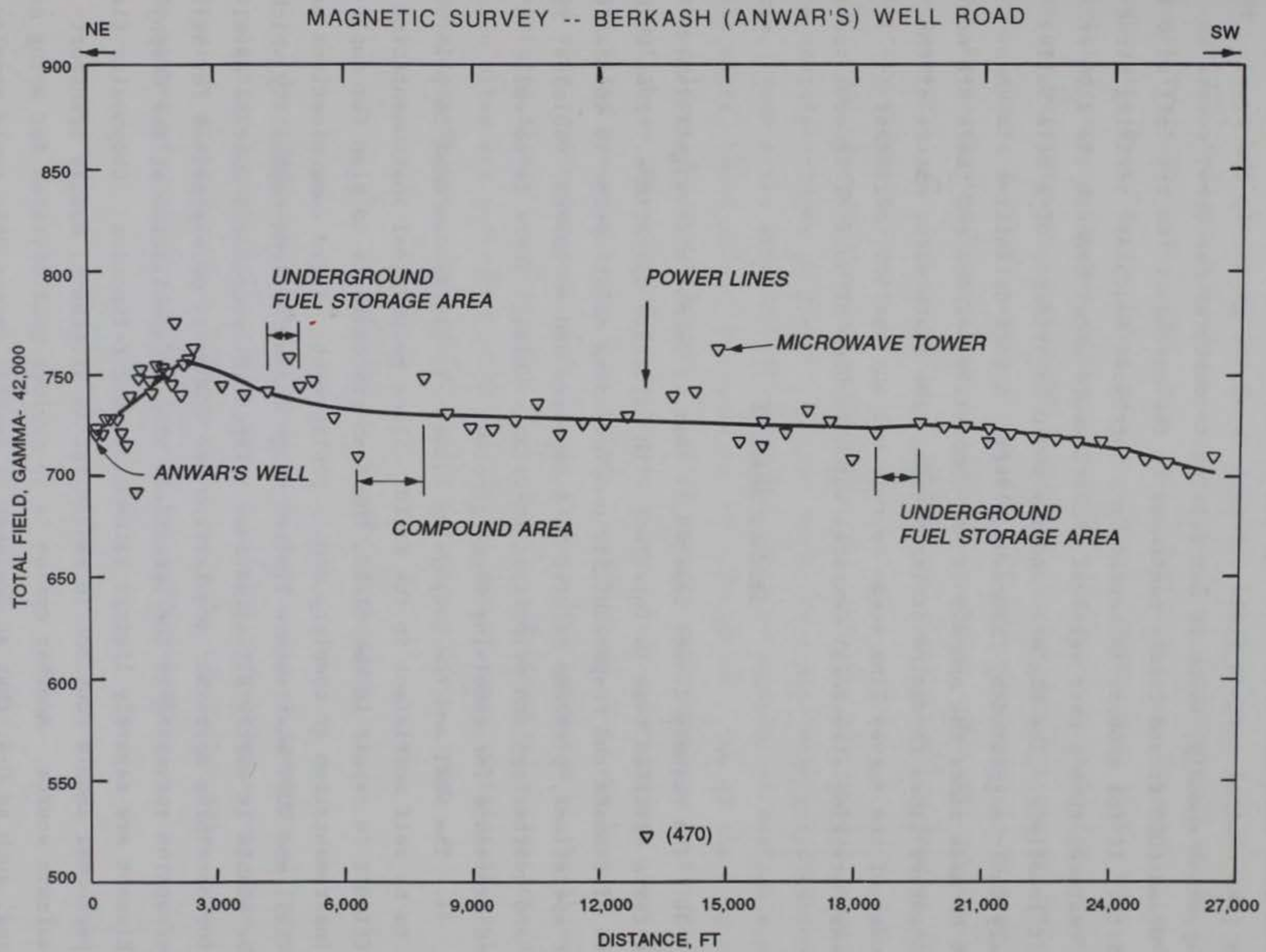
30

Figure 16. Results of the magnetic survey along the road from Cairo West to the Berkash (Anwar's) Well

805 m (0.5 mi) of the line. The data have been corrected for diurnal variations (drift). Locations of cultural features are indicated on the plot, and a smooth or "best fit" curve is shown. Except for anomalies apparently associated with cultural features, the variation along the line is less than 50 gammas (the nominal earth's field strength is 42,700 gammas in the area). The only apparent anomaly, which is not related to cultural features, occurs between 0 and 6000 ft and likely continues to the northeast (to the left of 0 in the plot). If the anomaly is caused by a northwest-southeast striking structural feature, then a near vertical contact would occur beneath the 1100 or 2200 ft locations. The magnetic anomaly could be evidence of a Nile Valley boundary fault suggested by LaMoreaux (1962). A more definitive statement cannot be made since the anomaly is not completely defined and there are no offset survey lines to define strike trends. The featureless nature of the remainder of the survey line seems to rule out any shallow, northwest-southeast striking structural features which involve offsets of igneous rocks.

Lessons Learned

30. The primary lesson learned is that it is not a straightforward matter for a civilian team to interface with military operations. Even when a chain of command and responsibility understanding exists prior to initiation of the operations, problems related to clearances and movements, vehicles, rations and quartering, and priorities inevitably arise. There is no well defined procedure for resolving these problems.

31. The WDRT and the Geophysics Element in particular must be prepared to be self sufficient in the field. Since geophysical instrumentation is difficult to repair in the field, the best procedure is to plan for duplicate instrumentation or complete module replacement. Field communications are essential, and WDRT must secure limited range communications capability which will be usable in nearly all situations. Expedient procedures must be developed for obtaining approval, acquisition and transport of explosives for seismic refraction surveying to the operations area. Capabilities of the Geophysics Element are severely limited without seismic refraction. Geophysics Element personnel should continue to search for an alternate, easily transportable seismic source. Another option is to explore possibilities for using explosives, such as C-4, that an Engineer or Special Forces Unit could provide.

PART IV: GALLANT EAGLE 86--FORT IRWIN, CALIFORNIA

Background

32. Gallant Eagle 86 was a joint services exercise held at the National Training Center (NTC), Fort Irwin, California (see Figure 17), and Twentynine Palms Marine Corps Base, California, during July 1986. WDRT activities were restricted solely to the NTC portion of the exercise. Seventeen persons participated in the WDRT deployment, as follows: WES--6; ETL/TAC--5; USGS, Denver--2; USGS, Reston--2; Office, Chief of Engineers--1; US Army Belvoir Research, Development and Engineering Center--1. The WDRT deployment was by commercial air transportation, and food and lodging was independent of the military exercise itself.

33. Personnel were divided into four teams for the initial aspects of the exercise--three geophysical survey teams and a data base verification team. Four sites were identified by the NTC base engineer as desirable water well sites, based solely on logistical considerations. Two of the four sites were relocated based somewhat on aerial imagery interpretation at ETL/TAC, and one of these two was further relocated after site reconnaissance. One of the four sites was eliminated from further consideration after the imagery study and site reconnaissance. Geophysical surveys were conducted at the three remaining sites--Langford Lake, Four Corners, and Arrowhead. Locations of the three sites are indicated in Figure 18 (portion of Trona, California, Joint Operations Graphic, JOG 1501 NI 11-2).

Geophysics Element Activities

34. Teams were formed to conduct three types of geophysical surveys: an electrical resistivity survey team; a seismic refraction survey team, and a transient electromagnetic (TEM) survey team. The tabulation below indicates the number of surveys at each site and the survey strategy:
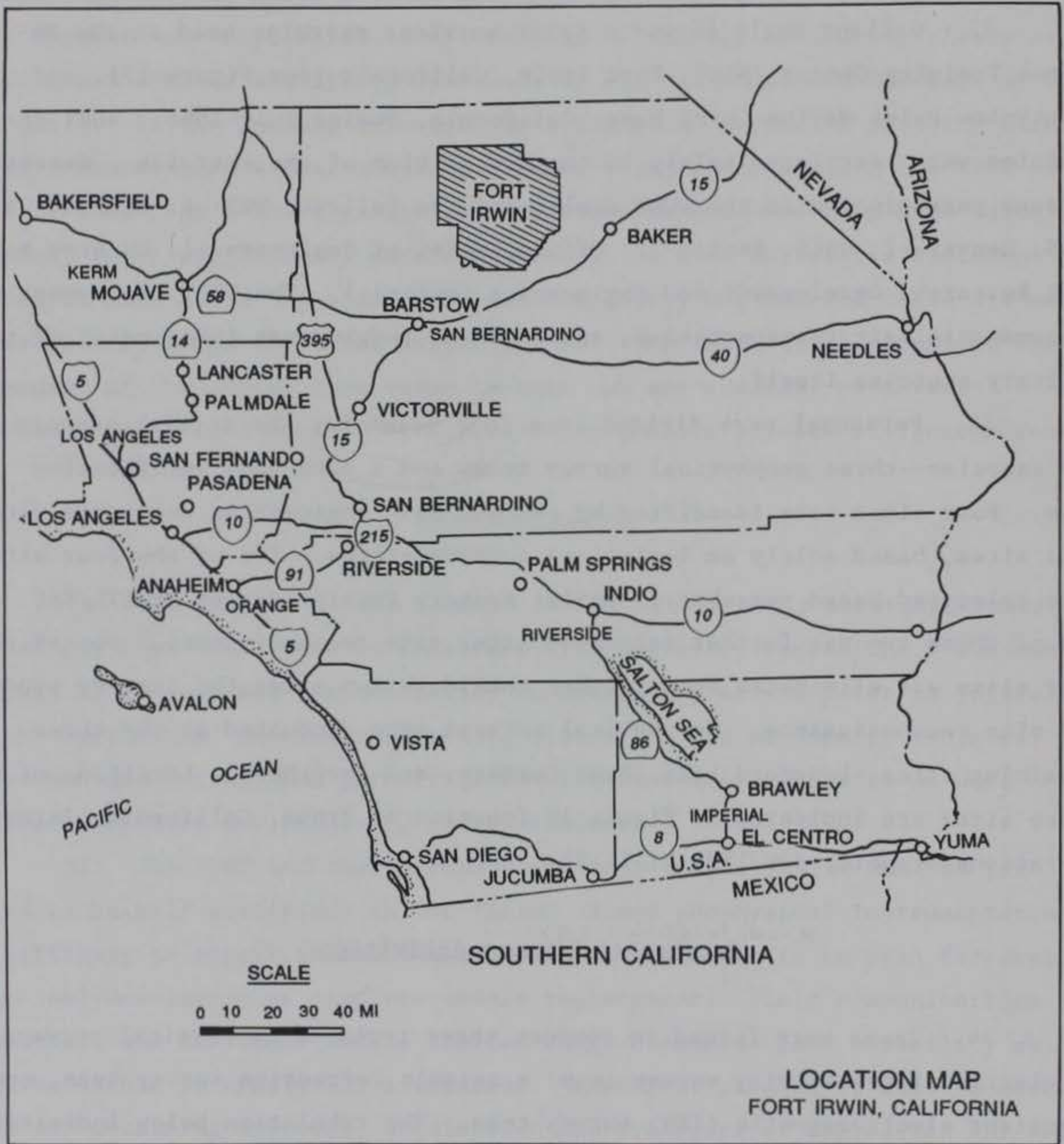
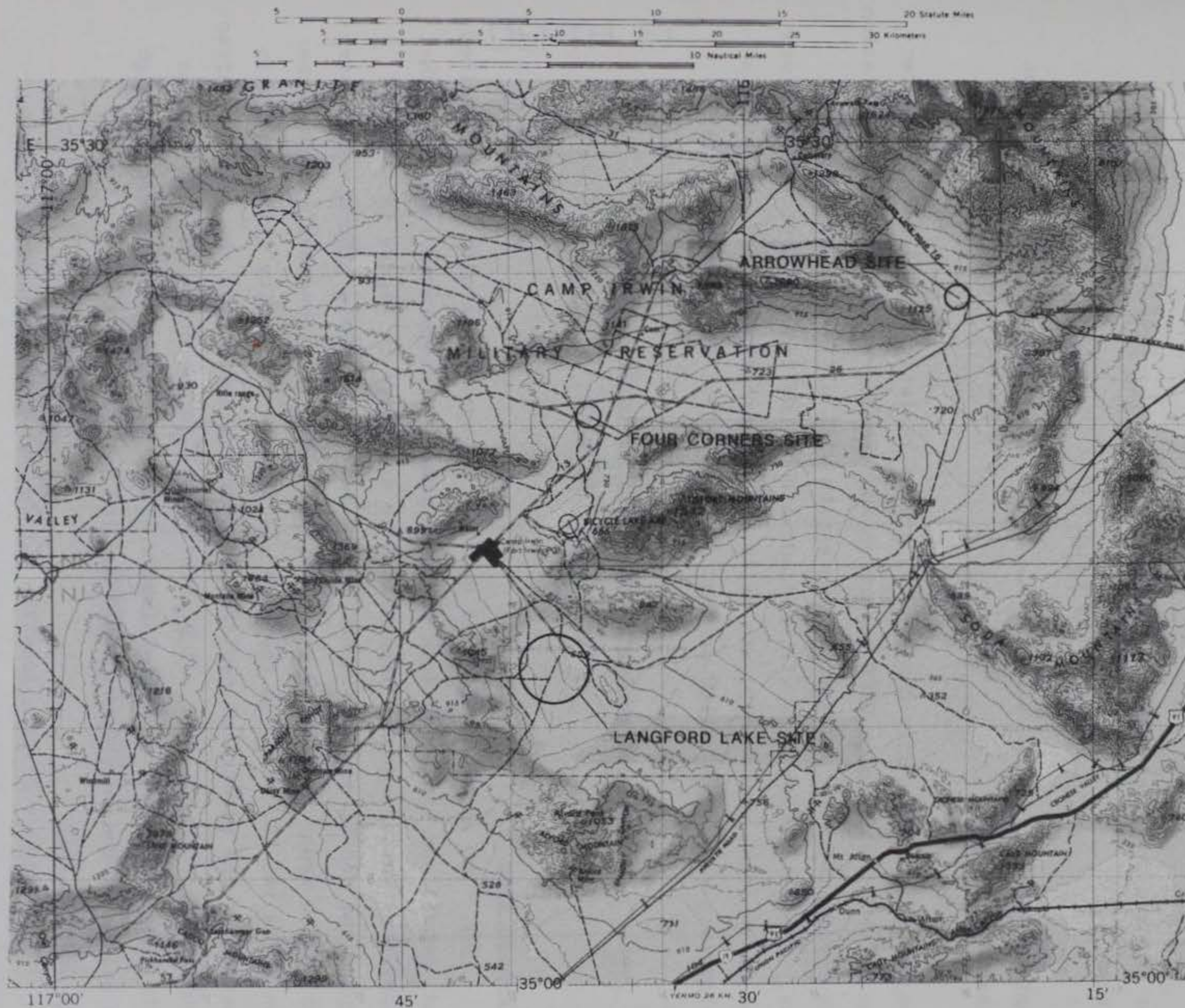Figure 17. Location map for Fort Irwin, California

Figure 18. Location map for the Langford Lake, Four Corners, and Arrowhead sites at Fort Irwin

| | Number of Geophysical Surveys | | | Survey |
Site	Refraction	Resistivity	TEM	Strategy
Arrowhead	1	1	-	Single Location
Four Corners Area	4	4	4	Profile
Langford Lake Basin	2	6	10	Basin Characterization

This report presents only the results of the resistivity and seismic refraction surveys; a separate USGS report on the TEM survey results and correlation with the resistivity and refraction results will ultimately be published. Also, the discussion here will concentrate on the results from the Langford Lake Basin area, where there are wells and exploratory borings and where an exploratory well was drilled as part of the Gallant Eagle 86 Exercise.

Survey Results, Hydrogeological Interpretations, and Drilling Results

Arrowhead site

35. The Arrowhead Site is desolate in appearance with coarse-grained sand, gravel and large boulders on the surface. Interpreted results of the geophysical surveys at the Arrowhead Site are shown in Figure 19. The geophysical models are consistent with a site with little ground water potential in the upper 140 ft (40 m). There is likely an impermeable rock formation below 140 ft, based on the high electrical resistivity value, which is detected by the electrical resistivity sounding but not by the seismic refraction survey. Ground water, if present at all in the upper 140 ft, must be quite pure (very low total dissolved solids), since the resistivity is high, and exist between the depths of 75 and 140 ft.

Four corners site

36. Figure 20 is a location map for surveys conducted in the Four Corners Area, near Bicycle Lake (Figure 18). Locations C2 and C3 are in a
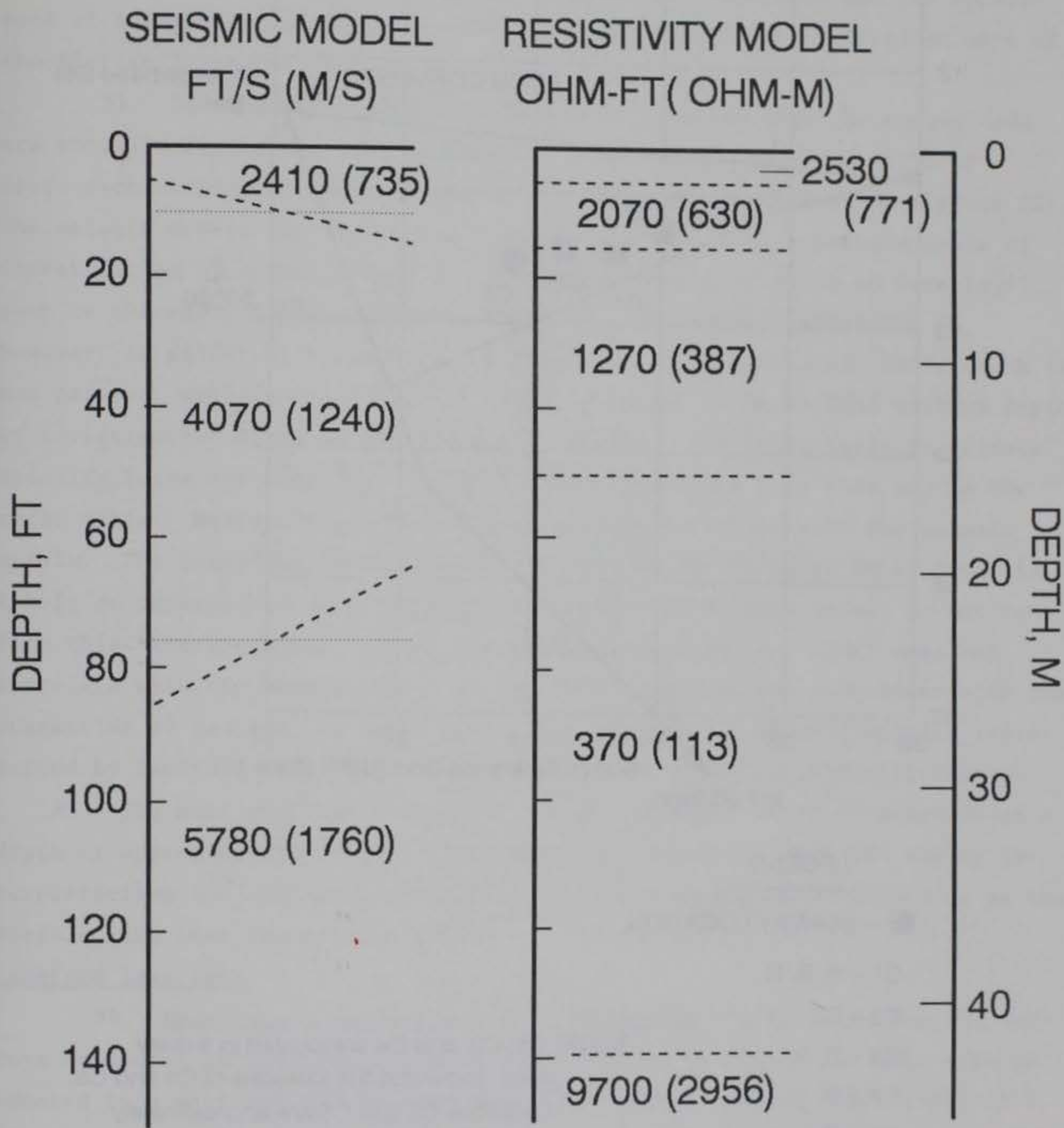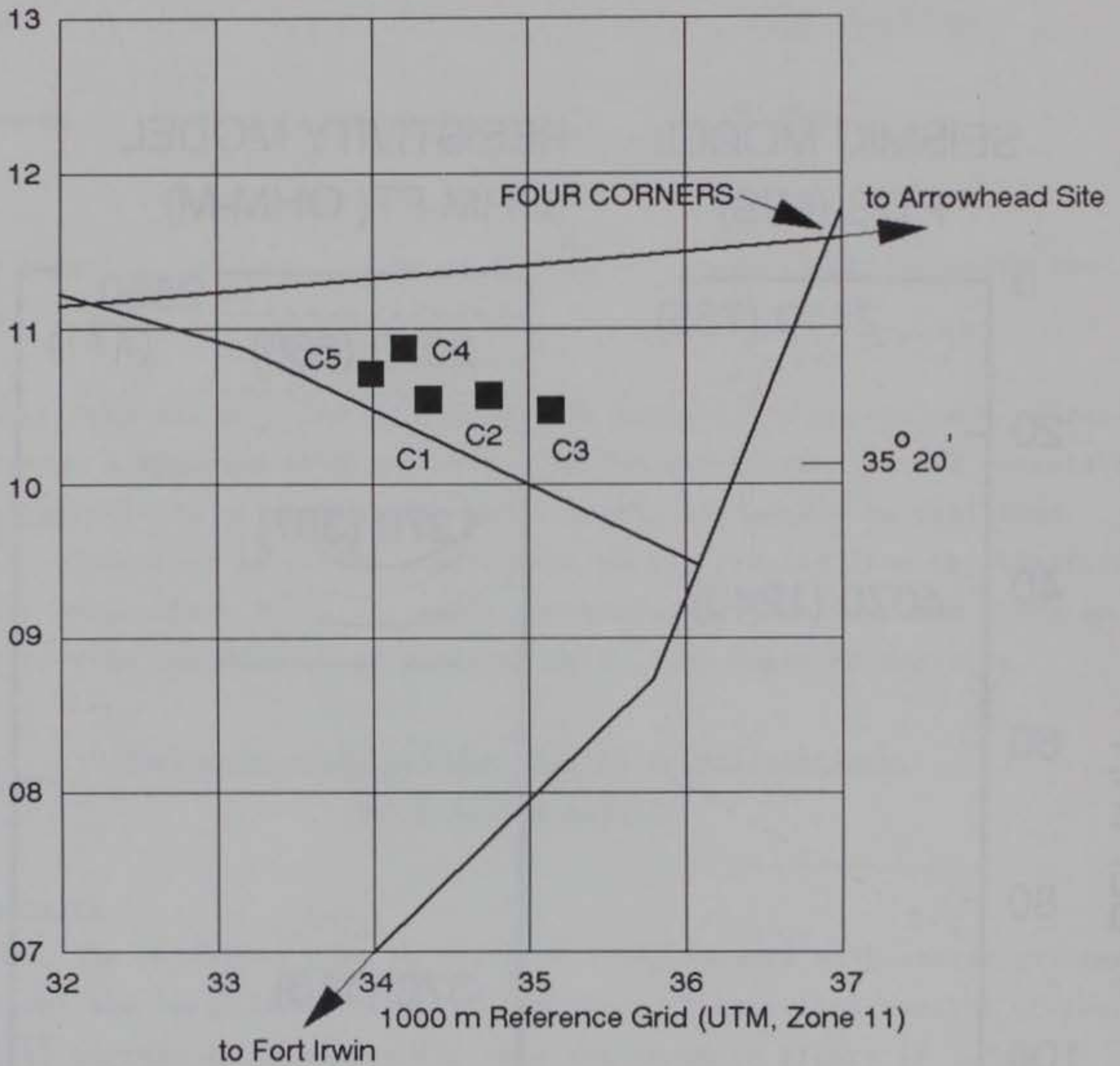
SEISMIC MODEL
FT/S (M/S)

RESISTIVITY MODEL
OHM-FT(OHM-M)

2410 (735)

4070 (1240)

5780 (1760)

2530
(771)

2070 (630)

1270 (387)

370 (113)

9700 (2956)

DEPTH, FT

DEPTH, M

0

20

40

60

80

100

120

140

0

10

20

30

40

Figure 19. Seismic velocity and electrical resistivity
interpretations (models) for the Arrowhead Site

FOUR CORNERS AREA

FOUR CORNERS → to Arrowhead Site

C5 ■ ■ C4

■ C1

■ C2

■ C3

35° 20'

to Fort Irwin

1000 m Reference Grid (UTM, Zone 11)

LEGEND:

■ -- SURVEY LOCATION

C1 -- S, R, R

C2 -- S

C3 -- S, R

C4 -- S

C5 -- R

R -- Resistivity Survey

S -- Seismic Survey

NOTE: C1, C2, and C4 are located in a draw
which separates the locations of C3 and C5.
Locations C3 and C5 are approximately
15 ft higher in elevation than C1, C2, and C4.

Figure 20. Site map for the Four Corners Area,
showing geophysical survey locations

draw or drainage channel with near-vertical banks on each side. C4 is also in a nearby drainage channel. Locations C3 and C5 are approximately 15 ft higher in elevation than the other locations and are on the areas surrounding the drainage channels. A refraction survey was not conducted at location C5 nor was a resistivity survey conducted at location C4. The site has the appearance of being structurally-controlled, and minor faulting is noted on maps of the Bicycle Basin/Lake area.

37. Seismic and resistivity models interpreted from the survey data are shown in Figure 21. The geophysical models are shown in profile or cross-section format, but note that C4 is actually out of section (Figure 20). The seismic models for C1, C2 and C3 agree closely, with a maximum depth of investigation of approximately 150 ft (maximum depth at which an interface, such as the water table, could be detected). The seismic model for C4, however, is different in nature; the interface at approximately 50 ft depth is not present, while an interface is detected at 280 ft depth (the maximum depth of investigation of C4 is approximately 300 ft). The characteristic seismic velocity below the interface at 280 ft depth indicates that this may be the water table. Resistivity models do not readily correlate with the seismic models. The interface in the resistivity models for C1/C2 at 60 ft depth is likely an impermeable rock formation, although the seismic models do not confirm this interpretation. Also, the resistivity model for C1/C2 does not correlate with the models for C5 or C3. These results are consistent with the suggestion of faulting in this area, since the lateral discontinuities represented by faulting will affect seismic and resistivity surveys differently.

38. The most positive indication for ground water is at location C4 at a depth of approximately 280 ft. This depth is consistent with TEM survey interpretations for this area and with water table depths reported nearby in the Bicycle Lake area (Montgomery 1981).
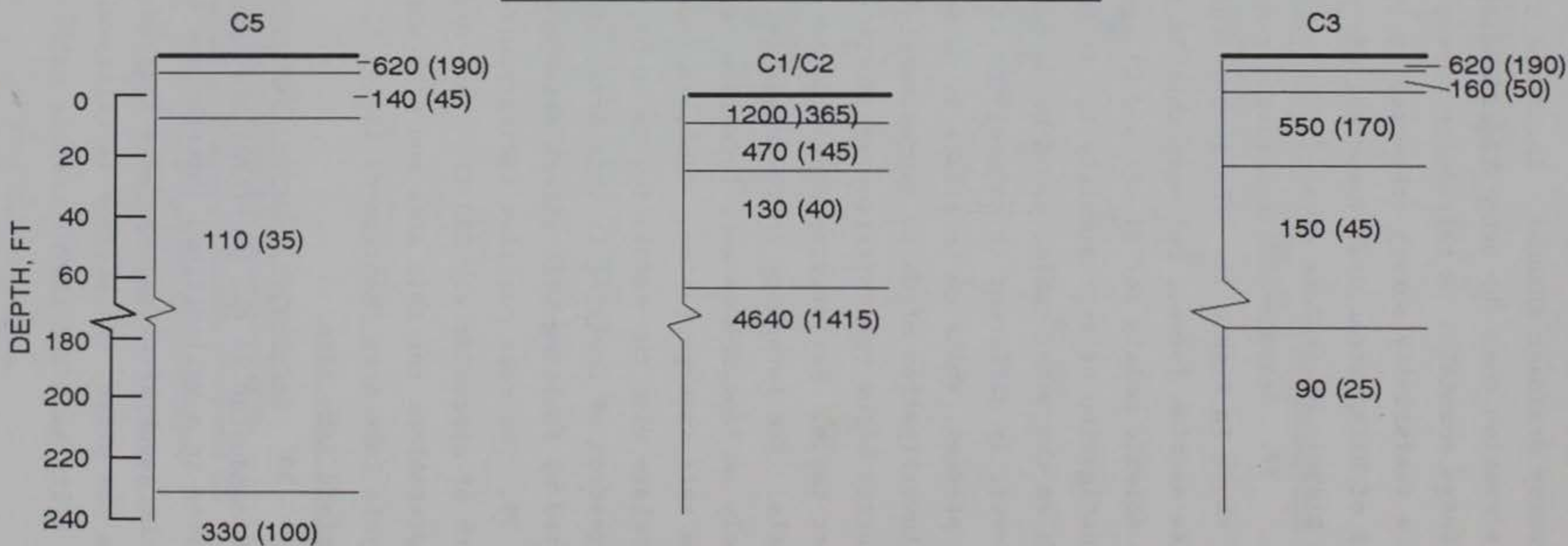
Langford lake site

39. Geophysical surveys and interpretations. A location map for surveys conducted in the Langford Lake area is shown in Figure 22. The site is located in a well-defined intermontane basin with a central playa lake. All of the geophysical surveys were located west of the Langford playa lake. Away from the playa, the surface is relatively featureless, with sparse vegetation and silty sand and gravel surface material. The Garlic Springs Fault,

SEISMIC MODELS, ft/s (m/s)

	C4	C1	C2	C3
				2200 (670)
	1450 (440)	1170 (355)	1690 (515)	3400 (1035)
	2900 (885)	3130 (955)	2680 (815)	
		4530 (1380)	3580 (1090)	4140 (1260)
	5120 (1560)			

DEPTH, FT
0
20
40
60
280
300
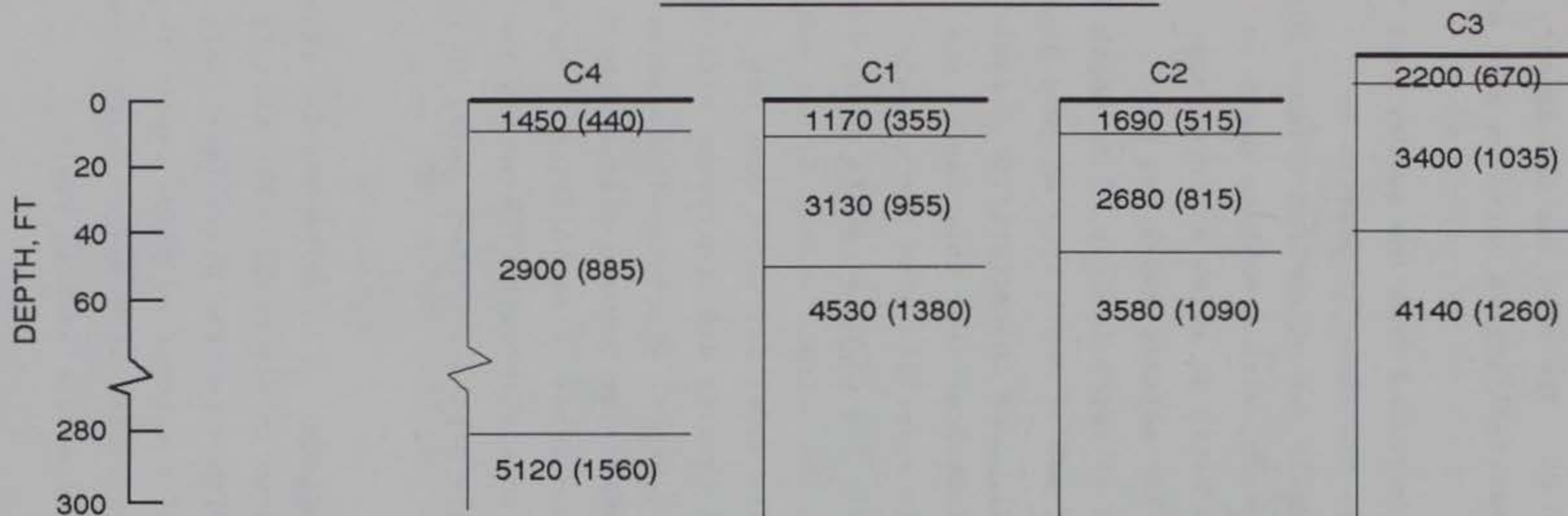
RESISTIVITY MODELS, ohm-ft (ohm-m)

C5
620 (190)
140 (45)
110 (35)
330 (100)

C1/C2
1200)365)
470 (145)
130 (40)
4640 (1415)

C3
620 (190)
160 (50)
550 (170)
150 (45)
90 (25)

DEPTH, FT
0
20
40
60
180
200
220
240

Figure 21. Seismic velocity and electrical resistivity models for the Four Corners Site
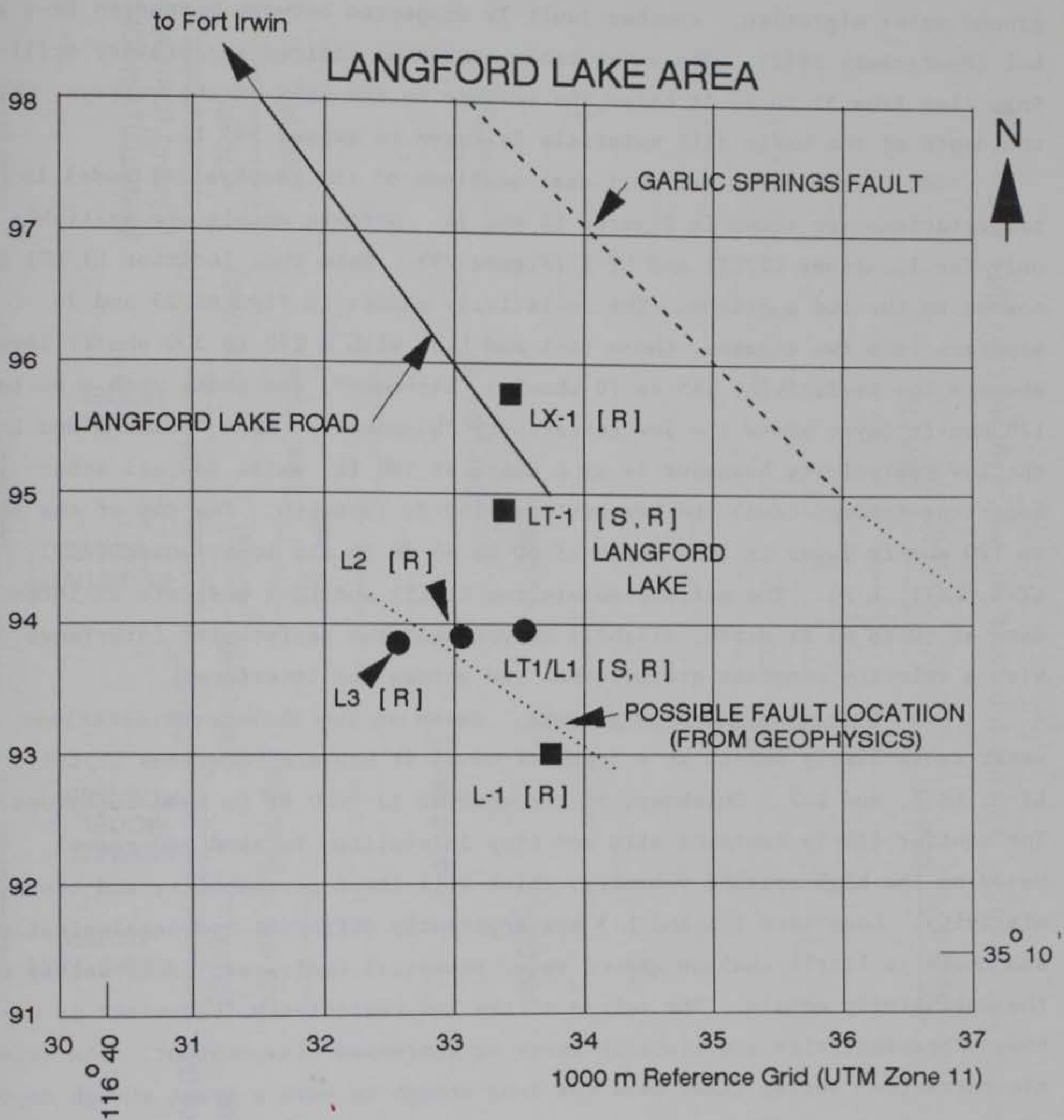
Figure 22. Site map for the Langford Lake Area,
showing the geophysical survey locations

41

Figure 22, is recent and represents a nearly impermeable barrier to lateral ground water migration. Another fault is suspected between boreholes LT-1 and L-1 (Montgomery 1981). The water table, based on limited exploratory drilling, lies from 55 to 85 ft below the surface in the area of the surveys, while the depth of the basin fill materials is known to exceed 585 ft.

40. North-south and east-west sections of the geophysical model interpretations are shown in Figures 23 and 24. Seismic models are available only for locations L1/LT1 and LT-1 (Figure 23). Note that location L1/LT1 is common to the two sections. The resistivity models in Figures 23 and 24 separate into two classes, those (L-1 and L-3) with a 290 to 300 ohm-ft layer above a low resistivity (45 to 70 ohm-ft) "basement", and those with a 90 to 120 ohm-ft layer above the low resistivity "basement". Also, for L-1 and L-3, the low resistivity basement is at a depth of 180 ft, while for all other locations (except LX-1) the basement is >250 ft in depth. The top of the 90 to 120 ohm-ft layer is at a depth of 40 to 65 ft in all locations (L1/LT1, LT-1, LX-1, L-2). The seismic models for L1/LT1 and LT-1 indicate an interface at 60 to 65 ft depth, slightly deeper that the resistivity interfaces, with a velocity contrast greater than two across the interface.

41. Hydrogeological assessment. Based on the above considerations, a water table likely exists at a depth of 40-65 ft beneath locations L1/LT1, LT-1, LX-1, and L-2. Thickness of the aquifer is >200 ft in some locations. The aquifer likely contains silt and clay in addition to sand and gravel, based on the high seismic velocity, which will limit permeability and transmissivity. Locations L-1 and L-3 are apparently different hydrogeologically, and there is little shallow ground water potential indicated, based solely on the resistivity models. The nature of the low resistivity "basement" is unknown; possibilities are brackish water or increased clay content. The seismic refraction survey lines were not long enough to have a great enough depth of investigation sufficient to detect this interface. The different character of the resistivity models for L-1 and L-3 compared to the other locations is consistent with a possible fault striking SE-NW between L-1 and LT-1 (Montgomery 1981).

42. Drilling results. Prior to Gallant Eagle 86, there were three exploratory wells in Langford Basin: L-1, completed in 1954; LT-1, completed in 1980; LX-1, completed in 1980 (Montgomery 1981). Based on periodic
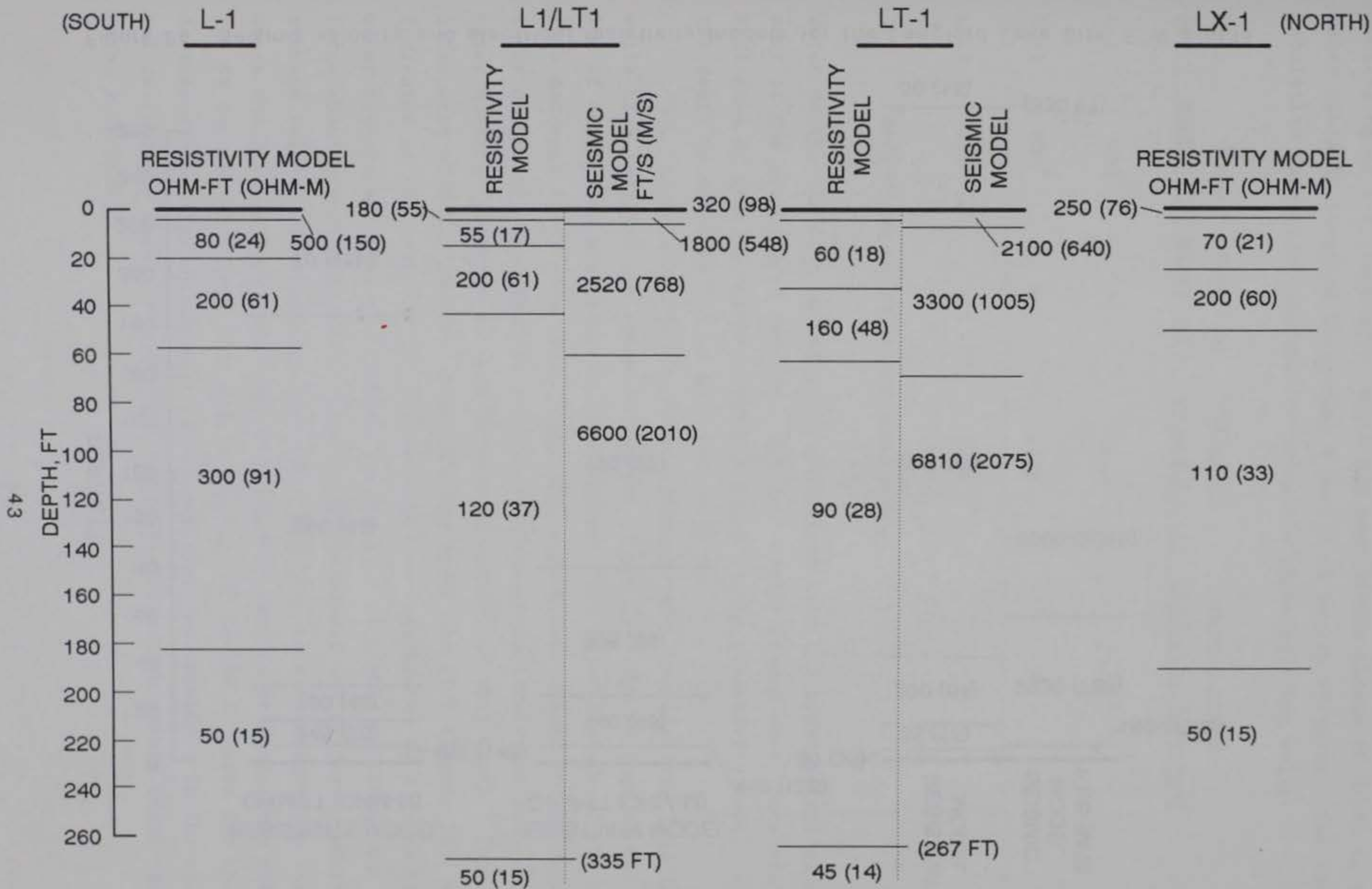
42

Figure 23. Seismic velocity and electrical resistivity models for the Langford Lake Site, N-S profile
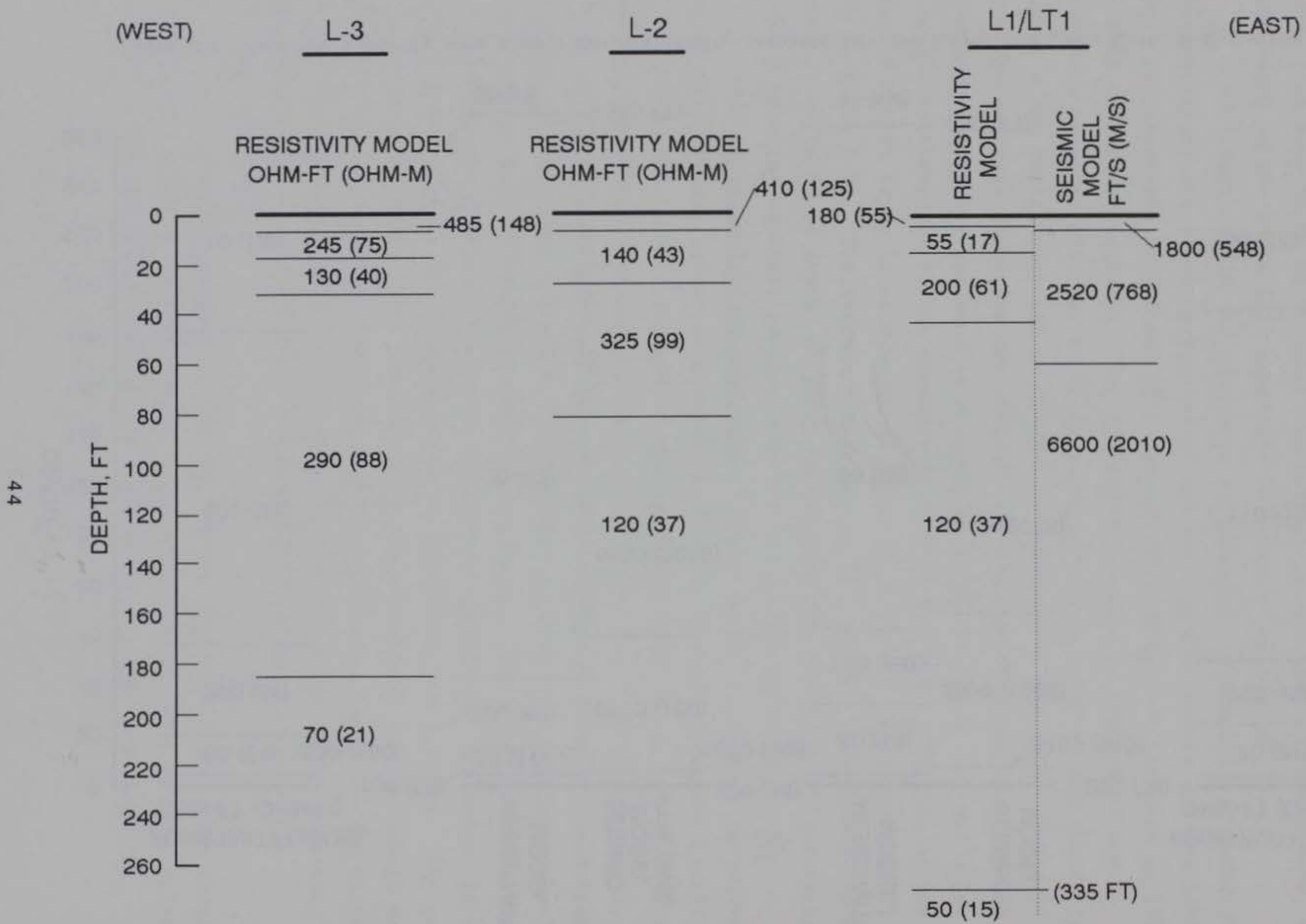
Figure 24. Seismic velocity and electrical resistivity models for the Langford Lake Site, E-W profile

monitoring of L-1 since 1954, there has been little change in depth to the
water table in Langford Basin over a period of nearly 30 years. The following
tabulation summarizes information about the three existing wells:

Well No.	Total Depth (ft)	Depth to Water (ft)	Specific Yield Est. (%)	Permeability Estimates (gpd/ft²)
L-1	500*	85	14.4	25-80
LT-1	600*	60	16.6	7
LX-1	585*	55	19.2	---

*Bedrock or basement not encountered.

Water depths for LT-1 and LX-1 are consistent with the hydrogeological assess-
ment of the geophysical results. For L-1, little ground water potential was
indicated at shallow depths (<100 ft) based on the resistivity model, while
the depth to water in L-1 is measured at 85 ft.

43.   Lithologic, spontaneous potential (SP), and electric logs for
wells LT-1 and LX-1 are shown in Figures 25 and 26. The SP logs do not show a
lot of definition attributable to lithology. The major feature of the SP log
is a decrease in SP with depth. For LT-1 a prominent change in the decrease
in SP occurs at approximately 270 ft; this change is likely due to a change in
water quality (increase in total dissolved solids) at this depth. This corre-
lates well with the electrical resistivity model for LT-1 (Figure 23), which
indicates an interface at 267 ft that could be interpreted as a fresh-brackish
water transition. The resistivity log for LT-1 is highly variable, but oscil-
lates about a nearly constant value to approximately 450 ft depth, where the
average resistivity increases by a factor of two; this correlates to the depth
where the lithology changes from predominately sand to predominantly gravel.
The SP log for LX-1 indicates nearly constant SP to 180 ft depth and then
decreases steadily, which again correlates with the interface in the electri-
cal resistivity model at that depth (interpreted as a possible fresh-brackish
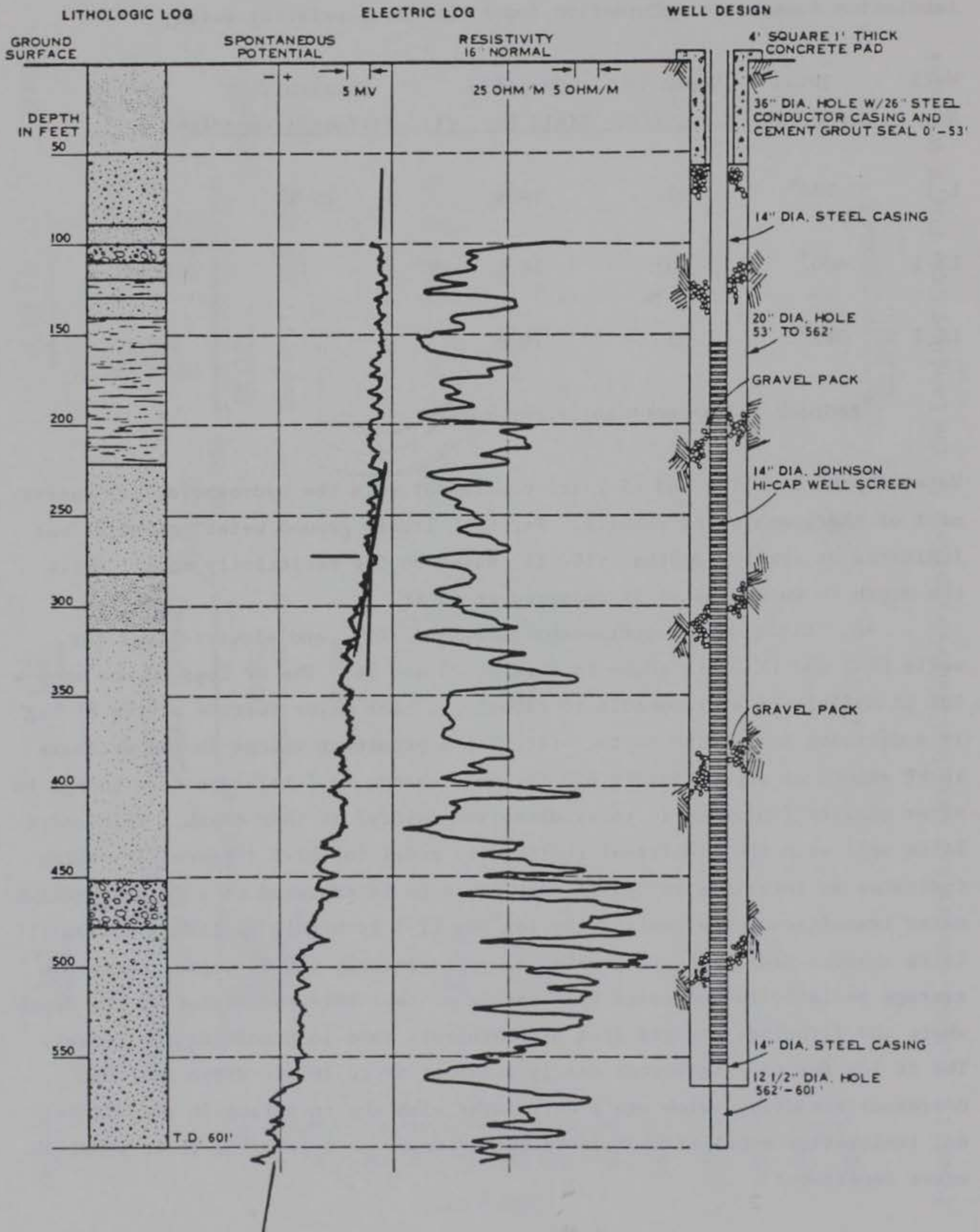water interface).

Figure 25. Lithologic log, geophysical logs, and well design information for LT-1
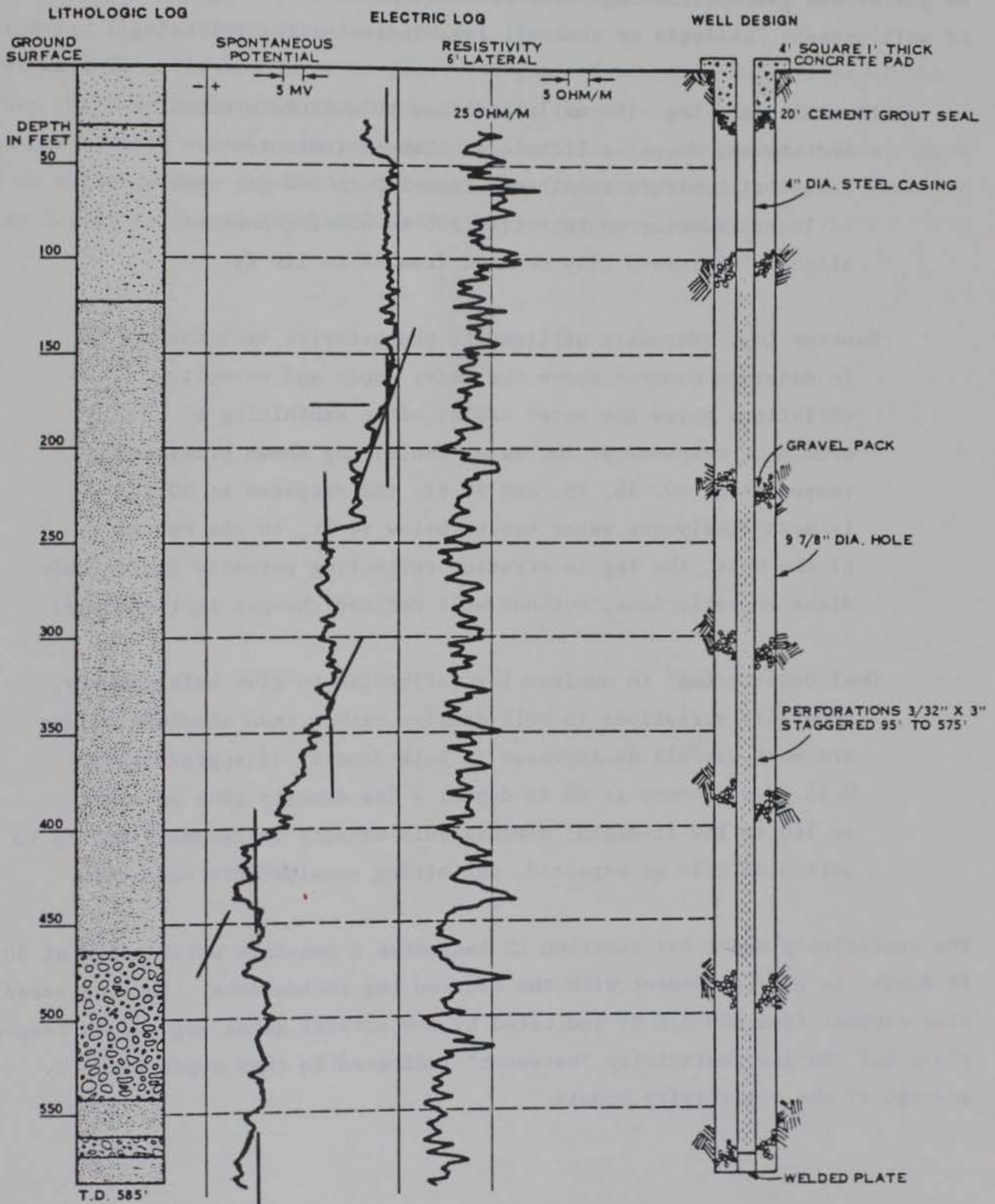
Figure 26. Lithologic log, geophysical logs, and well design information for LX-1

44.   Subsequent to the WDRT geophysical surveys at Langford Lake, an
Air Force Drilling Unit, assisted by an Army Unit, drilled a test well at
location L2 which is designated as well LT-2. The well was drilled to a depth
of 514 ft and geophysical logs were obtained prior to casing and installation
of well screen. Analysis of the well logs indicates the following:

> Natural Gamma Log: (Normally utilized to delineate clays
> and shales) No major lithologic changes indicated;
> Relatively uniform conditions from 120 to 300 ft; zone
> of increased clay content from 300 to 370 ft; zone of
> slightly decreased clay content from 90 to 110 ft.

> Neutron Log: (Normally utilized to characterize variations
> in moisture content above the water table and porosity
> variations below the water table, often exhibiting a
> prominent response at the water table) Log shows prominent
> responses at 40, 55, 75, and 90 ft; the response at 90 ft
> is most likely the water table; below 90 ft, to the bottom
> of the hole, the log is erratic, reflecting porosity and/or hole
> diameter variations, but not well defined changes in lithology;

> Dual Density Log: (A nuclear log calibrated to give bulk density,
> generally variations in bulk density rather than absolute values
> are most useful) An increase in bulk density of approximately
> 0.15 g/cm^3 occurs at 60 ft depth; a low density zone exists
> at 140 to 160 ft depth; overall bulk density increases from top to
> bottom of hole as expected, exhibiting considerable variation.

The resistivity model for location L2 indicates a possible water table at 80
ft depth, in good agreement with the neutron log indications. The increased
clay content from 300-370 ft indicated by the natural gamma log may be respon-
sible for the low resistivity "basement" indicated in that depth range by
several of the resistivity models.

48

45.   <u>Langford basin ground-water potential</u>.   Ground water is present
in Langford Basin at depths of 50 to 90 ft in the central portion of the
basin.   Maximum depth of the basin fill material exceeds 600 ft, indicating a
saturated thickness greater than 500 ft.   Production potential of the LT-2
test well is estimated to be at least 200 gpm.   Production capacities of the
other three wells are 350 to 400 gpm.   While there is evidence of faulting in
the basin which could exert some control over lateral ground water flow, there
is no evidence from the drilling results or the geophysical surveys of massive
clay layers or lenses that would effect resource development.

PART V: BRIGHT STAR 87 -- SOMALIA

Background

46. During the period 7-8 August 1987 personnel of the US Army's Water
Detection Response Team (WDRT) conducted a geophysical survey in Balli Doogle,
Somalia, in support of an Army well drilling unit. The WDRT deployment and
well drilling were associated with the Bright Star 87 Exercise. Balli Doogle
is located approximately 65 miles northwest of Mogadishu, the country's capi-
tal (Figure 27). Four personnel from ETL/TAC and four from WES participated
in the WDRT exercise.

47. The objective of the geophysical surveys was to determine the
depth to the water table or to any potential water-bearing formations. This
information will be used in the future by an Army well drilling team to aid
them in placing a well at this location. Water from this well will be used to
support personnel at a nearby US Army Special Forces camp, denoted as the
Spector Base Camp in Figure 28.

48. The test area is located on the relatively flat alluvial plain of
the Wabi Shabeelle. The vegetation consisted of thorny savannah/thorny forest
cover which hindered the layout of the survey lines. Bedrock consists of lime-
stones, marl sands, sandstone, and gypsum of Miocene and Pliocene age. A 425
ft deep boring in the vicinity of the site indicated a static water level of
195 ft.

Geophysical Survey Results

49. A sketch map of the geophysical survey lines is shown in Figure
28. Figure 29 presents a comparison between the seismic refraction and
electrical resistivity models for the Balli Doogle site. Both models indicate
four zones. The upper three zones in the refraction model, ranging in velocity
between 710 and 3760 fps, are interpreted as consisting of unsaturated over-
burden materials. The layer encountered at an approximate depth of 150 ft with
a velocity of 10,450 is indicative of bedrock. The top layer with a resis-
tivity of 414 ohm-ft is indicative of dry overburden material. The second
layer with a resistivity of 27 ohm-ft is interpreted as being moist and/or

Figure 27. Vicinity map for Mogadishu and Balli Doogle, Somalia
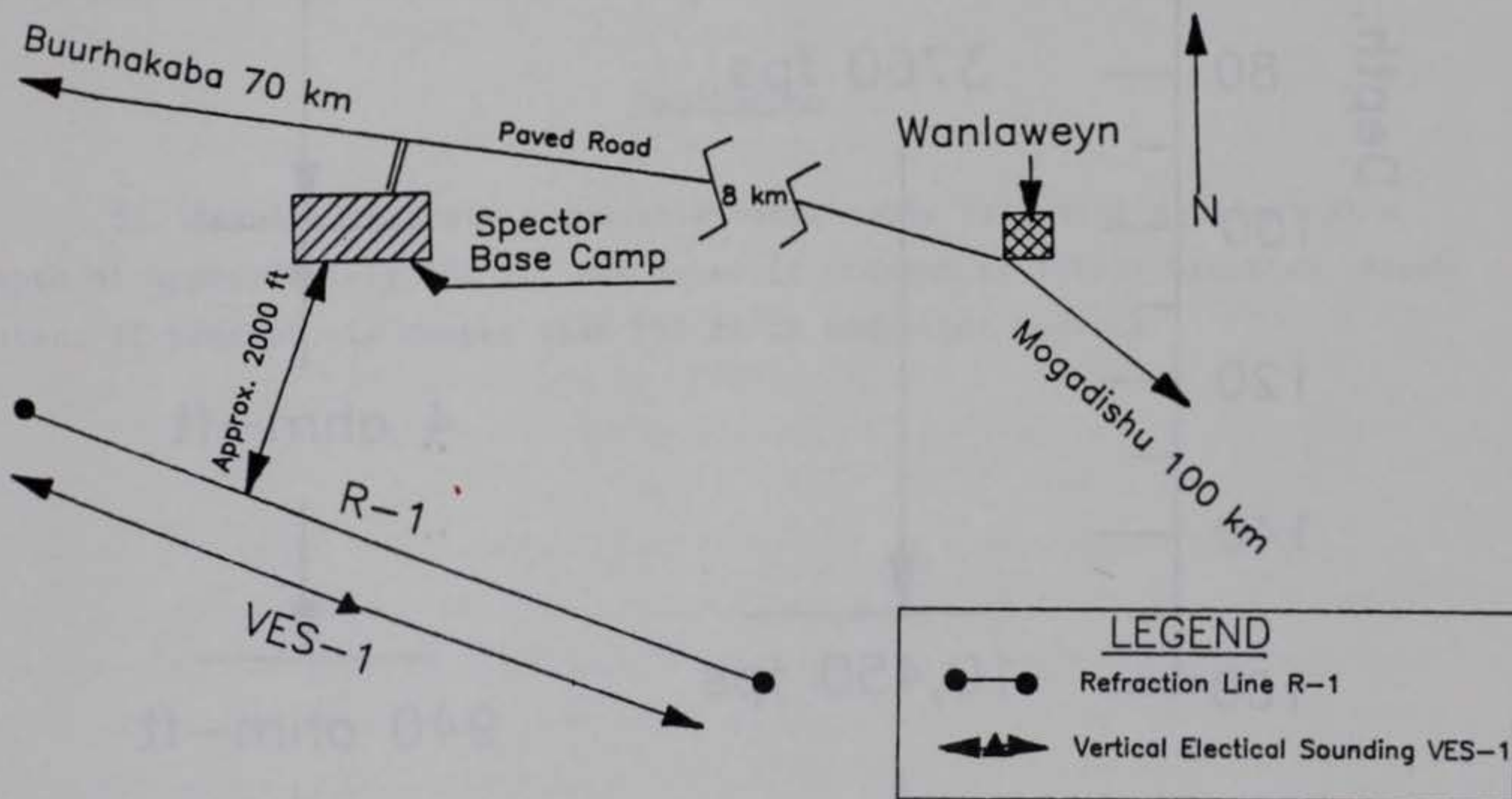
NOTE: SKETCH NOT TO SCALE

Figure 28. Site map for geophysical surveys near the
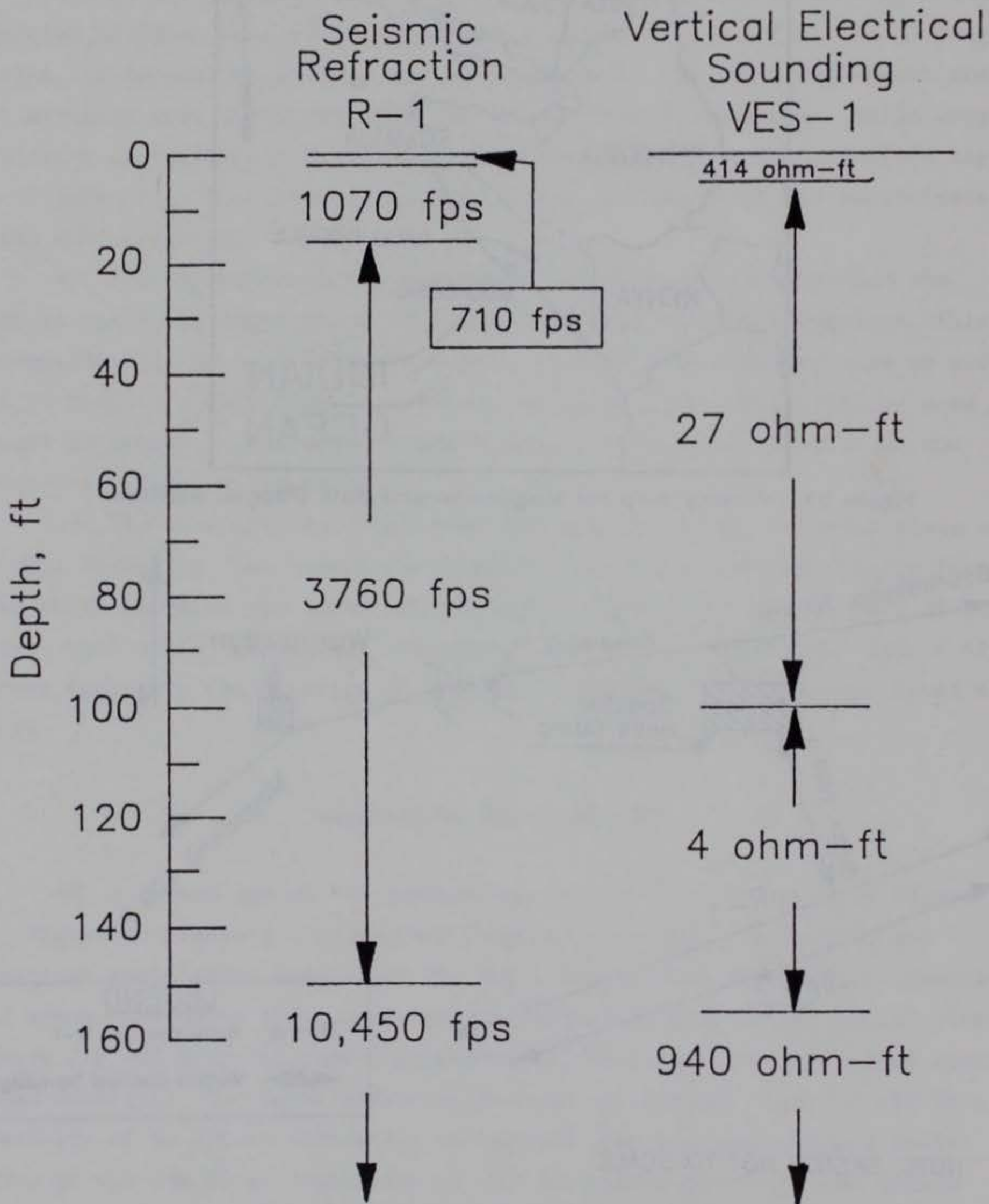Special Forces (Spector) Base Camp, Somalia

Figure 29. Seismic velocity and electrical resistivity models for surveys
conducted near the Special Forces camp

clayey overburden materials. The zone encountered at an approximate depth of 101 ft with a resistivity of 4 ohm-ft is interpreted to be either a clay layer or a layer of brackish water overlying bedrock.

50. There are at least two possible explanations for the differences between the interpreted refraction and resistivity models regarding the detection of a water table. The first possibility is that the interpreted water table does not exist (i.e., the layer is clay). Due to the "noisy" nature of the resistivity data the resistivity inversion computer program did not converge very well and therefore the thicknesses and/or resistivities might not be indicative of the true nature of the site. The second possibility for the difference is that the water table does exist as indicated by the resistivity sounding but was not resolved by the seismic refraction test. One inherent weaknesses or drawback of the seismic refraction technique is its inability to detect relatively thin layers. This effect is known as the blind zone problem. Calculations indicate that in order for the water table (5000 fps layer) to be detected, in this particular case, it would have to be greater than 60 ft in thickness. Referring to Figure 29 it can be seen that there is a possibility of the existence of a blind zone, since the resistivity sounding data indicates a possible 54 ft thick water layer.

Conclusion

51. Results indicate a possible water table (alluvial Aquifer) at a depth of approximately 101 ft; the water if present is likely brackish. Fresh water, if present, is deeper than 155 ft in competent bedrock.

PART VI: SUMMARY AND CONCLUSIONS

52. The Geophysics Element of the WDRT has demonstrated the utiliza-
tion of surface geophysical methods for siting water wells. Generally, the
operating scenario of the WDRT is to characterize the ground water potential
of an area of interest to the maximum extent possible utilizing existing data
sources. If the existing data is considered sufficient, water well drilling
sites will be prioritized. If existing data is insufficient, the Geophysics
and/or the Supporting Specialists Elements may be deployed to the area of in-
terest to collect additional information. The Geophysics Element is equipped
to conduct seismic refraction, electrical resistivity, and VLF electromagnetic
surveys. Sites for water well drilling have been successfully located during
several military exercises.

53. Some of the problems that have been identified and/or encountered
with the organization and operation of the WDRT are:

a. Difficulties in recruiting civilian volunteers for deployment to
area of operations in time of conflict;

b. Difficulties with clearances for short response time out-of-
country deployment;

c. Lack of clear chain of command for civilians during military
operations resulting in lack of logistical and other necessary support;

d. Inability to secure funding for the Geophysics Element for dedi-
cated equipment acquisition and for maintaining a state of readiness;

e. Inability to pursue the assessment of new geophysical technology
and automation of the field data acquisition and interpretation.

Resolution of these problems is currently being addressed. Present plans are
to transition the field deployment role of the WDRT to active or reserve
military units, which will eliminate many of the problems related to civilians
in the theatre of operations. A research and development work unit was
recently initiated which directly addresses issues of concern and interest to

the WDRT. The work unit considers techniques for automating the acquisition and interpretation of geophysical data for location of ground water. Also, the work unit considers the necessity of integrating various types of geoscience data for assessment of ground water potential of an area of interest.

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APPENDIX: MILITARY REQUIREMENTS FOR GEOPHYSICAL

GROUND WATER DETECTION AND EXPLORATION[*]

MILITARY REQUIREMENTS FOR GEOPHYSICAL GROUND WATER

DETECTION AND EXPLORATION

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Abstract

Adequate water supply is a critical requirement for support of
military operations in arid and semi-arid regions and for fixed military
bases. Ground water exploration typically will utilize all available
information to aid the interpretation of geophysical survey data and
produce an integrated assessment for an area. Situations are envisioned,
however, in which little or no supplementary information will be available
to aid or constrain the interpretation of geophysical survey data.
For this latter case, information about ground water table depth, aquifer
thickness, and water quality is required expeditiously at selected,
perhaps widely separated, locations. Ground water detection is a termin-
ology properly applied to rapid ground water assessments at selected,
widely-spaced locations. Case histories are presented illustrating
both ground water exploration and detection. A ground water detection
study at five locations on White Sands Missile Range, New Mexico, illu-
strates the application of seismic refraction, electrical resistivity,
loop-loop low induction number electromagnetic (EM), and transient EM
methods. Results of the geophysical methods are compared to known geo-
hydrological conditions.

Background

Ground water detection methodology is the subject of several research
projects at the U. S. Army Engineer Waterways Experiment Station (WES).
The methodology comes under the field of military hydrology, which is
a specialized field of study dealing with the effects of surface and
subsurface water on the planning and conduct of military operations.
Responsibility for management of a Military Hydrology Research Program
was assigned to WES by the Office, Chief of Engineers. Ground water
detection is part of the water supply thrust area; other thrust areas
are weather-hydrology interactions, state of the ground, and streamflow.

There is no device or black box that can be set on the ground at a given location and, with just the press of a button, determine with a 95-percent probability that potable ground water is present at a depth of X feet. Even in the foreseeable future, there is little likelihood that such a device will be available either in this country or elsewhere. In the majority of cases, ground water is usually detected as a matter of course in field investigations not specifically intended for ground water exploration. A Ground Water Detection Workshop was held at WES in January 1982. It was attended by Department of Defense representatives interested in improving military capability to develop and exploit local water sources to support military operations in arid regions. 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 need for ground water detection capability, 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 something closer to the desired capability than the near-term methodology.

Geohydrological Models

Geophysical exploration for ground water refers to surface remote sensing techniques as shown in Figure 1. The objective of the geophysical surveys in ground water exploration is the determination of subsurface structural or stratigraphic indicators of the presence of ground water

I. Direct Methods

    A. Drilling
    B. Surface Reconnaissance

II. Indirect

    A. Aerial/Satellite Remote Sensing Methods
        Objectives: Structural, Geomorphic, and Vegetative
                  Surface Indicators of Ground Water
                  Occurrence.
    B. Surface Remote Sensing (Geophysical) Methods
        Objectives: Structural, Stratigraphic, and Aquifer
                  Property Subsurface Indicators of Ground
                  Water Occurrence.

Figure 1. Methods for ground water exploration

or the measurement of a parameter that is an actual physical property of the aquifer itself. The indicators are indirect clues to the presence of ground water. A physical property of the aquifer itself could be a more direct clue of the presence of ground water. It is important to be aware of the various ways in which usable quantities of ground water may occur in the subsurface. Ground water occurrence can be illustrated by models which illustrate unconfined aquifers (Figures 2 and 3), confined aquifers (Figure 2), perched water (Figure 3), and water which is concentrated along fracture zones in otherwise nearly impervious rock (Figure 4). As suggested by Figures 2, 3, and 5, more than one of the above models or conditions will more than likely occur at a given site.

Detection Versus Exploration

Geophysical methods are routinely used throughout the world in exploration programs for the assessment and development of ground water resources. The geophysical methods that are predominantly used in these ground water 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 of the methods are used in a complementary approach. A geophysical ground water exploration program will normally 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.

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 ground water exploration assessment. Figure 6 is an example of the use of the seismic refraction method to delineate a buried channel in an arid region in western Kansas; identification of material type was made by correlation with exploratory borings near each end of the profile. In this example, the water table was actually detected by the occurrence of the characteristic seismic velocity (to be discussed later in this paper) 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.

The expression "ground water detection," in contrast to ground water exploration, applies to the concept of actually 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. It is envisioned, however, that many times the geophysical ground water surveys would be conducted
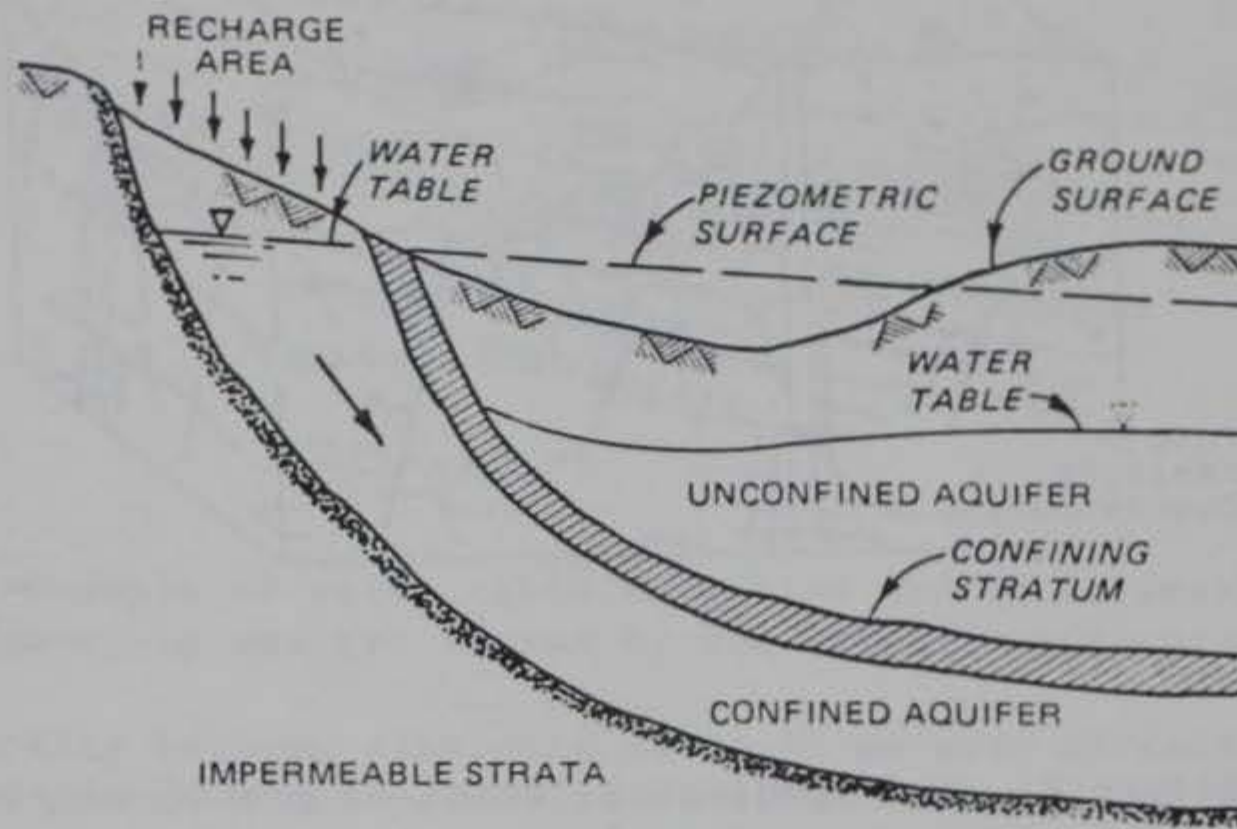
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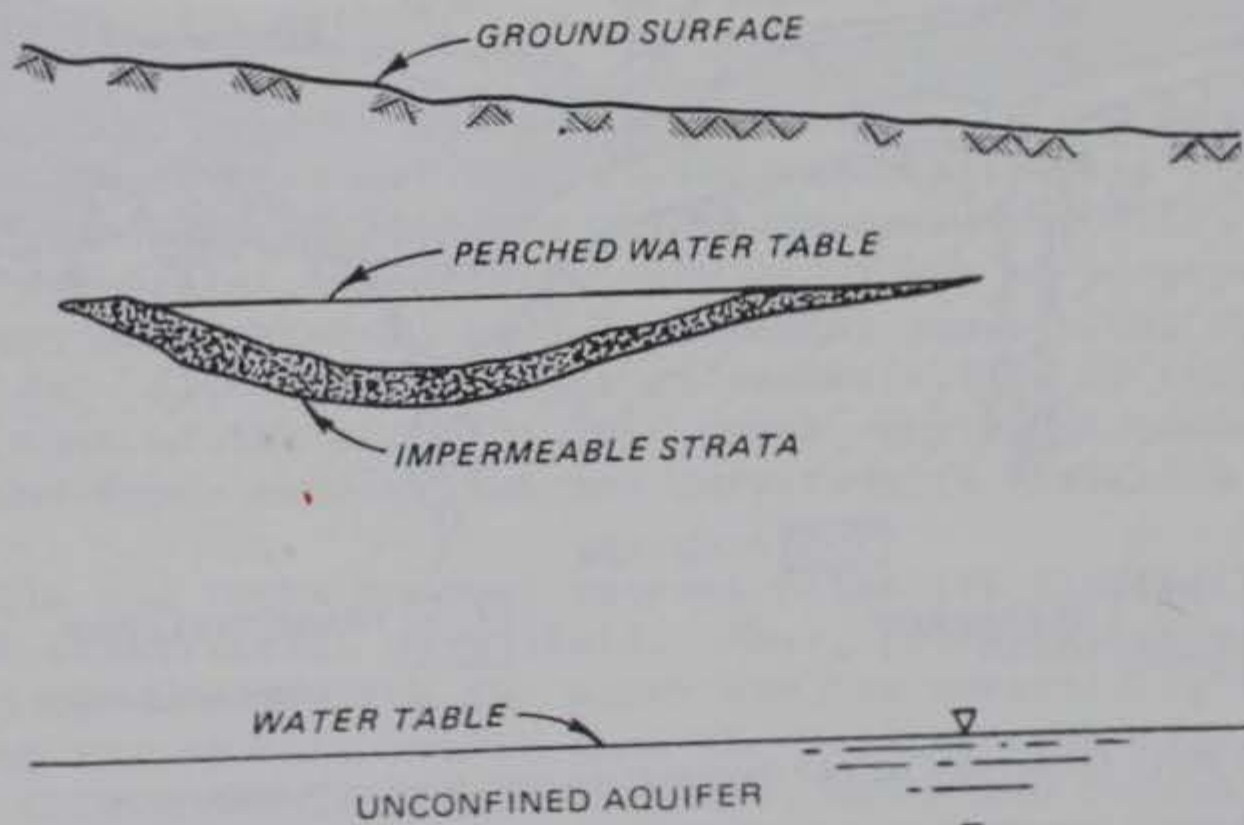Figure 2.   Hydrogeological model of confined and
unconfined aquifers

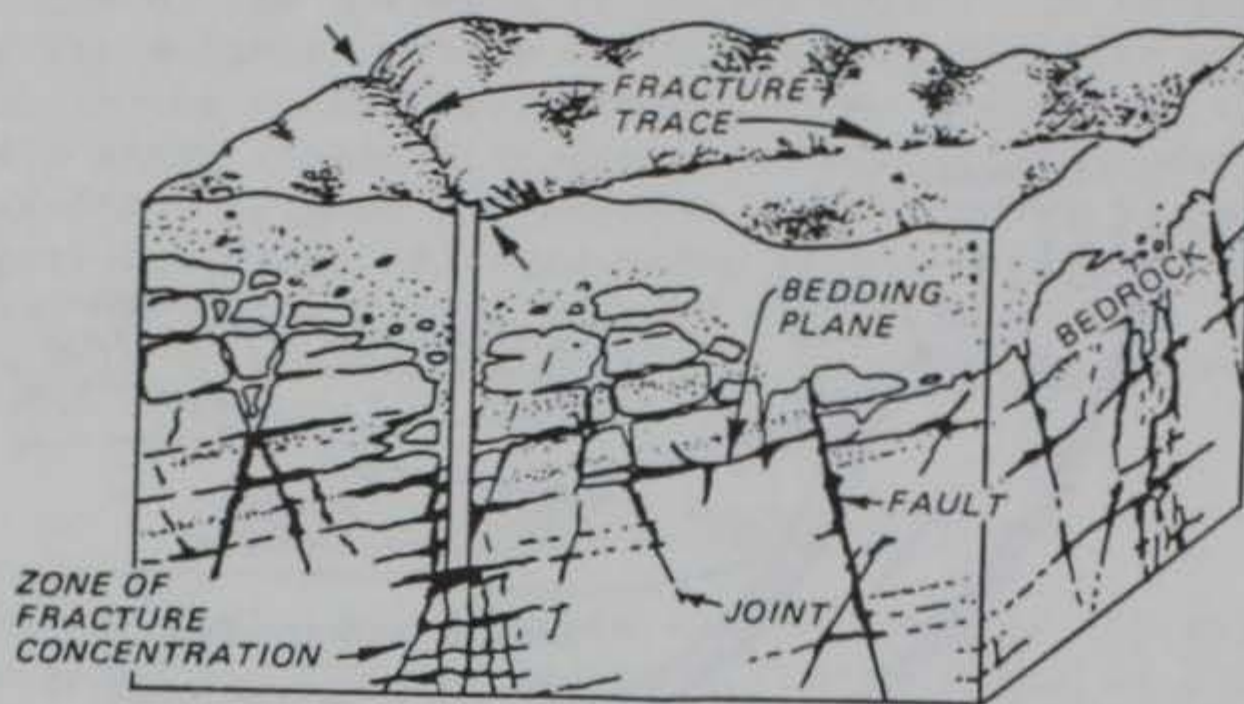Figure 3.   Hydrogeological model of perched water table

Figure 4.   Hydrogeological model of ground water
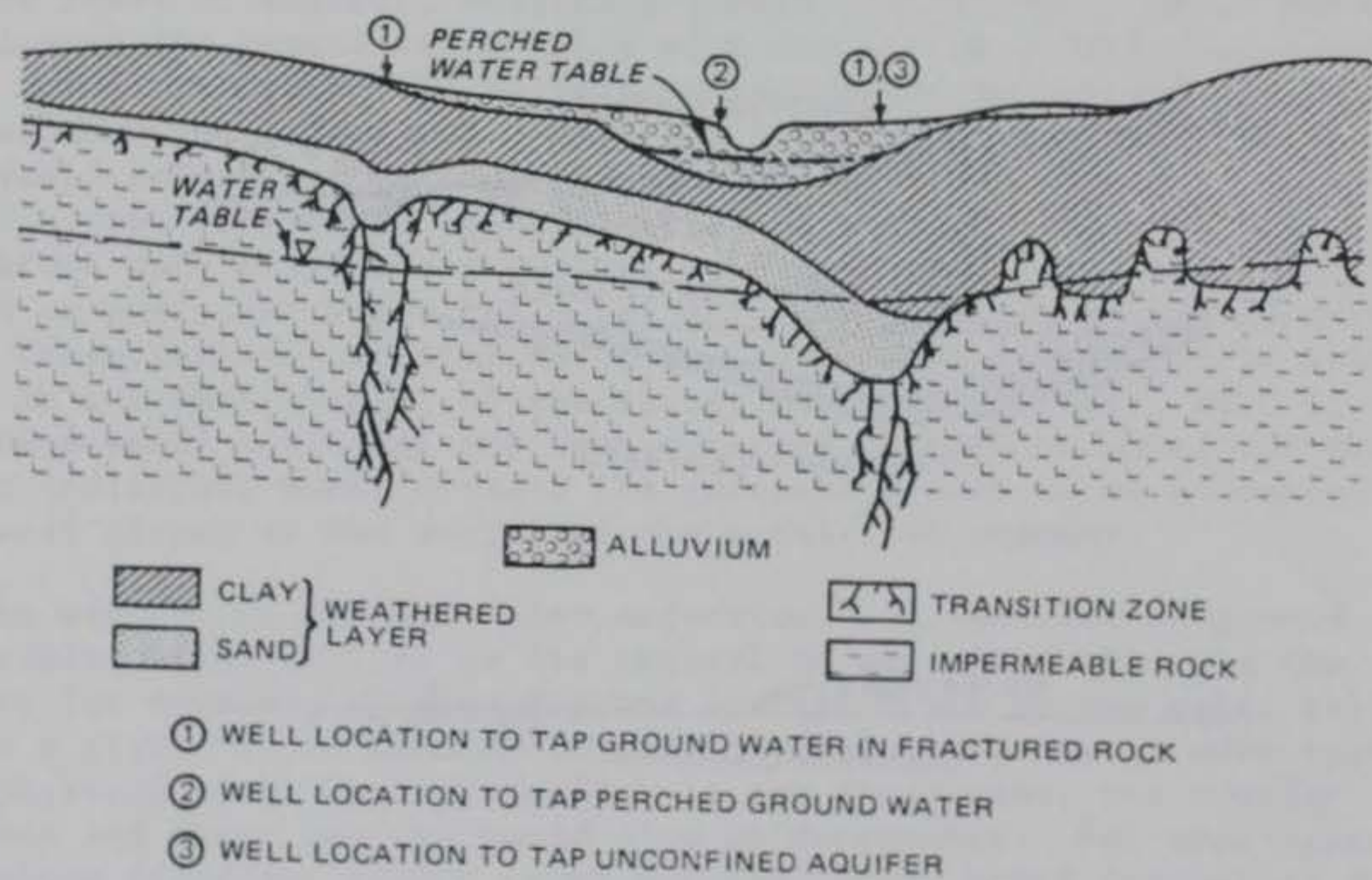concentrated on fracture zones

① WELL LOCATION TO TAP GROUND WATER IN FRACTURED ROCK

② WELL LOCATION TO TAP PERCHED GROUND WATER

③ WELL LOCATION TO TAP UNCONFINED AQUIFER

Figure 5.   Hydrogeological model illustrating multiple
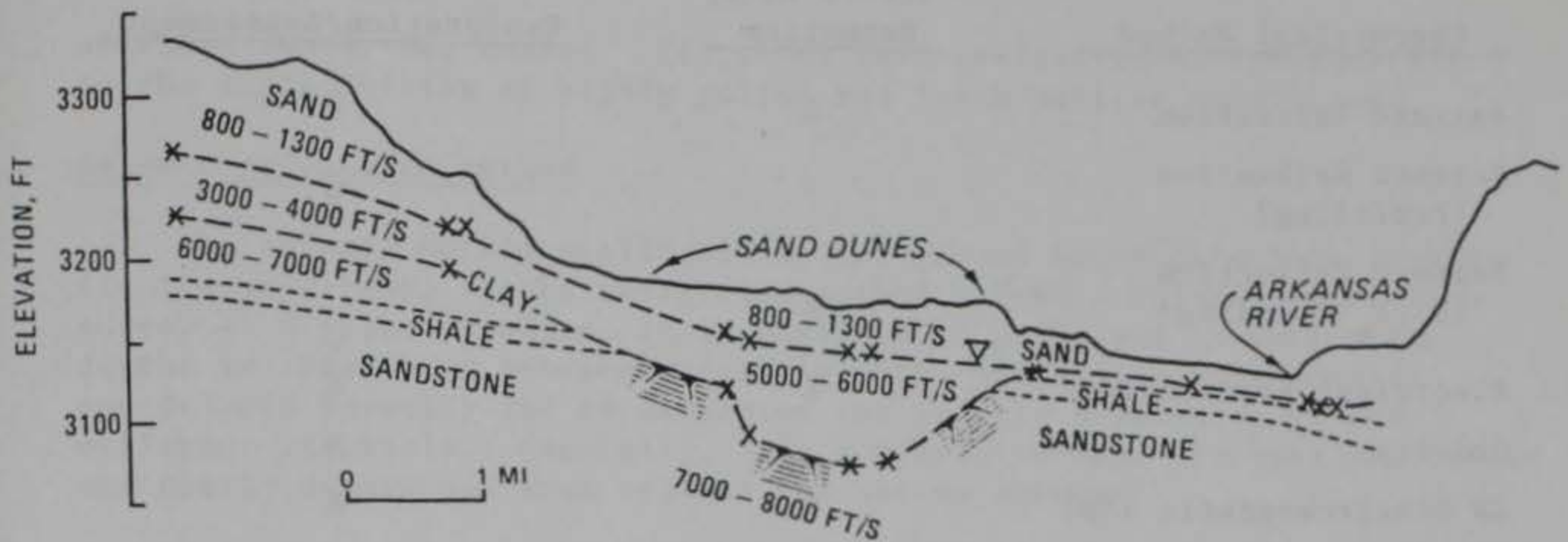modes of ground water occurrence

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Figure 6. Example of water table detection and of delineation of a
buried channel in western Kansas by the seismic refraction method

to aid in choosing between alternate sites in an area already identified
as having good ground water potential by other methods. Of the three
geophysical methods most commonly used in ground water exploration programs,
only two, electrical resistivity and seismic refraction, are applicable
to the ground water detection problem. Figure 7 summarizes geophysical
methods and their present or projected applicability to ground water
exploration and/or detection programs. Detection principles for the
electrical resistivity and seismic refraction methods are discussed below.

<div align="center">Detection Principles</div>

Electrical resistivity method

The electrical resistivity method 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 a fundamental geophysical property
of the material. Although the range of resistivities of geological
materials is that of the order of 10^{20} ohm-m, the range commonly encoun-
tered in ground water exploration and detection is typically 10^5 ohm-m.

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 following empirical equation:

$$\rho_b = a\rho_w \phi^{-m} S_w^{-n} ,$$

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Geophysical Method	Ground Water Detection	Ground Water Exploration/Assessment
Seismic Refraction	X	X
Seismic Reflection (Profiling)		X
Seismic Reflection (V_p/V_s Sounding)	X	
Electrical Resistivity	X	X
Gravity		X
CW Electromagnetic (EM)	?	X
Transient EM	X	X
Pulse "Radar" EM	?	?
Magnetic		X
Airborne (Gravity, Magnetic, EM)		X

Figure 7. Summary of applicability of geophysical methods
to ground water exploration and detection

where a , m , and n are constants which depend on the soil or rock
type. Below the water table S_w = 1 (100 percent saturation). Qualita-
tively, 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.

A common and successful use of resistivity sounding is for detecting
the fresh water/salt water interface, which will always be indicated
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 300 ohm-m and
greater; for fresh water, the resistivity at the water table will typically
decrease to a range of 20 to 100 ohm-m in areas like the southwestern
United States. In sediments with considerable clay content, the resistiv-
ity contrast will be much smaller and may be undetectable. At the fresh
water/salt water interface, the resistivity of the aquifer will decrease
considerably, perhaps to < 1 ohm-m. Zohdy et al. (1969, 1974) adopted
a qualitative criterion of ρ_b ~10 ohm-m to differentiate fresh 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

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-wave (P-wave) velocities are easily determined from seismic refraction surveys.

The physical principle involved in the detection of the water table by seismic methods is that the P-wave velocity of saturated sediments is considerably greater than the same sediments in dry or only partially saturated conditions. Typically, the P-wave velocity will increase from 300 - 700 m/sec to 1375 - 1675 m/sec at the water table, where the water table occurs at shallow depths ($<$ 30 m) in unconsolidated sediments (silts, sands, and gravels). The occurrence of a characteristic 1,500 m/sec velocity at shallow depths at a site is generally strongly indicative of a ground water table, although some weathered rocks and massive clay deposits can have this velocity also.

If the water table occurs at greater depths ($>$ 30 m, for example), the seismic velocity of the saturated sediments can be as high as 2,300 m/sec; but in these cases, the velocity of the unsaturated sediments just above the water table can be as high as 1,200 m/sec. The smallest velocity contrast at the water table will occur in very fine-grained sediments, where the velocity contrast can be as small as 150 m/sec. When the water table occurs as an unconfined surface in rock, there will always be a velocity increase at the water table, but it may be small. Where the ground water occurs in a confined rock aquifer, there may 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 will be detected or not 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 (blind zone problem).

Complementary methods

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, 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 method or to resolve ambiguities. Certain conditions, however, such as the presence of a fresh water/salt water interface, can be detected by one method but not the other.

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When depths to interfaces determined by geophysical methods are compared to "ground truth data" from nearby boreholes, typically the agreement is within ±10% for the seismic refraction method and ±20% 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 solutions in electrical resistivity interpretation. The problem of geophysical determination of the water table depth is complicated by the physical nature of the "interface." The "geophysical interface" commonly may be somewhere 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 will be greatest in fine-grained sediments and least in coarse-grained sediments.

Emerging Technology

An advancing technology is the use of seismic reflection methods to determine both compression (V_p) and shear-wave (V_s) velocities from primary reflection records (collections of all geophones receiving signals from a single source location). Thus, both compression- and shear-wave interval velocities can conceivably be determined from a single "split-dip" spread setup, although different sources might be required to generate separate compression- and shear-wave reflection records. In this procedure, V_p/V_s ratios would be determined as a function of depth and, due to the fact that shear-wave velocities are generally much less affected by water saturation than compression-wave velocities, the V_p/V_s profile should be highly indicative of the occurrences of ground water. Because only a single reflection spread setup is required, the logistical complexities associated with the continuous reflection profiling procedure are avoided.

Electromagnetic (EM) methods

If there is ever a device that even comes close to the "black box" water detector ideal, it will likely be an EM device. There are numerous EM techniques ranging from near-DC induction techniques to GHz wave propagation techniques. Hopefully, some innate property of the aquifer system will ultimately be amenable to interrogation or probing by an EM technique and allow direct ground water detection. Direct ground water detection, however, must be viewed as a long-term goal, and the immediate application of the EM methods is as a replacement or supplement to electrical resistivity in a complementary exploration or detection program.

There are several EM techniques such as magnetotellurics and various types of low frequency, continuous wave induction (CWEM) methods that can be used to determine resistivity or conductivity as a function of depth. Compared to the electrical resistivity techniques discussed

previously, these EM techniques can be more rapid and less logistically cumbersome, and they do not require surface contact.

One of the most promising of the emerging technologies is the transient electromagnetic (TEM) method. In the TEM method, a very broad bandwidth EM signal is input to the ground and, because the signal is transient (i.e., not a continuous wave source), very high power levels are possible and measurements can be made during the off-time of the transmitter. The return signal is interpreted to give resistivity as a function of depth. The exciting aspect of the TEM method is that as many as 20 soundings per day can be conducted under favorable conditions. The TEM method still has the same non-uniqueness as any other method used to determine resistivity as a function of depth; however, the TEM method has superior vertical and lateral resolution and is less effected by lateral variations than electrical resistivity and other EM methods.

Ground Water Detection Field Trials

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. Geophysical investigations at the field sites were conducted in two phases. In the first phase, electrical resistivity and seismic refraction surveys were conducted at five widely separated locations at White Sands and at one location at Fort Carson. During the second phase, CWEM surveys were conducted at the five locations at White Sands and at Fort Carson, and TEM surveys were conducted at four of the White Sands locations. This paper will specifically address selected results from the White Sands locations where all four geophysical techniques were applied. Complete details about the field test sites and the results of the first phase of field investigations are given by Butler and Llopis (1984), and results of the CWEM surveys of the second phase are given by Butler (1984).

Figures 8 and 9 illustrate the results of seismic refraction and electrical resistivity surveys at the SW-19 location at White Sands. The geophysical models resulting from the data in Figures 8 and 9 are shown graphically in Figure 10. A ground water assessment or geohydrological model is deduced from the geophysical models using the detection principles discussed earlier. The interpreted geohydrological model for SW-19 is shown in Figure 10.

Geophysical ground water assessments for all five locations at White Sands are summarized in Table 1. The known geological and ground water information about the five locations are summarized in Table 2. Comparison of Tables 1 and 2 indicates general qualitative agreement between the geophysical ground water assessments and the known ground water data for all the locations except HTA-1. The predicted water table depths are consistently too shallow, however, compared to borehole water depth measurements, by amounts ranging from 12 percent at SW-19 to 28 percent at B-30 and T-14. Direct application of the detection principles resulted in misidentification of the water table in the case
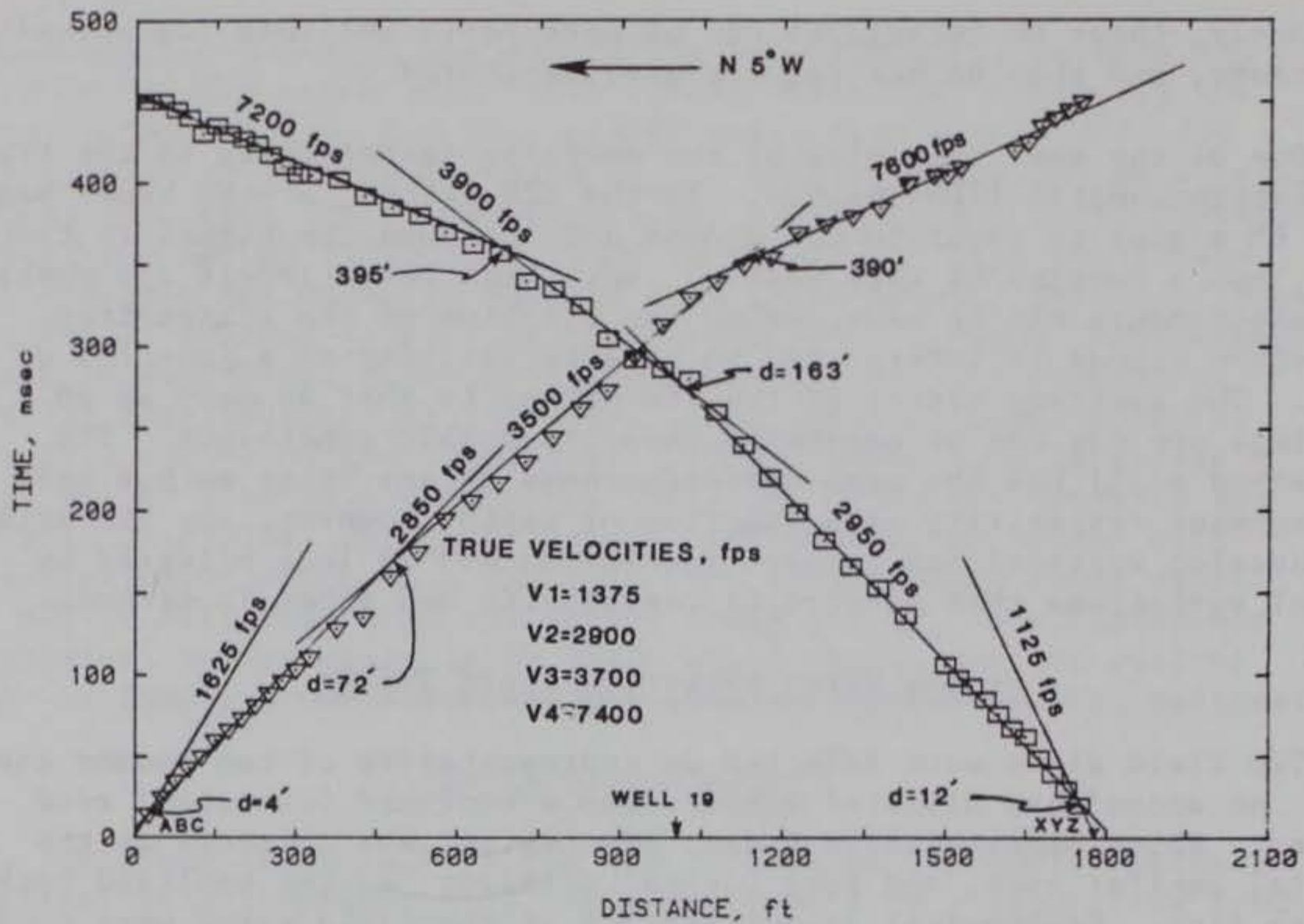
Figure 8.   Example of seismic refraction results, SW-19 site,
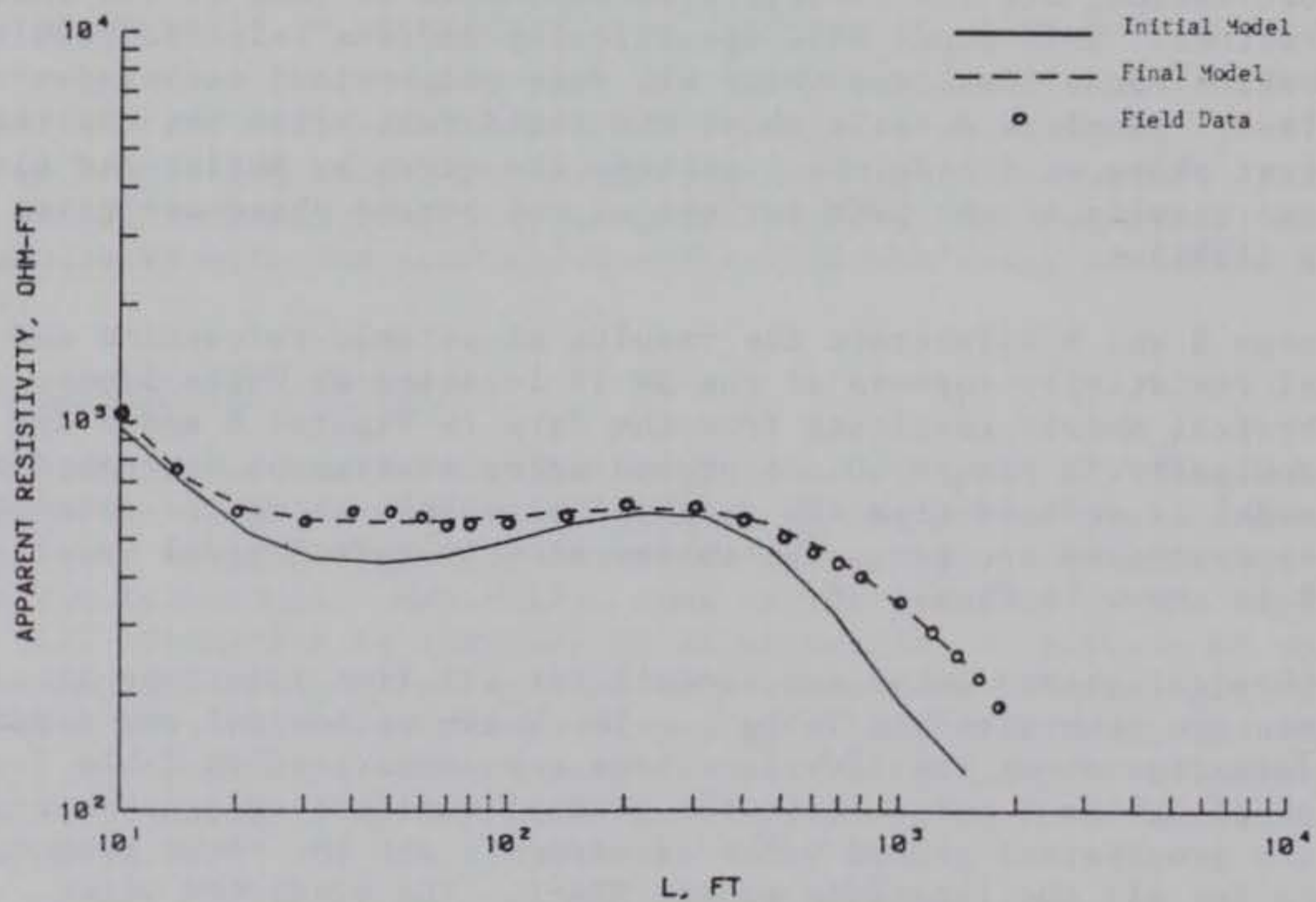White Sands, New Mexico

Figure 9.   Example of resistivity interpretation procedures for
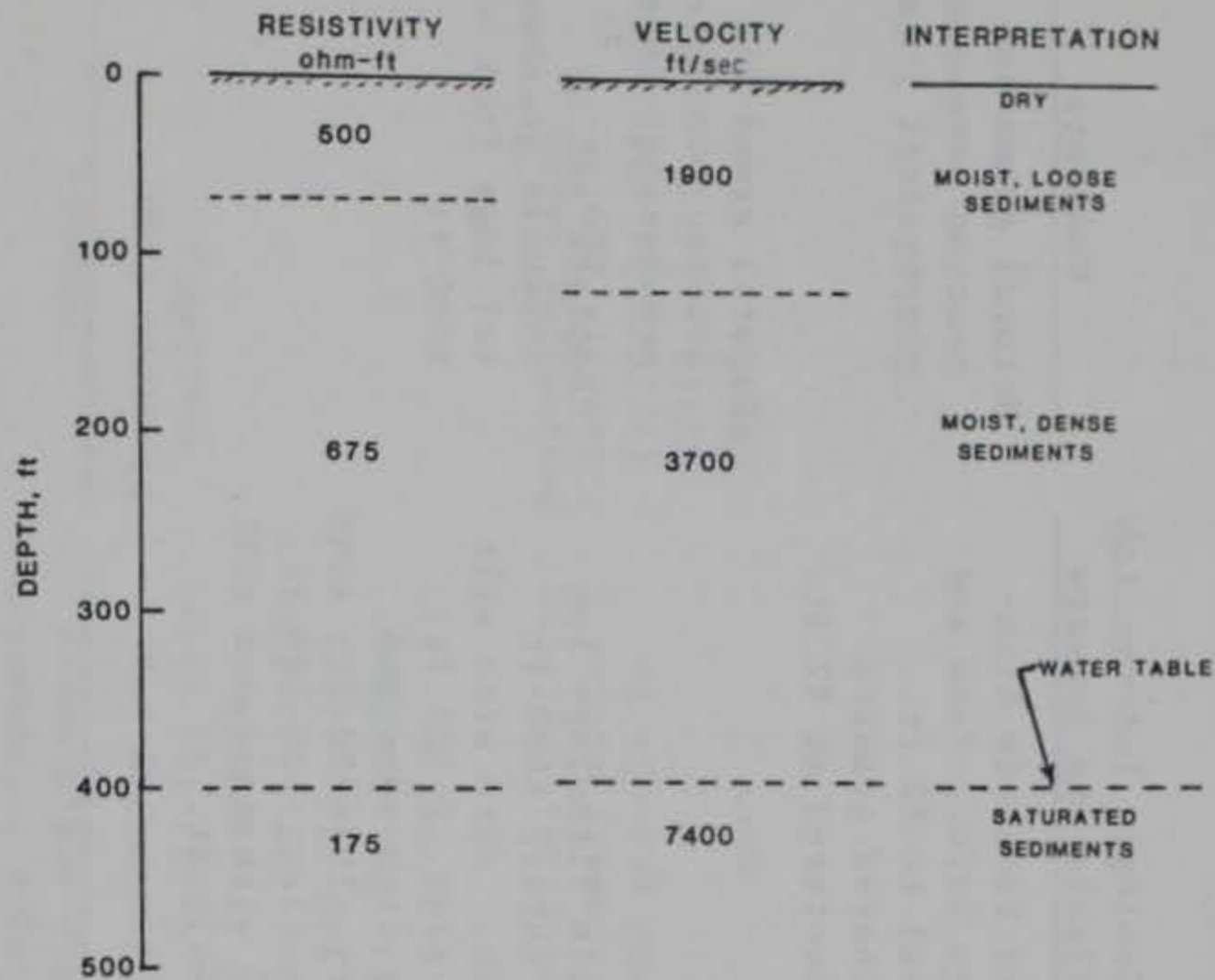SW-19 site, White Sands, New Mexico

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Figure 10. Geophysical models and interpretation for the SW-19 site,
White Sands, New Mexico

Table 1

Summary of White Sands Geophysical Ground Water Assessments

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

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Table 2

Summary of Geologic/Ground Water Information

For White Sands Test Locations

Location	Measured Water Table		Water Quality* (Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
	Depth, ft/ Date	Variation ft			
HTA-1	64 (2/14/83)	6	50 fresh	Limited borehole lithology 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)	1	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 geophysical logs from 400-6000 ft

(Continued)

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

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Table 2 (Concluded)

Location	Measured Water Table Depth, ft/ Date	Variation ft	Water Quality* (Resistivity) ohm-ft	Type Geologic Information Available and Summary	Comments
MAR	214 (MAR-2; 2/14/83) 220 (MAR-2; 1981)	1	32 (~300 ft 0.6 (@750 ft in MAR-2 and MAR-3) fresh (@300 ft)	Borehole lithology log. Gravel, 0-112 ft; clay, 112-160 ft; gravel, 160-165; clay, 165-200; gravel 220-210; clay, 210-225; etc, predominantly clay below 630 ft.	Electric logs available
SW-19	454 (2/25/83) (427 for SW-18) (514 for SW-20)	5	85 (>400 ft) fresh	Limited material descriptions. Poorly sorted sands and gravels to >900 ft.	Nonpumping water level: 409 ft (7/22/64) (402 ft, SW-18; 462 ft, SW-20)

of location HTA-1; although the confidence in the assessment was rated poor, due to lack of strong ground water indicators in the geophysical results.

In the second phase of the field investigations at White Sands, CWEM vertical soundings were conducted at the five locations using the Geonics EM 34 system. The EM 34 system is limited to three intercoil spacings (10, 20, and 40 m) and two coil orientations (vertical coplanar and horizontal coplanar), giving a maximum of six data points to define the vertical conductivity variation beneath a sounding location. Thus, the EM 34 is capable only of giving the general trend of conductivity variation with depth. Butler (1984) compares the EM 34 data to models deduced from the first phase electrical resistivity soundings in three ways: (1) directly, plotting measured EM 34 conductivity values at the "rule-of-thumb" depths of investigation (McNeill, 1980a); (2) indirectly, by determining equivalent two-layer models from the EM 34 data; and (3) indirectly, using the electrical resistivity multi-layer models, the EM response is calculated at the EM 34 intercoil spacings and coil orientations (McNeill, 1980b; Kaufmann and Keller, 1983). Results of the above comparisons and the results from the EM 34 survey at Fort Carson confirm that devices like the EM 34 will have applicability only to very shallow (< 40 m) ground water assessments and are best used in a horizontal profiling mode between widely spaced boreholes or electrical resistivity sounding locations.

TEM soundings were conducted at four of the White Sands locations, but data from the HTA-1 location were too noisy for interpretation. A Geonics EM 37 system (McNeill, 1980c) was used with 40, 80, and 160 m square transmitter loops. The TEM data were interpreted by fitting them to layered earth models using a non-linear, least-squares inversion procedure (Fitterman, 1984). Figure 11 shows the EM 37 sounding data (160 m transmitter loop) for location SW-19 and a four-layer model fit to the data, and Figure 12 illustrates the four-layer model. There are three key features about the results shown in Figure 12. First, the interface at 122 m depth agrees exactly with the depth to an interface detected by both the seismic refraction and electrical resistivity surveys and interpreted to be the water table. Second, an interface is shown at 230 m depth or 1.4 times the transmitter loop size; this is in contrast to the electrical resistivity sounding method, where a maximum outer electrode separation of 6 to 8 times the interface depth (1400 to 1900 m) would be required to detect the interface. Finally, the 160 m transmitter loop sounding interpretation was constrained by the results of a two-layer model interpretation of the 40 m transmitter loop sounding which "detected" the high resistivity surface layer. The 40 m and 160 m transmitter loop soundings were both conducted in considerably less time than the electrical resistivity sounding required.

Table 3 gives a comparison of measured and interpreted depths at three of the White Sands locations. For B-30 and T-14, the ground water assessments utilized the seismic refraction data to predict water table depths and interpreted the resistivity interface as reflecting a change from fresh to saline water quality conditions at depth below the water table. The measured water table depths for B-30 and T-14 are intermediate
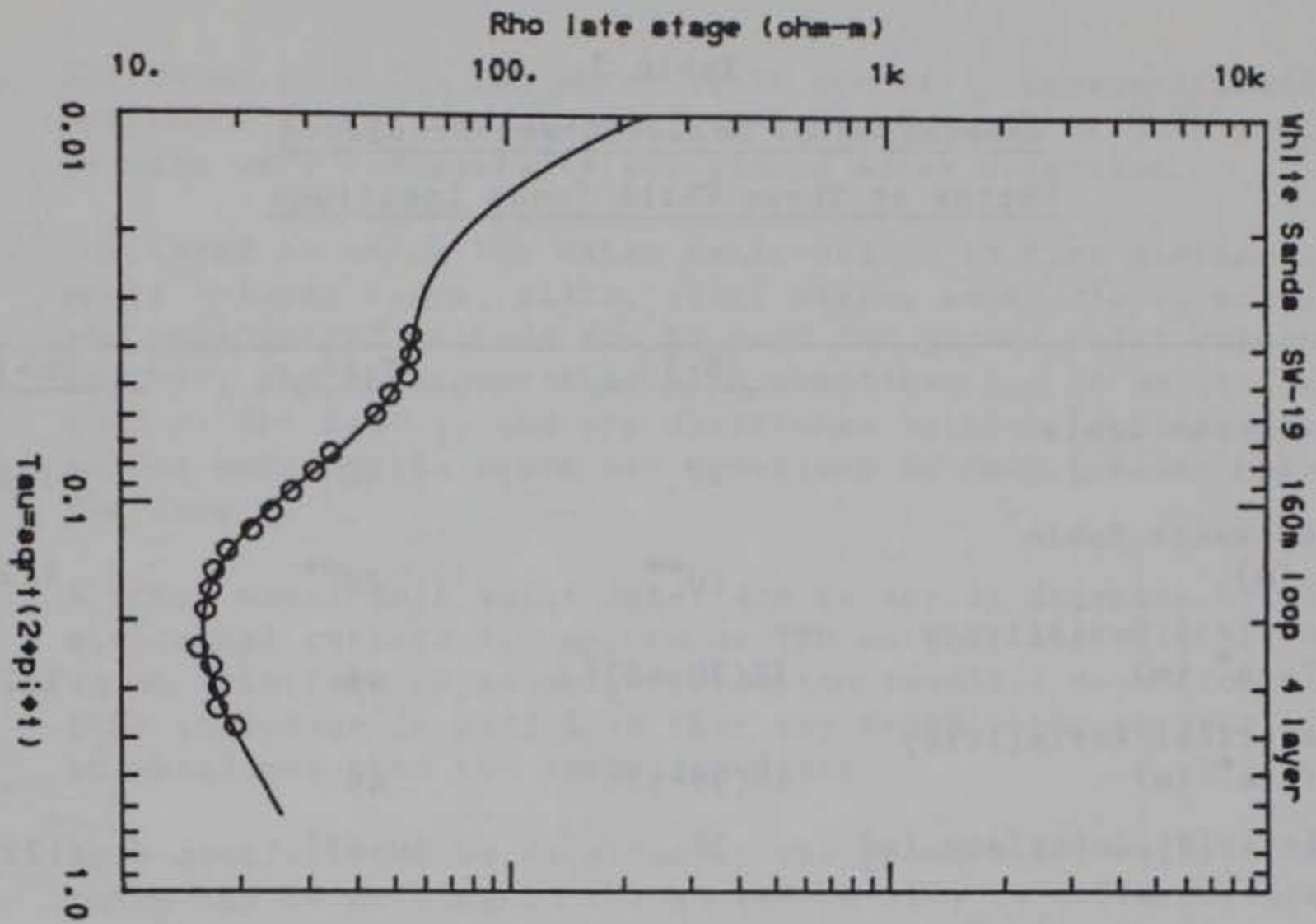
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Figure 11.   Late stage TEM apparent resistivity data (circles) and a four-layer model fit to the data (solid curve), SW-19 site
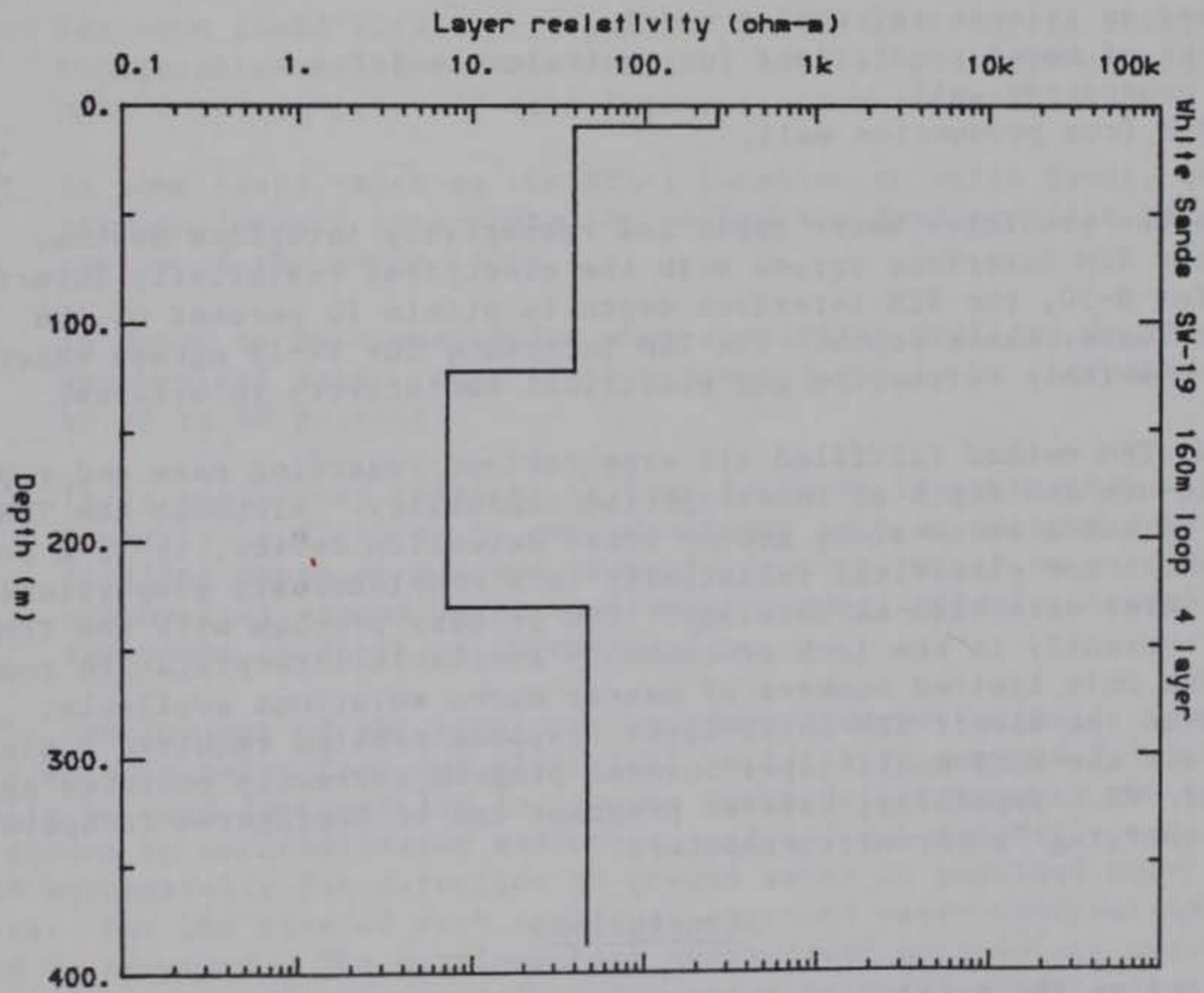

Figure 12.   Resistivity model for SW-19 site corresponding to the solid curve in Figure 11

Table 3

Comparison of Measured and Predicted

Depths at Three White Sands Locations

	B-30	T-14	SW-19
Measured Water Table Depth (m)	27	40	138[††]
Predicted Water Table Depth (m)	20[**]	29[**]	122
WES Electrical Resistivity Interface[*] (m)	38(30-46)[+]	46	122[†††]
USGS Electrical Resistivity Interface[*] (m)	46(39-57)[+]	49	--
TEM Resistivity Interface (m)	30	50-62[+]	122[†††]

[*]   Selected White Sands data were also interpreted using a USGS inversion program.
[**] Based on seismic refraction model.
[+]   Range of model predictions for equivalent solutions.
[††] At production well.
[†††] 150 m from production well.

between the predicted water table and resistivity interface depths. For T-14, the TEM interface agrees with the electrical resistivity interface; while for B-30, the TEM interface depth is within 10 percent of the measured water table depth. The TEM interface for SW-19 agrees exactly with the seismic refraction and electrical resistivity interfaces.

The TEM method fulfilled all expectations regarding ease and rapidity of field use and depth of investigation capability. Although the TEM method is not a stand-alone ground water detection device, it is a possible replacement for electrical resistivity in a complementary geophysical ground water detection methodology. The primary problem with the TEM method currently is the lack of commonly available interpretation tools. There are only limited numbers of master curve solutions available. Also, even the direct TEM multi-layer response problem requires a minicomputer, and the USGS multi-layer inverse program currently operates on a VAX 11/780. Hopefully, inverse programs can be configured to operate on the emerging "super-microcomputers."

Conclusions

Based on the results of this work and other work reported in the literature, the following conclusions are made regarding the applicability of a complementary geophysical methodology for ground water detection:

a. For cases in which the water table occurs in coarse-grained 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 fine-grained 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 fresh water/salt water interface is easily detected by the electrical resistivity method or TEM 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.

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.

g. In order to be conservative when specifying drilling depths, geophysical water table depth estimates should be increased by 30 to 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.

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. The complementary geophysical methodology currently fieldable consists of seismic refraction and electrical resistivity methods. In the near future, the TEM method may advantageously replace the electrical resistivity method.

Military Deployment of Geophysical
Ground Water Detection Capability

Development of ground water detection and assessment capability in the military is developing in conjunction with water well drilling and production capability. Geophysical methodology will never be applied in a stand-alone mode but always as part of an integrated system approach. Figure 13 illustrates a possible flow sequence for field deployment.

The key problems which must be addressed are the skill levels required for the geophysical survey teams and the organizational structure. If the decision is made to develop a geophysical ground water detection/exploration capability in or for the 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 which receive intensive specialized training.

b. Utilize teams with special training 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 data bases into the ground water assessments.

c. Develop geophysical survey expertise in National Guard or Reserve units which already have identified professional geoscience expertise.

c. 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 data bases. A quick-reaction team is a possible approach.

It is important that the military track and contribute to 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 as a ground water indicator. Another important area is the development of training manuals and programs for geophysical survey operators and for geophysical ground water interpretation procedures. The ultimate goal is the development of an automated system for assessing ground water potentials as part of a totally integrated system that would incorporate (1) existing water resources-related information, (2) remote imagery analysis and interpretation capabilities, and (3) geophysical expertise.
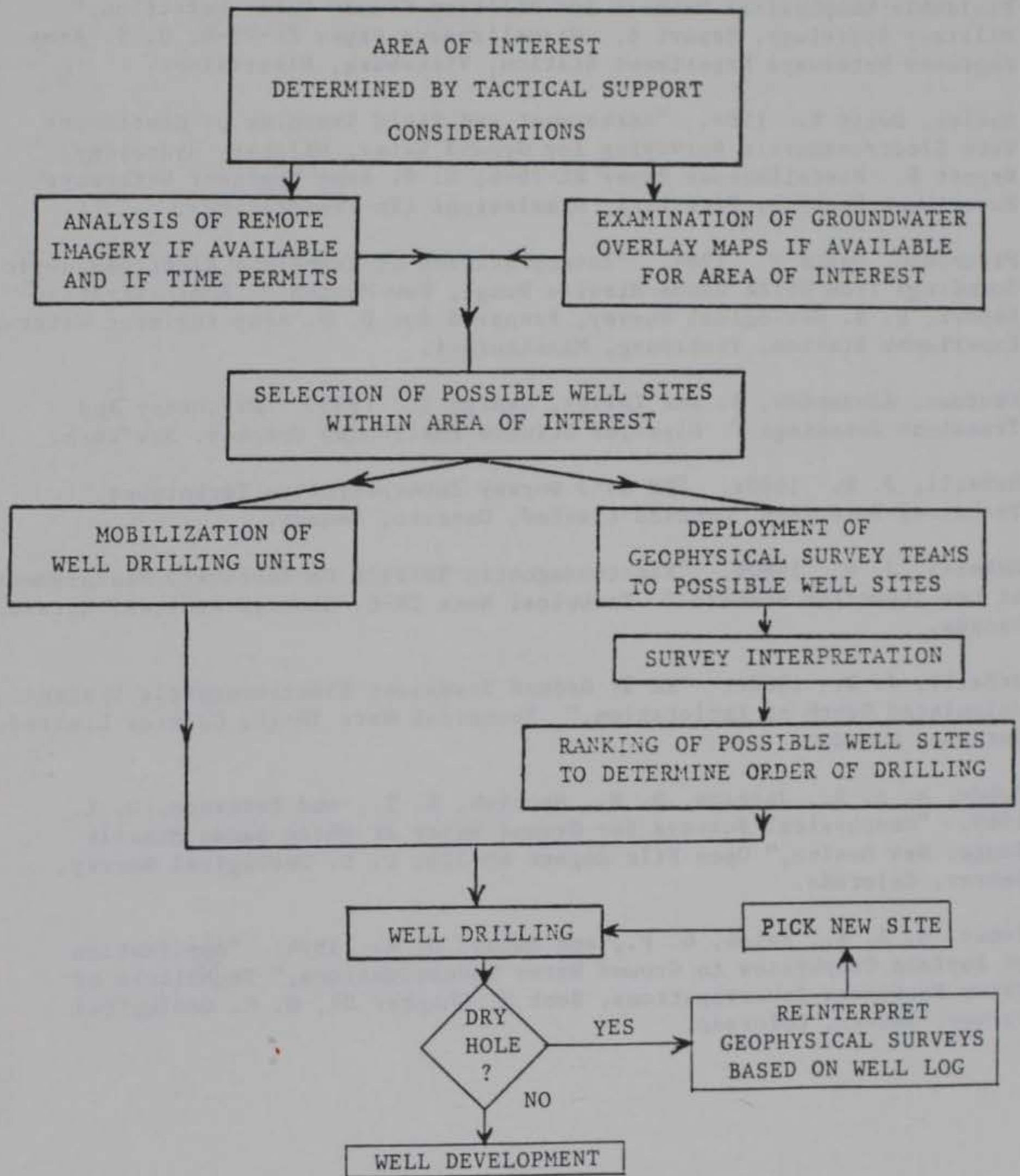
Figure 13. Flow diagram illustrating utilization of geophysical survey team for selection of well sites—resulting in reduced risk of dry holes

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