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DRILLING AND CORING METHODS THAT MINIMIZE THE DISTURBANCE OF CUTTINGS, CORE, AND ROCK FORMATION IN THE UNSATURATED ZONE, YUCCA MOUNTAIN, NEVADA

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Abstract

A drilling-and-casing method (Odex 115 system)[4] utilizing air as a drilling fluid was used successfully to drill through various rock types within the unsaturated zone at Yucca Mountain, Nevada. This paper describes this method and the equipment used to rapidly penetrate bouldery alluvial-colluvial deposits, poorly consolidated bedded and nonwelded tuff, and fractured, densely welded tuff to depths of about 130 meters. A comparison of water-content and water-potential data from drill cuttings with similar measurements on rock cores indicates that drill cuttings were only slightly disturbed for several of the rock types penetrated.

Coring, sampling, and handling methods were devised to obtain minimally disturbed drive core from bouldery alluvial-colluvial deposits. Bulk-density values obtained from bulk samples dug from nearby trenches were compared to bulk-density values obtained from drive core to determine the effects of drive coring on the porosity of the core.

Rotary coring methods utilizing a triple-tube core barrel and air as the drilling fluid were used to obtain core from welded and nonwelded tuff. Results indicate that the disturbance of the water content of the core was minimal.

Water-content distributions in alluvium-colluvium were determined before drilling occurred by drive-core methods. After drilling, water-content distributions were determined by nuclear-logging methods. A comparison of the water-content distributions made before and after drilling indicates that Odex 115 drilling minimally disturbs the water content of the formation rock.

[4]Use of the brand name is for descriptive purposes only and does not constitute an endorsement by the U.S. Geological Survey.

Introduction

Investigators studying both saturated and unsaturated flow and transport phenomena in the field often need borehole geologic samples that have physical and chemical properties representative of the formation rock. In addition, these same investigators often require that the formation rock be relatively undisturbed by drilling and coring activities, so that in-situ borehole testing can be initiated under ambient conditions. In practice, to obtain completely undisturbed geologic samples (core and cuttings) and to drill a borehole without disturbing the surrounding formation rock is impossible. Therefore, the goal of most investigators has been to minimize the disturbance of both geologic samples and formation rock.

Workers concerned with minimizing the disturbing effects of drilling have had some success in relatively easy-to-drill formations. Auger drilling has long been considered an excellent method for minimally disturbing many types of unconsolidated rock (Acker, 1974). Another good method, but which has limited applicability, involves driving or spinning casing into easily penetrable sediments and then drilling the sediments out of the casing by rotary methods (Scalf et al., 1981). Finally, rotary drilling with reverse circulation specifically is designed to minimize the disturbance of the formation, and it can be used successfully in a wider variety of stable, consolidated rock types (Campbell and Lehr, 1973). Reverse air-vacuum rotary drilling (Whitfield, 1985) (these proceedings) utilizes air as the drilling fluid and employs a vacuum to circulate the drilling fluid. Reverse circulation uses a dual string of pipe to contain drilling fluid moving to the drill bit and drilling fluid moving away from the drill bit to the ground surface. However, reverse-circulation methods using air as the drilling fluid are not designed for use in unstable formations that can cave in on the drill pipe.

Various methods that are considered to yield minimally disturbed geologic samples in various rock types are reviewed in a report by the U.S. Bureau of Reclamation (1972). Shelby-tube or thin-walled samplers work well in fine, unconsolidated sediments. Thicker walled solid-tube or split-tube (split-spoon) samplers have been used successfully in coarser sediments, but they disturb samples more than Shelby tubes. Denison and Pitcher core barrels yield representative samples from more consolidated sediments.

All of these drilling and sampling methods are not suitable for rock types that are more difficult to drill and core, such as fractured, densely welded tuff and bouldery alluvial-colluvial material that occurs at Yucca Mountain. Standard rotary-drilling and rotary-coring methods utilizing polymer mud or air foam as drilling fluids have been used successfully to drill the rocks on Yucca Mountain and to drill other difficult-to-drill rock types. Polymer mud or air foam help stabilize the walls of holes, prevent lost circulation, cool and lubricate the bit and efficiently remove cuttings from the hole. Unfortunately, they also contain varying proportions of water; therefore, they may significantly alter the water content of geologic samples, as well as formation rock.

at Yucca Mountain, Nevada, utilizing air as the drilling fluid. Forty-six shallow neutron-access holes (total depth less than 22 m) and four deeper core holes (total depth less than 130 m) were drilled using these methods in various rock types, including bouldery alluvial-colluvial valley fill, poorly consolidated ash-fall tuff, and highly fractured and densely welded tuff. This paper describes these drilling and coring methods and attempts to quantify the effects these methods have on the in-situ water content of formation rock and geologic samples.

The work described in this paper is a part of the U.S. Geological Survey's studies at Yucca Mountain, Nevada, designed to provide information to the U.S. Department of Energy for their use in evaluting the hydrologic and geologic suitability of this site for storing high-level radioactive waste in an underground mined repository. The U.S. Geological Survey's studies are a part of the Nevada Nuclear Waste Storage Investigations Project conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802.

Drilling and Casing Methods

Two types of boreholes are discussed in this paper. Neutron-access holes were drilled to permit neutron-moisture logging designed to measure infiltration in the near-surface (less than 22 m) unsaturated zone. Shallow core holes were drilled primarily to measure both matric potential and unsaturated hydraulic conductivity of core taken from nonwelded and bedded tuff located approximately within the top 120 m of formation rock.

Criteria for selecting a drilling method for neutron-access holes are the following: (1) The method should minimize the disturbance of the formation rock by drilling fluids; (2) the method should be capable of drilling in a variety of difficult rock conditions; and (3) the method should permit the insertion of the casing into unstable unconsolidated deposits, and it should minimize the void space between the casing wall and formation rock.

Specialized drilling methods also were required for core holes. Parts of difficult rock regions were drilled rather than cored. In addition, cored parts of hole needed to be enlarged by drilling to accept downhole moisture-sensing instruments. Criteria for selecting a drilling method for the core holes were similar to drilling criteria for neutron-access holes, even though the purposes of the holes were different. In short, the method should permit installation of casing just above the core point, to protect the hole from drilling fluids, and to provide a method of protecting formation rock from drilling fluids during reaming.

Results of studies concerning the effects of water contained in drilling fluids on natural water content of core are inconclusive. Rotary coring of soft sandstone, using polymer mud, produced cores with moisture contents 2 to 6 percent greater than drive cores that were assumed to be undisturbed (Eugene Shuter and W. E. Teasdale, U.S. Geological Survey, written commun., 1985). Whitfield (1985, these proceedings) concluded that the moisture content of core from tuffaceous rock, obtained by using air foam as a drilling fluid, did not differ significantly from cuttings obtained from reverse air-vacuum drilling. These cuttings were assumed to be minimally disturbed. The studies do suggest that rock type may be an important factor. Water content and water-content-dependent properties of low-porosity and low-permeability core are likely to be affected less by water in drilling fluids than by high-porosity and high-permeability core. Other factors, such as coring rate and depth of fluid in the hole, may affect the water content of core.

Considerable evidence exists that water in drilling fluids may affect the water content of formation rock substantially during coring and drilling activities. These effects mainly occur as a result of lost circulation. For example, during the drilling and coring of the first geologic borehole on Yucca Mountain (USW G-1), more than 11,600 m^3 of drilling fluid containing water and an organic polymer were lost to the formation. Three years later during the drilling of borehole USW UZ-1, located approximately 300 m to the northwest of borehole USW G-1, perched water was encountered at approximately the 380-m level (Whitfield, 1985) (these proceedings). This perched water contained the same organic polymer that was used in the drilling fluid during the drilling of borehole USW G-1. It has been postulated that the drilling fluid "lost" during the drilling of borehole USW G-1 formed a perched water zone extending to borehole USW UZ-1.

Air can be used as a drilling fluid in rotary drilling (Campbell and Lehr, 1973) and rotary coring (Teasdale and Pemberton, 1984); however, the ability of air to stabilize the walls of the borehole, prevent vibration of the drill pipe, and prevent lost circulation is considerably less than these same abilities in drilling fluids containing water. Opinions vary concerning the effect air has on the water content of geologic samples and formation rock; few reliable data are available. Some investigators argue that air dries the formation rock and core; other investigators claim that air wets both formation and samples. Wetting is thought to occur when compressed air, exiting the core and drill bits, rapidly expands, cools, and condenses water. Eugene Shuter and W. E. Teasdale (U.S. Geological Survey, written commun., 1985) have collected data that show that air dries core samples below ambient water contents and heats core above ambient temperatures.

The authors of this study believe that these apparent disadvantages of using air as a drilling fluid are overshadowed by the potential hydrologic and geochemical problems that may occur in the formation if polymer mud or air-foam drilling fluids containing water are lost in large quantities to the formation rock. With the above in mind, the U.S. Geological Survey, in cooperation with Reynolds Electrical & Engineering Co., Inc., designed and carried out a "state-of-the-art" drilling and coring program

After careful consideration of a variety of methods, the Odex 115 drilling system was selected for drilling both types of boreholes. This method was developed in Sweden for drilling through and casing off unconsolidated overburden, such as glacial till overlying bedrock. This method drills and advances casing equally well through unconsolidated deposits and consolidated bedrock. To this date, this method mainly has been used in the United States for civil-engineering and mineral-prospecting purposes. However, the method has great potential for use in geohydrologic investigations.

The Odex 115 method used a downhole percussion hammer to drill and ream at the bottom of a casing. A pilot bit, in conjunction with an eccentric reamer, drills a hole slightly larger than the outside diameter of the casing (Figure 1). The percussion hammer also impacts on the casing through a shoe attached to the bottom joint of the casing. Thus, the casing is advanced downward as the hole is drilled deeper. Drill cuttings are returned to the surface through the inside of the casing, thereby minimizing the disturbance of borehole walls with drilling fluids.

Air foam is recommended as the drilling fluid by the manufacturer; however, air was used successfully for all the neutron access and unsaturated-zone core holes at Yucca Mountain. Large volumes of air were required to remove cuttings from the deeper core holes: 25 m^3 at 1,250 kPa were required in the lower parts of these holes. The use of air did not appear to amplify problems, such as lost circulation or excessive friction between the casing and formation walls. The use of air did cause a large vibration in the drill string that probably would be reduced significantly by using other types of drilling fluids. This vibration, coupled with the rotation of the drill pipe, caused the threaded connection between the drill bit and the guide assembly (Figure 1) to unscrew. The threaded connection between the hammer and the guide sleeve on the drill pipe unscrewed on another occasion. Those problems were solved by pinning these threaded connections together.

Another problem, which also related to the use of air, involved the separation of the bottom-casing shoe from the casing on a number of occasions. Probably excessive vibration and stress, caused by the operation of the percussion hammer in air, resulted in shearing the threaded connection between the shoe and the casing. The length of the casing shoe was increased from 0.66 to 8.23 m to move the threaded connection between the shoe and the casing farther away from the vibration of the downhole percussion hammer. This change in the design alleviated the separation problem.

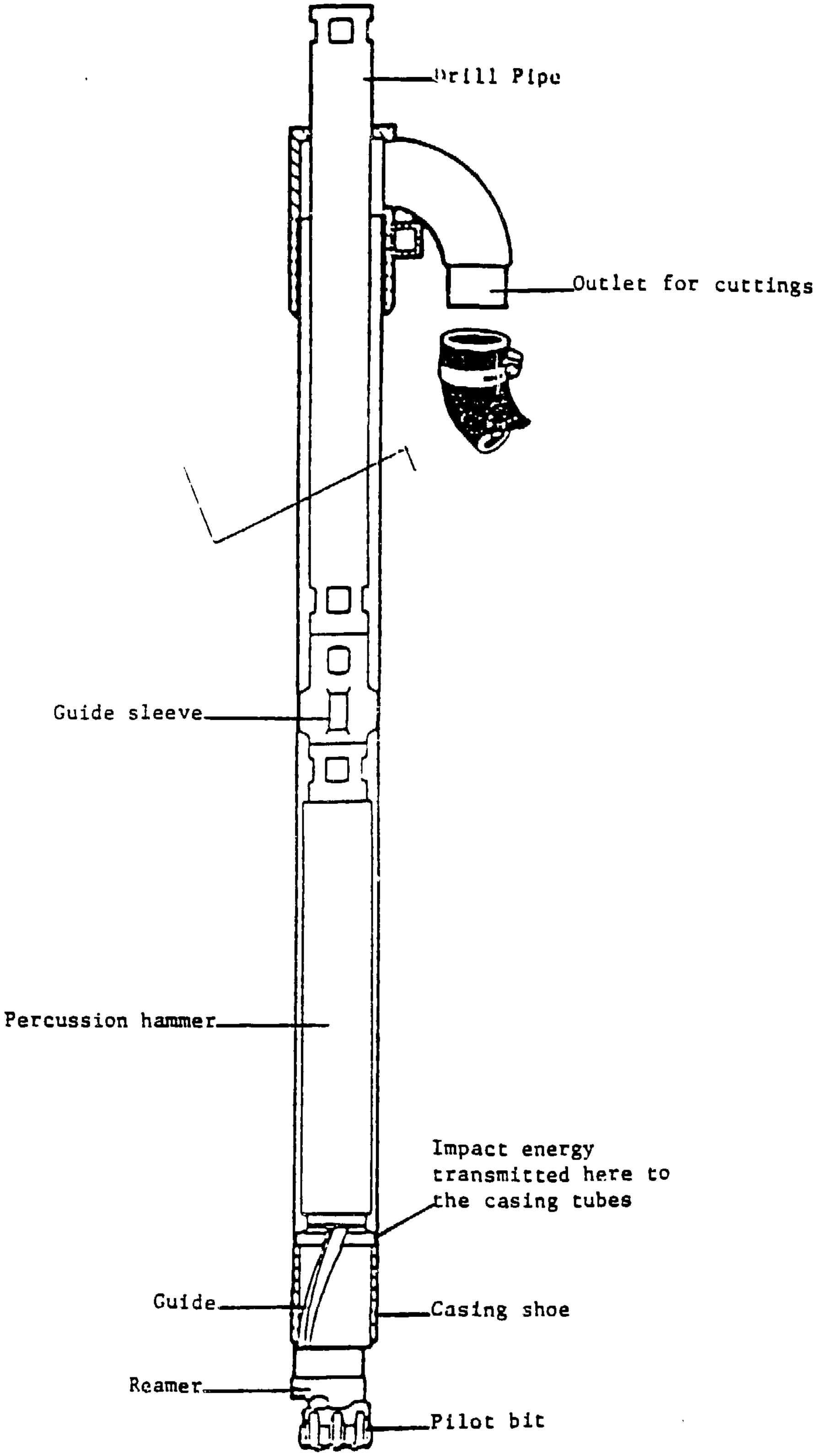

Figure 1. Odex 115 drilling system.

The Odex 115 system advanced a 14.0-cm outside diameter (O.D.) casing into an approximately 15-cm diameter drill hole. In moist unconsolidated formations, the cuttings appear to be forced up into, and to seal off, the small annular spacing between the casing and the formation rock, thereby eliminating any void space around the casing. Television logs show that this "rind" of compacted cuttings remains after the casing is removed from nonwelded tuff units, making the hole diameter approximately 14.0 cm rather than 15 cm. A similar phenomenon probably occurs in moist alluvial-colluvial material, except near the ground surface, where some caving probably occurs around the casing. In several situations where casing was removed from alluvial-colluvial material because of drilling problems, the holes remained open, except for some minor sloughing near the ground surface.

This sealing-off process around the casing also probably occurs in consolidated welded tuff. When a hole is started in consolidated rock, cuttings and air usually stop coming to the surface from the annular spacing between the casing and the rock formation by the time the hole reaches 3 m in depth. This condition indicates that cuttings are filling the annular space. However, because the cutting particle size generally is large, and the moisture content generally is small for consolidated welded tuff, this rind of cuttings does not stay in place when the casing is pulled. Cuttings from welded-tuff units fall to the bottom of the hole when the casing is pulled up from these regions, yielding varying quantities of fill.

Holes were drilled in 1.52-m depth intervals using 1.52-m long joints of casing and drill pipe. Most neutron-access holes were drilled with a CME 550 all-terrain drill rig; most core holes were drilled with a Joy 225 core rig. All neutron-access holes located in alluvial-colluvial materials were drilled through the entire thickness of these deposits and at least several meters into underlying consolidated bedrock. Neutron-access holes in welded tuff generally were drilled to 15 m, although some holes were slightly deeper and some holes were shallower. The casing was left in place in all neutron-access holes.

In core holes, the Odex 115 system was used to drill and drive the casing down to the desired depth for coring. Core then was collected in 1.52-m core runs and wirelined out of the hole. Core was taken to depths as great as 30 m below the bottom of the casing. When the core hole became unstable and circulation became a problem, the core hole was reamed and cased down to the bottom with the Odex 115 system. Coring then was resumed at the bottom of the casing.

The percussion hammer in the Odex 115 system yields drill cuttings with a relatively large average particle size and a relatively small surface area when drilling consolidated rock. Therefore, evaporation of water from these cuttings when being transported to the ground surface in the air stream should be small, and the water-content and water-content-dependent properties of these cuttings should, in theory, be fairly representative of the formation rock. In alluvial-colluvial material and soft, poorly consolidated nonwelded tuff, the penetration rate of the system is fast, thereby minimizing the exposure of the formation rock at the drill bit to air. However, the average particle size of these cuttings is much smaller, and the surface area is larger than cuttings from consolidated rock; therefore, more drying is likely to occur when these cuttings are transported from the bit to the ground surface by air. With this consideration in mind, a testing program was carried out to determine if samples of drill cuttings could be used to estimate water content of formation rock. This program is described in greater detail hereinafter.

Drive-Core Methods

An innovative method was employed to obtain core samples from bouldery alluvial-colluvial material, using heavy-duty solid-tube and split-tube samplers. The bouldery nature of the rock prevented the tube samplers from being pushed into the formation, either by the drop-weight method, or by using the hydraulic system on the drill rig. Personnel from Reynolds Electrical & Engineering Co., Inc., suggested that the samplers be attached directly to the percussion hammer, and that the hammer be used to drive the tube samplers into the bouldery material. This method of driving the sampler proved successful, and core recovery averaged more than 90 percent.

Drive core was taken at prescribed depth intervals in alluvial-colluvial deposits, primarily using heavy-duty 10.16-cm I.D. by 0.61-m long solid-tube samplers. The tubes were fitted with two 15.2-cm and four 7.6-cm long brass liners to contain the unconsolidated samples when removed from the tube samplers. During the drive-core sampling of the first few neutron-access holes, manually pushing the brass liners from the solid tube was impossible without disturbing the core. A power core extrusion device then was designed and built by Reynolds Electrical & Engineering Co., Inc., for the 10.16-cm I.D. samplers. Drive cores were taken from several boreholes (UE-25 UZ-N4, -N6, -N8, -N12, -N13, -N14, -N60, and USW UZ-N69) (Figure 2), before this core-extrusion device could be built. The drive core from these holes was disturbed, and properties that are dependent upon the natural volume of the samples (for example, bulk density, porosity, and volumetric water content) could not be measured. The core-extrusion device was used successfully on boreholes UE-25 UZ-N1, and USW UZ-N85, -N90, -7 (Figure 2).

A heavy-duty, split-tube sampler was used on borehole UE-25 UZ-4. Split tubes made the removal of the brass liners an easy process. However, these split tubes became distorted when they encountered cobbles or boulders. After several core runs, the split tubes could not be closed. Two split tubes were destroyed during the coring of borehole UE-25 UZ-4.

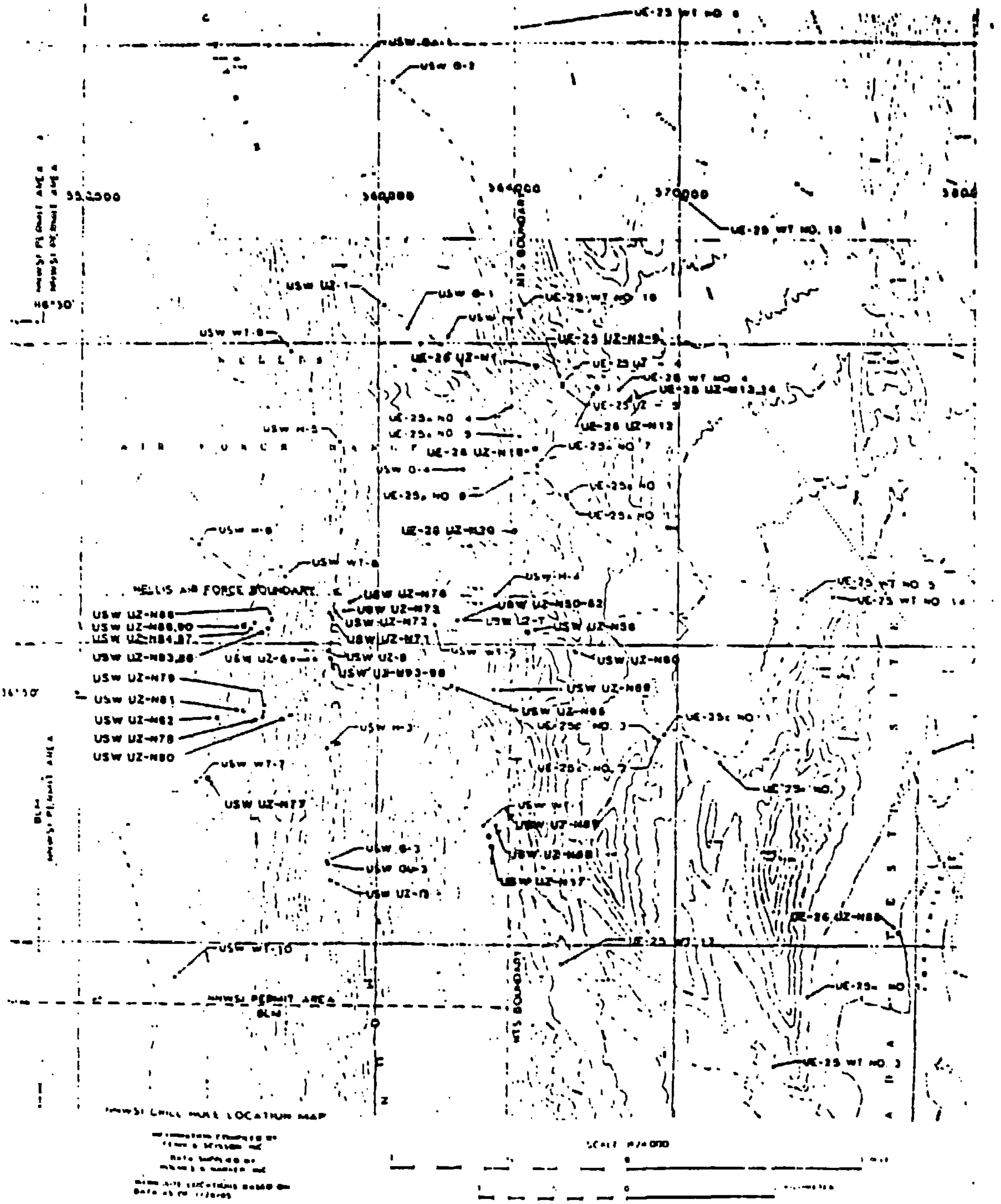

Figure 2. Location of drill holes on and in vicinity of Yucca Mountain, Nevada.

Drive core was taken in selected holes generally at 1.52-m intervals. A 1.52-m section of casing was drilled into the ground with the Odex 115 system, and 0.61 m of drive core was taken. Another 1.52-m joint of casing then was driven into the ground with the Odex 115 system, enlarging the 0.61-m section of drive-core hole, and drilling 0.91 m of new hole. This procedure was repeated until the required depth was reached.

Rotary Core Methods

Recently, the U.S. Geological Survey successfully used rotary air-coring techniques on nonwelded tuff in New Mexico (Teasdale and Pemberton, 1984). Based on their success (92 percent recovery), a modification of their technique was used to core selected intervals in welded tuff and continuously to core nonwelded tuff sections in core holes. Coring was done with a 1.52-m triple-tube, HWD4-size wireline core barrel modified by Norton Christensen, Inc., for air coring.

The type of core bit used depended on the formation rock. All core bits contained 0.317-cm-diameter discharge ports. In relatively soft, poorly consolidated rock, a tungsten-carbide, stagger-tooth, pilot-type, face-discharge bit, modified according to Teasdale and Pemberton's (1984) specifications, was used. In hard, densely welded tuffs, surface-set diamond bits were used. Oversized bits (10.79-cm diameter), constructed by Norton Christensen, Inc., for air coring, did not prove any more effective than smaller diameter bits (10.13-cm diameter) designed for conventional drilling fluids. Norton Christensen, Inc., currently is working with Reynolds Electrical & Engineering Co., Inc., and the U.S. Geological Survey to develop optimum bit design and coring techniques for the extremely hard and glassy welded tuff at Yucca Mountain.

Geologic-Sample Collection and Handling

During the sampling and handling procedures described hereinafter for both cuttings and core, every effort was made to minimize the opportunity for water to evaporate from the samples. Quality-assurance procedures were designed to minimize the disturbance of water content of samples from the time the samples left the borehole to the time water-content measurements or water-content-dependent measurements were made.

Drill Cuttings

Drill cuttings from the borehole were diverted through a flexible hose to a dry cyclone separator located nearby. In most holes, samples of drill cuttings were collected at 0.61-m intervals. After a 0.61-m interval had been drilled, a gate valve located at the bottom of the separator was opened, and cuttings were allowed to fall into collection vessels. A 0.47-L paper carton was filled first, for the purpose of describing lithology and for archiving cutting samples. One or two 0.94-L glass jars designated for laboratory measurements of water cont and water potential then were filled with cuttings and capped with air tight lids. When sample collection was completed, the remaining cutti in the separator were emptied. If cuttings were moist and sticking to the inside walls of the separator, a large hammer was used to knock the cuttings off the inside walls, thus completely emptying the separator for the next 0.61-m interval. Drilling usually would not stop during these sampling activities.

After the collection of samples from the separator was completed, samples in glass jars quickly were taken to the laboratory located on the drill site for processing. If this action was not possible, samples were stored in a large water cooler to minimize condensation inside the glass jars caused by the heating and cooling of the rock in response to ambient-temperature fluctuations and solar radiation. Inside the laboratory trailer, the 0.94-L jars of cuttings were placed inside a humidified glove box to minimize evaporation from samples during subsequent handling. Initially, during drilling of the first few neutron-access holes, three different types of samples were taken from the glass jars for gravimetric water-content measurements: composite, coarse, and fine samples. These measurements determined the distribution of water between particle-size fractions of cuttings and determined which fraction yielded water contents most representative of the formation rock. In later holes, only composite or coarse samples or both were taken. Samples of cuttings taken from the glass jars and placed in large (400-cm^3) moisture cans were designated composite samples. Samples of cuttings obtained by sieving the remaining contents of the jars with a screen (0.159-cm openings) and filling moisture cans with coarse fragments from the screen were designated coarse samples. Samples of cuttings obtained by filling moisture cans with the smaller diameter fragments that passed through the screen were designated fine samples. Smaller samples of coarse and fine cuttings also were taken during the sieving process for the purpose of making water-potential measurements with a Richard's thermocouple psychrometer. Samples of both coarse and fine drill cuttings were taken from the first few neutron-access holes drilled at each depth interval and placed in small jars (0.38-L capacity or less). In the majority of holes, only coarse cuttings were collected for water-potential measurements. After collection, the lids on these jars were taped and waxed to minimize evaporative losses while awaiting water-potential measurements.

Drive-Core Samples

Solid-tube and split-tube samplers were transported to the field laboratory and placed in a humidified glove box as soon as possible after they were pulled from the hole. Brass liners containing unconsolidated rock were extruded from the solid-tube sampler or lifted from the split-tube sampler. One 15.2-cm segment generally was selected for tritium analysis; one 7.6-cm segment generally was selected for gravimetric water-content and water-potential measurements; two 7.6-cm segments generally were selected for matric-potential and permeability-related measurements; and the last 7.6-cm segment generally was selected for volumetric water-content, bulk-density, grain-density, and porosity analyses. The 15.2-cm segment located in the uppermost part of the tube samplers usually contained some rubble from the bottom of the hole, in ddition to a sample of formation rock. The rubble was discarded, and the sample was used to supplement samples for tritium or gravimetric water-content analysis or both. Gravimetric water-content measurements were made in the field laboratory immediately from a major part of the contents of one of the 7.6-cm brass-liner segments. The remaining part of rock from this liner was placed in a 0.38-L glass jar, capped, taped, waxed, and transported to a nearby U.S. Geological Survey laboratory for water-potential measurements with thermocouple psychrometers. All other liner segments were capped, taped, waxed, and stored between 20 and 25°C until the specified tests could be carried out.

Rotary Core Samples

In most cases, a 1.52-m core run was made with the 1.52-m triple-tube core barrel. After the core run was completed, the split tube was removed from the core barrel at the drill site and immediately taken to the drill-site laboratory and placed in a humidified glove box for processing. The natural fractures were described, and a preliminary lithologic description was made on the intact 1.52-m section of core. An approximately 7.6-cm segment of core then was removed, both from the bottom and approximately 0.76 m above the bottom, for water-potential and gravimetric water-content measurements. Two additional 7.6-cm segments and two 15.2-cm segments also were taken from the bottom and mid-sections of the core runs. The smaller segments were designated for matric-potential measurements, and the larger segments were designated for permeability-related tests. These, with the remaining core, were placed in split PVC liners, capped, taped, labeled, waxed, and stored in an air-conditioned environment, until designated laboratory testing could be carried out.

Sample Testing Procedures

Water-Content, Density, and Porosity Measurements

Gravimetric water-content determinations were carried out in the laboratory located at the drilling site, using standard gravimetric oven-drying methods (Gardner, 1965). Volumetric water-content, bulk-density, and grain-density measurements were made on selected drive core and rotary core by Holmes and Narver's Material Testing Laboratory, Mercury, Nevada, using standard American Society of Testing Materials procedures. Porosity values were calculated from bulk and grain densities.

Water-Potential Measurements

Water potential is defined here as the sum of matric and osmotic potentials. Water potential was measured in this study with the SC-10 thermocouple psychrometer and with a NT-3 nanovoltmeter (Decagon Devices, Pullman, Washington). The SC-10 consists of a stationary thermocouple psychrometer and 10 sample chambers that can be rotated to the thermocouple psychrometer. The Richards method (Richards and Ogata, 1958) was used to condense water on the thermocouple junction in the measurements described here. In these measurements, calibration solutions were measured concurrently with actual rock samples to compensate for the zero drift of the amplifier of the nanovoltmeter. Generally, three of the sample chambers contained calibration solutions equivalent to known water potentials, six of the sample chambers contained samples of cuttings and core, and the remaining tenth chamber contained distilled water. Thermocouple output (voltage) first was measured on known calibration standards, followed by measurements of output from rock samples, followed by measurements of calibration standards again. The average of "before" and "after" voltage outputs for each calibration standard was used to construct the calibration curve of water potential versus voltage. Calibration curves were nearly linear over the range of water potentials measured (-0.1 to -7 MPa). Regression coefficients (r^2) typically ranged from 0.994 to 1.000, with most coefficients equal to 1.000.

The SC-10 sample chamber was loaded with calibration solutions and rock samples in a humidified glove box to minimize evaporation. After loading was completed, at least 1/2 h was allowed to pass before measurements were made to permit the approach to temperature and vapor equilibrium. To avoid temperature fluctuations, all measurements were made inside the glove box at room temperatures between 20 and 25°C. All equipment, including the thermocouple junction, was meticulously cleaned after each set of measurements to prevent carryover of salts or dust to the next set of measurements.

Matric-Potential Measurements

Matric potential was measured on selected drive core and rotary core, using a tensiometer-transducer system assembled by the U.S. Geological Survey. Small, 0.63-cm diameter, 0.1 MPa high-flow ceramic tips (Soilmoisture Equipment Corp., Santa Barbara, California) were placed in contact with the rock. Each tip was hydraulically connected to 68.9 kPa differential-pressure transducer and carrier demodulator (Validyne Engineering Corp., Northridge, California). A four-way valve was placed between the transducer and ceramic tip to permit filling the system with water and purging air bubbles from the system. Energy of water in the tensiometer system was allowed to equilibrate with energy of water in the matrix of the rock. This quasi-equilibrium state was assumed to be reached when two potential readings taken at least 24 h apart were within several tenths of a kilopascal of negative pressure.

Results and Discussion

Drill Cuttings

The Odex 115 system, using air as a drilling fluid, produces drill cuttings with a slightly lower gravimetric water content than core taken from the same depth interval. This was found for all particle-size fractions of cuttings, types of core, and rock units penetrated. Table 1 summarizes the results of linear-regression analyses carried out between the water content of composite samples of core and the water content of

different particle-size fractions of drill cuttings. For most rock units penetrated, the correlation between the water contents of sieved coarse cuttings and composite core was found to be higher than the correlation between the water contents of other particle-size fractions and composite core. The small positive intercepts of the regression equations (Table 1) indicate that a small amount of drying of drill cuttings occurs at least at low-formation water contents. The near unity slopes combined with the small intercepts for nearly all regression lines indicate that the water contents of cuttings do not differ greatly from the water contents of core at water contents greater than zero. The regression coefficient multiplied by 100 gives the percentage of the total variation between the water content of core and the water content of the cuttings which can be accounted for by the linear relation defined by the slope and intercept values of the regression equation.

In alluvium-colluvium deposits, the highest correlation ($r^2=0.744$) was found between the water content of sieved coarse drill cuttings and composite drive core (Table 1). This data is graphically presented in Figure 3. A lower correlation ($r^2=0.593$) was found between composite drill cuttings and composite drive core (Table 1). If data from UE-25 UZ-4, -N6, and -N4 are excluded from these regression analyses, higher regression coefficients are obtained (Table 1).

Several factors may be responsible for the implied poorer correlation between variables in UE-25 UZ-N4, -N6, and -N4. For example, in UE-25 UZ-N4 and -N6, drill cuttings were obtained at 1.52-m intervals which did not overlap with drive-core intervals. In UE-25 UZ-4, continuous drive coring may have significantly disturbed the water content of the thin rind of formation rock surrounding the core hole. Later, this rind was converted to drill cuttings when the core hole was reamed or enlarged with the Odex 115 system. In all other boreholes, 0.61 m of drive core were taken every 1.52 m.

These factors also may be responsible, in part, for the low regression coefficient ($r^2=0.307$) found between the water contents of sieved fine drill cuttings and composite drive core for the few depths examined (Table 1). In this analysis, 12 of the 14 data pairs were obtained from UE-25 UZ-N4, -N6, and -N4. Additional data is needed to more clearly define the relation between the water contents of sieved fine drill cuttings and unsieved composite drive core.

In welded tuff, the highest correlation ($r^2=0.997$) is found between the water contents of composite drill cuttings and composite rotary core for a sample population of nine data pairs (Table 1). A good correlation ($r^2=0.856$) also was found between the water contents of coarse drill cuttings and rotary core for a much larger sample population of 28 data pairs (Table 1, Figure 4). More data need to be collected before it is known which particle-size fraction of drill cuttings is most representative of the water content of rotary core in welded tuff units.

Table 1. Summary of linear-regression analyses for water contents of core versus particle-size fractions of cuttings

Rock type	Hole numbers	Dependent variable	Independent variable	Number of samples	Regression coefficient	Intercept	Slope
Alluvium-colluvium.	UE-25 UZ-N1, -N8, -N12, -N13, -N14, -N60; USW UZ-N69.	Gravimetric water content of unsieved composite drive core.	Gravimetric water content of unsieved composite drill cuttings.	28	0.747	0.012	0.996
---do-----	UE-25 UZ-N1, -N4, -N6, -N8, -N12, -N13, -N14, -N60, -4; USW UZ-N69.	-----do--------------	-----do--------------------	42	.593	.012	1.102
---do-----	UE-25 UZ-N60, -N85; USW UZ-N90, -7.	-----do--------------	Gravimetric water content of sieved coarse drill cuttings.	27	.799	.004	1.133
---do-----	UE-25 UZ-N4, -N6, -N60, -N85, -4; USW UZ-N90, -7.	-----do--------------	-----do--------------------	41	.744	.002	1.102
---do-----	UE-25 UZ-N4, -N6, -4; USW UZ-7.	-----do--------------	Gravimetric water content of sieved fine drill cuttings.	14	.307	.028	.783
---do-----	-----do----------------	-----do--------------	Gravimetric water content of sieved fine drive core.	17	.769	.003	.642
---do-----	-----do----------------	-----do--------------	Gravimetric water content of sieved coarse drive core.	17	.885	.008	.927
Welded tuff.	UE-25 UZ-4, -5.	Gravimetric water content of unsieved composite rotary core.	Gravimetric water content of unsieved composite drill cuttings.	9	.997	.0003	1.259
---do-----	UE-25 UZ-4, -5; USW UZ-7, -13.	-----do--------------	Gravimetric water content of sieved coarse drill cuttings.	28	.856	.005	1.005
Nonwelded [illegible]	[illegible]	[illegible]	Gravimetric water content of unsieved composite drill cuttings.	45	.751	.062	1.481
---do-----	-----do----------------	-----do--------------	Gravimetric water content of sieved coarse drill cuttings.	45	.804	.036	1.314
---do-----	UE-25 UZ-4, -5; USW UZ-7, -13.	-----do--------------	-----do--------------------	143	.605	.007	.875

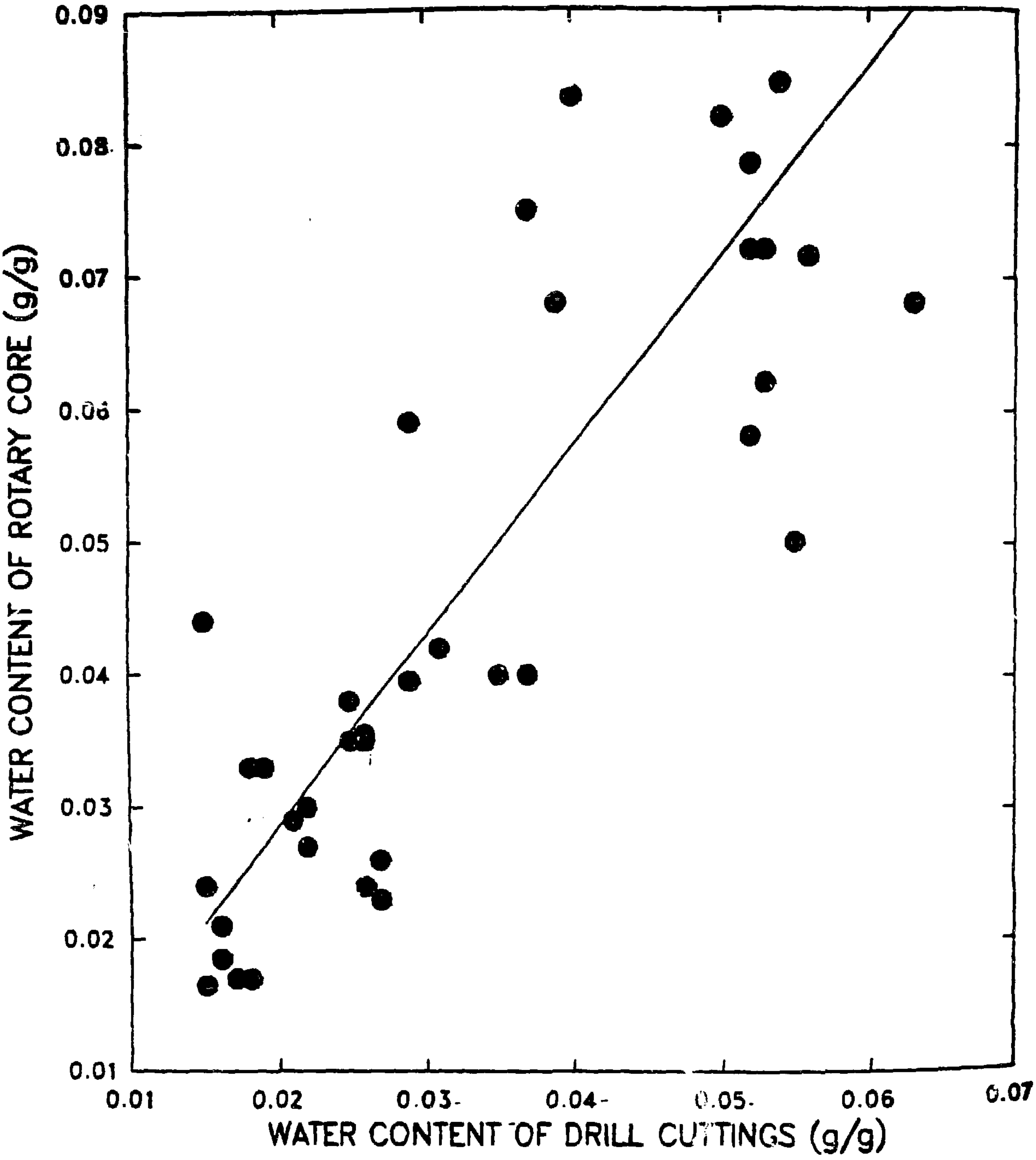

Figure 3. Gravimetric water content of coarse drill cuttings compared to drive core data taken at similar depths in alluvium—colluvium, and the resulting linear regression line (g/g, gram per gram).

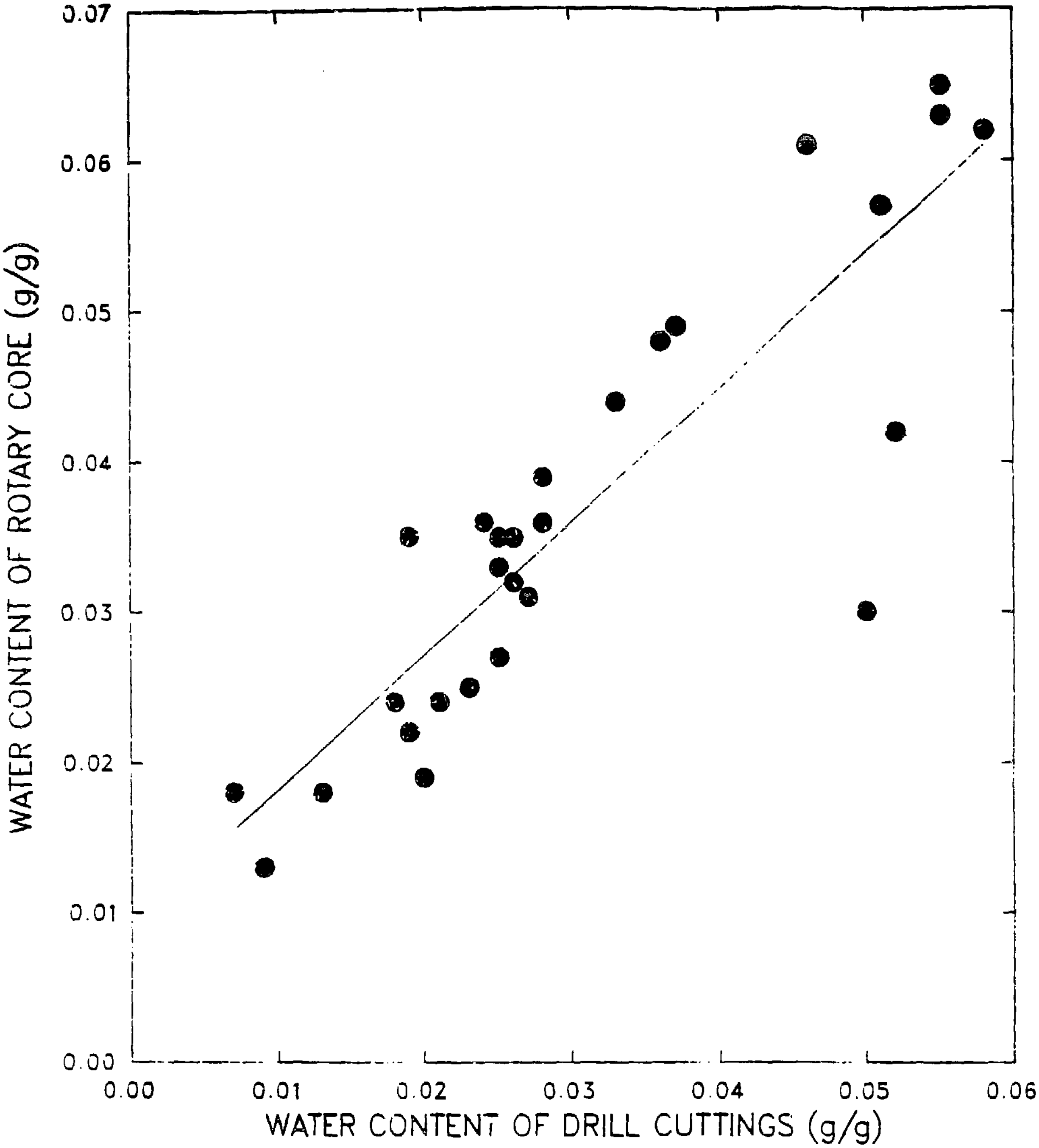

Figure 4. Gravimetric water content of coarse drill cuttings compared to rotary core data at similar depths in welded tuff, and the resulting linear-regression line (g/g, gram per gram).

Drive-core samples from alluvium-colluvium deposits were sieved to determine the distribution of water between particle-size fractions of cuttings. The results of linear-regression analyses of water contents measured in different particle-size fractions are given in Table 2. The slopes of the regression equations indicate that the sieved fine fraction of drive core contains more water on a weight basis than the sieved coarse fraction. Greater amounts of water in the fine fraction suggests that water recently has infiltrated into the system. Recent infiltration will not have had the opportunity to equilibrate with low-porosity and low-permeability coarse fragments. Fines in these deposits have a high porosity and permeability and therefore preferentially conduct and store recent infiltration water.

Finally, a correlation coefficient (r^2) of only 0.605 is found between the water contents of sieved coarse drill cuttings and composite rotary core taken from nonwelded and bedded tuff intervals (Table 1, Figure 5). As discussed previously, coring in these sections of holes commonly was carried out to depths of 30 m or more below the cased-off part of the hole. Formation walls near the starting point of a core run were exposed to air for long periods of time during coring, and formation walls near the end point of a core run were exposed to air for only short periods of time. Drill cuttings were obtained during reaming (enlarging) the core hole. Because formation walls were exposed to air for varying amounts of time, it is not surprising that the correlation between the water contents of cuttings and core is lower for these sections of hole. The scatter in the water-content data caused by differential drying also probably is responsible for the slope of the regression equation (less than unity). This slope probably has no physical significance. To minimize the disturbance of the formation walls, coring needs to be carried out in shorter depth intervals, and casing needs to be drilled down to the bottom of the core hole after each interval. Enlarging the hole with the Odex 115 system probably removes much, if not all, of this disturbed part of the hole.

The water potentials of drill cuttings generally were found to be lower than the water potentials of core for all rock types. This finding was expected because the water potentials of rock are dependent on water content. Linear-regression analyses (Table 2, Figure 6) indicate excellent correlations between the water potentials of cuttings and core for alluvium-colluvium. No correlation was found between these variables for welded tuff and nonwelded- and bedded-tuff sections of hole (Table 2). The relatively high regression coefficients (r^2=0.867, r^2=0.952) between variables in alluvium-colluvium are somewhat surprising, considering the potentially large error involved (mainly) in the subsampling process. Usually, water potential is measured on only one small subsample (volume less than 1 cm^3) of cuttings and core. This small subsample may or may not be representative of the more than 1,000-cm^3 volume of cuttings obtained from each 0.61 m of hole. These sampling problems are more amplified in densely welded tuff and are discussed in detail later in this report.

Table 2. Summary of miscellaneous linear-regression analyses

Dependent variable	Independent variable	Number of samples	Regression coefficient	Inter-cept	Slope
Water potential of coarse drive core from alluvium-colluvium.	Water potential of coarse drill cuttings from alluvium-colluvium.	60	0.867	0.393	0.737
Water potential of composite drive core from alluvium-colluvium.	Water potential of composite drill cuttings from alluvium-colluvium.	27	.952	1.151	.529
Water potential of rotary core from welded tuff.	Water potential of coarse drill cuttings from welded tuff.	29	.040	13.188	.147
Water potential of rotary core from nonwelded and bedded tuff.	Water potential of coarse drill nonwelded and bedded cuttings from tuff.	133	.023	.008	-3.240
Bulk density of drive core.	Depth (mid-interval) of drive core.	23	.044	1.770	-.003
Bulk density of sand-cone sample.	Depth (mid-interval) of sand-cone sample.	15	.654	1.470	.032
Formation volumetric water content measured by neutron-moisture-meter logging.	Volumetric water content of drive core from alluvium-colluvium.	20	.225	.126	.240
Formation gravimetric water content obtained from neutron-moisture-meter logging and sand-cone bulk-density data.	Gravimetric water content of drive core from alluvium-colluvium.	41	.754	.028	.768

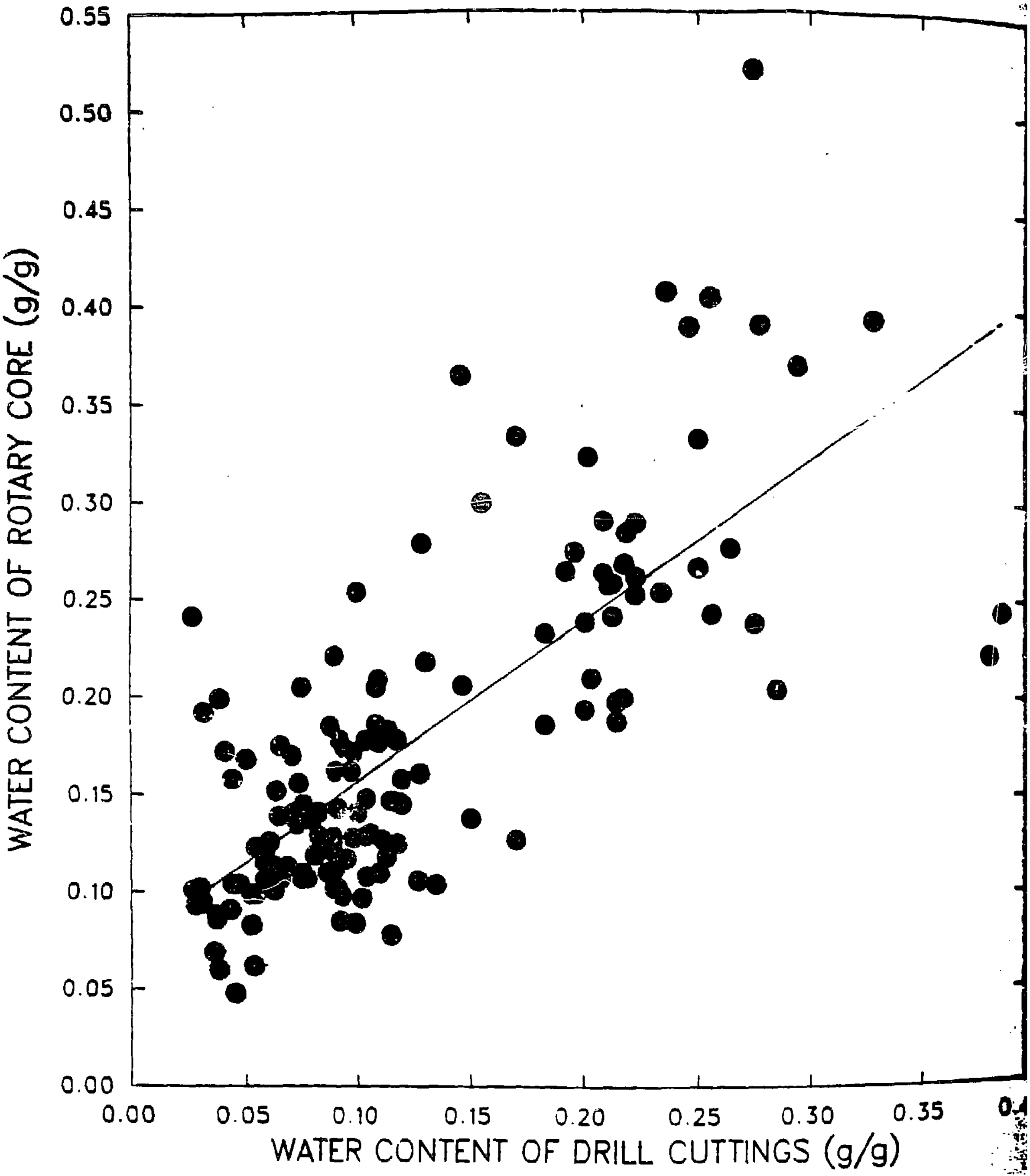

Figure 5. Gravimetric water content of coarse drill cuttings compared to rotary core data at similar depths in nonwelded and bedded tuff, and the resulting linear-regression line (g/g, gram per gram).

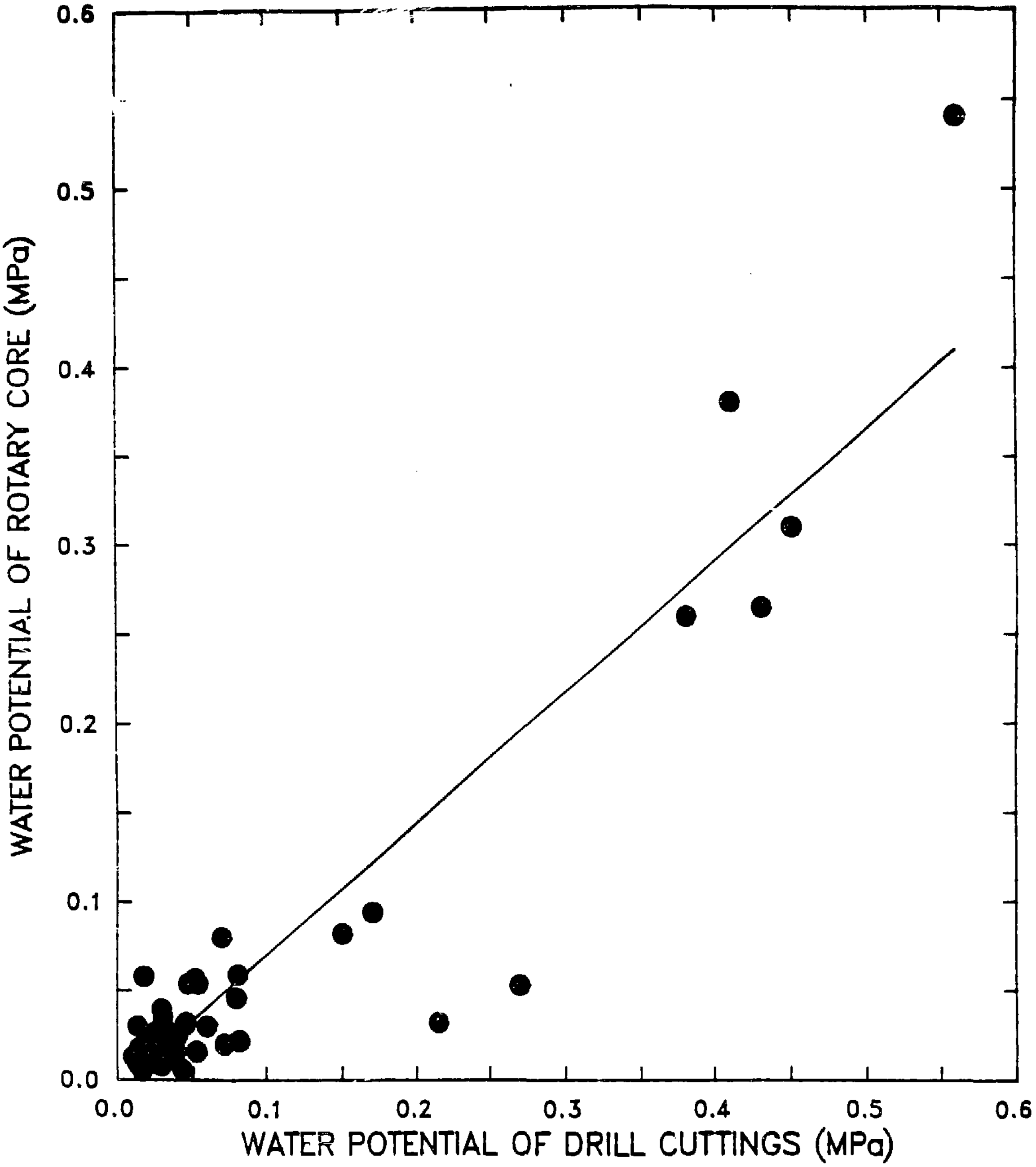

Figure 6. Water potential of coarse drill cuttings compared to drive core data at similar depths in alluvium-colluvium, and the resulting linear-regression line (MPa, megapascals).

The lack of correlation between water potentials in drill cuttings and core from bedded and nonwelded tuff is believed to be due primarily to the differential drying that occurred during the coring of these sections of hole. The absence of a correlation between these variables in welded tuffs probably is due to three factors. First, the potential for sampling error in fractured welded tuff is very high. Second, if fractures conduct water, it is likely that the walls of the fractures and the secondary mineral deposits in fractures will be wetter (higher water potential) than the interior matrix of the rock. The relatively large sample size used in water-content measurements (approximately 400 cm^3) probably contains representative parts of both fractured wall material and interior rock matrix material. However, the small sample size used for water-potential measurements conceivably could be biased toward either type of sample.

The small porosity of welded tuff is a third factor that may affect the correlation between the water potential of cuttings and core from welded tuff. Montazer and Wilson (1984) discuss the effect that small porosities of welded tuff have on the error in water-content and water-potential measurements. A small change in water content introduced during drilling and handling could cause a significant change in water potential.

The relatively high regression coefficients discussed before sugges that drill cuttings may be used to estimate water content, and, in some cases, water potential in core. Coring is an expensive, time-consuming operation; Odex 115 drilling is comparatively inexpensive and fast. If a good correlation can be established between the properties of drill cuttings and core, it is possible that Odex 115 drilling could be substituted for coring to obtain geologic samples for certain applications.

Drive Core

Drive core should yield samples with a gravimetric water content that is representative of the formation, providing care is taken to minimize evaporation after the core is removed from the hole. The process of pushing the sample tube into the formation should not add or take away water from the sample, except if excessive heat is generated. In this study, no evidence was found that samples were heated excessively during the sampling process. Also, the compressed air that powers the percussion hammer, which in turn, drives the tube sampler into the formation, does not come in direct contact with the sample. Compressed air vents from the hammer several meters above the sampler.

Drive coring does appear to affect density of the core sample. As expected, bulk-density data from bulk samples, obtained from trenches in alluvial-colluvial material by the sand-cone method indicate that bulk density increases with depth (Table 3). Also, a linear-regression coefficient of 0.654 is obtained when regressing depth versus bulk density (Table 1). However, no correlation is observed between bulk density and depth in drive-core samples (r^2=0.044). Bulk density and volume-dependent physical properties of drive core are given in Table 4.

Average bulk density for 7 drive-core samples taken between depths of 1.52 to 3.05 m is 1.74 g/cm^3; the average bulk density for six drive-core samples taken between depths of 3.05 and 6.10 m is 1.69 g/cm^3; average bulk density for seven drive-core samples taken between depths of 6.10 and 9.14 m is 1.70 g/cm^3. These data indicate that the method of drive coring used in this study increases the density of uncompacted near-surface materials by compacting the sample and reducing the porosity. Moreover, this method appears to disturb the packing of sediments in higher density deposits lying at greater depths, yielding drive-core samples with densities lower than the formation rock. Further evidence that drive coring disturbs volume-related properties of drive core is the low correlation (Table 2) between volumetric water content of drive core and volumetric water content of formation rock, determined by neutron-moisture, geophysical-logging methods. These volumetric water-content data are summarized in Figure 7.

Table 3. Bulk density of bulk alluvium-colluvium samples determined by the sand-cone sampling method

[m, meter; gm/cm^3, gram per cubic centimeter]

Depth interval (m)	Bulk density (g/cm^3)	Average bulk density for depth interval (g/cm^3)
0.08-0.23	1.43	1.43
0.08-0.23	1.40	
0.08-0.23	1.46	
0.76-0.91	1.44	1.57
0.76-0.91	1.51	
0.76-0.91	1.76	
1.37-1.52	1.80	1.70
1.37-1.52	1.66	
1.37-1.52	1.63	
3.05-3.20	1.80	1.79
3.05-3.20	1.08	
3.05-3.20	1.61	
4.05-4.19	2.03	1.88
4.05-4.19	1.82	
4.05-4.19	1.79	

Table 4. Physical properties of drive core

[m, meter; g/cm³, gram per cubic centimeter; cm³/cm³, cubic centimeter per cubic centimeter]

Hole number	Interval (m)	Bulk density (g/cm³)	Volumetric water content (g/cm³)	Grain density (g/cm³)	Porosity (cm³/cm³)
UE-25 UZ-N1	2.06-2.13	1.71	0.102	2.51	0.320
---do------	5.12-5.18	1.42	.175	2.55	.443
---do------	8.08-8.15	1.66	.156	2.53	.347
USW UZ-N90	2.36-2.44	1.65	.187	2.51	.345
---do------	3.66-3.73	1.80	.159	2.53	.288
---do------	5.12-5.18	1.70	.144	2.52	.325
---do------	6.40-6.48	1.99	.171	2.51	.207
---do------	9.83-9.91	1.69	.155	2.49	.329
UE-25 UZ-4	1.14-1.22	1.86	.193	2.55	.278
---do------	1.68-1.75	1.74	.165	2.54	.317
---do------	2.36-2.44	1.76	.206	2.55	.311
---do------	2.59-2.68	1.64	.346	2.52	.350
---do------	2.74-2.82	1.91	.122	2.49	.233
---do------	4.57-4.65	1.70	.156	2.55	.333
---do------	6.25-6.32	1.53	.198	2.54	.399
---do------	6.40-6.48	1.60	.181	2.53	.368
---do------	7.62-7.70	1.66	.136	2.51	.339
---do------	8.92-8.99	1.75	.122	2.52	.303
---do------	11.13-11.20	1.68	.119	2.52	.336
USW UZ-7	1.68-1.75	1.85	.143	2.53	.271
---do------	3.28-3.35	1.63	.116	2.52	.351
---do------	4.80-4.88	1.94	.085	2.50	.225
---do------	6.25-6.40	1.81	.064	2.50	.277

Rotary Core

The extent to which air coring disturbs rotary-core samples is very difficult to determine. A method that has been used by other investigators (Eugene Shuter and W. E. Teasdale, U.S. Geological Survey, written commun., 1985) involves taking both drive core and rotary core from the same or adjacent depth intervals, and comparing the water content of the respective cores. Drive core is assumed to yield undisturbed samples. This approach was attempted in two different nonwelded tuff units near the surface at Yucca Mountain. In both instances, the nonwelded tuff unit proved to be too consolidated to obtain drive-core samples.

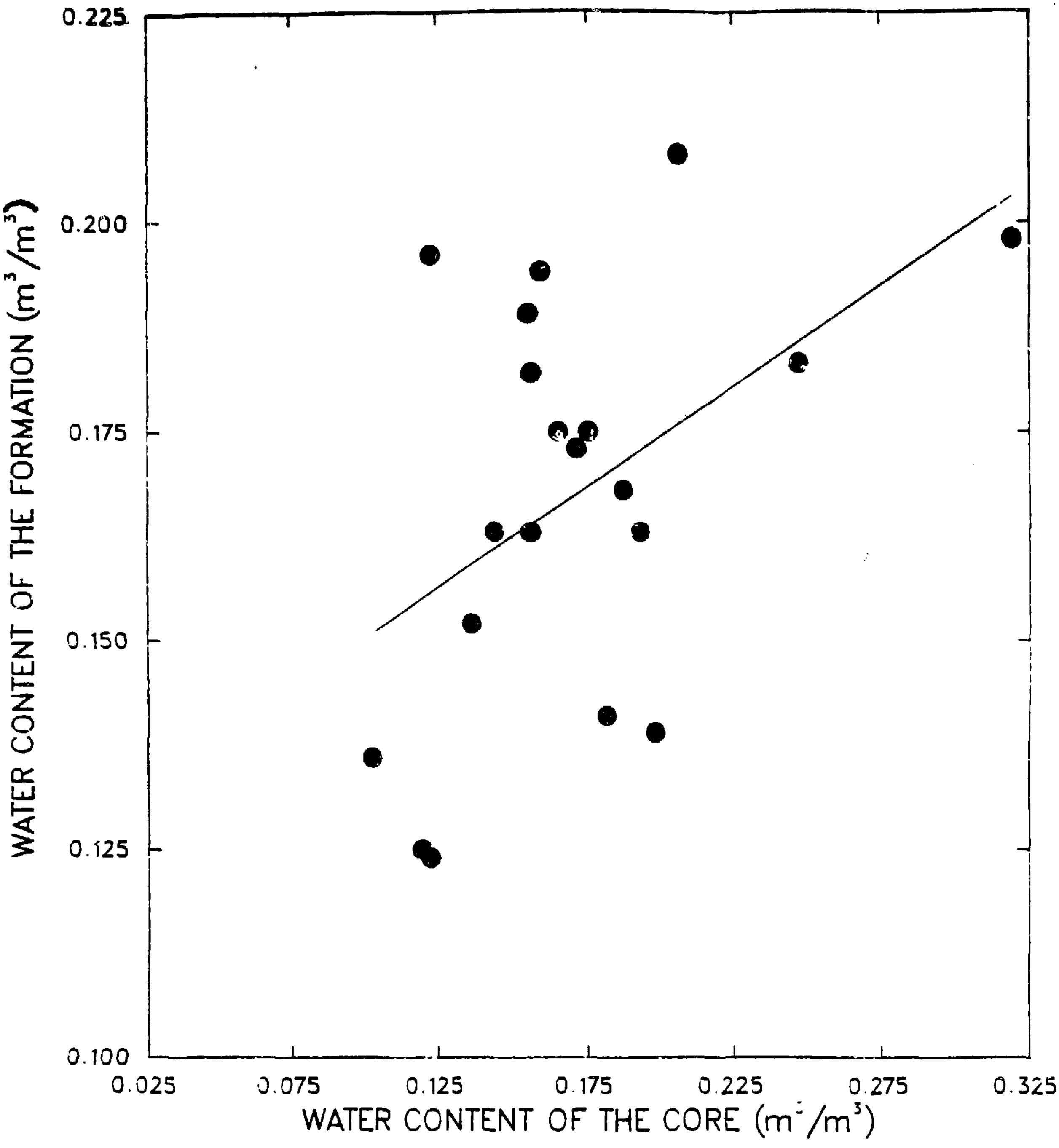

Figure 7.—— Volumetric water content of core compared to that of the formation at similar depths and resulting linear regression line (m^3/m^3.cubic meter per cubic meter).

Various lines of indirect evidence indicate that disturbance of the water content of rotary-core samples is not large. First, visual examination of the core surface in a humidified glove box indicated that surface drying of the core was minimal. A noticeable drier "rind" never extended more than a few millimeters below the core surface in nonwelded tuff, and never more than a few tenths of a millimeter below the core surface in welded tuff. Second, no evidence existed that the coring process generated significant amounts of heat or raised the temperature of the core. All core when brought to the land surface was cool to the touch. Probably the low revolution per minute (less than 30) and bit weight (approximately 900 kgs) used in air-rotary coring at Yucca Mountain are responsible, in part, for keeping the heat production low. Third, in test boreholes UE-25 UZ-4 and UZ-5, a very wet region of nonwelded rock was encountered between approximately 24 to 30 m below ground surface. Free water was not observed; however, core and cuttings appeared to be nearly saturated. Tensiometer measurements made on rotary-core samples from these regions yielded samples with matric potentials as low as -7.6 kPa in borehole UE-25 UZ-4 and -7.7 kPa in borehole UE-25 UZ-5. Examination of moisture-retention curves made on several core samples taken from this rock unit (Figure 8) shows that at these matric potentials, the core samples are very close to complete saturation (greater than 97 percent). Assuming these moisture-retention curves also are representative of the formation rock, these data show that air coring does not change saturation of the core by more than 3 percent. This disturbance is a maximum percentage, and it assumes that the rock formation was initially 100-percent saturated, which, of course, it was not. The quantity "saturation" is equal to volumetric water content divided by porosity.

Formation Rock

In this section, it is assumed that Odex 115 air drilling is entirely responsible for any disturbance of formation-rock water content. Air-rotary-core holes were enlarged with the Odex 115 system; as mentioned above, this reaming process probably removes much of the rock that has been disturbed by air-rotary coring.

The ideal way to determine the disturbance effects of drilling is to determine the moisture content of the formation before drilling and again after drilling has been completed, preferably using the same method of measuring moisture content in both cases. The authors are not aware of a method that would permit this type of analysis. However, measurements of water content were made before and after drilling on alluvial-colluvial deposits, using different methods to measure water content. Measurements of gravimetric and volumetric water content were made before drilling by using drive-core methods. Drive-core methods were assumed to yield representative values of formation gravimetric water content only. Measurements of volumetric water content after drilling were made with a laboratory-calibrated, neutron-moisture logger. Laboratory calibrations were carried out in a chamber containing the same size casing as used in boreholes. This calibration procedure is described in detail in another paper presented at this conference (Hammermeister et al., 1985, these proceedings).

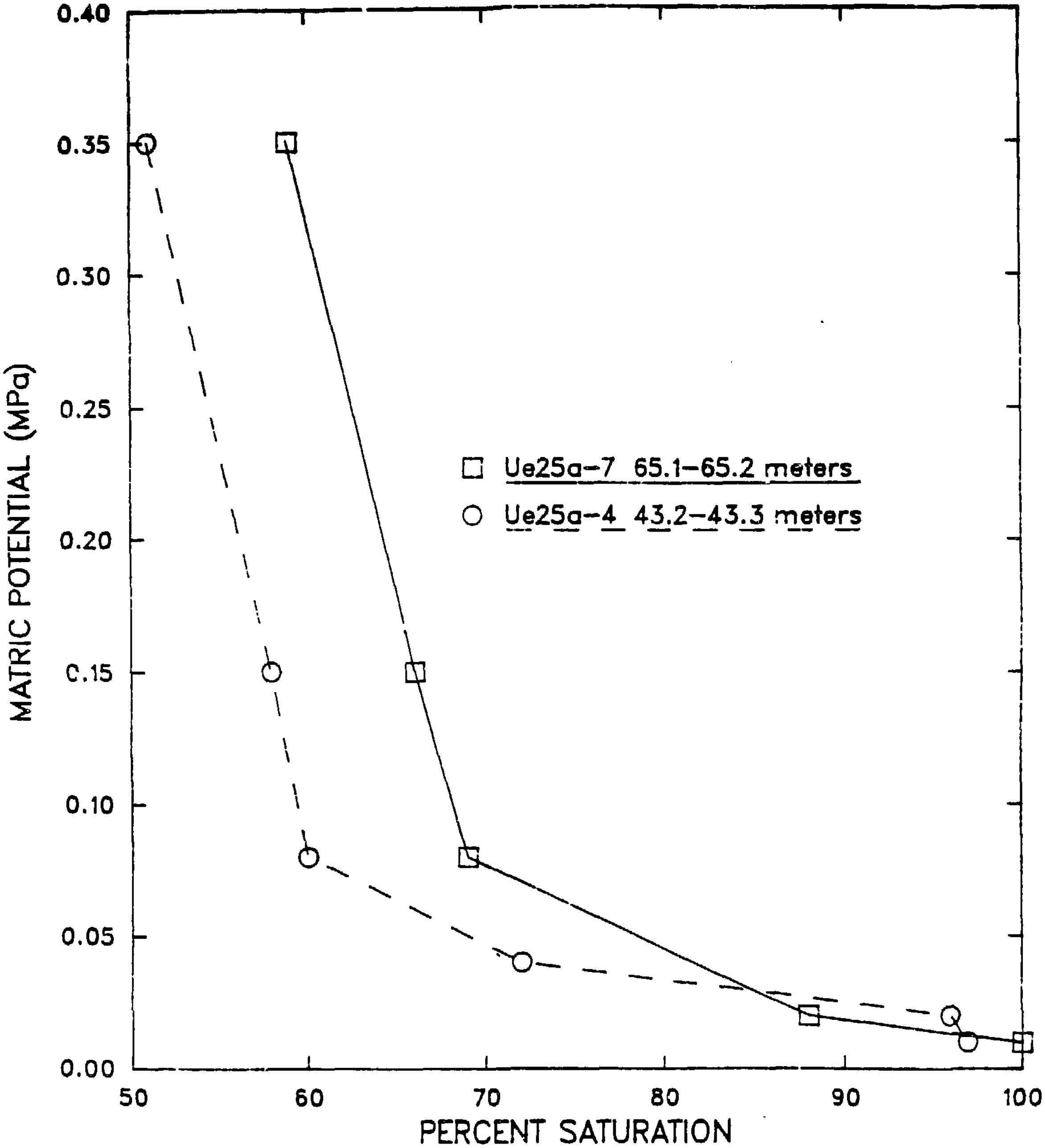

Figure 8. Moisture-retention curves for cores taken from the nonwelded base of the Tiva Canyon Member of the Paintbrush Tuff (MPa, megapascals).

To compare water contents before and after drilling, volumetric water content obtained with a neutron-moisture meter need to be converted to gravimetric water content. This conversion was done by dividing by bulk densities obtained by the sand-cone method (Table 3). Bulk density of the formation is assumed to be 1.79 g/cm^3 between 1.52 and 3.05 m in depth; 1.89 g/cm^3 between 3.05 and 4.57 m in depth; and 1.99 g/cm^3 below 4.57 m in depth. This gravimetric water-content data of core and formation is summarized in Figure 9. A fair correlation ($r^2=0.754$) exists between these "before" and "after" measurements (Table 2). However, "before" gravimetric water contents are lower than "after" gravimetric water contents. If these water-content measurements are correct, they would indicate that drilling causes the formation to become wetter. Since this indication is unlikely, probably some problems exist with the assumptions made in the conversion of formation volumetric water content to gravimetric water content, or with the laboratory calibration curve of the neutron-moisture meter, or both. Regardless, these water contents measured "before" and "after" are in reasonable agreement, indicating that drilling with the Odex 115 system does not disturb the water content of alluvial-colluvial material significantly.

Volumetric water-content profiles (water content versus depth) measured over a period of 9 months (Figures 10 and 11) give further evidence that drilling with the Odex 115 system does not disturb significantly the water content of alluvial-colluvial deposits and welded-tuff bedrock. Neutron-access hole UE-25 UZ-N9 (Figure 2) is located in alluvial-colluvial material; neutron hole USW UZ-N96 (Figure 2) is located in moderately welded tuff. If drilling with the Odex 115 system significantly altered the water content of formation rock around the borehole, water would be expected to move into or out of this altered region, to attempt to equilibrate with the energy of water in undisturbed regions of formation rock. Water-content profiles show no appreciable change over a period 9 months after the holes were drilled, indicating that drilling with the Odex 115 system probably does not appreciably alter water content of formation rock.

Data for borehole UE-25 UZ-N8 (Figure 12) is included to show that the neutron-moisture logging method is capable of detecting changes in formation-water content. The borehole is located in a normally dry wash that was partly filled with runoff for less than 1 h on August 19, 1984. Measuring water-content profiles by neutron-moisture logging techniques is discussed in greater detail in a companion paper (Hammermeister et al., 1985) (these proceedings).

Conclusions

Drilling and coring methods were selected to minimize the disturbance of cuttings, core, and rock formation in the unsaturated zone. Data indicate that drive-core and rotary-air-coring techniques yield samples with water contents representative of formation rock. The Odex 115 drilling system produces cuttings with relatively undisturbed water contents and water potentials; in addition, this drilling system minimally disturbs water content of formation rock.

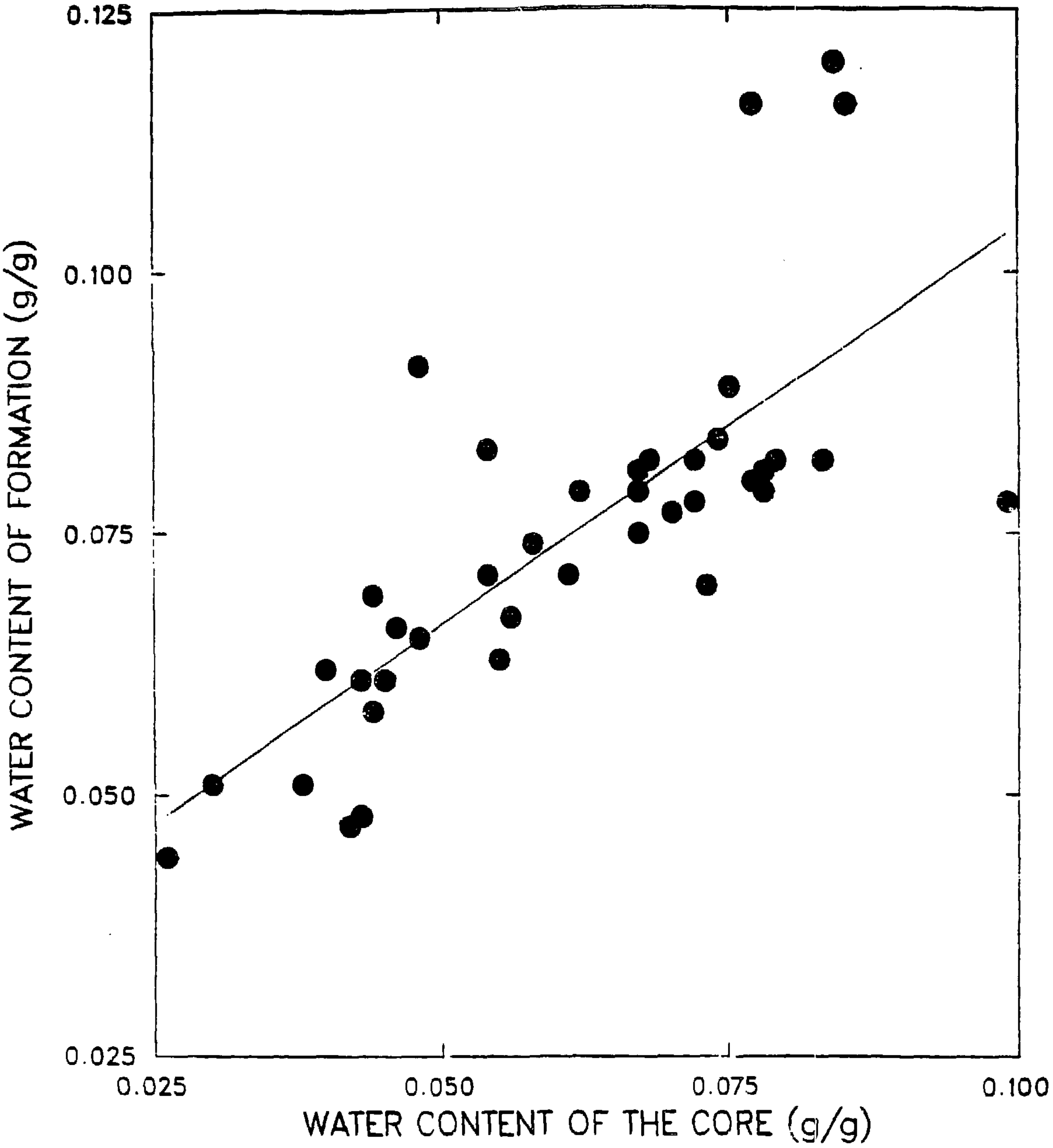

Figure 9.—— Gravimetric water content of core compared to that of the formation at similar depths, and resulting linear regression line (g/g, gram per gram).

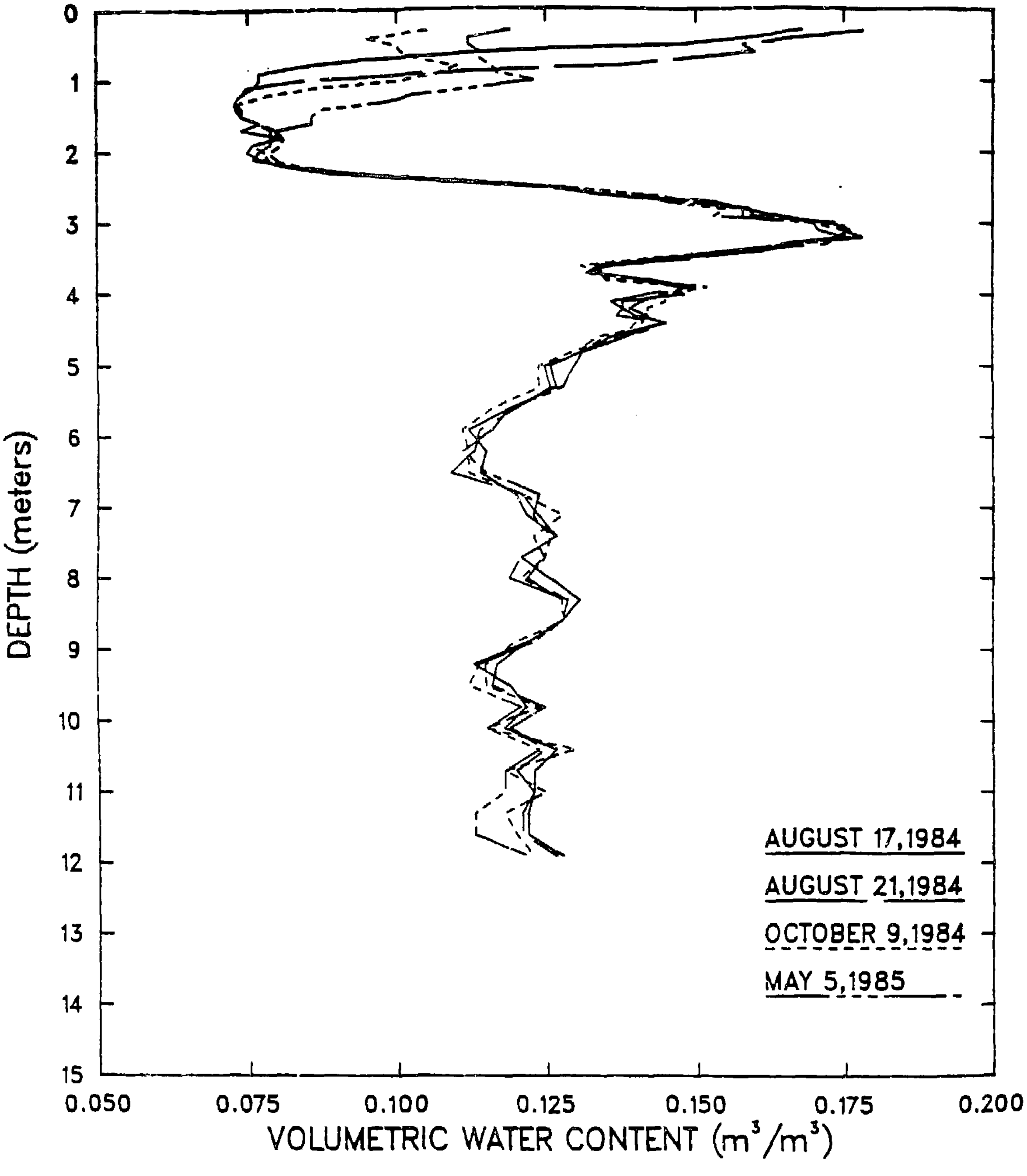

Figure 10. Moisture-content profiles of UE-25 UZ-N9 located on terrace above channel of wash (m^3/m^3, cubic meter per cubic meter).

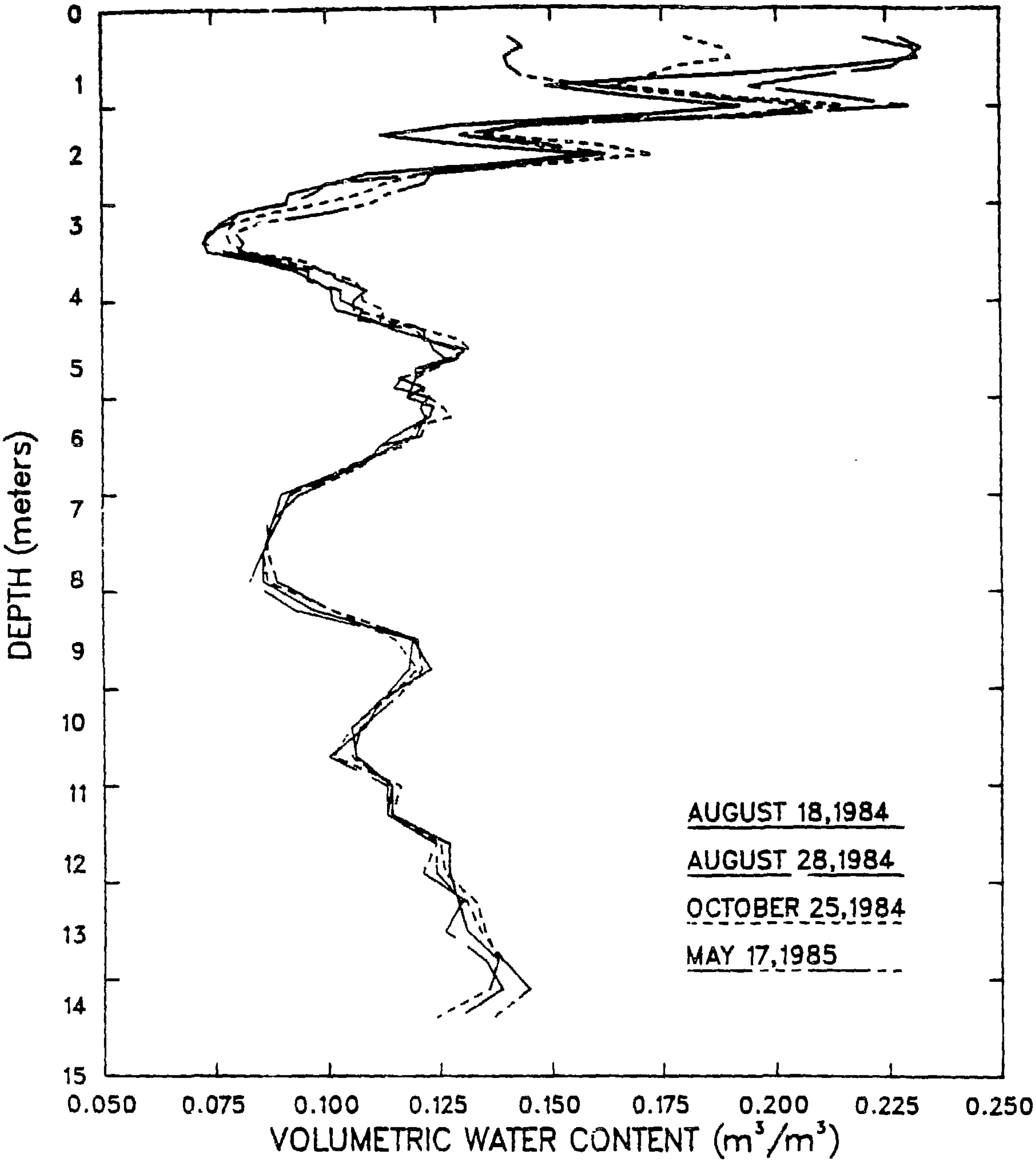

Figure 11. Moisture-content profiles of UE-25 UZ-N96 in moderately welded tuff (m^3/m^3, cubic meter per cubic meter).

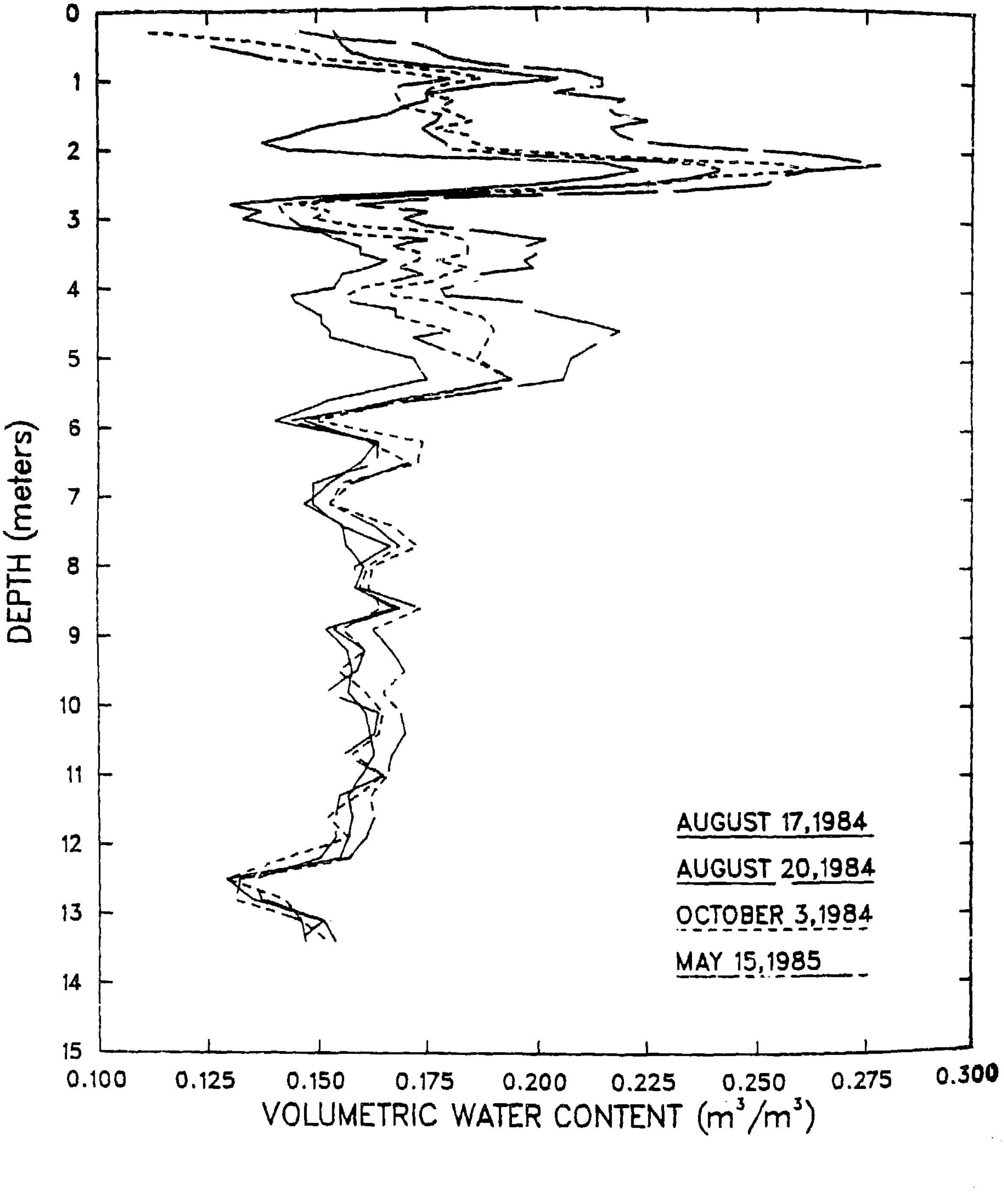

Figure 12. Moisture-content profiles of UE-25 UZ-N8 located in center of wash (m^3/m^3, cubic meter per cubic meter).

Conversion Table

Multiply	By	To Obtain
centimeter (cm)	0.394	inch (in.)
cubic centimeter (cm^3)	0.061	cubic inch (in^3)
meter (m)	3.281	foot (ft)
cubic meter per minute (m^3/min)	35.34	cubic foot per minute (ft^3/min)
kilometer (km)	0.621	mile (mi)
liter (L)	33.78	ounce (oz)
liter (L)	2.113	pint (pt)
liter (L)	1.056	quart (qt)
kilogram (kg)	2.204	pound (lb)
megapascal (MPa)	.000145	pound per square inch (lb/in^2)

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Biographical Sketch

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Daniel Blout received a Bachelor of Arts degree in Earth Science from the University of Northern Colorado, Greeley, in 1979. He worked for the U.S. Geological Survey for waste-storage investigations in Colorado and Utah. Since 1980, he has been working for Fenix & Scisson, Inc., at the Nevada Test Site on the potential Yucca Mountain high-level nuclear waste repository. His address is: Fenix & Scisson, Inc., P.O. Box 498, Mercury, NV 89023.

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