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APR 2 1984

MEMORANDUM FOR: Hubert J. Miller, Chief
Repository Projects Branch
Division of Waste Management

THRU: Seth M. Coplan, Section Leader
NTS Section
Repository Projects Branch
Division of Waste Management

FROM: Atef Elzeftawy
NTS Section
Repository Projects Branch
Division of Waste Management

SUBJECT: CONFERENCE ON CHARACTERIZATION AND MONITORING OF THE UNSATURATED ZONE

During December 7-11, 1983, I attended a conference entitled, "Characterization and Monitoring of the Vadose (Unsaturated) Zone" which was held in Las Vegas, Nevada. The conference was sponsored by the National Water Well Association (NWWA) and the U.S. Environmental Protection Agency (EPA). The conference addressed a variety of topics concerning the movement of water and chemicals (hazardous and radioative waste) through the unsaturated zone. The flow of water and chemicals from the surface into unsaturated soils, and similar geologic formations is especially relevant to the performance of shallow land burial of low level waste disposal and uranium mill tailings recovery and disposal. Although, no high level waste (HLW) problems were directly discussed or presented, the presentations and discussions did deal with state-of-the-art procedures to characterize the unsaturated zone which are relevant to the HLW program with respect to the flow and transport in fractured rocks. In addition, understanding the processes responsible for water, water vapor and chemical movement through unsaturated porous media such as soils is important to DOE in formulating their plans for NNWSI and to NRC staff in reviewing those plans dealing with HLW. The conference was well attended by scientists, engineers, and hydrogeologists interested in the unsaturated zone hydrogeology.

During the conference I presented my paper entitled, "Vadose Moisture Migration in Semi-Arid and Arid Environments" (See Attachment). This paper was scheduled to be delivered at this conference prior to my employment with NRC. The results presented were that (1) thermocouple psychrometers functioned well under the extremely arid condition of alluvial sediments in southern Neveda and (2) water movement (liquid and vapor) through thick unsaturated sediments (about 150') is affected by precipitation sooner and at greater depth than

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previously postulated. These results may have implication regarding moisture movement through the Yucca Mountain site. These findings would be important to DOE in formulating their plans for site characterization and to the NRC staff in providing guidance and reviewing DOE program of HLW at the Nevada site. The paper was well received and following my presentation more than ten questions were addressed and answered.

USGS personnel working on characterization of Yucca Mountain at Nevada attended the conference and heard and discussed the paper results.

The following are some of my observations about a few presentations related closely to the NRC Waste Management program:

1. Herman Bouwer of USDA evaluated the effects of stones in the unsaturated zone on the downward movement of water and the conservative transport of solutes. He concluded that the downward pore velocity could be calculated as the Darcy velocity divided by the volumetric water content and that the dispersivity of the boulder-sand mixture was much higher that that for sand alone. These conclusions have great impact on the modeling results of water and solute flow through desert alluvial sediments.

2. Carol J. Miller of STS Consultants introduced the concept of Peclet Number for unsaturated flow provide a measure of the relative important of the advection and diffusion terms in Fokker-Planck equation. She concluded that unsaturated flow models must be sufficiently robust to distinguish between the convective and diffusive flow of water prior to their application and use. The importance of her conclusion is related to the usage of flow models and codes to simulate porous and fracture movement of water within unsaturated natural geologic sediments. It is well documented that porous flow in most geologic sediments is viscous flow, however, fracture flow may be viscous or turbulant depending upon fluid and fractured media properties.

3. William A. Jury of the University of California at Riverside presented field data of several experiments involving downward movement of chemicals applied on the soil surface. The field observations were analyzed using computer transport models of the unsaturated zone. It was shown that the conventional convection-dispersion equation does not adequately describe chloride movement through the top 4 to 5 meters of soil but a stochastic-convective model taking into account velocity variations is able to predict and describe the movement. This particular

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finding is important because it raises questions related to the high-level, low-level and uranium mill tailing waste. Mainly, two questions are raised; (1) what is the proper scale factor that should be addressed for using transport codes to predict the radionuclides movement through unsaturated sediments on large field scale? and (2) should the complex nature of the movement of radionuclides through sediments be distinguished in models and codes? and to what extent this problem should be recognized?

4. James M. Cahill of USGS is investigating the water movement through unsaturated sediments at the low-level radwate site near Barnwell, S. C. to provide hydrogeologic guidelines to waste management in a humid environment. He stated that preliminary results indicated that moisture movement is towards the waste burial trenches. He also indicated that summer rains must satisfy the deficiency due to evapotranspiration before percolation of water occurs.

Atef Elzeftawy
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ABSTRACT

"Vadose Moisture Migration in Semi-Arid and Arid Environments"

by

Atef Elzeftawy and Martin D. Mifflin

A study was made to directly observe moisture migration in semi-arid and arid environments of the Western Great Basin. Thermocouple psychrometers were emplaced at six stations in volcanic foothill and mountain terrain near Reno, Nevada, and at five stations in carbonate rock terrain derived alluviam in mountain and alluvial fan environments in the Las Vegas region. Most emplacements do not exceed 9 feet in depth, however, at one alluvial fan station instrument emplacement reaches 150' below land surface. The psychrometers are in small diameter holes constructed without drilling fluids, and in 1982 good records of soil moisture potential were obtained. Evidence for recharge was noted, but the majority of moisture potential data indicates upward migration of moisture over the period of record. The deep installation displayed a recharge pulse to 150' depth after a high intensity storm of 5 inches in a few hours. Antecedent moisture potential conditions at the same station indicate long term upward movement of moisture at the site where the regional saturation is 840 feet below land surface. Methodology of drilling, instrument emplacement, and experiment deficiencies are also discussed.

INTRODUCTION

The recharge mechanics of groundwater in the Great Basin of the U. S. arid region are not well understood. Often the processes by which recharge occurs have been postulated from either indirect evidence or suposition; however, the specific factors that affect the phenomenon have not been documented, nor have the relative importance of influencing factors been established. The approach adopted here has been to study the occurrence and transport of soil moisture in the unsaturated zone as the recharging water enters and travels the unsaturated surficial sediments.

THEORETICAL ANALYSIS

The complex nature of the pore space in porous earth materials such as soils and fractured rocks and the moisture held therein makes it difficult to specify directly the force fields acting on the moisture. The description of soil moisture movement on a microscopic scale depends not only on quantification of the force fields but also on the specification of the solid matrix geometry. These factors affect the soil moisture in the vadose zone at all times. For specific systems some factors dominate and a particular approach can be used to describe the system in terms of these dominant factors.

Theories of moisture transport through the vadose zone are based on empirically derived transport equations and established physical principle. In the published work, three approaches deal with the moisture transport, namely: 1) the hydrodynamic approach, 2) the equilibrium thermodynamic approach, and 3) the non-equilibrium thermodynamic approach. The hydrodynamic approach have been used to describe liquid flow for cases in which salt and temperature effects are not considered to be significant factors. When salts are a contributing factor, diffusion and dispersion mechanisms must be incorporated into theory and the concepts of electrostatics and electrokinetics are applicable and useful. For flow systems in which temperature and salt concentration are variable, as well as salts, the developed theories of equilibrium and irreversible thermodynamics processes have been applied to soil moisture flow.

Recently, several attempts have been made to extend the theoretical base to the molecular domain. The flux laws of Darcy (1856) and Buckingham (1907) were derived without relying directly on experiments, a new molecular interpretation of soil moisture conductivity and diffusivity was developed and a proof resulted that the diffusivity for anisotropic soil is a symetric tensor of the second rank. Results relating to the properties of the vector matrix flux potential were published by Gupta et. al., (1977). However, none of the published work has dealt with the simultaneous transport of moisture, heat, and solute especially through very dry (arid) soils and earth materials.

The branch of theoretical physics that deal most fundamentally with the description of transport processes at the molecular level is non-equilibrium statistical mechanics. Sposito (1978) used this approach to derive the macroscopic differential equations of mass and momentum balance for moisture in unsaturated soil. It was found that the hydraulic conductivity of the unsaturated sediments can be expressed in terms of an integral over time of the correlation function for the velocities of the water molecules.

The application of non-equilibrium thermodynamics to transport problems has developed rapidly since 1950. This has come about through the philosophical concept of entropy changes during natural processes. An isolated system which is not in equilibrium will spontaneously move toward equilibrium. In doing so, the entropy approaches a maximum, i.e., the components of the system move toward the most random and probable arrangement.

Before discussing the methodology and results of this study we will define several important soil moisture concepts based on the porous media model that are critical to understanding and predicting soil moisture movement through the vadose zone.

Hydrodynamic Approach

Classical hydrodynamics is applicable to moisture flow through soils and earth materials providing the flow system is adequately described. Such description is not usually possible on a microscopic scale because of the complicated flow paths and dissolved solids in the soil moisture. However, some equations derived from classical hydrodynamics are very useful in describing the soil-moisture behavior.

Soil Moisture Potential: Soil moisture contains energy in different forms and quantities. The two principle forms of energy are kinetic energy, a function of velocity and potential energy that is a function of position of internal condition of the system. Since moisture moves very slowly in soils and other porous media, kinetic energy can generally be ignored in the study of soil moisture systems; however, potential energy is of primary importance in determining the state and the movement of moisture in soil.

The spontaneous and universal tendency of all matter in nature is to move from a point of high potential energy to a point of low potential energy until an equilibrium condition is reached. Soil moisture systems obey this universal tendency towards equilibrium.

A soil moisture system is subjected to a number of force fields, which causes its potential to differ from that of free moisture. The force fields commonly considered are gravitational potential, ϕ_g, pressure potential, ϕ_p, osmotic potential, ϕ_o, and gas potential, ϕ_a. The total potential, ϕ_T, of the soil moisture system can be considered as the sum of the individual potentials.

$$\phi_T = \phi_g + \phi_p + \phi_o + \phi_a \qquad (1)$$

The gravitational potential, ϕ_g, and the pressure potential, ϕ_p, are the primary force fields in soil moisture systems. The Osmotic potential, ϕ_o, is dependent upon the presence of dissolved solids in the soil moisture system. The gas potential, ϕ_a, is dependent upon external or internal gas pressure in the system. If the osmotic potential and gas potential are considered to have minor influence on the potential, then Equation (1) can be simplified as follows:

$$\phi_T = \phi_g + \phi_p \qquad (2)$$

At a height z above an arbitrary reference level, the gravitational energy of moisture in soil, E, can be stated as follows:

$$E = Mgz = \gamma_w gzV \qquad (3)$$

In Equation (3), γ_w is the density of moisture (liquid water), g is the acceleration of gravity and V is the volume of the mass, M. From Equiation (3), the gravitation potential energy, ϕ_g, can be expressed as follows:

$$\begin{aligned} \phi_g &= gz \text{ (per unit mass, M)} && (4) \\ &= \gamma_w gz \text{ (per unit volume, V)} && (5) \\ &= z \text{ (per unit weight, W)} && (6) \end{aligned}$$

In Equation (6), ϕ_g depends only on z and is defined as the gravitational head in soil moisture systems.

Pressure potential, ϕ_p, is negative for unsaturated soil systems and positive for saturated systems. It can be shown that the pressure potential concept allows for the consideration of the entire moisture profile in the field in terms of a continuous potential field extending from the unsaturated region to the saturated region, above and below the water table.

The positive pressure potential for a saturated soil moisture system is fairly well understood. The negative pressure potential - less well understood - has often been termed capillary potential, soil suction, or (more accurately) matrix potential. This potential results from the capillary and absorptive forces developed in the soil matrix.

In discussing pressure for unsaturated soil moisture systems, the capillary tube analogy is useful. Soil can be assumed to be a porous medium composed of capillary tubes of different sizes. In Figure 1 the air - liquid water interfaces throughout the soil consists of menisci in which the curvature or radii indicate the state of tension in the soil moisture (much as a capilliary tube does). As the moisture content of the soil is reduced, the air water interfaces recede into the smaller pores, the radii of curvature decrease, and the moisture tension increases.

In the capillary tube model, it can be shown that the height, h, to which the water will rise in the capillary tube is related mainly to the surface tension, σ, and radius, r, of the meniscus by the following equation:

$$h = \frac{2\sigma\cos\theta}{\gamma_w\, gr} \tag{7}$$

Assuming that cosine $\theta \approx 1$ for water in soil, and that the curvature of the water in the soil matrix is similar to that in a capillary tube of the same size, the pressure potential per unit mass can be expressed from Equation 7 as follows:

$$\phi_p = -\frac{2\sigma}{r\gamma_w} = gh \qquad (8)$$

The negative sign is used in Equation 8 because the pressure potential in an unsaturated soil moisture system is less than atmospheric pressure and because h would have a negative value in an unsaturated system.

From Equations 2, 4, and 8 the total potential per unit mass, excluding the osmotic potential and gas potential, can be stated as follow:

$$\Phi_T = gz + gh \qquad (9)$$

On a unit weight basis, normally used in soil moisture studies, Equation 9 can be shown in the following form:

$$H = z + h \qquad (10)$$

In Equation 10, H is the total soil moisture head, z is the gravitational head, and h is the pressure head. The pressure head is negative (suction) in unsaturated soil moisture systems and positive for saturated soil.

To summarize, the criterion for equilbrium in soil moisture systems is that the total moisture potential be equal throughout the system. To facilitate the analysis of particular systems, the total moisture potential is partitioned into various components that can be measured. Typically, the gravitational potential is determined by use of a measuring tape, the pressure potential by a piezometer for saturated systems and a tensiometer or psychrometer for unsaturated systems, and the gas potential by a pressure gauge.

<u>Soil Moisture Characteristic Function</u>: The relationship expressed in a soil moisture characteristic function is a soil property of fundamental importance in the analysis of moisture equilibrium and flow behavior in soil. Figure 2 shows relative soil moisture characteristic curves for three different soils. Physically, the curve tells (at any given moisture content) how much energy (per unit quantity of moisture removed) is required to remove moisture from the soil. It indicates how tightly moisture is held in the soil. Hillel (1973), Taylor and Ascroft (1972), Kirkham and Powers (1972), and Rose (1966) have presented detailed explanations of how moisture is held in soil. Childs (1969) has considered the mechanisms of moisture held in both swelling and non-swelling soils in great detail.

Croney, Coleman, and Bridge (1951) have described the methods used to determine the soil moisture characteristic curve--those used most frequently are the tensiometer, direct suction, pressure plate, and centrifuge methods. Because no single method can cover the entire moisture tension range, several measurement methods are generally used in determining these curves.

Hysteresis effects (Figure 3) will often occur between soil moisture characteristic curves for drying and wetting. The hysteresis for the drying and wetting conditions arises from the influence of pore size distribution on water held in the soil. A complete moisture characteristic curve should consist of a drying (desorption) curve and a wetting (sorption) curve. The drying curve should start at saturated moisture content (close to zero suction) and continue to a low moisture content at a high level of suction. The wetting curve should start at the high level of suction and low moisture content and proceed to saturation. This would characterize an envelope for water-content and suction values in the given range. The influence of small moisture content changes on soil suction is shown by the smaller hysteretic curves inside the desorption and sorption curves in Figure 3.

A useful simplification occurs when the soil suction is given in units of water head. A suction of 20 cm will lift a column of water 20 cm above a free water surface. Therefore, the suction on the moisture characteristics curve can be equated to the distance above a water table for equilibrium conditions. Also, by use of the soil moisture characteristic curve it is possible to estimate the equilibrium water content at various positions above the water table.

Hydraulic Conductivity Function: The flow of moisture through soils and other porous earth materials is often unsteady and unsaturated. The general nonlinear partial differential equation that describes the transport of moisture can be written as follows:

$$\frac{\partial \theta}{\partial t} = \nabla . (K \nabla \phi) \qquad (11)$$

where θ is the volumetric moisture content defined as the ratio of the volume of water, V_w, to the total volume of soil, V, ∇ is the vector differential operator. K is the hydraulic conductivity, and ϕ is the total potential. For a complete derivation of Equation 11, the reader is referred to Childs (1969) and Kirkham and Powers (1972). An equation of this type applies to any nonreactive liquid in the porous medium; since we limit ourselves in this study to moisture, it is convenient to take the length of water column as the unit of potential. Potential gradients are then dimensionless, and if the time, t, is expressed in hours, the unit of hydraulic conductivity is centimeters per hour.

When the total potential is composed of only gravitational and negative pressure (capillary) components, Equation 11 may be written:

$$\frac{\partial \theta}{\partial t} = \nabla . (K \nabla h) + \frac{\partial \theta}{\partial z} \qquad (12)$$

where h is the suction (negative pressure) potential, and z is the vertical ordinate, positive upward.

When h and K are single-valued functions of θ, Equation 12 becomes

$$\frac{\partial \theta}{\partial t} = \nabla . (D \nabla \theta) + \frac{\partial K}{\partial z} \qquad (13)$$

where

$$D(\theta) = K(\theta) \frac{\partial h}{\partial \theta} \qquad (14)$$

Childs and Collis-George (1950) called D the diffusivity of soil water and found it to be a function of θ. Rogers and Klute (1971) have shown that hydraulic conductivity, K, is uniquely related to soil moisture content, θ. Two physical properties of the soil that enter into a saturated-unsaturated flow problem are hydraulic conductivity, $K(\theta)$, and soil moisture retention $h(\theta)$; these properties must be known if a solution of Equation 13 is to be obtained.

Childs and Collis-George (1950), Millington and Quirk (1961) Green and Corey (1971), and others have explored the possibility of predicting the hydraulic conductivity of soils and other porous materials on the basis of pore size distribution. Such predictions are of interest because the hydraulic conductivity function, $K(\theta)$, is relatively difficult to measure, whereas pore size distribution is easily obtainable by the standard measurement of moisture content versus suction (negative pressure).

Green and Corey (1971) concluded that hydraulic conductivity prediction equations yield reasonable values of the hydraulic conductivities for a range of soil types if a matching factor is used. Elzeftawy and Mansell (1975) and Elzeftawy and Dempsey (1977) stated that a matching factor at water saturation (the ratio of the measured to the calculated saturated hydraulic conductivity) has a distinct advantage because inaccuracies in calculated and experimentally evaluated $K(\theta)$ can be more easily tolerated at lower moisture content.

Units for Soil Water Potential: The normal methods of expressing potential in soil water systems are shown in Table 1 for the various measurement systems. For potentials expressed as a per unit weight or as a per unit volume, the dimensions are those of length (centimeter, meter, or foot) or of pressure (dyne/square centimeter, newton/square meter, or pound/square foot), respectively. Equations for converting between the three forms of potential are stated as follows:

$$\frac{\text{energy}}{\text{mass}} = g \, \frac{\text{energy}}{\text{weight}} \tag{15}$$

$$\frac{\text{energy}}{\text{volume}} = \gamma_w \, \frac{\text{energy}}{\text{mass}} \tag{16}$$

$$\frac{\text{energy}}{\text{volume}} = g_\gamma \, \frac{\text{energy}}{\text{weight}} \tag{17}$$

Equilibrium Thermodynamic Approach

Equilibrium thermodynamic allows the derivation of a mathematical equation relating the soil-moisture potential to its four components (gravity potential, matric potential, osmotic potential, and pneumatic potential). The equation relating Gibbs free energy G and other stat variable is

$$G = U - TS + PV \tag{18}$$

where U = internal energy
T = temperature
S = entropy
P = pressure, and
V = volume.

For a multicomponent system,

$$dU = TdS - PdV + \Sigma_j \mu_j dn_j \tag{19}$$

where μ_j and n_j are the chemical potential and the amount (in grams or moles) respectively, of the jth component. If moisture is one of the j components, therefore

$$dG = -SdT + VdP + \mu_w dn_w + \Sigma_i \mu_i dn_i \tag{20}$$

where w denotes the moisture component. It is μ_w which is of interest, since it is the chemical potential or the partial specific energy $\partial G/\partial n_w$ for soil-moisture in the case being considered.

Under equilibrium conditions, if it can be assumed the $\bar{V}_w$ is a constant and the solute potential of the soil moisture is equal everywhere in the system, the pneumatic component must be equal to the matric potential. Therefore, it can be shown

$$\bar{V}_w (P - P^o) = \int_{n_w^o}^{n_w} \frac{\partial \mu_w}{\partial n_w} dn_w \tag{21}$$

where $\bar{V}_w$ and n°_w are the partial molar volume of water and moisture content at saturation, respectively.

The left-hand term of equation (21) $(P - P^o)$, where V_w is taken to be equal unity, is referred to as soil suction or soil moisture tension, or soil moisture potential.

For the vapor pressure of soil moisture, assuming the vapor as an ideal gas at standard temperature, we have:

$$d\mu_v = \bar{V}_v \, dp \qquad (22)$$

where μ_v is the chemical potential of the vapor, $\bar{V}_v$ is the partial molar volume of the vapor, and p is the vapor pressure. Integrating equation (28) and using the relation $\bar{V}_v = RT/P$ we get

$$\mu_v - \mu_v^o = RT \ln P/p^o \qquad (23)$$

where μ_v^o and p^o are for standard conditions and R is the universal gas constant. The term $(\mu_v - \mu_v^o)$ is defined as the soil moisture vapor potential, or soil moisture potential.

Nonequilibrium Thermodynamics Approach

The application of nonequilibruim thermodynamics to transport problems has been developed rapidly during the last 25 years. This development has come about through the philosophical concept of entropy change during natural processes. An isolated system which is not in equilibrium will spontaneoulsy move toward equilibrium. In so doing, the entropy reaches a maximum, i.e., the components of the system move toward the most random and probable arrangement.

For arid regions, it can be shown that in a multicomponent system, such as soils and earth materials, any given flux will depend on both the driving forces and flow of all constituents (Nielson *et al*., 1972). It can be assumed that the active components are moisture, solute, heat, and the soil matrix. The net flux in the system must depend upon all other fluxes and the time rate of entropy change, i.e.:

$$J = -\left[\frac{\rho \quad T\,\sigma}{\rho_g\left(\frac{d\phi}{dz}\right)\;2}\right] \quad \frac{d}{dz} - \frac{j_q}{T\rho_g \quad \frac{d\phi}{dz}} \quad \frac{dT}{dz} \qquad (24)$$

$$\sum_{i=1}^{3} \quad \left[\frac{J_i T \quad \rho_1}{\rho_g \quad \frac{d\phi}{dz}} \quad \frac{d\mu}{dz}\right]$$

Unfortunately, equation (24) is not very useful in a practical sense because the functions in brackets are variables rather than constants. However, it can be shown that under some conditions it should be possible to choose constants which can be used in place of the variable functions. Therefore, the approach could prove to be useful in studying the transport of water, heat, and solute in arid regions; however, more theoretical research is needed.

METHODS AND MATERIALS

The main thrust of the soil moisture monitoring was to install, in selected hydrogeologic environments, instruments designed to document soil moisture movement through the unsaturated zone as recharge events. Fundamental problem in this type of effort is the difficulty of reaching desired instrument emplacement depths without introducing drilling water or other fluids. The hollow stem auger drilling method was used to install all psychrometers except the site near Jean, Nevada in which the dual tube reverse circulation rotary method was successfully used.

Soil Moisture Potential Monitoring

The movement or flow of moisture through the vadose zone of earth materials such as soils and fractured rocks is more complex than flow occuring under saturated conditions. The main reason for this complexity is that the hydraulic conductivity of the earth materials change as the moisture contents change. As moisture potential becomes more ne gative, smaller pores will partially drain, and the total cross- sectional area available for moisture flow will become progressively reduced. As a result, the moisture potential and its distribution with time and depth in the soil profile affects not only the hydraulic conductivity but also the hydraulic gradient within the unsaturated system.

The in-situ measurement of moisture potential in earth materials is very important to determine the direction and the quantity of moisture flow. The driving forces responsible for the transport of moisture in the unsaturated and saturated zones are gradients in the free energy status of moisture. In unsaturated sediments moisture potentials are negative and moisture moves from regions where the total potential is higher (less negative) to regions where the total potential is higher (less negative) to regions where the total potential is lower (more negative).

Soil moisture potential can be measured in-situ by using soil moisture blocks made of ceramic or nylon (Richards, 1965), thermocouple psychrometers (Richards and Ogata, 1969), standard tensiometers (Richards, 1969) and osmotic tensiometer (Peck and Rabbidge, 1969). During this study soil thermocouple psychrometers have be en used to evaluate the unsaturated zone moisture potential changes with time and depths.

Thermocouple Psychrometer

Thermocouple psychrometers measure the unsaturated zone relative humidity, and the relationship between moisture potential and relative humidity can be described, at equilibrium, by the follow ing equation (Wiebe et al., 1971):

$$\phi_T = \frac{RT}{V} \quad \ln \frac{H}{H_o} \qquad (25)$$

Where ϕ_T is the moisture potential, H/H_o is the relative humidity, R is the ideal gas constant, T is the absolute temperature, and V is the volume of a mole of liquid water. It should be noted that psychrometer measures the matric and osmotic components of the total moisture potential [see equation (1)] of the unsaturated materials. Measurements are made by using control units or meters available from several manufacturers. The units provide the required switching and cooling circuitry and measurement devices. The psychrometer response is read in microvolts and data can be converted to moisture potential in bars or millibars.

For more detailed information about soil psychrometery with regards to theory, calibration procedures, equipments, and other factors the reader is referred to an excellent review by Evans (1983).

Geologic Environment and Psychrometers Installation

Thermocouples psychrometers were installed in duplicates at eleven stations within two types of hydrogeologic terrain in the northwest and extreme south in the state of Nevada. Table 2 shows the detailed of each station with regard to their location and other factors such as depth of psychrometers, land surface and geologic environment. Statons GG-1A, GG-1B, GG-2A, GG-2B, GG-2C, and DRI are located in mountain soils derived from volcanic terrain of northwestern Nevada near the city of Reno. Stations KC-1A, KC-1B and MM-1A are located in alluvial soils derived from carbonate rock terrain near the city of Las Vegas. Stations J-1A and J-1B are located near Jean, Nevada, within an extremely arid basin. The surface elevation where moisture monitoring stations are located ranges from 3260 feet to 6710 feet above mean sea level. The annual precipitation ranges from 4 inches or less at stations J-1A and J-1B to about 18 inches at stations GG-1A and GG-1B.

Before field installation, soil thermocouple psychrometers were calibrated in the laboratory using a series of salt solutions (Na Cl) having known osmatic potentials.

In order to avoid the introduction of moisture during drilling and the creation of a large disturbed zone around emplaced instruments, the hollow stem auger drilling method was used to drill all boreholes for psychrometer stations with the exception of J-1A and J-1B (see table 2). The auger used in this project has dimensions of 6 inches O.D. and 3 inches I.D. Due to the limited engine power supplied to the auger and the rocky or cemented nature of the alluvial sediments, it was not possible to install psychrometers deeper than 8 to 9 feet below the land surface. However, at stations J-1A and J-1B near Jean the dual tube reverse circulation rotary drilling method was used with great success. Utilizing this method, it was possible to reach a depth of approximately 940 feet for a groundwater exploration project. Psychrometer station J-1B borehole was drilled with water and compressed air and subsequently an aluminum access tube for the neutron probe moisture monitoring and thermocouple psychrometers were installed to a depth of 20 feet below the land surface. Station J-1A was drilled using only air to its total depth of 150 feet. Stations J-1A and J-1B are about 20 to 30 feet apart.

Figures 4 and 5 are the design drawings of the soil thermocouple psychrometers emplacements in all boreholes and J-1A station near Jean, Nevada; respectively. On each borehole, efforts were made to backfill all boreholes with the cuttings and sediments as they originally were in the soil profile. The bentonite clay was used to provide a seal between psychrometers at different depths of installation and also a seal from the surface precipitation which may percolate through the disturbed boreholes area.

Soil moisture potentials and soil temperatures were recorded at all monitoring stations as frequent as possible during the year 1982 (duration of the project).

RESULTS AND DISCUSSION

Moisture movement studies at specific site require a knowledge of the hydraulic gradient and hydraulic conductivity to obtain a solution to the following Darcian type equation

$$q = -K(\theta)[\nabla\phi + \nabla Z] \qquad (26)$$

where q is the moisture flux, $K(\theta)$ is the hydraulic conductivity, $\nabla\phi$ is the moisture potential gradient measurable with soil thermocouple psychrometers, and ∇Z is the gravitational gradient not included in psychrometric measurements (0.0294 bars/foot).

Soil Moisture potential values measured at two depths within the soils profiles on selected dates during the year 1982 for GG-1A, GG-2B, DRI, and KC-1A stations are presented in Figures 6 and 7. All data points are corrected for soil temperature and are the average of two psychrometers readings at each depth. It is clear from these two figures that reliable data were obtained from psychrometers installed at all monitoring stations. Three observations are noted; first, psychrometers located at depth of 8 feet below the land surface of GG-1A station exhibit a near saturation condition from May through October, 1982. Second, the two psychrometers located at MM-1A station did not record any soil moisture potential values within measurement range during the entire period of data collection; ie., the soil moisture potential at 8 feet below the surface at this location is always less than -80 or-90 bars (out-of-range of the soil psychrometery). Third, the soil potentials at the shallow and deep psychrometers location of GG-1A, GG-2B, and DRI stations exhibit a clear pattern of seasonal fluctuations. The soil moisture potential decreases (becomes more negative) during late spring and middle of summer. Another peak of soil moisture potential is seen during the months of August, September, and October 1982. As expected, the shallow psychrometers are responding to the seasonal fluctuations with greater magnitude than the deeper ones (see Figure 6). It is clear that moisture from precipitation and evapotranspiration processes are reflected in the data recorded by the shallow psychrometers of all stations presented in Figures 6 and 7. However, the changes of soil moisture potentials at 5 or 8 feet below the land surface are less pronounced in response to climatic changes.

In as much as the product of the hydraulic conductivity and the hydraulic gradient give the soil moisture flux as presented in equation 32, the most important relationship with respect to evaluating the occurrences of recharge events is the direction of the hydraulic gradients as function of time within the unsaturated zone of the studied locations. The gravitational gradient must be considered where the unsaturated sediments are very near saturated conditions. However, under conditions encountered for stations located in the Geiger Grade - Reno area [stations GG-1A, GG-1B, GG-2A, GG-2B, GG-2C, and DRI (see Figure 6)] and stations KC-1A, KC-1B and MM-1A near Las Vegas, Nevada, the gravitational gradient (Z = 0.0294 bars/foot) can be ignored with reference to most of the soil moisture potential values recorded during the monitoring period of the year 1982. Figure 6 shows that the soil moisture potentials measured at all shallow emplacements (2 or 4 feet below the soil surface) are more negative than values measured at 5 or 8 feet during the monitoring period which started on the sixth of April and ending during the month of November 1982. The only exception is at station GG-1A where the shallow emplaced psychrometer exhibited a less negative soil moisture potential value than the ones at 8 feet below the soil surface. That is to say, the unsaturated earth sediments monitored at Geiger Grade - Reno and Kyle Canyon - Las Vegas areas are loosing soil moisture through the upward movement process during the period of data collection. The soil moisture potential gradient at station GG-1A reversed its direction and therefore an apparent recharge event is observed during late April and early May 1982. The magnitudes of downward or upward moisture flux at this or other stations could be measured with the determination of hydraulic conductivity of the unsaturated sediments.

Figure 8 and 9 show the dynamic nature of soil moisture potential during the year 1982 as a function of depth and time through the upper 150 feet of the unsaturated alluvium for station J-1A at Jean, Nevada. The field-log of formations of the nearby hole designated test hole A3-1 (Appendix A) indicates the static level of the regional groundwater is about 840 to 845 feet below the land surface at this location. No perched water table was recognized between the land surface and the regional groundwater level at 845 feet. The description of the penetrated materials indicates that some layering exists and gravel, silt, and clay are abundant types of sediments with some degree of cementation.

During the monitoring period from January to June 1982 of J-1A station as shown in Figure 8, two distinct moisture potential zones are evident within the alluvium. First, the upper zone of about twenty to thirty feet thick is considered to be "dry" materials. The term "dry" is defined to be that no measurable soil moisture potential was possible to record by using the existing state-of-the-art soil thermocouple psychometery. Second, the lower zone from 35 to 150 feet below the surface exhibits a relatively wetter zone than the upper part of the profile. Here soil moisture potential values ranged from 10.57 to 51.75 negative bars. It could be argued that in extremely coarse sediments low negative values of soil moisture potential may not reflect a significantly wetter zone within the unsaturated part of the J-1A profile; however, the abundant silt and clay within the alluvium as determined by the field-log clearly indicates that higher moisture content can exist within the sediments and that the data reflects real moisture content differences.

Precipitation recorded by a standard rain gauge at station J-1A and J-1B of Jean Site, Nevada, is shown in Table 3 for the period of January 1982 through January 1983. A lenghty dry period from January through the first part of August 1982 is recorded (no rain had occured). As a result of severe thunderstorms, five inches of rain was recorded on August 24 and 0.19 inches was recorded three days later. Three precipitation events occurred during the following five months.

Comparison of the soil moisture potentials data for all depths at J-1A presented in Figure 8 before and after August 24 and 27, 1982 indicate changes and in some cases a reversal of potential gradient within the profile to a depth of 150 feet. To illustrate these relationships, the same data of Figure 8 are plotted in Figure 9 where the soil moisture potentials at selected dates are drawn as function of depths. As previously discussed, the gravitational gradient is neglected in this analyses because of its small value (0.0294 bars/foot). In Figure 9 the soil moisture potentials measured on January 27, May 4, and June 2, 1982, below depth of 20 feet exhibit an increase (become less negative) down to the 150 foot depth. Therefore, the hydraulic gradient in the lower part of the profile causes an upward flux of soil moisture toward the dry zone above. In other words, there appeared to have been a long term net flux of moisture towards the land surface when the monitoring was initiated.

The soil moisture potential changes after the August storm indicate that the flux of moisture, normally upward in the area, was reversed to as deep as 150 feet. However, as the saturated zone is about 845 feet below the land surface in the area, it is unclear if the pulse of recharge was of sufficient strength to pass through the entire unsaturated zone. More likely, it was attenuated to little or no net downward flux below 150 feet and above the zone of regional saturation.

In summary, the J-1A station data shows the dynamic nature of the moisture potentials within the monitored upper 150 feet of the unsaturated sediments during what is believed to normal conditions and after an extreme precipitation event. It is also clear that the hydraulic gradients ($\frac{dh}{dz}$, where h is the measured moisture potential by soil psycrometers) data indicate upward movement of moisture from the deeper profile in response to evapotranspiration from the upper portion of the profile (about 20-30 feet thick) due to the extreme aridity of the area. However, recharge to at least 150' has been observed as a result of a near maximum intensity thunderstorm and subsequent events totaling more than 6.0 inches of precipitation.

An aluminum access tube was installed to a depth of 20 feet with psychrometers emplaced outside the tube in the test hole A3-1 of a groundwater exploration project near Jean, Nevada. This hole was renamed J-1B. The test hole was drilled to below the depth of regional groundwater table at 845 feet below the land surface. The dilling was done using a small amount of water and compressed air and as a result the unsaturated sediment surrounding the borehole retained an unknown amount of moisture. The soil moisture conditions were monitored by the neutron probe and soil psychrometers at at 5, 15, and 20 feet below the land surface.

Soil moisture potentials at the monitored three depths of J-1B for the period of June 1982 through the first part of February 1983 are shown in Figure 10. The amount and dates of precipitation are also shown in the figure. It is clear that the moisture potentials profiles are changing in response to the precipitation occurrences. Even through the hydraulic gradient is shown to be in the upward direction for the total profile, the moisture potential values for the three depths have increased in response to a small change of moisture content of the sediments. The magnitude of change in the values are much less than changes observed for the nearby J-1A station. We believe this is related to two factors: soil psychrometers are not sensitive to moisture changes within the near saturated conditions, i.e., soil moisture potential values within the range of 0.0 to 2-3 of negative bars, and the infiltration from the storms had minor effect on the local environment near the borehole due to the antecedent very local higher moisture content from drilling water.

Figure 11 presents changes of soil moisture content as measured by the in-situ neutron probe in % by volume of the sediments of station J-1B for three depths at 5, 15 and 20 feet. The most important observation is that the profile sediments moisture contents has not changed very significantly during the entire year of 1982. It is assumed that the range of moisture measurement error approximately within $\pm$ 1.0%. However, the moisture content changes can be seen as movement of moisture through the profile. No detailed records were kept with regards to the moisture disturbances which may have occured during the drilling process for the exploration project. However, the normal rate of addition of drilling water to the air was 1-2 gpm. More information was expected from monitoring J-1B; however, the period of data collection proved too short before the August, 1982 storms to extract valuable and meaningful results from J-1B station in terms of the time necessary to readjust to original pre-drilling moisture conditions assumed to be similar to nearby J-1A.

An attempt was made to compare the changes of soil moisture potentials within the upper 20 feet of the unsaturated earth sediments of stations J-1A (drilled "Dry") and J-1B (drilled

"Wet") of the Jean site, Nevada. Figure 12 shows the soil moisture potential profiles for both stations monitored on June 2, August 27, and November 9, 1983; and February, 1983. During these eight months about 7.0 inches of precipitation have been recorded on site after a prolonged dry period. The data demonstrate that soil moisture potentials at all 4 depths in the "Dry" drilled profile have changed in response to precipitation events, however, little changes have been observed for the "Wet" drilled hole. It is postulated that due to the insensitivity of soil thermocouple psychrometers in the near saturated zone of moisture content (large values of negative soil moisture potential; i.e., values near 0.0 to 2 negative bars) recharge events were not detected by psychrometers.

CONCLUSION

The investigation has demonstrated the feasibility of directly monitoring soil moisture potential with thermocouple psychrometers in the semi-arid and arid environments of the Great Basin. Instrument emplacement using hollow stem auger or reverse circulation rotary drilling methods (no addition of water or other drilling fluids) are believed necessary. This requirement limited the depth of instrumentation in the present investigation; however, it was also demonstrated that the reverse circulation rotary drilling technique using air has the potential for deep instrument emplacement.

The data developed on soil moisture potential are useful for determining the vertical component of moisture migration. Review of the developed soil moisture potential data within the context of station environments, frequency of data collection, and apparent results lead to some general conclusions. In the cases of the Northern Nevada foothill and mountainous stations, and the higher Kyle Canyon stations in Southern Nevada, moisture potential values indicting near-saturation conditions occurring at the base of the monitored profiles suggest that recharge to those levels occurred at or near those sites. Two possibilities explain these observations in light of the dominance of upward potential gradients: recharge occurred near the sites and moved laterally to the station sites along the underlying hard and low permeability zones which generally stopped the drilling, or 2) the frequency of data collection was insufficient to recognize short term pulses of infiltration and percolation (potential gradient reversals). The later does not seem as likely as the former, but neither can be ruled out. These observations suggest that deeper instrumentation and a greater frequency of instrument readings would greatly aid in the interpretation of the data.

Generally, based on the direct available evidence, upward gradients dominate.

The data from stations MM-1 and J-1A, in the lower, more arid environments of Southern Nevada, demonstrate the prolonged conditions of very low moisture contents and upward potential gradients. These data indicate little or no recharge occurs in such environments with the possible exception of the unusual precipitation events. The storm in August, 1982 at the J-1A station clearly generated a recharge pulse to 150 feet of depth, but it is not clear if the pulse traversed the entire 840 feet of unsaturated material. The storm, producing 5 inches in a few hours, probably represents the extreme precipitation event of the present climate. Frequency of such precipitation events is unknown, but they likely do not occur more than a few times in any locality per century. After monitoring ceased at the MM-1 site, an unusual precipitation event occurred in the Spring of 1983 which produced a total of 5 inches in 48 hours. Evidence of important infiltration occurred in the form of the seepage of one foot of water into a half basement of the house at that site. The relationships suggest that infiltration into the uppermost soil profile and lateral percolation on a well developed caliche layer caused the local concentration of seepage into the basement. There is approximately 500 feet of unsaturated material at this site. The off scale (dry) thermocouple psychrometer readings during the prior year of monitoring and a 12 year history of the basement without moisture or seepage suggest the precipitation event was exceptional.

In summary, it is concluded that infiltration and percolation at least occasionally occurs in the more arid bajada environments of Southern Nevada, but it is not clear if downward migration of moisture fully penetrates the thick unsaturated zones. The data from the higher elevation stations also suggests infiltration has occurred, but it is not clear where it occurred or what the fate may be. These data point out the need for monitoring profiles that at minimum fully penetrate the upper zone where roots and seasonal moisture changes occur. Ideally, the majority of the unsaturated zone should be monitored when relatively thick. Frequent instrument reading intervals and long monitoring periods are also desirable. In order to quantitatively estimate vertical flux, neutron access tubes are needed to determine a history of moisture content in the monitored profile next to the thermocouple psychrometer installations. By evaluating or measuring the unsaturated hydraulic conductivities, as would be permitted with the moisture content data (see the discussion in the Theorectical Analysis), equations of flow can be solved and a budget of moisture migration could be established at each station with the two types of data. Unfortunately, the original difficulties encountered in instrument emplacement and loss of funding for a second phase of investigation have prevented this next step to date.

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Table 1. Potential expressed in the major measurement systems.

Potential	cgs system	mks system	English system
$\frac{\text{energy}}{\text{mass}}$	$\frac{\text{dyne cm}}{\text{gm}} = \frac{\text{erg}}{\text{gm}}$	$\frac{\text{Newton meter}}{\text{kg}} = \frac{\text{Joule}}{\text{kg}}$	$\frac{\text{ft lb}}{\text{slug}}$
$\frac{\text{energy}}{\text{weight}}$	$\frac{\text{dyne cm}}{\text{dyne}} = \text{cm}$	$\frac{\text{Newton meter}}{\text{Newton}} = \text{meter}$	$\frac{\text{ft lb}}{\text{lb}} = \text{ft}$
$\frac{\text{energy}}{\text{volume}}$	$\frac{\text{dyne cm}}{\text{cm}_3} = \frac{\text{dyne}}{\text{cm}_2}$	$\frac{\text{Newton meter}}{\text{meter}_3} = \frac{\text{Newton}}{\text{meter}_2}$	$\frac{\text{ft lb}}{\text{ft}_2} = \frac{\text{lb}}{\text{ft}_3}$

$$10100 \text{ kM/m}^2 = \begin{cases} 1 \text{ bar} \\ 14.5 \text{ psi} \\ 29.5 \text{ in Hg} \\ 75.1 \text{ cm Hg} \\ 33.4 \text{ ft water} \\ 1020 \text{ cm water} \end{cases}$$

Table 2. Locations, elevation, depths of installed psychrometers, and the geologic environments of soil moisture monitoring stations.

Station	Location	Surface Elevation in ft-MSL	Geologic Environment	No.	Psychrometers Depth below surface in feet
GG-1A	Sec. 8, T17N, R21E, Virginia City Quad.	6710	Alluvial Soils, Mt., Vol.	2 2	4 8
GG-1B	Sec. 8, T17N, R21E, Virginia City Quad.	6700	Alluvial Soils, Mt., Vol.	2 2	4 8
GG-2A	Sec. 28, T18N, R21E, Chalk Hills Quad.	5800	Alluvial Soils,	2	4
GG-2B	Sec. 28, T18N, R21E, Chalk Hills Quad.	5800	Alluvial Soils,Mt. Vol.	2 2	4 8
GG-2C	Sec. 28, T18N, R21E, Chalk Hills Quad.	5800	Alluvial Soils, Vol.	2 2	4 8
KC-1A	Sec. 27, T19S, R57E, Charleston Peak Quad.	6400	Alluvial Terrace, Mt., Carb.	2	8
KC-1B	Sec. 27, T19S, R57E, Charleston Peak Quad.	6400	Alluvial Terrace, Mt., Carb.	2	8
J-1A	Sec. 4, T25S, R59E, Goodsprings Quad.	3360	Alluvial Fan, Bajada, Carb.	2	5,10,15,20,35 70,100,150
J-1B	Sec. 4, T25S, R59E, Goodsprings Quad.	3260	Alluvial Fan, Bajada, Carb.	2	5,15,20
MM-1A	Sec. 8, T19S, R59E, Corn Creek Quad.	3760	Alluvial Fan, Bajada, Carb.	2	8
DRI	Sec. 25, T20N, R19E,	4900	Alluvial Soils, Mt., Vol.	2 2	2 5

Table 3. Precipitation recorded at Stations J-1A and J-1B, Jean, Nevada, during the period of January 27, 1982 through February 16, 1983.

Date	Precipitation in inches
08-24-82	5.00
08-27-82	0.19
09-7-82	0.09
12-01-83	1.28
01-11-83	0.35

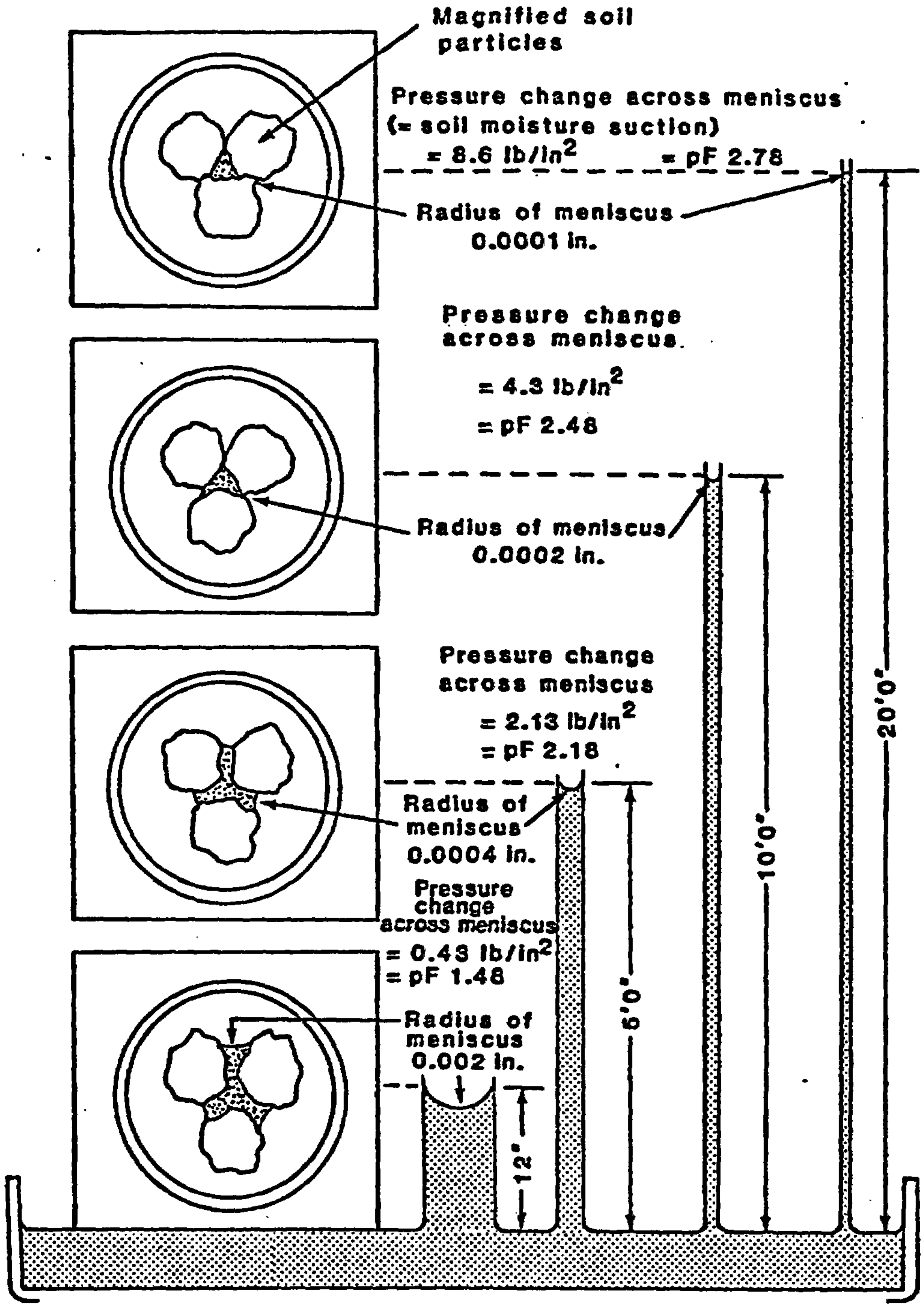

Figure 1. Capillary tubes showing configuration of the air water interfaces at different heights (after Dempsey and Elzeftawy, 1976).

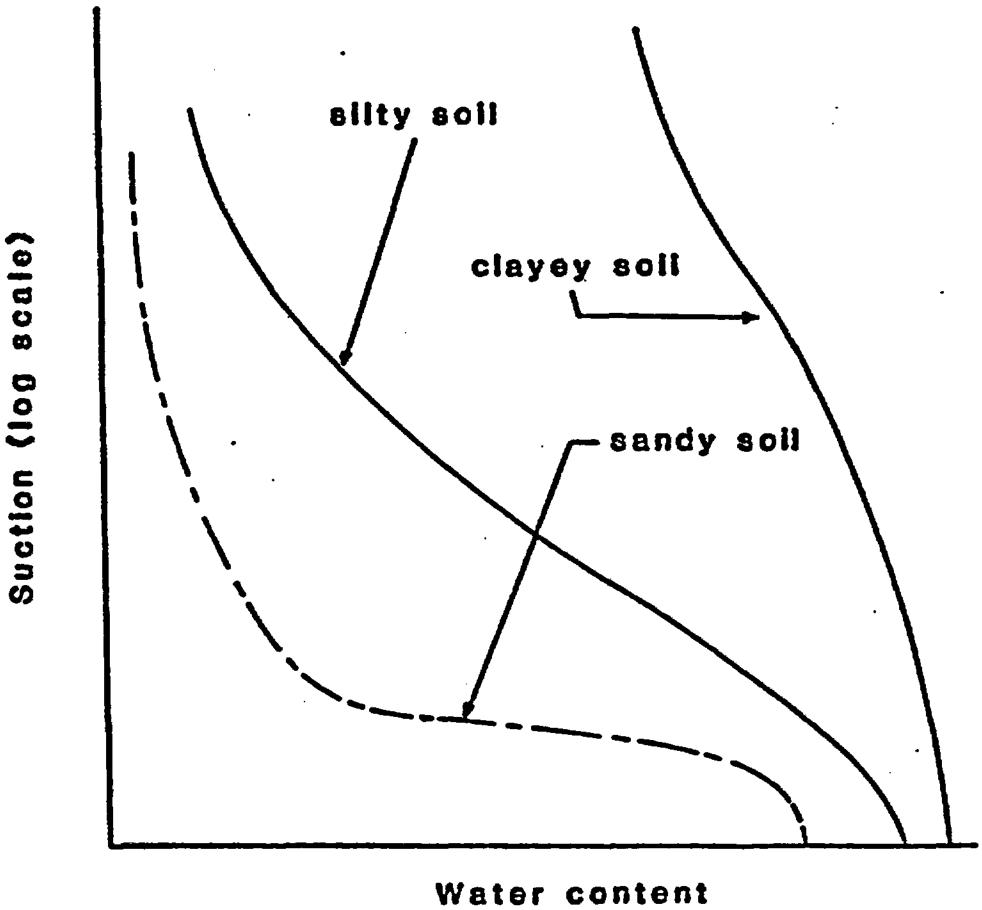

Figure 2. Relative soil moisture characteristic curves for sandy, silty, and clayey soils.

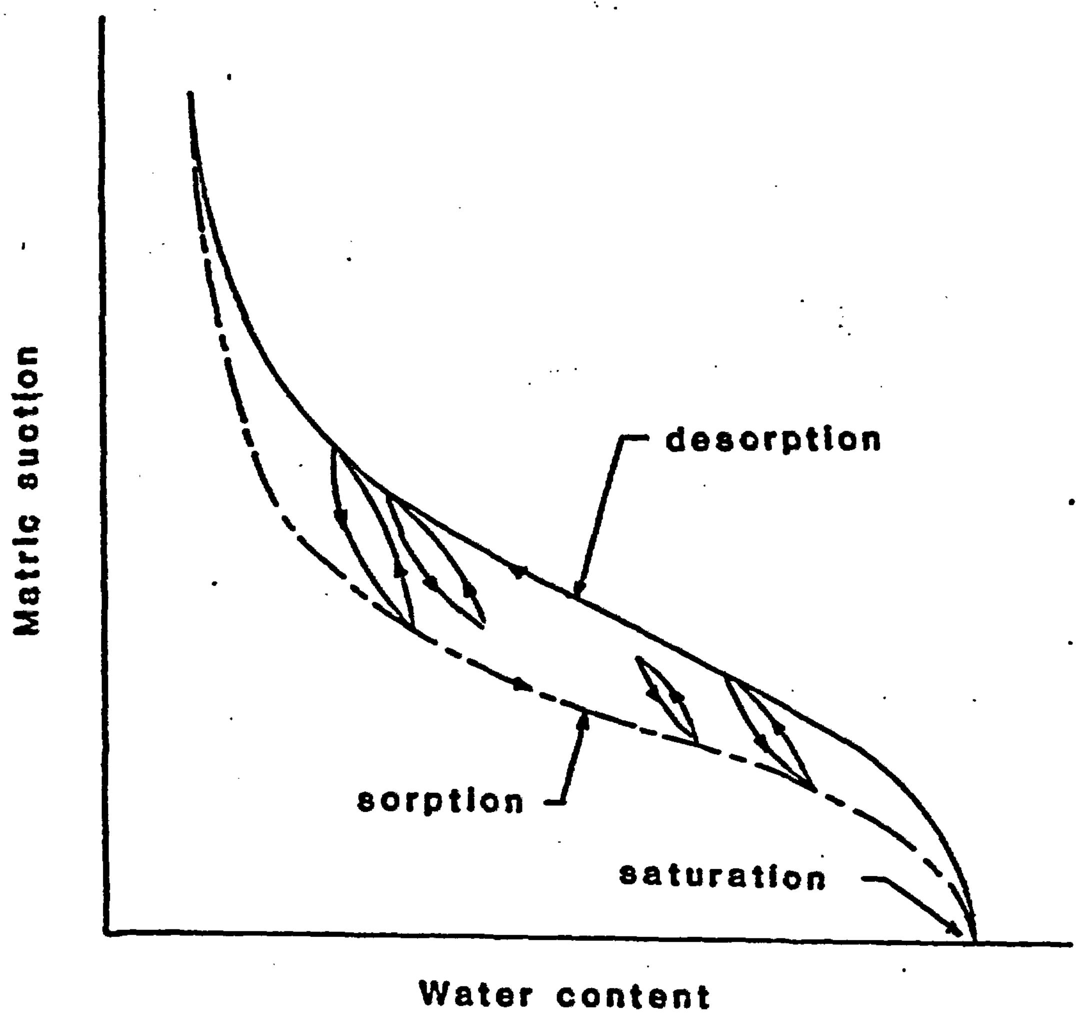

Figure 3. Hysteresis effects of drying and wetting conditions on moisture potential (matric suction).

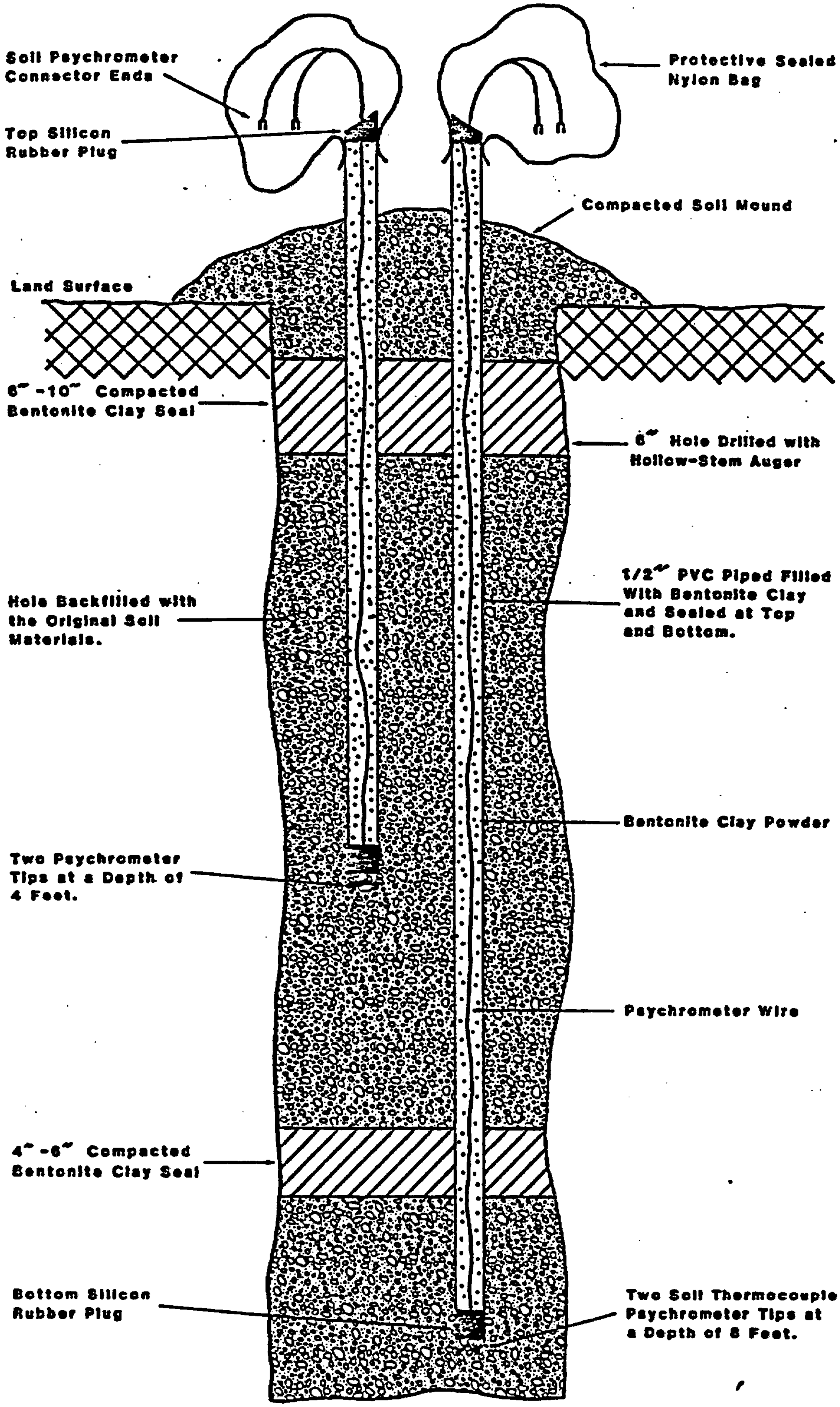

Figure 4. Schematic of soil psychrometers installation at moisture

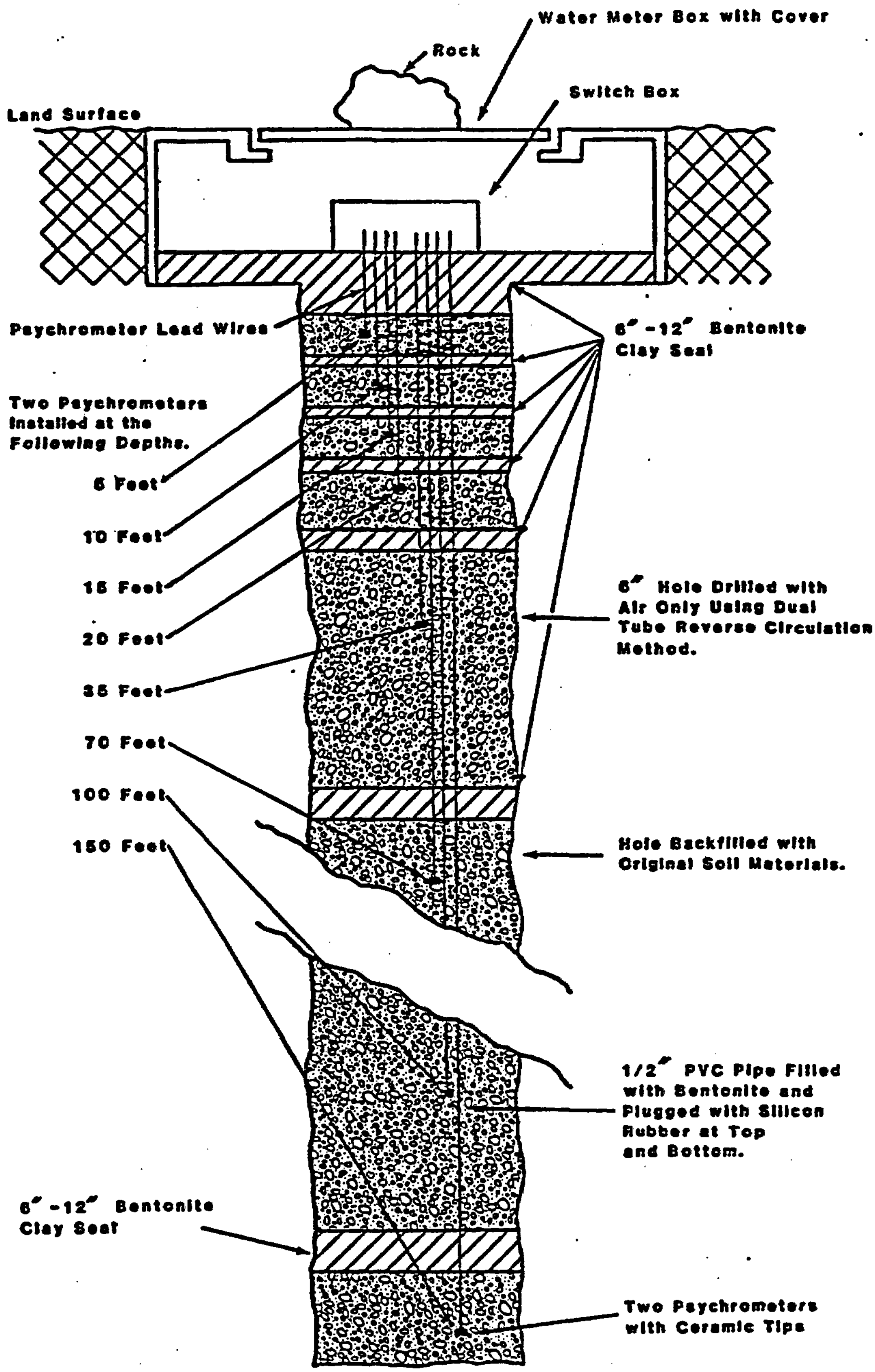

Figure 5. Schematic of soil psychrometers installation at J-1A station near Jean, Nevada.

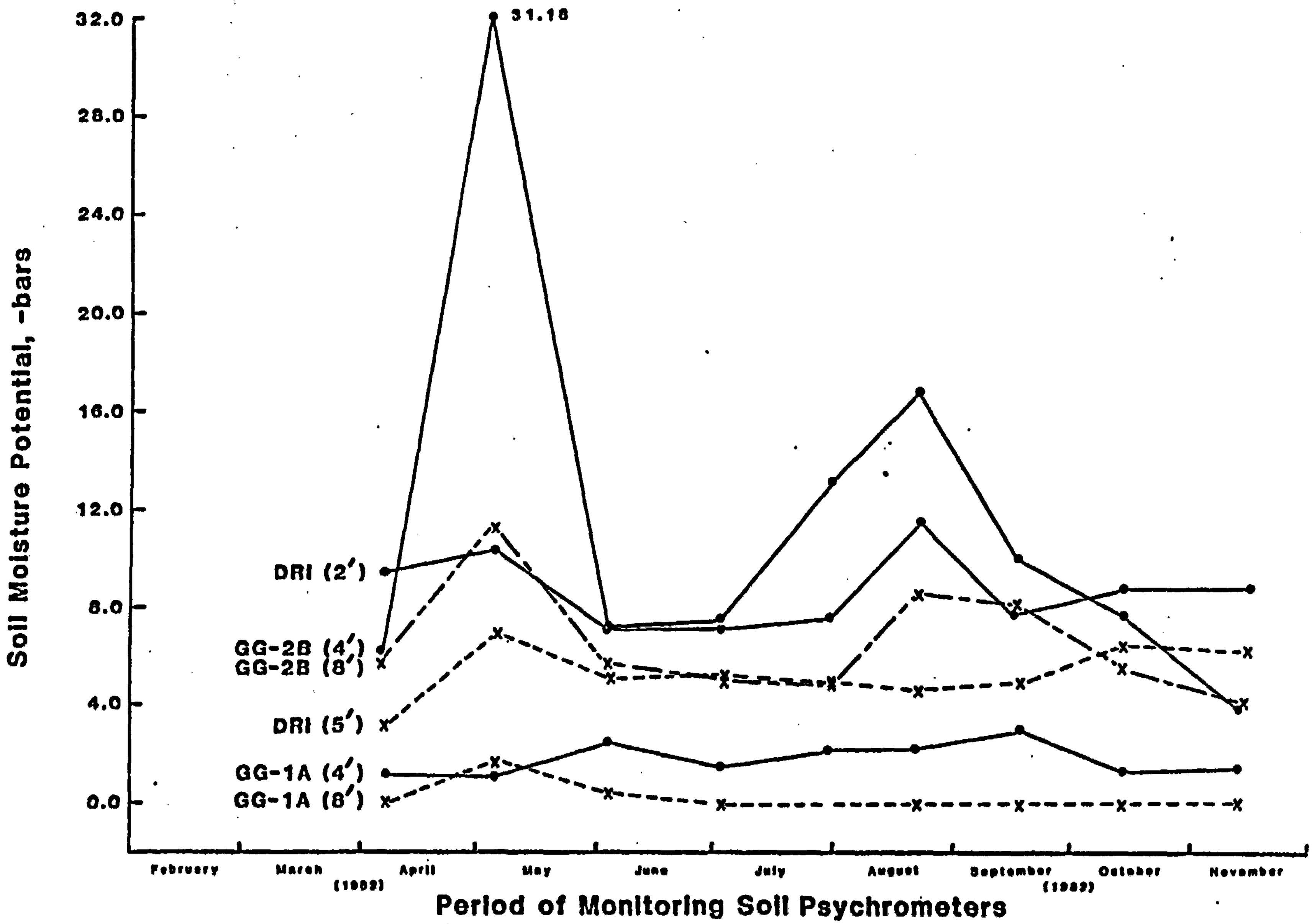

Figure 6. Soil psychrometers data for stations GG-1A, GG-2B, and DRI during the period of 1982 (stations located near Reno, Nevada).

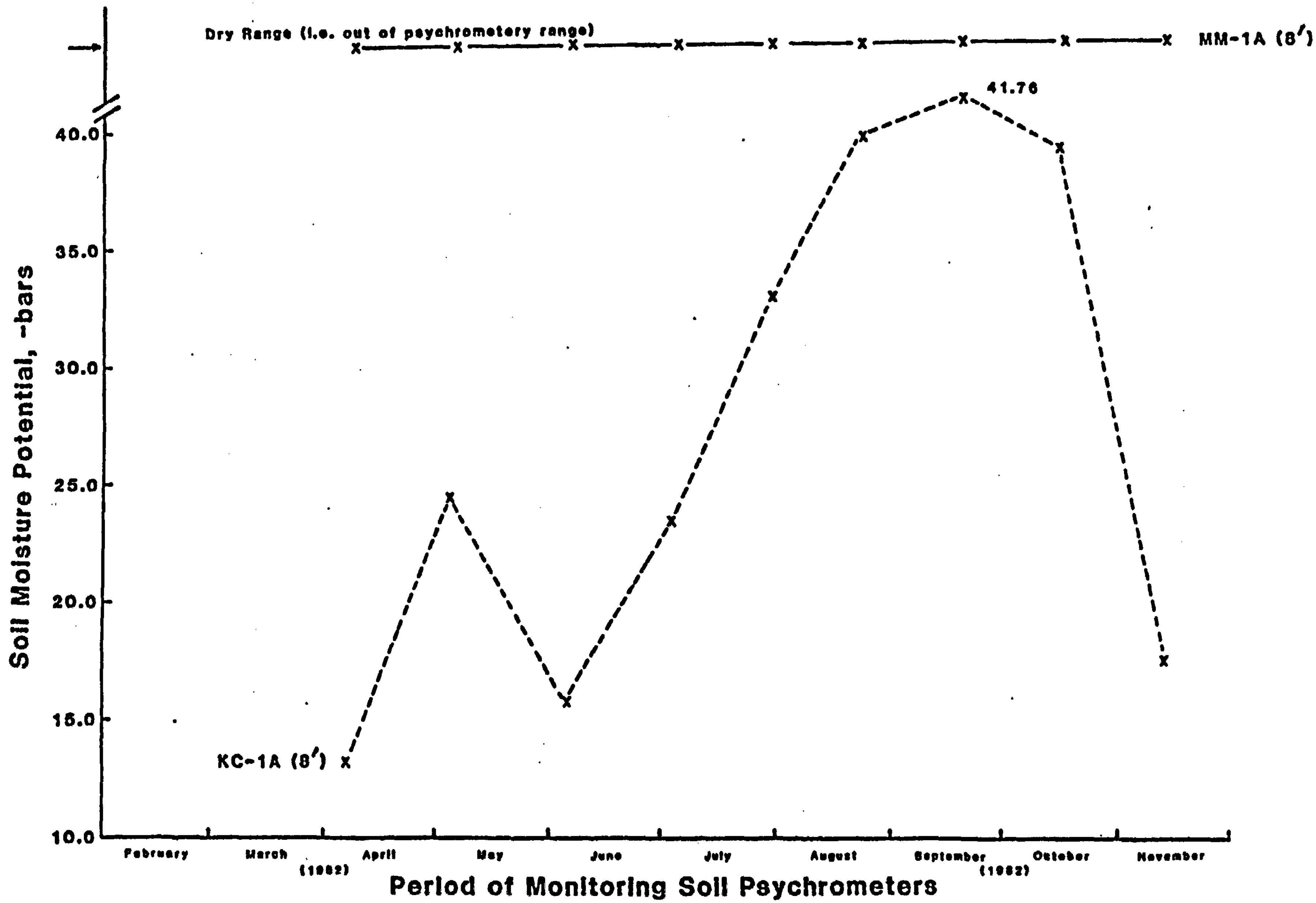

Figure 7. Soil psychrometers data for stations KC-1A and MM-1A for the period of 1982 (stations located near Las Vegas, Nevada).

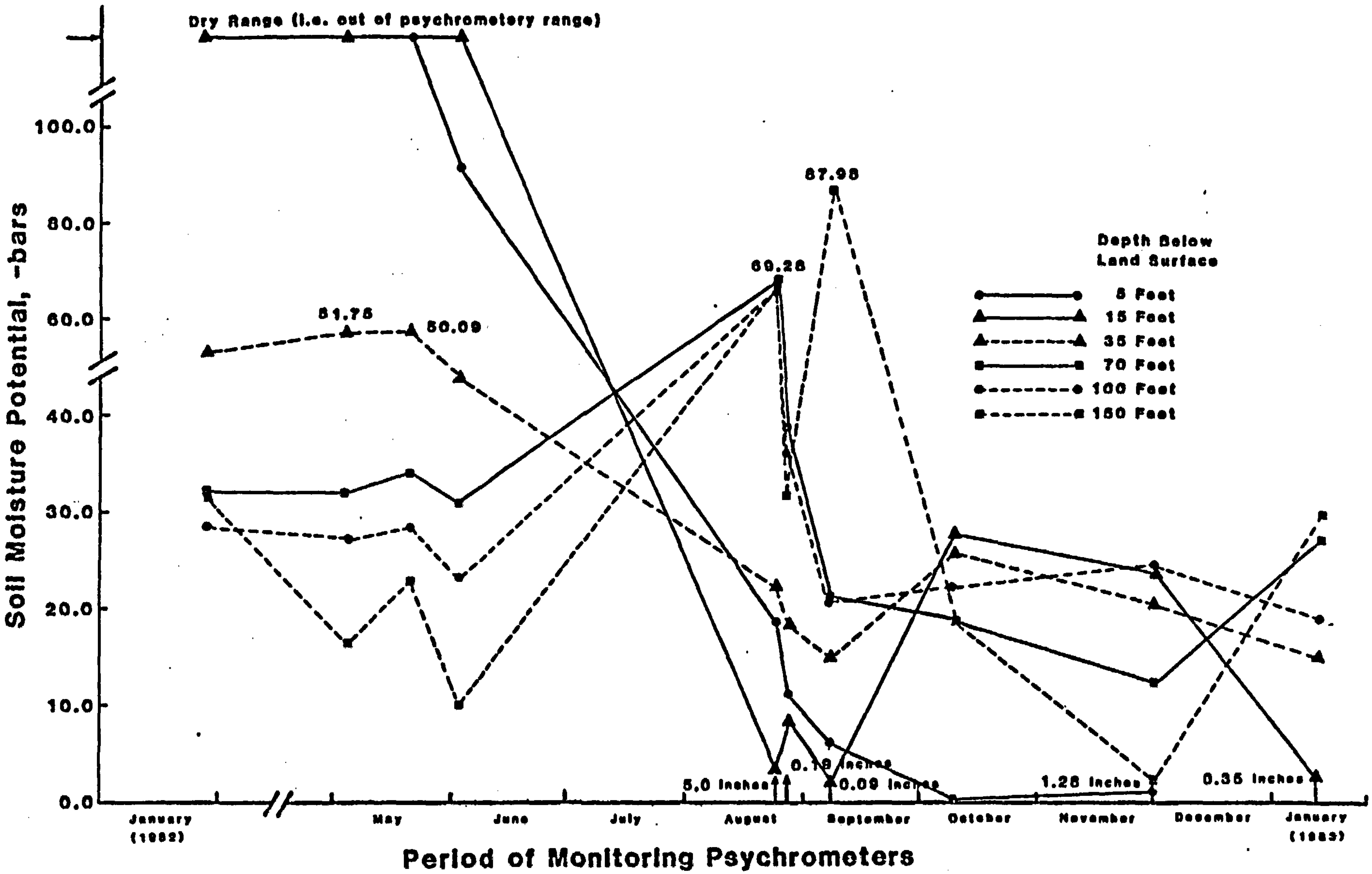

Figure 8. Soil psychrometers data for station J-1A during the year 1982 (station located near Jean, Nevada).

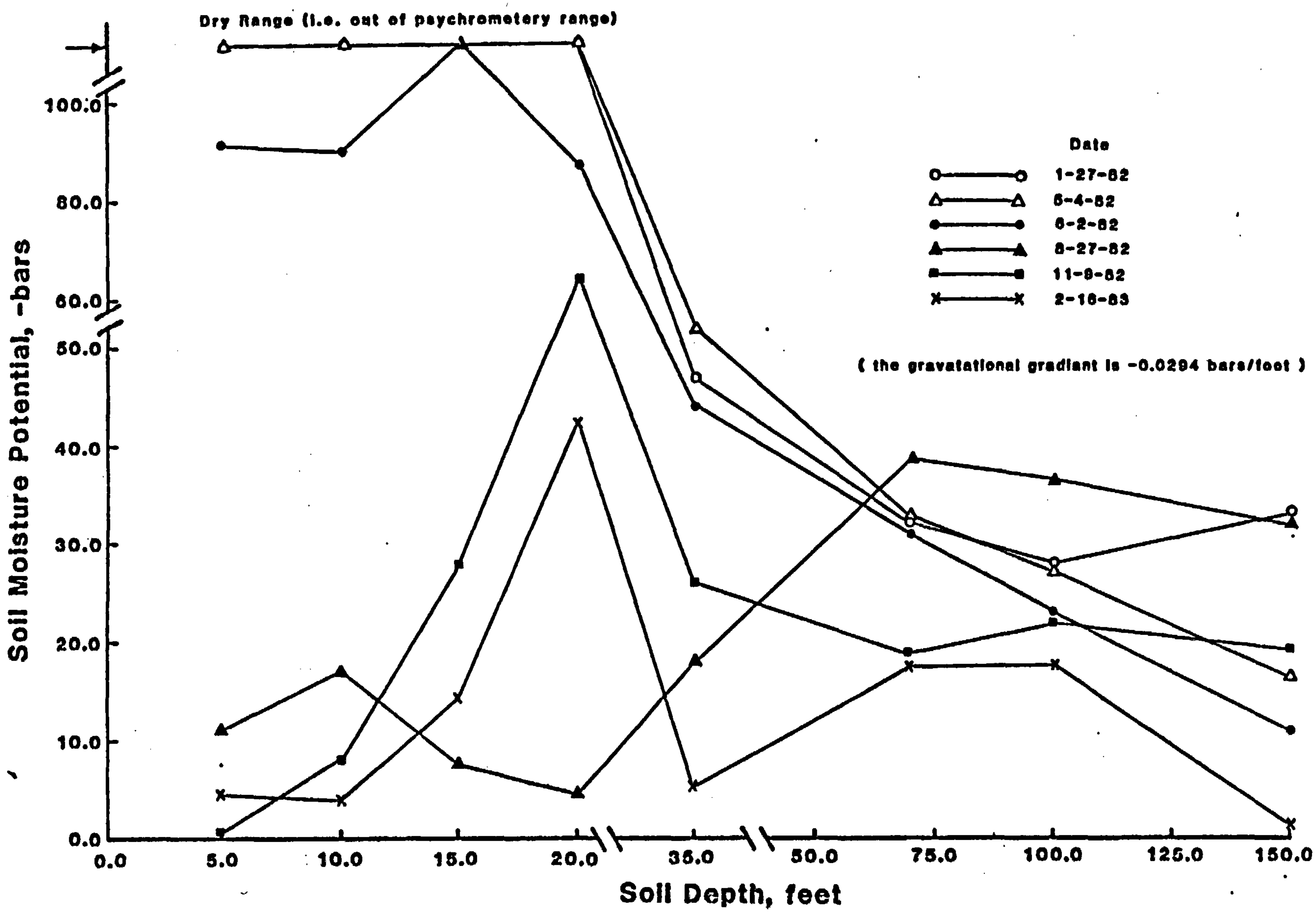

Figure 9. Soil psychrometer data for station J-1A as function of soil depth (station located near Jean, Nevada).

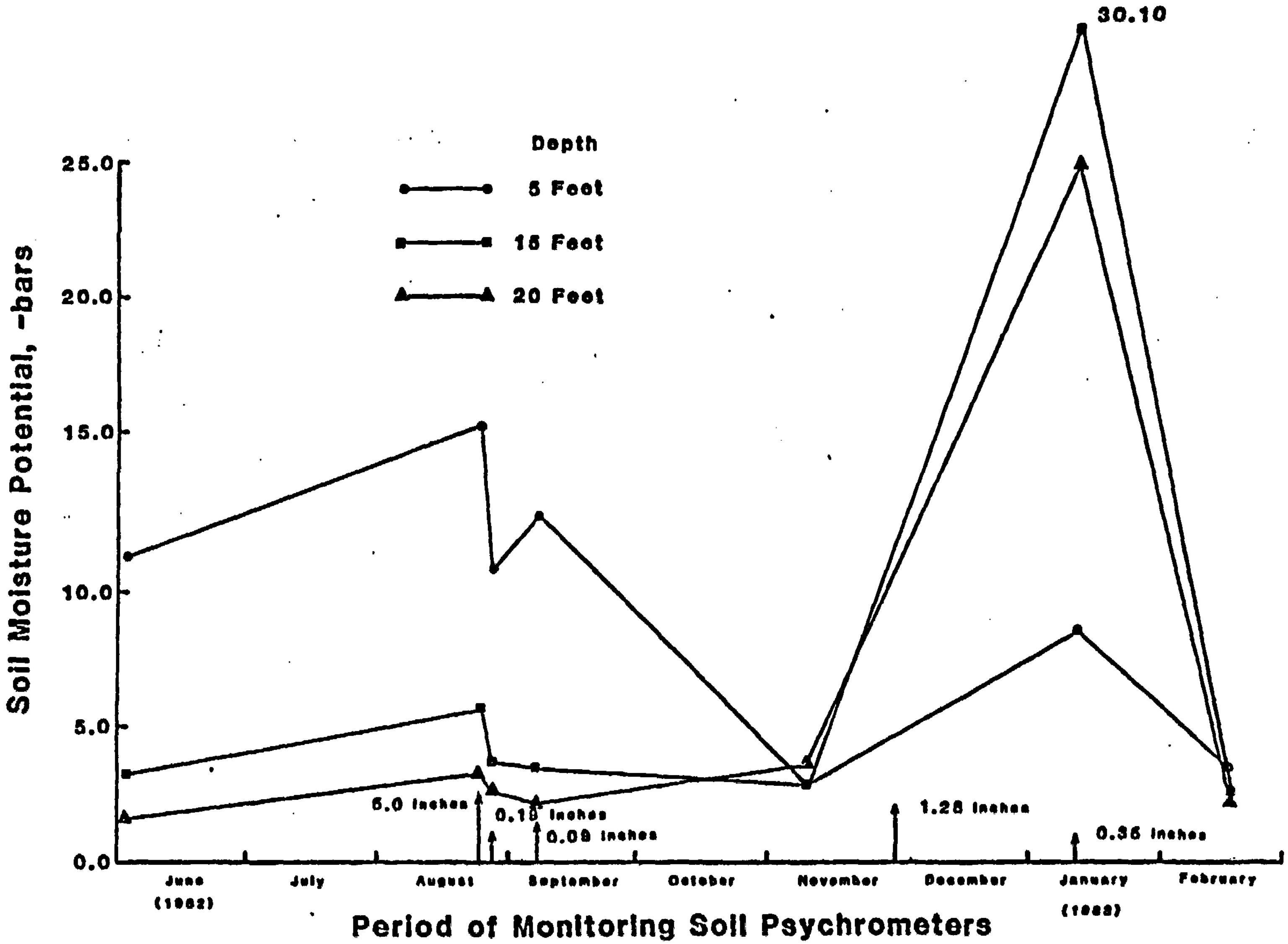

Figure 10. Soil psychrometers data for station J-1B during the year 1982 (J-1B is located about 20-30 feet from J-1A).

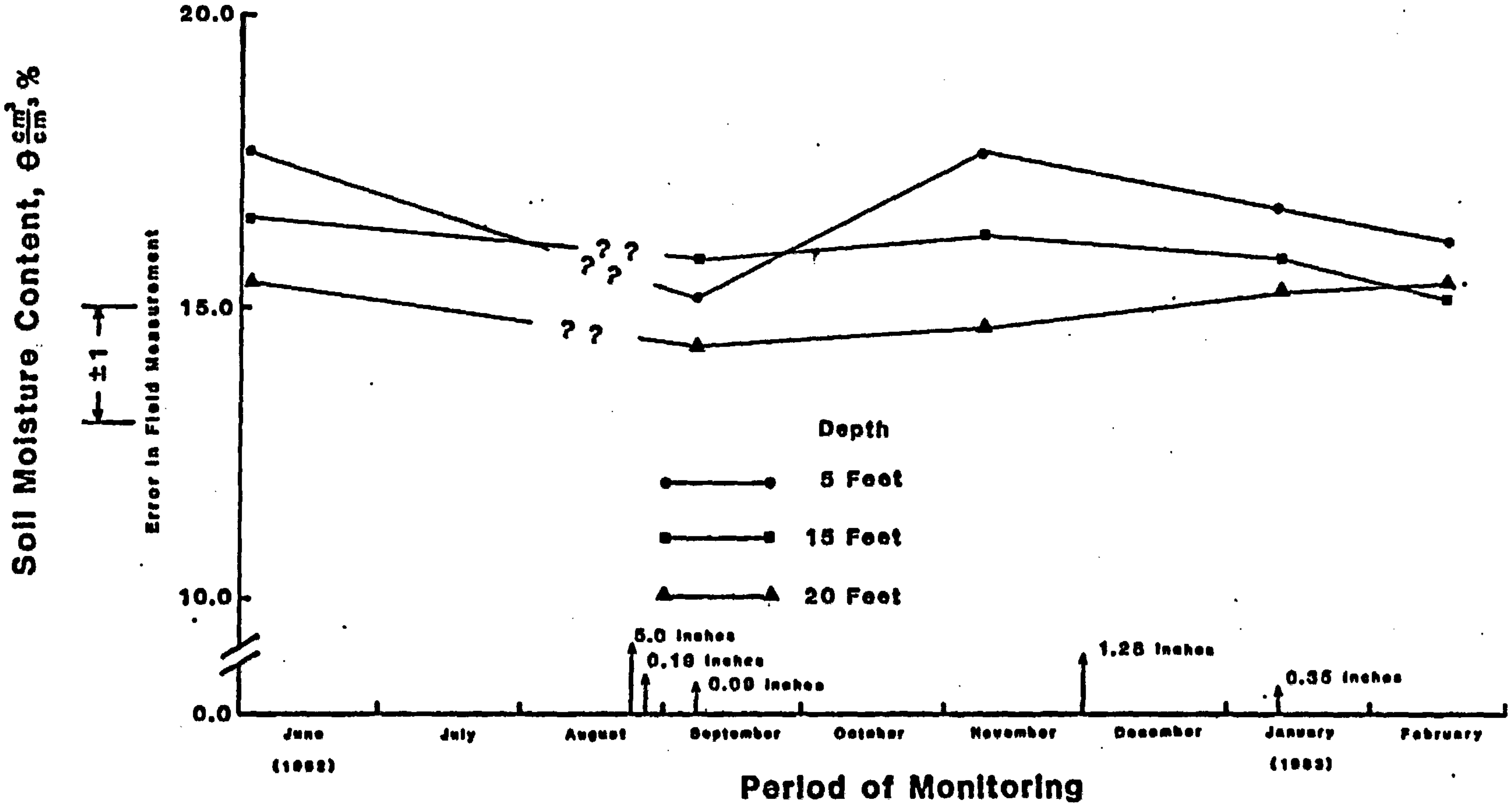

Figure 11. Soil moisture contents data by volume, as measured by Neutron Probe, during the year 1982 for station J-1B near Jean, Nevada.

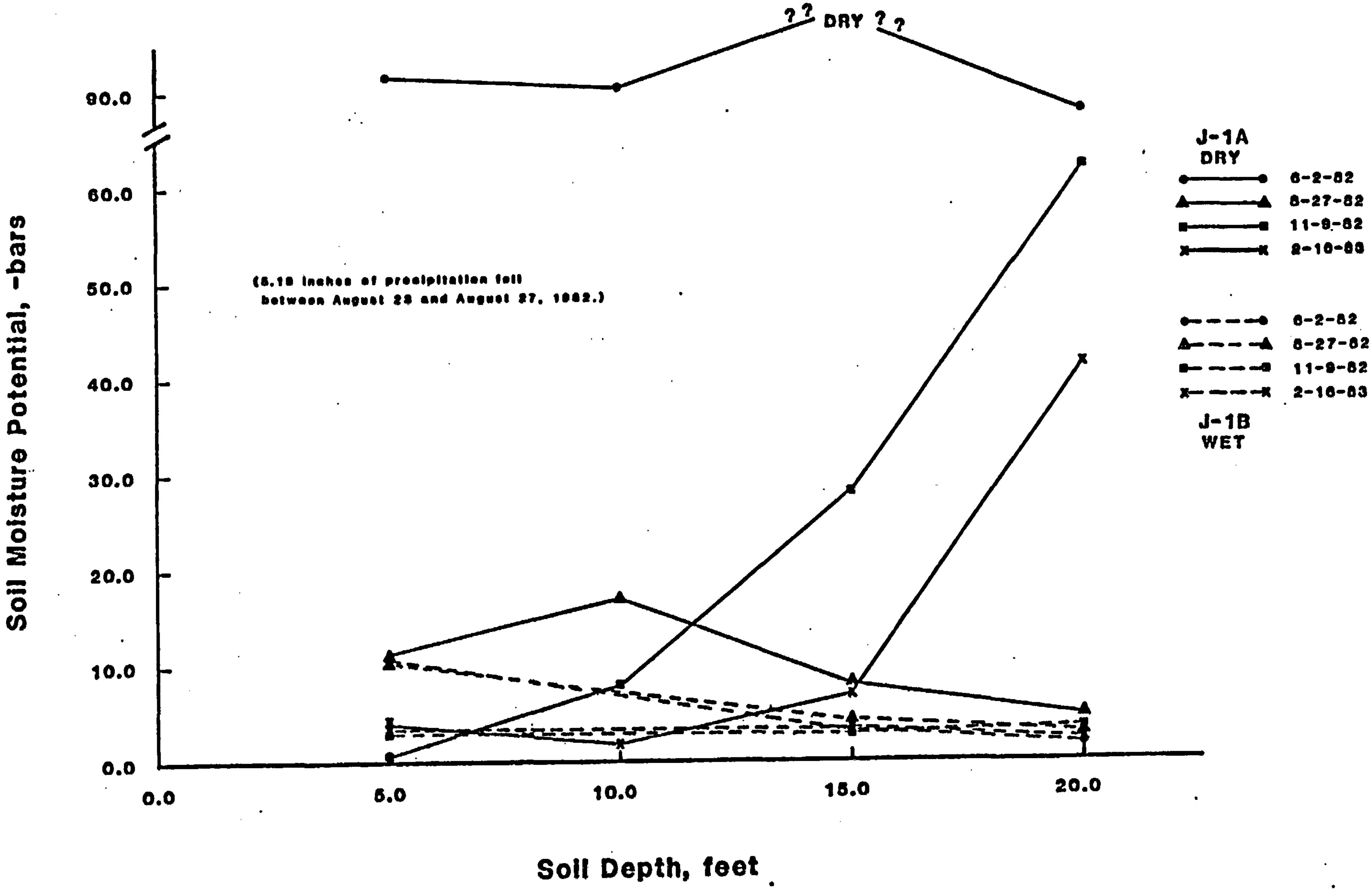

Figure 12. Comparison of soil moisture potential between J-1A and J-1B stations at Jean, Nevada, as a function of depth and time during the 1982/83 monitoring period.

Test Hole A3-1
Field Log of Formations

From (ft)	To (ft)	Description of Material
0	5	Limestone gravel, silt and clay
10	15	Limestone gravel, silt and clay
20	25	Limestone gravel, silt and clay
30	35	Limestone gravel, silt and clay
40	45	Limestone gravel, silt and clay
50	55	Limestone gravel, silt and clay
60	65	Limestone gravel, silt and clay
70	75	Limestone gravel, silt and clay
80	85	Limestone gravel, silt and clay
90	95	Coarse sand & ls gravel - bits of silt & clay
100	105	Well cemented gravel - small pebbles
110	115	Well cemented gravel - small pebbles
120	125	Coarse sand and gravel, abundant clay
130	135	Coarse sand and gravel, abundant clay
140	145	Coarse sand and gravel, abundant clay
150	155	Coarse sand and gravel, abundant clay
160	165	Coarse sand and gravel, abundant clay
170	175	Coarse sand and gravel, abundant clay
180	185	Coarse sand and gravel, abundant clay
190	195	Coarse sand and gravel, abundant clay
200	205	Coarse sand and gravel, abundant clay
210	215	Coarse sand & gravel, cemented gravel, abundant clay
220	225	Coarse sand & gravel, cemented gravel, abundant clay
230	235	Coarse sand & gravel, cemented gravel, abundant clay
240	245	Coarse sand & gravel, cemented gravel, abundant clay
250	255	Coarse sand & gravel, cemented gravel, abundant clay
260	265	Coarse sand & gravel, cemented gravel, abundant clay
270	275	Coarse sand & gravel, cemented gravel, abundant clay
280	285	Coarse sand & gravel, cemented gravel, abundant clay

Test Hole A3-1
Field Log of Formations (con't.)

From (ft)	To (ft)	Description of Material
290	295	Coarse sand & gravel, cemented gravel, abundant clay
300	305	Coarse sand & gravel, cemented gravel, abundant clay
310	315	Coarse sand & gravel, cemented gravel, abundant clay
320	325	Coarse sand & gravel, cemented gravel, abundant clay
330	335	Coarse sand & gravel, cemented gravel, abundant clay
340	345	Coarse sand & gravel, cemented gravel, abundant clay
350	355	Coarse sand & gravel, cemented gravel, abundant clay
360	365	Coarse sand & gravel, cemented gravel, abundant clay
370	375	Clay - white like caliche
380	385	Clay - white like caliche - tan ls
390	395	Tan silty ls
400	405	Tan silty ls
410	415	Tan silty ls
420	425	Tan silty ls
430	435	Tan silty ls
440	445	Tan silty ls
450	455	Tan silty ls
460	465	Tan silty ls
470	475	Tan silty ls
480	485	Tan silty ls
490	495	Tan silty ls
500	505	Tan silty ls
510	515	Tan silty ls
520	525	Tan silty ls
530	535	Tan silty ls
540	545	Tan silty ls
550	555	Tan silty ls
560	565	Tan silty ls
570	575	Tan silty ls

Test Hole A3-1
Field Log of Formations (con't.)

From (ft)	To (ft)	Description of Material
580	585	Tan silty ls
590	595	Tan silty ls
600	605	Tan silty ls
610	615	Tan silty ls
620	625	Light grey to tan silty ls
630	635	Tan to light grey silty ls
640	645	Tan to light grey silty ls
650	655	Tan to light grey silty ls
660	665	Tan to light grey silty ls
670	675	Tan to light grey silty ls
680	685	Tan to light grey silty ls, some calcareous siltstone
700	705	Tan silty ls and calcareous siltstone
710	715	Tan silty ls and calcareous siltstone
720	725	Tan silty ls and calcareous siltstone
730	735	Tan silty ls and calcareous siltstone
740	745	Tan silty ls and calcareous siltstone
750	755	Tan silty ls and calcareous siltstone
760	765	Tan silty ls and calcareous siltstone
770	775	Tan silty ls and calcareous siltstone
780	785	Tan silty ls and calcareous siltstone
790	795	Tan silty ls and calcareous siltstone
800	805	Tan silty ls and calcareous siltstone
810	815	Tan silty ls and calcareous siltstone
820	825	Tan silty ls and calcareous siltstone
830	835	Light grey ls & tan calcareous siltstone
840	845*	Light grey ls & tan calcareous siltstone EC 1150, Temp. 19.2°C, pH 8.2
850	855	Light grey ls & tan calcareous siltstone

*Water Sample

Test Hole A3-1
Field Log of Formations (con't.)

From (ft)	To (ft)	Description of Material
860	865	Light grey ls & tan calcareous siltstone
870	875	Light grey ls & tan calcareous siltstone
880	885	Light grey ls & tan calcareous siltstone
890	895	889 - 894 ls with fractured quartz
900	905*	Tan to grey ls (dolomite)
		EC 1330, Temp. 24.1°C, pH 8.34
		5 gal./38 sec.
910	915	Tan to grey ls (dolomite)
920	925*	Tan to grey ls (dolomite)
		EC 1340, Temp. 24.8°C, pH 8.21
		5 gal./24 sec.
930	935	Tan to grey ls (dolomite)
	TD @ 939*	EC 1325, Temp. 27.3°C, pH 8.12

*Water Sample