TRIAXIAL-COMPRESSION EXTRACTION OF PORE WATER

FROM UNSATURATED TUFF, YUCCA MOUNTAIN, NEVADA

By In C. Yang; A. Keith Turner, presently affiliated with Colorado School of Mines, Golden, Colo.; Ted M. Sayre, presently affiliated with Colorado School of Mines, Golden, Colo.; and Parviz Montazer, presently affiliated with Earth Technology Corporation, Long Beach, Calif.

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CONTENTS

FIGURES

CONVERSION FACTORS

Metric (International System) units in this report may be converted to inch-pound units by using the following conversion factors:

Multiply metric unit	*By*	*To obtain inch-pound unit*
centimeter (cm)	3.937×10^{-1}	inch
cubic centimeter (cm^3)	6.102×10^{-2}	cubic inch
cubic meter (m^3)	6.102×10^{4}	cubic inch
gram (g)	2.2×10^{-3}	pound, mass
gram per cubic centimeter (g/cm^3)	3.6×10^{-2}	pound per cubic inch
kilometer squared (km^2)	1.076×10^{7}	square foot
kilometer (km)	6.214×10^{-1}	mile
kilonewton (kN)	224.8	pound, force
meganewton (MN)	224,800.0	pound, force
megapascal (MPa)	144.7	pound per square inch
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter per year (m/yr)	8.98×10^{-3}	foot per year
microgram per liter (µg/L)	[1]1	part per billion
micrometer (µm)	3.937×10^{-5}	inch
milligram (mg)	2.2×10^{-6}	pound
milligram per liter (mg/L)	[1]1	part per million
milliliter (mL)	6.102×10^{-2}	cubic inch
millimeter (mm)	3.937×10^{-2}	inch
newton (N)	2.248×10^{-1}	pound, force

To convert degree Celsius (°C) to degree Fahrenheit (°F) use the following formula:

$$°F = 9/5(°C)+32.$$

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[1]Approximate for concentrations of dissolved solids less than about 7,000 milligrams per liter.

TABLES

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ABSTRACT

The unsaturated tuff at Yucca Mountain, Nevada, is being evaluated by the U.S. Department of Energy to determine the suitability for a potential repository to store high-level radioactive wastes. The purpose of the experiment discussed in this report was to design and validate methods for extracting uncontaminated pore water from nonwelded parts of this tuff. Pore water is needed for chemical analysis to help characterize the local hydrologic system.

A standard Hoek-Franklin[1] triaxial cell was modified to create a chemically inert pore-water-extraction system. Experimentation was designed to determine the optimum stress and duration of triaxial compression for efficient extraction of uncontaminated pore water. Experimental stress paths consisted of a series of increasing stress levels. Trial axial stress levels ranged from 41 to 190 megapascals with lateral confining stresses of 34 to 69 megapascals. The duration of compression at any given stress level lasted from 10 minutes to 15 hours. A total of 40 experimental extraction trials were made.

Tuff samples used in these tests were collected from drill-hole core from the Paintbrush nonwelded unit at Yucca Mountain. Pore water was extracted from tuff samples that had a water content greater than 13 percent by weight. Two stress paths have been determined to be applicable for future pore-water extraction from nonwelded tuff at Yucca Mountain. The initial water content of a sample affects the selection of an appropriate period of compression. For tuff samples that have a water content greater than 15 percent, efficient extraction of pore water is likely to be achieved after 2.5 hours by progressing through three axial stress levels from 76 to 152 megapascals, with lateral stresses of 59 to 62 megapascals. For tuff samples that have a water content of 13 to 15 percent, the same stress levels are applicable; however, the third stress level needs to be extended for several hours, until water extraction becomes negligible.

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[1]The use of trade, product, industry, or firm names in this report is for identification or location purposes only and does not constitute endorsement of products by the U.S. Geological Survey nor impute responsibility for any present or potential effects on the natural resources.

MANUSCRIPT APPROVED FOR PUBLICATION OCTOBER 12, 1988.

Chemical analysis of extracted pore water indicated some preliminary relations between increasing triaxial stresses and trends in fluid composition. As axial stress was increased from 40 to 180 megapascals, the concentrations of silica and sodium increased by about 5 milligrams per liter. The calcium concentration seemed to decrease. Concentrations of magnesium and potassium did not change substantially within this stress range. The chloride and sulfate concentrations seemed to increase only at axial stresses greater than 140 megapascals. Data scatter was too broad to recognize any conclusive trends for concentrations of iron, manganese, strontium, and zinc.

INTRODUCTION

Yucca Mountain, Nevada, is the site under consideration by the U.S. Department of Energy for the Nation's first mined geologic repository for storing high-level radioactive wastes. The U.S. Geological Survey has been investigating Yucca Mountain and the surrounding region to help assess the suitability of the site for a repository. These investigations are done in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802.

Using current (1988) conceptual designs, the radioactive wastes would be placed within the thick section of unsaturated volcanic tuff at Yucca Mountain. Investigations are underway to evaluate the hydrologic conditions, processes, and properties of the unsaturated zone at this site. The physics of water flow in thick, fractured-rock unsaturated zones is not well understood. Established techniques are lacking for testing and evaluating this hydrological system. The use of chemical analysis of pore water should help to better understand this hydrologic system.

A prototype method is presented for extracting pore water from unsaturated, nonwelded tuff. This method uses a modified Hoek-Franklin triaxial cell to compress the rock and to collect the extracted pore water. A set of optimum extractive procedures is provided, including magnitudes and durations of triaxial stress.

Water is present in several different forms within unsaturated, nonwelded tuff. In addition to water in the pore space of the tuff, water also may be bound to smectite and zeolite minerals. Refinement of the extractive method is critical to minimize collection of this bound water.

Isotopic and chemical compositions of pore-water samples will be used to estimate the residence time of pore water within the tuff, to provide information about sources and timing of recharge, and to evaluate the types and magnitudes of chemical reactions in the unsaturated tuff. Such information ultimately will be used to estimate dispersive and corrosive effects of unsaturated-zone water on high-level radioactive-waste canisters.

Purpose and Scope

This report describes the design and validation of laboratory experimental procedures for extracting uncontaminated pore water from nonwelded, unsaturated tuff at Yucca Mountain. These procedures involve the modification of a standard Hoek-Franklin triaxial cell to create a chemically inert pore-water collection system. Experiments were done to determine the optimum stress levels and the duration of triaxial compression for efficient extraction of uncontaminated pore water.

A total of 40 triaxial compressions were made to develop a practical means of extracting uncontaminated pore water. Trial axial stress levels ranged from 41 to 190 MPa, with compressive durations of 10 minutes to 15 hours. Preliminary results from chemical analysis of extracted water were used to help select optimum extractive conditions.

Location of Sample Sites

Samples used for the development and validation of the pore-water-extraction method were collected from drill holes UE-25 UZ #4 and UE-25 UZ #5; these holes are located about 20 m apart on the eastern margin of Yucca Mountain (fig. 1). Yucca Mountain is in and west of the southwestern part of the Nevada Test Site (NTS). The NTS, used principally by the U.S. Department of Energy for underground testing of nuclear weapons, is in Nye County, Nevada, about 100 km northwest of Las Vegas.

REVIEW OF PREVIOUS WORK

The efficient design of the experimental apparatus and procedures depended on the results of previous studies of three general topics: (1) Hydrochemistry of clay- and zeolite-enriched zones, (2) pore-water-extraction techniques, and (3) definition of tuff properties that affect pore-water drainage. Each of these topics has a major effect on the extraction of chemically representative pore-water samples.

Hydrochemistry of Clay- and Zeolite-Enriched Zones

Water may exist in several forms within the nonwelded tuff. The water may be either in the pores of the tuff, or adsorbed on or within clay minerals. During diagenesis, disassociated water ions may become an integral component of the clay mineral structure. Water also may exist within the tubular openings between elongated zeolitic structural units (Grim, 1968).

Smectite clay and zeolite have been determined to be abundant mineral constituents of the tuffs at Yucca Mountain. Water retention of the tuff is increased by the interactions of clay and zeolite with pore water. Smectite-clay particles generally are surrounded by several layers of water molecules. The zeolite clinoptilolite retains water in two different sizes of structural channels. Both argillization and zeolitization tend to decrease the permeability of the tuff; they may be partially responsible for creating zones of substantial moisture content above the water table. Tuff samples of moist, clay-enriched intervals are potential samples for pore-water extraction. However, careful consideration needs to be given to the possibility of extracting bound water along with the pore water.

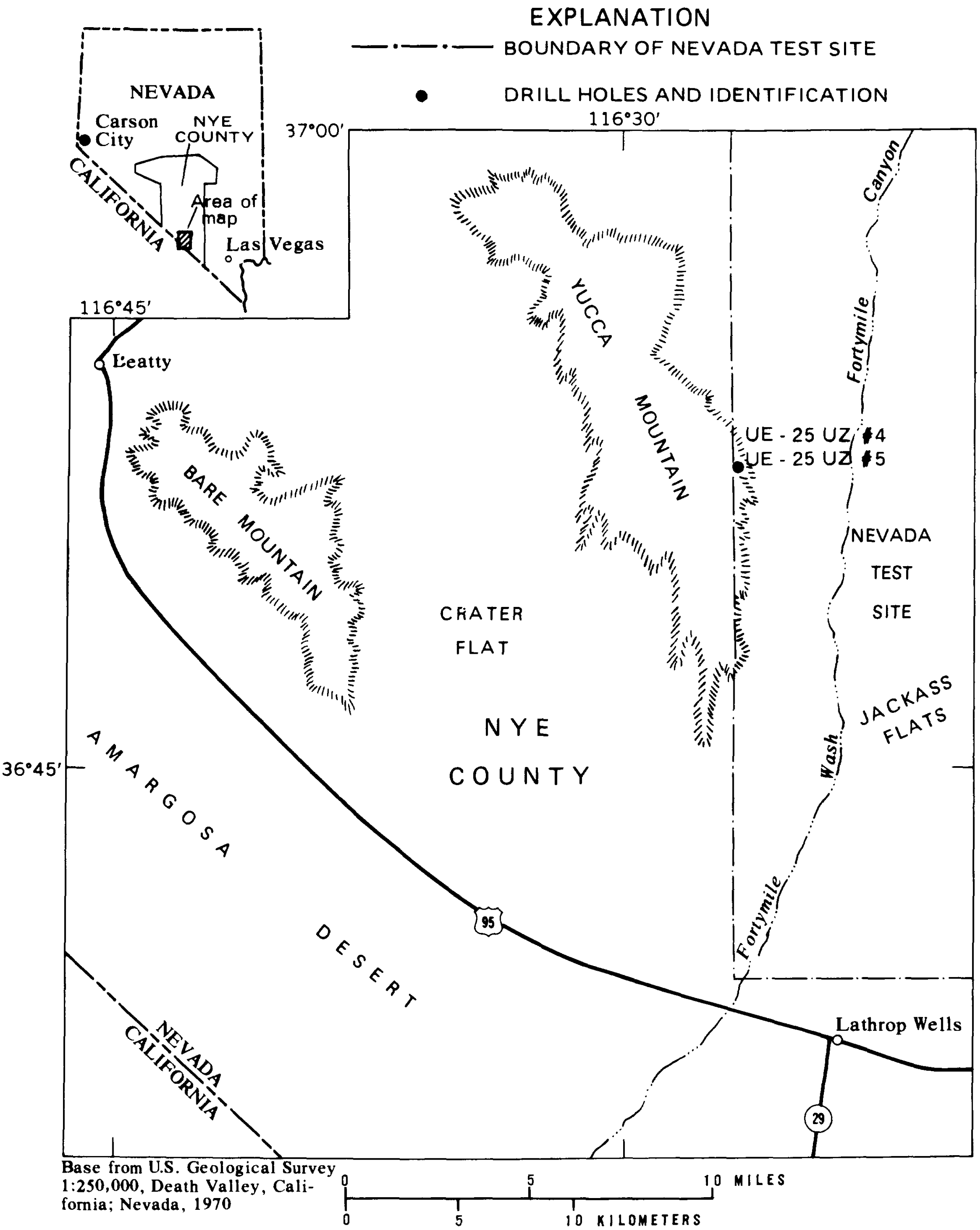

Figure 1.--Location of drill holes UE-25 UZ #4 and UE-25 UZ #5, and nearby geographic features in southern Nevada.

Clay particles generally have a negative electrical surface charge that attracts cations and hydrogen ions from the pore water. Successive layers of water molecules are adsorbed around each particle. Movement of these molecules is restricted, especially in directions away from the clay particle; the terms "immobilized layers," "bound water," and "adsorbed water" commonly are used to describe this water.

Zeolites are composed of a hydrated aluminosilicate framework composed of $(Si,Al)O_4$ tetrahedra (Hay, 1966). The framework has a net negative charge, that generally is balanced by calcium, sodium, or potassium cations. The zeolite framework contains channels and interconnected cavities in which cations and water molecules are bound loosely. Water molecules and cations readily can be removed or replaced without disrupting the framework bonds. Zeolites also have a cation-exchange capacity that generally decreases with loss of water (Deer and others, 1966).

Experimental evidence from work by Koyama and Takeuchi (1977) and Knowlton and others (1981) indicates that many zeolites have three classes of adsorbed water: (1) Externally adsorbed water that is readily removed, (2) loosely bound water that can be removed with some effort, and (3) tightly bound water that can be removed only by heated evacuation.

These hydrochemical interactions have important applications to pore-water extraction and subsequent age dating. The most suitable pore water for analysis needs to have a chemistry that is representative of percolating pore water.

To extract any pore water, the stress levels must exceed the forces holding water within the pores. Therefore, only a certain range of compressive stress will yield a pore water that has suitable composition for chemical analyses. For example, Grim (1968) concluded that of two adsorbed molecular water layers on a vermiculite clay, the water layer farthest away from the clay particle required 120 MPa hydrostatic stress for removal, whereas the closer water layer required 520 MPa hydrostatic stress for removal. These experimental extraction stresses matched predictions determined theoretically from water-adsorption curves of vermiculite. Kriukov and Komarova (1954) compressed sodium-bentonite clay and determined that there was an abrupt increase in the extraction of electrolyte-deficient adsorbed water at stresses greater than 59 MPa. They also concluded that the threshold for removing adsorbed water from sodium bentonite was a function of the dissolved-solids concentration of the pore water. When less mineralized or interstitial water with a minimal dissolved-solids concentration was used, smaller stresses affected the composition of the extracted pore water.

Pore-Water-Extraction Techniques

Two prior studies were undertaken to determine the feasibility of extracting pore water from tuff samples collected at the NTS by triaxial compression. Butters and others (1975) stated that they were successful in extracting 30 to 50 percent of the total water content from an ash-fall tuff collected from Area 12 of the NTS; this area is located about 50 km northeast of Yucca Mountain. However, this study provides few specific details about the experimental procedures that were used.

Dropek and Levinson (1975) also were successful in extracting pore water from tuff samples collected at the NTS. Their study provides an outline of the experimental procedures used to extract the pore water and the chemical results from cation analysis of the water. However, no information was provided about the physical properties of the tuff samples used for extraction.

Dropek and Levinson (1975) subjected 14 tuff samples to either simple hydrostatic compression or a multiple cycling of compression. Stress paths that illustrate how stress was changed with time for both of these compressive methods are shown in figures 2 and 3. For the multiple-cycle compression, a tuff sample initially was compressed hydrostatically; then the lateral stress was maintained at a constant level while the axial stress was increased and decreased rapidly many times, followed by diminishing of the stress. This total stress path was repeated three times in rapid succession in an attempt to extract pore water from the tuff. The duration of compression for both types of stress ranged from 5 to 10 minutes.

Only a few tests have been used to obtain data for a large range of stress. The stress levels used for tests ranged from a hydrostatic compression test at 33 MPa to a multiple-cycle test with a lateral stress of 300 MPa and an axial stress of 445 MPa.

Dropek and Levinson (1975) presented the following conclusions about the effects of their experimental stress paths on the chemistry of extracted pore water:

1. Cation concentrations (calcium, magnesium, sodium, and potassium) from the hydrostatic-compression tests always were greater than those from the multiple-cycle triaxial-compression tests.

2. In general, greater lateral stresses resulted in smaller cation concentrations.

3. No repeatable trends were determined for silica concentrations in extracted pore water.

The first two conclusions are significant to this study because they indicate that the probability of extracting bound water increases when tuff samples are subjected to large lateral stresses or to multiple-cycle compression. The decrease in cation concentration determined for these more energetic stress paths may correlate with the extraction of bound water.

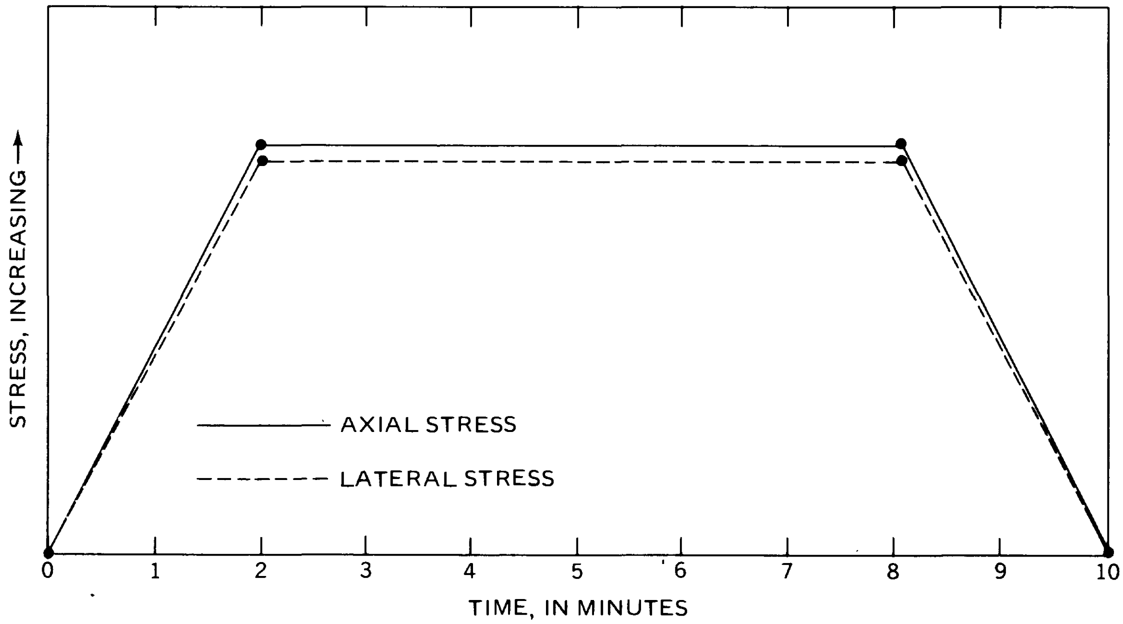

Figure 2.--Stress path illustrating hydrostatic compression.

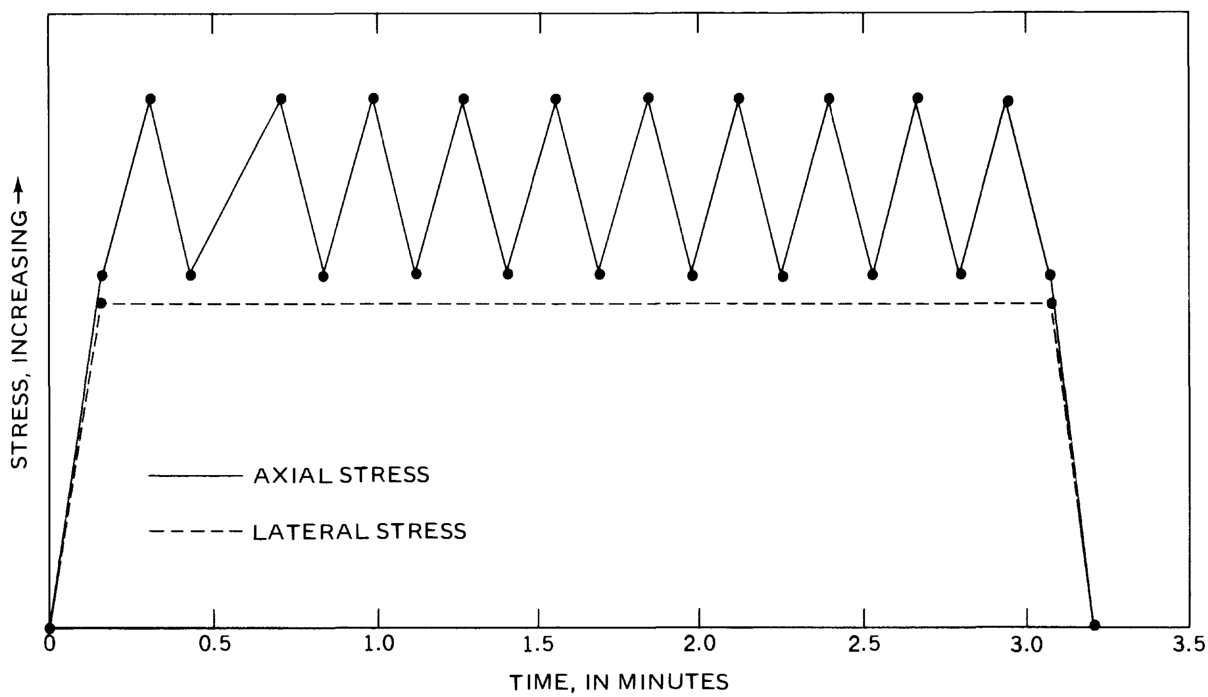

Figure 3.--Stress path illustrating repeated cycling of axial stress and constant lateral stress.

Generally, the ionic concentration of extracted pore water decreases as bound water is contributed by various clay and zeolite minerals (Deer and others, 1966; Manheim, 1966; Kriukov and Komarova, 1954).

Stress paths that involve multiple cycling of compression or lateral stresses in excess of 69 MPa have been avoided in the experiments done for this study. Data from preliminary chemical analysis of extracted pore water have been analyzed in order to identify the threshold stress levels that induce extraction of bound water.

Tuff Properties Affecting Pore-Water Extraction

Pore-water extraction is affected by several material properties of the tuff. The degree of welding affects the matrix permeability and deformation characteristics of the tuff. The sample saturation affects effective permeability. Textural characteristics affect tortuosity and porosity. Most of these properties undergo progressive alteration when a sample is subjected to triaxial compression. The initial properties of the tuff, and the various ways these properties change during sample compression, affect the drainage of pore water from tuff samples. Montazer and Wilson (1984) grouped the rocks in the unsaturated zone beneath Yucca Mountain into informal hydrogeologic units (fig. 4), based on their physical properties. Some representative average values for the Paintbrush nonwelded unit are listed in table 1.

Table 1.--*Representative average properties of the Paintbrush nonwelded unit*

[From Montazer and Wilson (1984) or this report, as listed]

Bulk density = 1.2 to 1.6 grams per cubic centimeter (from table 4)
Porosity = 46 percent
Saturation = 61 percent
Water content = 19 percent
Saturated permeability = 9×10^{-3} meter per day
Water potential = 0.3 megapascal (from figure 12)

Permeability

Permeability of the tuff matrix is controlled by the size and interconnection of pathways for water movement. Pore size within the tuff may be less than tens of micrometers (Scott and others, 1983). Pore passages also have substantial tortuosity and are not well connected (Waddell and others, 1984). Both of these factors contribute to the small permeability of the tuff matrix.

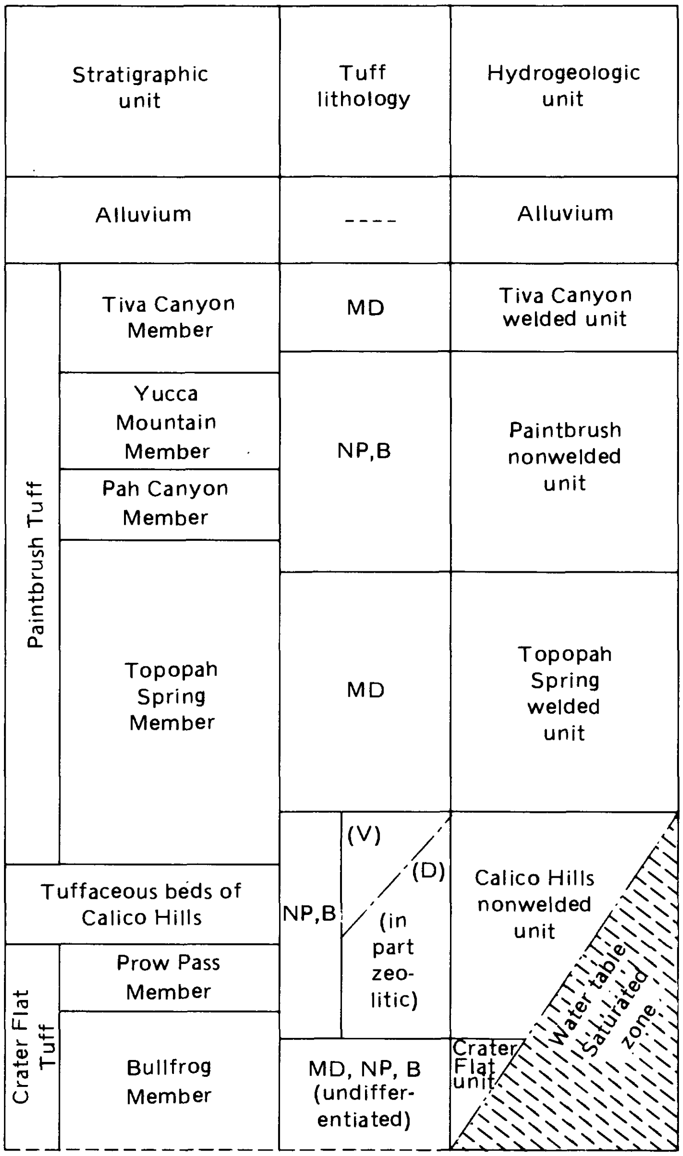

Figure 4.--Hydrogeological units at Yucca Mountain [modified from Montazer and Wilson (1984), table 1]. MD, moderately to densely welded; NP, non-welded to partially welded; B, bedded; (V), vitric; (D), devitrified.

When a tuff sample is subjected to mechanical compression in a triaxial cell, microfracturing of the pore structure initially may provide additional pathways for water to drain from the sample. With further compaction and elimination of pore space, the effective porosity is likely to decrease and the permeability of the sample, thus, would decrease. As a result, the rate of water extraction from the sample is likely to be most rapid initially, then progressively decrease as peak compressive stresses are attained.

Matric Potential

Water is held more tightly by the tuff as it becomes drier. This change can be monitored by measuring the matric potential (water potential) of the tuff with a tensiometer (from 0 to 80 kPa). In unsaturated tuff, water is held with a negative pressure; this pressure is referred to as matric suction (equivalent to the absolute value of matric potential). Matric suction substantially increases as water is extracted progressively from the tuff by triaxial compression; therefore, the remaining water in the tuff becomes increasingly difficult to extract by external compression. Some water may be retained by the tuff in this manner, even under extreme stress.

Texture and Mineralogy

Texture and mineralogy are important characteristics that affect the potential for pore-water extraction and the chemistry of the extracted water. Porosity and permeability, reflected by texture, may determine the capability to extract pore water from the tuff. Mineralogy of a tuff sample can affect the specific changes in pore-water chemistry if a rapid increase in stress occurs.

The texture of an ash-flow tuff is controlled largely by the eruptive and cooling history of the deposit. The extent of welding within a sample of tuff affects its deformational characteristics. Generally, an increase in welding correlates with an increase in brittleness. Densely welded tuff fractures readily, whereas nonwelded tuff does not fracture readily.

Nonwelded tuff will compact progressively during triaxial compression. Variable fractions of rigid, dense lithic fragments and soft, porous pumice fragments are present in nonwelded tuff. As the fraction of lithic fragments increases, a decrease occurs in the total compaction during pore-space closure. In contrast, as the fraction of pumice fragments increases, the compactability of the tuff also increases.

Post-depositional mineralogic changes, such as alteration of glass shards to zeolite or montmorillonite, affect permeability of the tuff. The chemical composition of pore water will change during its movement through the tuff matrix. Incongruent dissolution of glass along the flow path causes a progressive increase in dissolved solids. At some point along the flow path, conditions may become favorable for the formation of montmorillonite or zeolite (Claassen and White, 1979). Permeability of the tuff may be decreased as these minerals begin to form.

Secondary alteration also affects the texture and strength characteristics of the tuff. Thin silicified intervals within the tuff may mark zones of hydrothermal alteration. The precipitation of silica from silica-enriched solutions in nonwelded tuff causes the rock to become more rigid, and, therefore, increases brittleness. In contrast, clay alteration of the nonwelded tuff is likely to decrease brittleness.

Strength Characteristics

A series of experiments to determine strength characteristics of tuff from the NTS has been performed by Olsson and Jones (1980). They concluded that the degree of welding, indicated by porosity, is the dominant variable that affects strength characteristics of tuff. Olsson and Jones (1980) also state that values for Young's Modulus, cohesion, maximum differential stress, and the angle of internal friction are all functions of porosity. Samples used for testing were collected from drill hole UE-25a #1 at Yucca Mountain and from the Grouse Canyon Tuff exposed in the G Tunnel at Ranier Mesa.

The scatter in their experimental data is large, due to the other variables, such as mineralogy, which may vary with degree of welding; however, a relation between strength and porosity may exist. The predicted relation between strength and porosity, based on the data of Olsson and Jones (1980) is shown in figure 5.

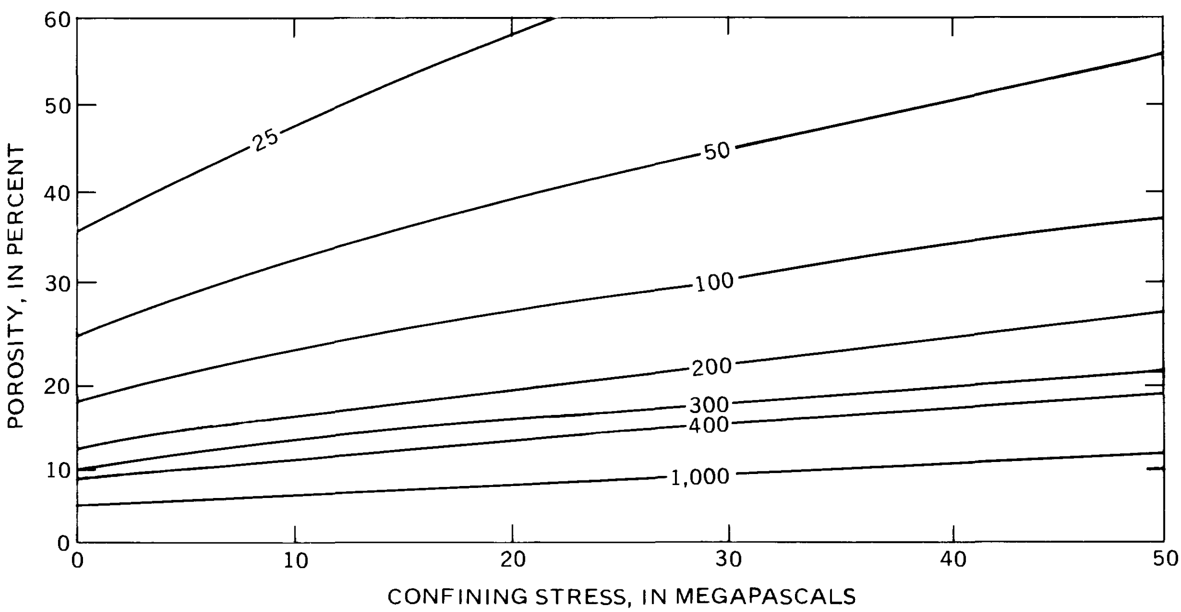

Figure 5.--Representation of a strength-prediction equation. The solid lines represent maximum differential stress, in megapascals, before sample failure (data from Olsson and Jones, 1980).

Deformation Characteristics

A series of 44 uniaxial- and triaxial-compression experiments was made using samples of tuff from the Calico Hills nonwelded unit by Price and Jones (1982). Porosity of tuff from the Calico Hills nonwelded unit is similar to that of tuff samples from the Paintbrush nonwelded unit. If the relation between porosity and strength characteristics determined by Olsson and Jones (1980) is valid, then the mechanical response of the Paintbrush nonwelded unit is likely to be similar to that of the Calico Hills nonwelded unit, and the data of Price and Jones (1982) can be used to guide further triaxial tests of the Paintbrush nonwelded unit.

Price and Jones (1982) concluded that samples of tuff from the Calico Hills nonwelded unit were ductile under triaxial-compression conditions. An idealized curve that shows the relation between differential stress and axial strain for the Calico Hills nonwelded unit is shown in figure 6. The initial concave-upward part of the curve (segment AB) indicates pore collapse and compaction. The linear part (segment BC) indicates a zone of elastic deformation. The final concave-downward part (segment CD), which includes the point of peak differential stress, indicates a region of inelastic behavior. The gradual strength loss shown by this curve indicates that deformation is distributed throughout a large volume of the sample, rather than along a few prominent fractures.

This gradual strength loss indicates that most pore collapse and compaction occurs during early stages of deformation. The onset of pore collapse may occur at hydrostatic stresses of 15 MPa (Heard and others, 1971). If pore collapse forces water out of the tuff, then the majority of water is likely to be extracted from the tuff during initial stages of triaxial compression. Further increases of the compressional stresses will result in elastic and ductile deformation after most of the pore collapse already has occurred. Therefore, only relatively minor quantities of water will be extracted under greater compressive stresses.

DEVELOPMENT OF PORE-WATER-EXTRACTION METHODS

The initial selection of appropriate pore-water-extraction methods using triaxial compression was based on a thorough review of the previous work in the areas of hydrochemistry, pore-water extraction, and tuff properties that affect pore-water extraction. The results from previous work indicate that the most efficient extraction of uncontaminated pore water will occur at the lesser stress levels of triaxial compression. As compressive stresses are increased gradually, the sample permeability is likely to increase initially, and then gradually decrease. Deformation characteristics of the tuff indicate that most of the pore water is likely to be extracted during early compression because of rapid initial pore collapse. The last traces of water remaining in a sample become increasingly difficult to extract as a result of increased matric suction. The possibility of extracting bound water also increases as greater compressive stresses are used. The selected procedures incorporated these considerations along with the practical aspects of triaxial-cell design and operation.

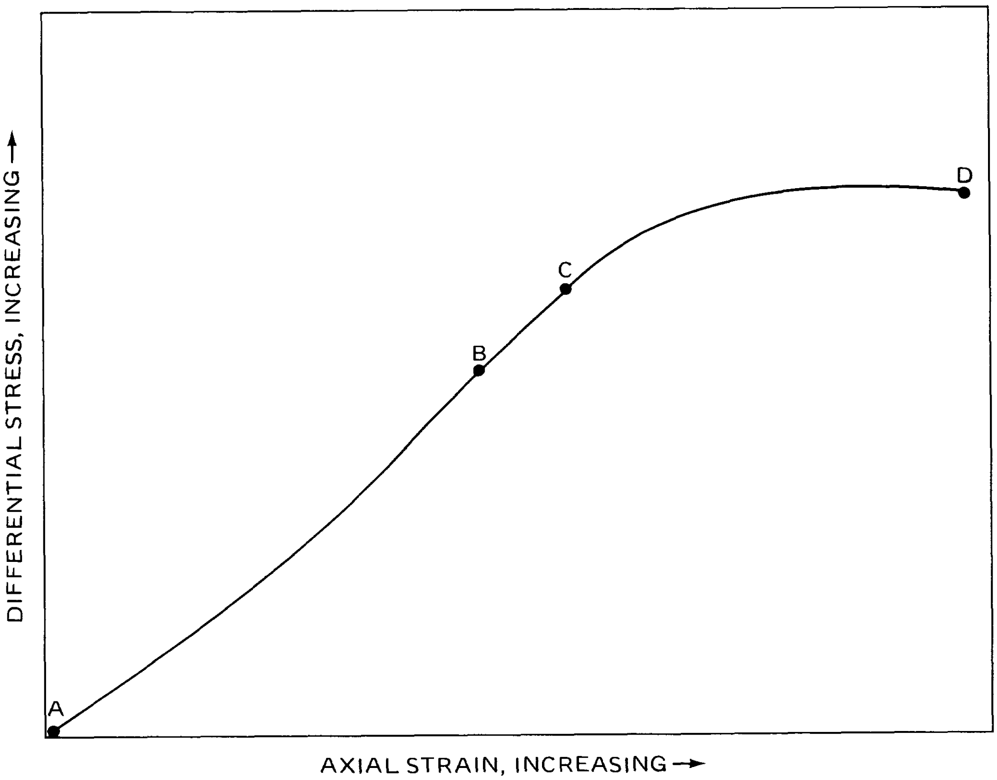

Figure 6.--Idealized relation between differential stress and axial strain for a drained tuff sample deformed under triaxial compression. Curve is based on data from Price and Jones (1982).

Design of a Triaxial Cell for Pore-Water Collection

The technology of triaxial compression testing is well documented. A number of commercially available triaxial cells are manufactured to accommodate the stress ranges that would be required for the tests, based on the results of previously discussed work. However, the objective of the proposed tests, to extract and collect uncontaminated pore water from the rock samples, departs from normal operations. The primary concern was to design an efficient pore-water collection system that would eliminate all sources of sample contamination.

Previous Designs

An illustration of the triaxial cell used in prior experiments by Dropek and Levinson (1975) is shown in figure 7. This high-pressure compression cell drains extracted water from one end of the sample into an internal void space. The collection chamber is made of stainless steel. A permeable stainless steel porous disc, that has a mean pore diameter of 30 µm was used to filter the pore water and to prevent the sample from extruding into the collection chamber. The core sample rested on the collection chamber, and both units were jacketed together with two wraps of polyurethane. The sample and chamber were sealed with rubber splicing compound and stainless steel lock wire. After a period of compression was completed, the sample and collection chamber were removed from the vessel, and the extracted water was drained into a suitable container.

This triaxial-cell configuration can be improved. To minimize the magnitude of stress and duration of compression, a pore-water collection system that has a highly efficient design is essential. Compressing efficiency would be increased by collecting pore water from both ends of the sample. The system can be made more chemically inert by sealing the sample with Teflon rather than rubber. Extracted water needs to be collected outside the cell to allow incremental sampling of water at various stresses. Disposable pore-water filters need to be used to avoid potential water-contamination problems by reusing the stainless steel porous discs.

Some of these characteristics are found in a low-pressure sediment squeezer designed by Kalil and Goldhaber (1973) (fig. 8). This design has been used for removing interstitial water from ocean sediments with only minor air contact. The squeezer is made of plexiglass, Teflon, and rubber and uses two external syringes for collection of pore water. While this squeezer is not suitable for water extraction from tuff, several of its features have been incorporated into the final design used in this study.

Modified Design

The design of the pore-water-extraction system developed for this study (fig. 9) is based on the Hoek-Franklin triaxial cell (Vutukuri and others, 1974). This cell originally was intended to measure the behavior of rocks under realistic geologic stresses. Several modifications to this configuration have resulted in a chemically inert pore-water-extraction system. The modified triaxial cell used in this study is shown in figure 10. The triaxial cell was manufactured by the Slope Indicator Company and includes a mild-steel body and end caps, and a urethane membrane. The vented pore-pressure platens initially were intended for monitoring and control of pore-water pressures within the core sample. However, these platens work equally well for transferring extracted water to external collectors.

To collect extracted water, two syringes were connected to the ports of the pore-pressure platens. Two types of syringes were used during experimentation. Initially, Hamilton gas-tight syringes were used; these syringes are made with glass bodies and Teflon-coated plungers; however, water leaks were detected around the plunger seals. Disposable plastic Hamilton syringes were used subsequently; these worked well. Both types of syringes were connected to oversized stainless steel hypodermic needles that had Luer-Lock fittings.

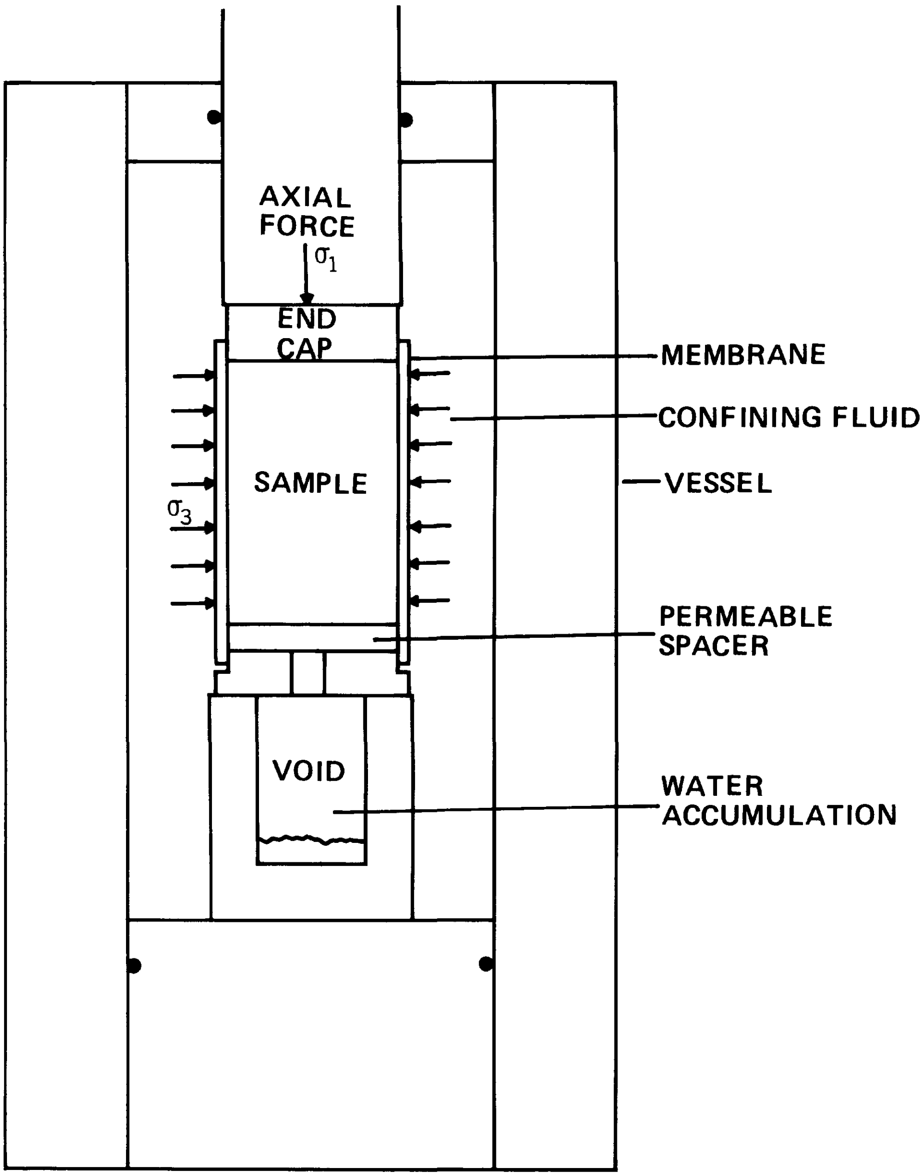

Figure 7.--Triaxial test configuration used in a previous study (Dropek and Levinson, 1975).

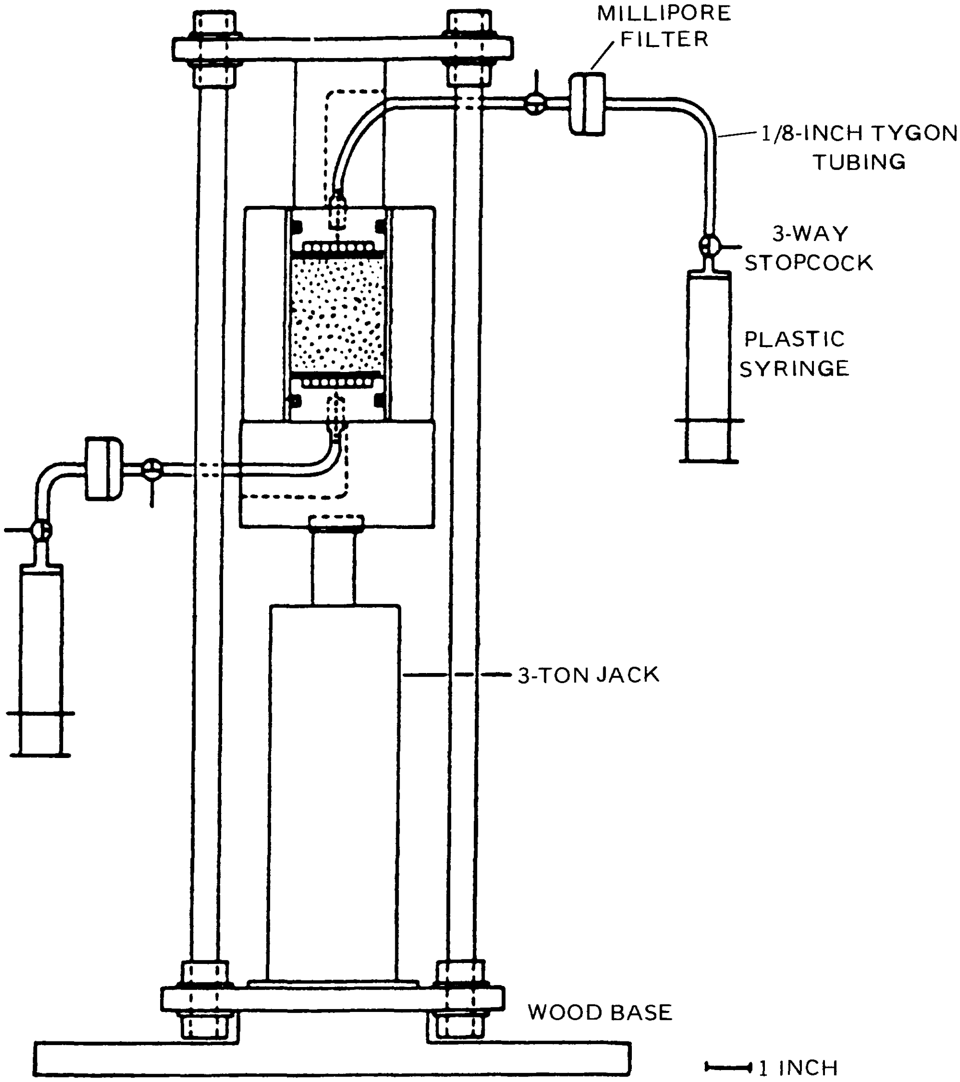

Figure 8.--Design of a sediment squeezer (Kalil and Goldhaber, 1973).

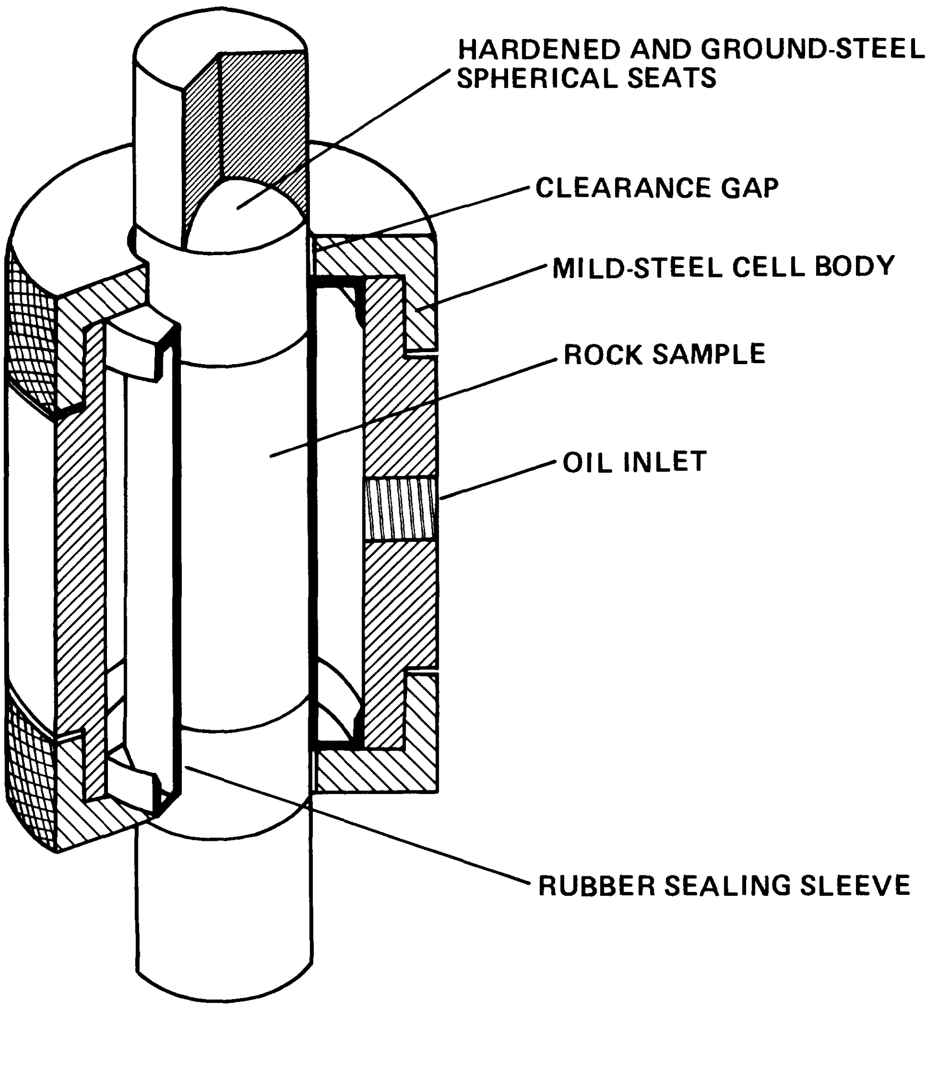

Figure 9.--Hoek-Franklin triaxial cell (modified from Vutukuri and others, 1974).

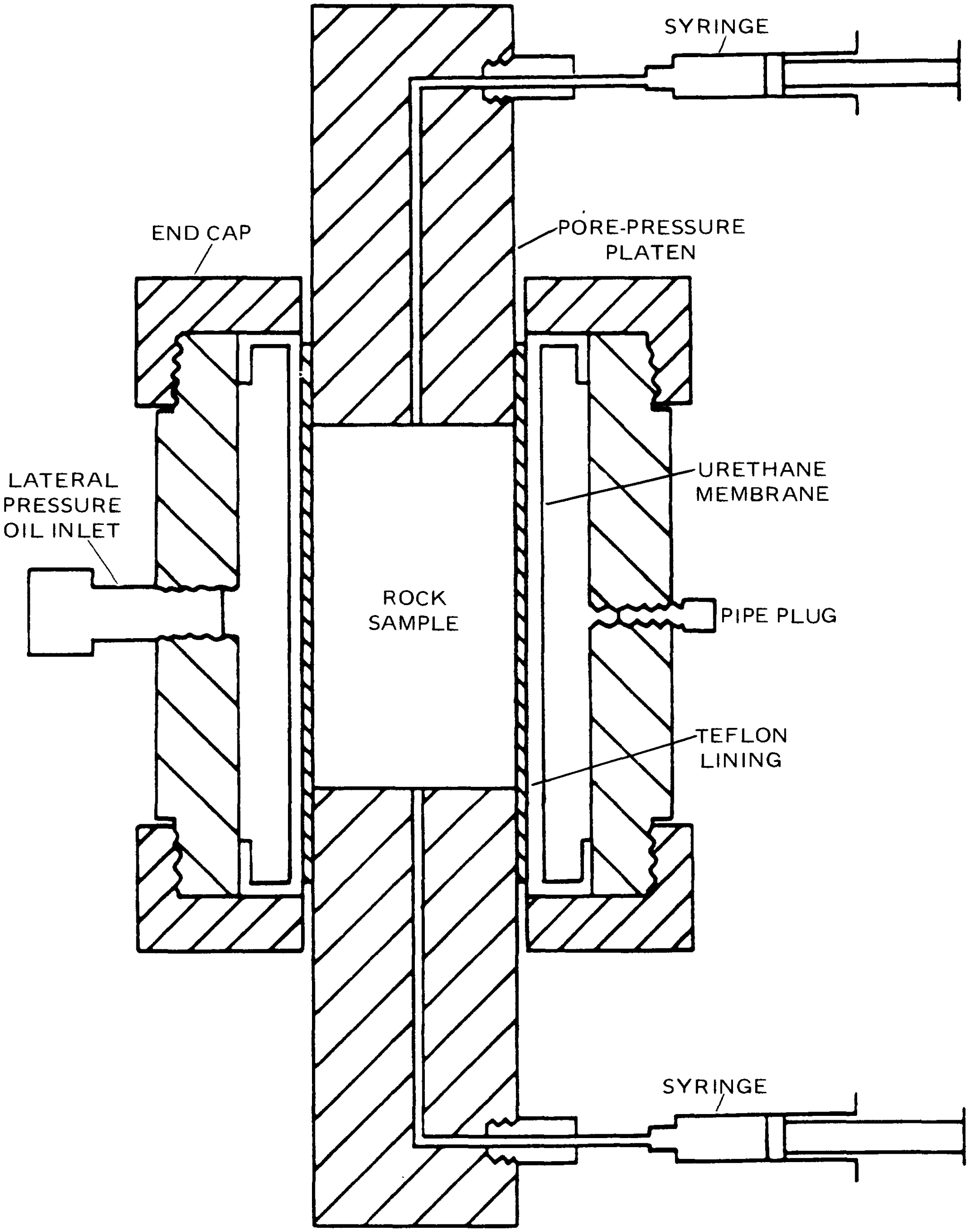

Figure 10.--Modified triaxial cell used for pore-water extraction.

The triaxial cell is assembled as shown in the photographs in the following figures. First, a core sample is placed between two pore-pressure platens (fig. 11). The sample is then wrapped with a layer of Teflon (fig. 12) and then sealed with the urethane sleeve (fig. 13). This entire assembly then is enclosed by the main barrel of the triaxial cell; finally, the syringes are attached (fig. 14).

Axial pressure was applied to the sample by a Soiltest load-frame that had a capacity of 1.1 MN. Lateral confining pressure was applied with hydraulic oil that was pressurized by Enerpac and High Pressure Equipment hand pumps. The triaxial cell has a maximum lateral confining pressure capacity of 69 MPa. This cell accommodates core samples that have a length of 103 to 113 mm and a diameter of 60 mm.

Before inserting a piece of core into the triaxial cell, the sample was jacketed with one wrap of Teflon. This Teflon lining protects the urethane sleeve from the irregular surface of the tuff. In addition, this lining aids in ensuring that the pore-water-extraction cell is more chemically inert by preventing direct contact between the urethane sleeve and the rock sample.

Several advantages are inherent in this new design compared to the previous design used by Dropek and Levinson (1975). Pore water is collected from both ends of the core, theoretically quadrupling the drainage efficiency (Bishop and Henkel, 1957). Quantities of extracted water also may be inspected during collection; this allows the calculation of pore-water-extraction rates. In addition, several water samples can be collected at various stresses without disassembly of the triaxial cell.

Operation

When axial stress (σ_1) and confining stress (σ_3) are applied to the sample, water is forced from the tuff. The water exits through both ends of the tuff into ports that carry the water through the platens and into the syringes. The extracted water moves the plunger of the syringe back as the water accumulates; atmospheric contamination or evaporation of extracted water is prevented. The syringe is emptied by disconnecting it from the hypodermic needle and attaching it directly to a Nuclepore 0.4-μm filter. The plunger then is depressed, which forces water through the filter into a suitable sample container.

Experimental Method

As stated previously, the purposes of this study included the design of a triaxial pore-water-extraction system and the determination of the optimal extractive methods. Such a determination involved experimental test extractions; these extractions were done to define the appropriate magnitude of stress and duration needed for water extractions.

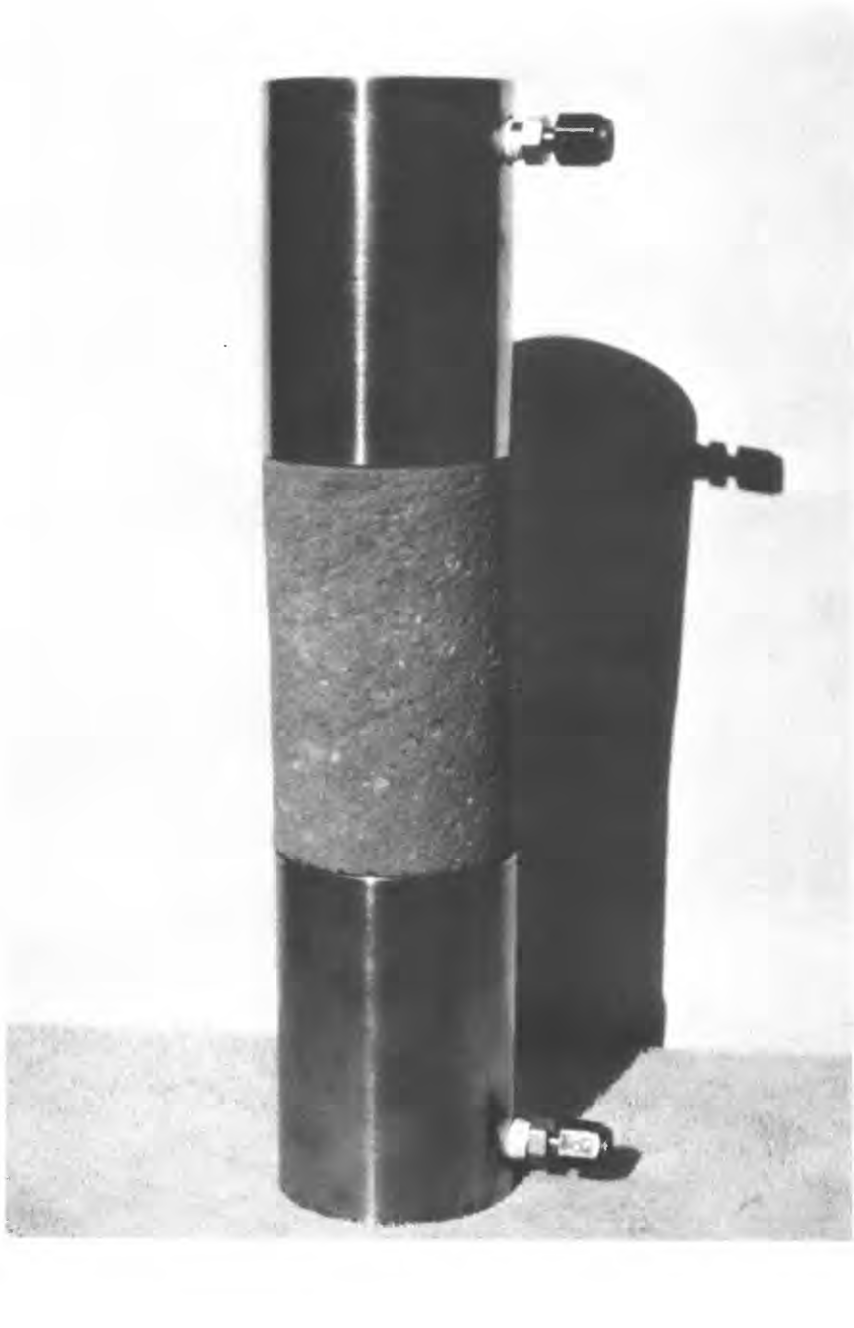

Figure 11.--Pore-pressure platens placed on both ends of a core sample; sample length is 105 millimeters.

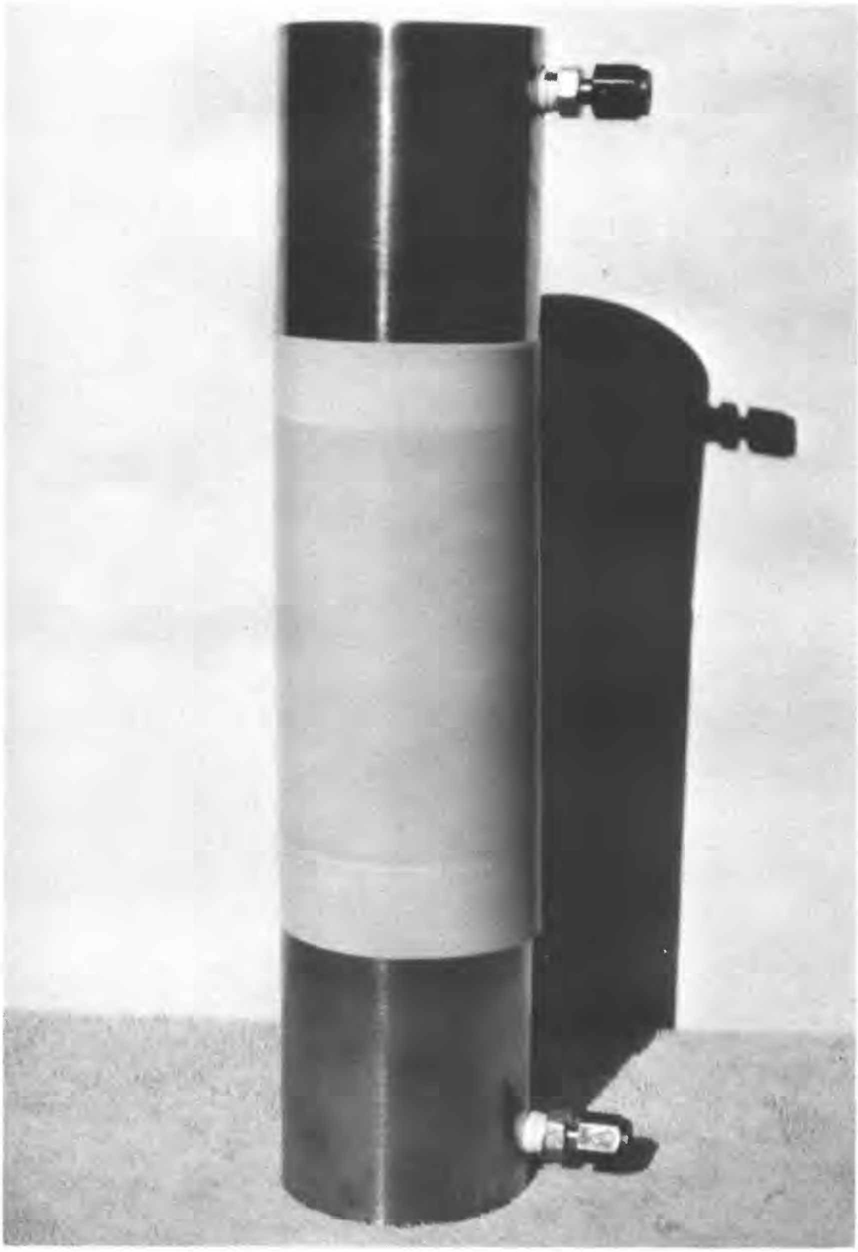

Figure 12.--Core sample wrapped in a layer of Teflon.

Figure 13.--Position of the urethane sleeve that seals the Teflon and core sample.

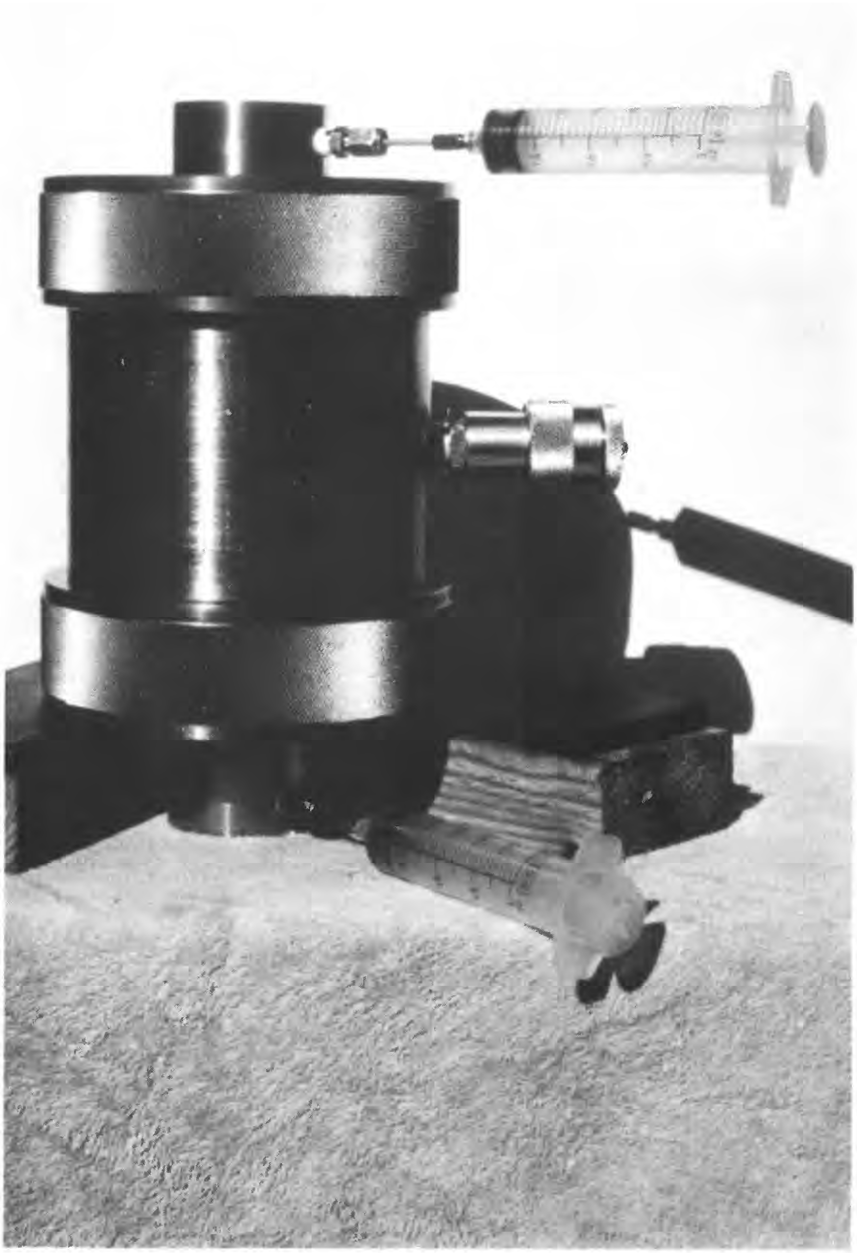

Figure 14.--Fully assembled pore-water-extraction cell.

Selection of Variables

To develop an effective and practical method for water extraction, two variables were selected for experimental testing. Both the magnitude of stress and the duration of triaxial compression affect the extraction of pore water. Experimental conditions that yield only insubstantial additional quantities of water during extremely long periods and large levels of stress are impractical. Preliminary chemical analysis of extracted pore water was used to identify the threshold stress level that causes the extraction of bound water.

The experiments were designed to identify the smallest possible stresses and shortest periods of compression consistent with collecting adequate volumes of extracted water. Small compressive durations are used to minimize potential reactions between pore water and new mineral surfaces created by microfracturing during compaction. The use of small stresses decreases the possibility of extracting bound water from clay minerals. A highly efficient pore-water collection system is essential to minimize the stress and duration of compression.

Selection of Stress Paths

Based on the results of a previous pore-water-extraction study by Dropek and Levinson (1975), stress paths that involve multiple-compression cycles were avoided in these experiments. Instead, the selected stress paths involve applying a series of increasing stresses in steps. A typical stress path used in this experiment is shown in figure 15. Trial axial stresses ranged from 41 MPa to 190 MPa with confining stresses of 34 MPa to 69 MPa. The duration of compression at any given stress level lasted from 10 minutes to 15 hours. Periods of compression generally were continued until no additional pore-water could be extracted in 30 minutes. Separate pore-water samples, representative of a specific stress level, were collected at the end of each stress level.

LABORATORY TESTS

Laboratory tests involve three basic components: sample collection and preparation, water extraction, and equipment calibration and data-error limits.

Sample Collection and Preparation

Sample-handling procedures affect the success of extracting uncontaminated water from tuff. Evaporation of pore water increases with sample-exposure time in the dry climate of the NTS or in Denver. In addition, suitability of the pore water for carbon-14 or tritium dating decreases with increased sample exposure, because modern carbon and hydrogen may begin to contaminate the pore water. Strict precautions were taken to avoid contamination or evaporation of pore water from the tuff samples.

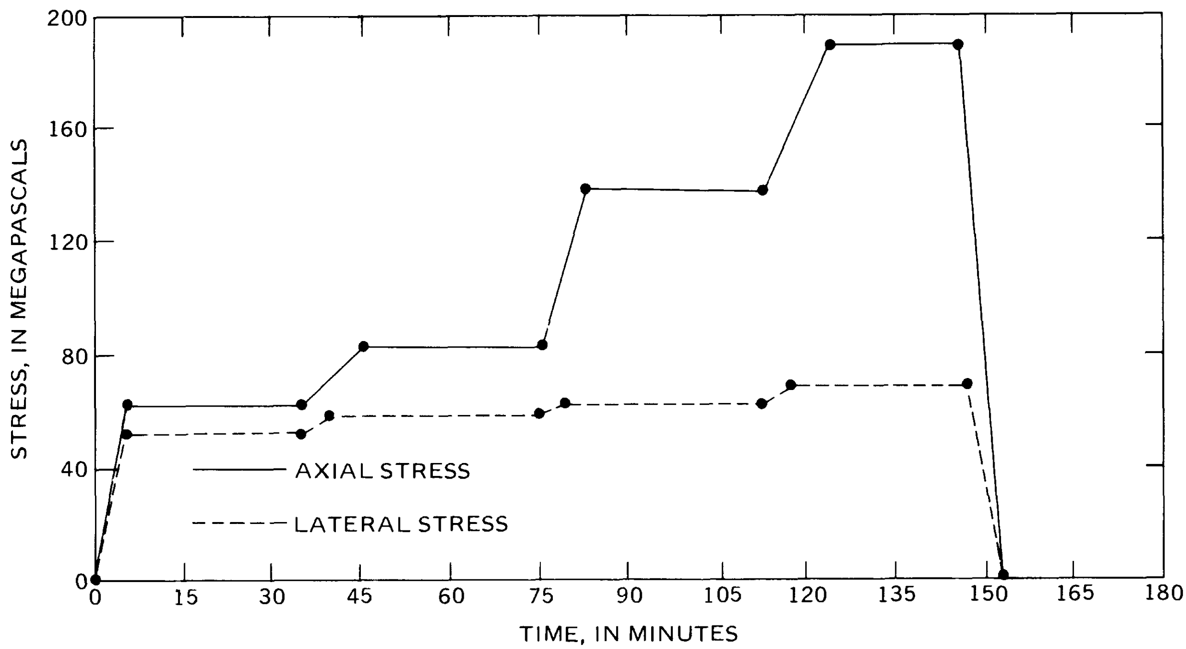

Figure 15.--Typical stress path used during pore-water-extraction experimentation.

Although some moisture loss was inevitable while core was collected by air drilling, precautions were taken to minimize evaporative loss after core was taken from the drill hole. Core was wrapped in aluminum foil and waxed or sealed in PVC (polyvinyl chloride) tubes. The sealing of core generally was completed within 5 to 20 minutes after it was removed from the drill hole. After sealing the cores, they were carefully packed into plastic coolers and transported from the NTS to Denver. The cores then were stored at a temperature of 6 to 10 °C until they were removed for cutting and pore-water extraction.

Samples were prepared for extraction by cutting the core cylinders into segments about 108 mm long. Dropek and Levinson (1975) previously used a mechanical circular saw, with distilled water as a coolant, when cutting core collected from the NTS to proper length. They assumed that the coolant water used during cutting essentially would not penetrate the rock; this assumption may not be valid.

For this study, another method of cutting was used in order to avoid heat build-up and the subsequent need for a cooling fluid. All cuts were made by a hacksaw equipped with a tungsten carbide blade. Ends of the cut sample seemed parallel to the eye; however, they probably departed from the perpendicular to the specimen axis by more than the maximum 0.25 degree specified for general triaxial testing by the American Society for Testing and Materials (1970). However, these tolerances are not as critical for pore-water extraction as for the usual measurement of strain and strength properties.

Cutting was done on a table exposed to air or in a glove box filled with nitrogen gas. Cutting in the open air usually required 10 to 20 minutes per sample, depending on the hardness of the tuff. Use of the glove box for cutting was awkward and usually took about twice the time as that required for cutting in open air. Chemical data are not yet available to establish the affect of these two cutting methods on pore-water chemistry. Samples generally were compressed within a few hours after cutting. During the interim period, cut samples were sealed in three layers of plastic bags.

Water-Extraction Method

The water-extraction method is described below in detail and also includes the assemblage of the triaxial cell used for the extraction of pore water.

Triaxial-Cell Assembly

Assembly of the triaxial cell is not complex, but must be done carefully to avoid leakage of hydraulic fluid after the cell is pressurized. All major parts of the triaxial-cell configuration are shown in figures 10 through 14. First, a clean urethane membrane is inserted into the central barrel of the cell. The two end caps then are screwed onto the central barrel. The end caps are to be hand tightened sufficiently to ensure a metal-to-metal contact between the end of the core barrel and the inner surface of the caps. The caps are to be screwed on slowly near the end to avoid being jammed too tightly against the barrel.

The pipe plug then is removed from the central barrel, and approximately 250 mL of hydraulic oil is poured through this opening into the cell. The cell is tilted back and forth to help air escape from the cell interior. The oil within the cell is then topped off, and the pipe plug is threaded a few turns back into its hole. The pipe plug should receive a new wrap of Teflon-sealing tape for each insertion.

A core sample 108 mm long (±5 mm), jacketed by one wrap of Teflon, is inserted into the membrane within the barrel. The core is centered within the membrane, and one pore-pressure platen is inserted into the bottom of the cell until the sample is gently contacted.

The assembly is carefully placed onto the lower jaw of the press. To prevent the cell from sliding down over the lower platen, two shims (approximately 50 mm thick) are inserted to support the main body of the triaxial cell. The confining-pressure supply line is connected to the quick-disconnect oil inlet. After opening the bleed valve on the confining-pressure hand pump, the pipe plug is fully tightened into the cell. Finally, two needles and syringes are tightly connected to the fittings on the pore-pressure platens.

Application of Stress

A small axial stress (approximately 1 MPa) is slowly applied to the sample by means of the loading frame. The cell needs to be shaken to ensure that all surfaces are seated firmly and are well aligned. The bleed valve on the hand pump is closed, and the pump is operated to raise lateral oil pressure to 0.7 MPa. The shims from the base of the cell are removed. The starting time for the following compression needs to be recorded.

Loading the cell is continued by increasing axial and lateral stresses in steps, so that the axial stress is always larger than the lateral stress. This precaution prevents extrusion of the cell membrane into the gap between platens and the end surfaces of the sample. A stress condition such that the axial stress is always larger than the lateral stress by 34.5 MPa is maintained, until the desired lateral stress is reached; then, the axial stress is increased as predetermined. The time after the beginning of when the desired stress is reached is recorded. As a precaution to avoid fracturing of the sample, axial stress should not exceed confining stress by more than a factor of three at any time after the cell has been pressurized.

As a period of compression continues, axial and confinement stresses generally decrease, pore compaction occurs, and water is extracted from the sample. If a sample begins to barrel out across its midsection, confinement stress may be increased. Axial and confining stresses need to be constantly monitored and adjusted to maintain the desired levels. The triaxial cell also needs to be carefully inspected during compression for any leakage of hydraulic oil.

Pore-Water Collection

After one compression period, the syringes are detached at the needle fittings. If additional stresses are to be applied, two other clean syringes need to be attached to the needles.

The extracted water is filtered by attaching the syringe to the Nuclepore filter holder and by depressing the syringe plunger slowly to force water through the filter and into a suitable container. Glass vials are used when tritium or carbon-14 analyses are done. Plastic vials are used when ion concentrations are to be analyzed.

Unloading

After all desired levels of compression have been completed, the stresses are removed from the sample. The confinement stress is removed slightly before the axial stress when the sample is unloaded. Axial stress should not exceed confining stress by more than a factor of three during unloading. Axial and confining stresses are removed until both are zero.

Disassembly and Cleaning

The entire cell assembly is removed from the load frame. The pipe plug is unscrewed and the hydraulic oil is drained from the cell. To remove the sample without damage to the membrane, the end caps are unscrewed and the membrane and the rock are removed from the triaxial cell. If the sample is jammed inside the membrane, it can be removed using a blunt tool.

All surfaces of the apparatus that were in contact with the sample or pore water need to be thoroughly washed and then rinsed with distilled water. This cleaning entails removal of the platen fittings that are used to attach the syringe needles. All components need to be dried before reuse.

Equipment Calibration and Data-Error Limits

The press used for applying load to the triaxial cell was calibrated against a load cell by Earth Mechanics Institute personnel in June 1985 (directly before extraction use); the press readings were accurate to within ±2.5 percent. The gage used to monitor lateral-confinement stress was calibrated against a dead-weight pressure device in February 1985; gage readings were accurate within ±3 percent.

All reported compressive durations are accurate within 2 minutes. During periods of triaxial compression, axial and confinement stresses were maintained within ±3 percent of reported values. Volumes of extracted water are accurate within ±0.5 mL.

EXPERIMENTAL DATA

The experimental data include: (1) Values that describe the experimental compression conditions from the pore-water-extraction trials, (2) volumes and chemical characteristics of the extracted pore water, (3) physical properties and strain characteristics of the tuff, and (4) equipment performance. In addition, these experiments were designed to provide some important data about the strain behavior of these tuffs and the performance of the triaxial cell.

Pore-Water-Extraction Trials

The "Supplemental Information" section (at the back of the report) contains individual stress-path diagrams (figs. 26-55) for each extraction trial, which show the experimental compression conditions under which each pore-water sample was collected. A summary of sample depth, water content, total volume of fluid collected from each trial, axial stress, and duration of stress is listed in table 2.

Table 2.--*Summary of pore-water-extraction data for drill holes*

[Depth is distance from land surface to top of core-sample interval; gravimetric water content was measured on core segments adjacent to those used for pore-water extraction]

Extraction trial number	Depth (meters)	Water content[1] (percent)	Extracted water (milliliters)	Maximum axial stress (megapascals)	Total duration (minutes)
DRILL HOLE UE-25 UZ #5					
1	81.5	13	0	103	60
2	87.8	12	0	103	25
3	92.3	15	[2]2	172	12
4	92.4	15	[2]0.5	138	15
6	86.4	12	0	138	40
7	86.6	12	0	138	40
8	67.0	10	0	172	30
9	67.7	9	0	138	12
10	31.6	20	35	152	1,000
11	76.9	13	0	152	90
12	77.1	13	1	190	87
13	79.3	13	3	172	963
14	92.9	18	[2]0	138	25
15	92.8	18	[2]14	172	80
DRILL HOLE UE-25 UZ #4					
16	91.6	31	48	172	150
17	91.3	28	39	190	153
18	91.4	29	41.5	172	170
19	91.5	30	45	138	100
21	95.3	22	[2]17	110	65
22	95.6	22	21.5	124	120
23	96.5	21	[2]10	138	60

Table 2.--*Summary of pore-water-extraction data for drill holes*--Continued

Extraction trial number	Depth (meters)	Water content[1] (percent)	Extracted water (milliliters)	Maximum axial stress (megapascals)	Total duration (minutes)
		DRILL HOLE UE-25 UZ #5			
[3]30	97.0	25	23	152	125
[3]31	97.3	21.5	4	152	125
[3]32	104.4	20	7.5	172	150
[3]33	104.5	20	5	152	20
[3]34	96.3	20	30	69	5
35	97.2	22	31.5	152	85
36	93.6	22	[2]0	76	10
37	94.3	24	34	152	100
38	94.1	23	35	152	155
39	37.6	17	11	152	116
40	32.6	18.5	18.5	152	67
41	30.4	22	42	152	105
42	72.5	13	0	152	100

[1]Source: D.P. Hammermeister (U.S. Geological Survey, written commun., 1984).
[2]The volume of water may be small because of an equipment malfunction.
[3]The core sample was partially silicified.

Chemical Analyses of Extracted Pore Water

Chemical analyses have been completed on 28 of the samples of extracted pore water collected during early extraction trials, and a summary of these analyses is listed in table 3. Progressive changes in concentration of some ions are indicated with increasing triaxial stress. These changes are examined in the "Interpretation of Data" section of this report.

Physical Properties of the Tuff

Various degrees of diagenesis and welding within tuff result in a wide range of petrological and mechanical characteristics. For example, porosity varies from 27 to 60 percent within the Paintbrush nonwelded unit (Parviz Montazer, U.S. Geological Survey, written commun., 1984). By using a stress path that progresses through several levels of increasing stress, water often may be extracted from the tuff despite variation in material properties.

Core samples for this study were obtained from Yucca Mountain drill holes UE-25 UZ #4 and UE-25 UZ #5. Hydrogeologic-unit divisions and depth profiles of water content and matric potential for drill hole UE-25 UZ #5 are shown in figure 16. Bulk density, grain density, porosity, and permeability for both drill holes are listed in table 4.

Strain Behavior

Approximate values of total axial strain were calculated by measuring the length of 12 core samples (to the nearest 2 mm) before and after triaxial compression. For a group of 12 core samples (individual values shown in the figures in the "Supplemental Information" section at the back of the report), the axial strain ranged from 6.4 to 39 percent with an average value of 22 percent. Therefore, core samples commonly were shortened from an initial length of 105 mm to a final length of 82 mm. Generally, core samples did not develop visible barreling (lateral strain).

Equipment Performance

Several mechanical problems were encountered during use of the triaxial cell produced by the Slope Indicator Company. These malfunctions resulted in gradual or explosive escape of hydraulic oil from the cell while a sample was pressurized. The end caps also occasionally seized to the main barrel of the triaxial cell. These problems were caused by poor design of the triaxial-cell end caps. After several triaxial compressions at confinement stresses near maximum design specifications, the end caps began to show deformation because of permanent yielding of the metal. New, stronger, thicker end caps were designed and provided; no additional design-related problems were encountered. Core samples had to be increased in length from 105 mm to 108 mm to accommodate the new caps.

Two presses were used to apply axial stress to the triaxial cell. Initially a Tinious Olsen press was used that had a capacity of 535 kN. For reasons not yet determined, the motor of this press would overheat and cause premature shutdown. After this, a Soiltest press with a capacity of 1.1 MN was used. This press performed without fault for the duration of pore-water-extraction tests.

INTERPRETATION OF DATA

Interpretation of experimental data had three goals: (1) Evaluation of the deformation of the tuff, (2) evaluation of observed variations in the chemistry of the extracted water, and (3) selection of optimal stress paths for future work.

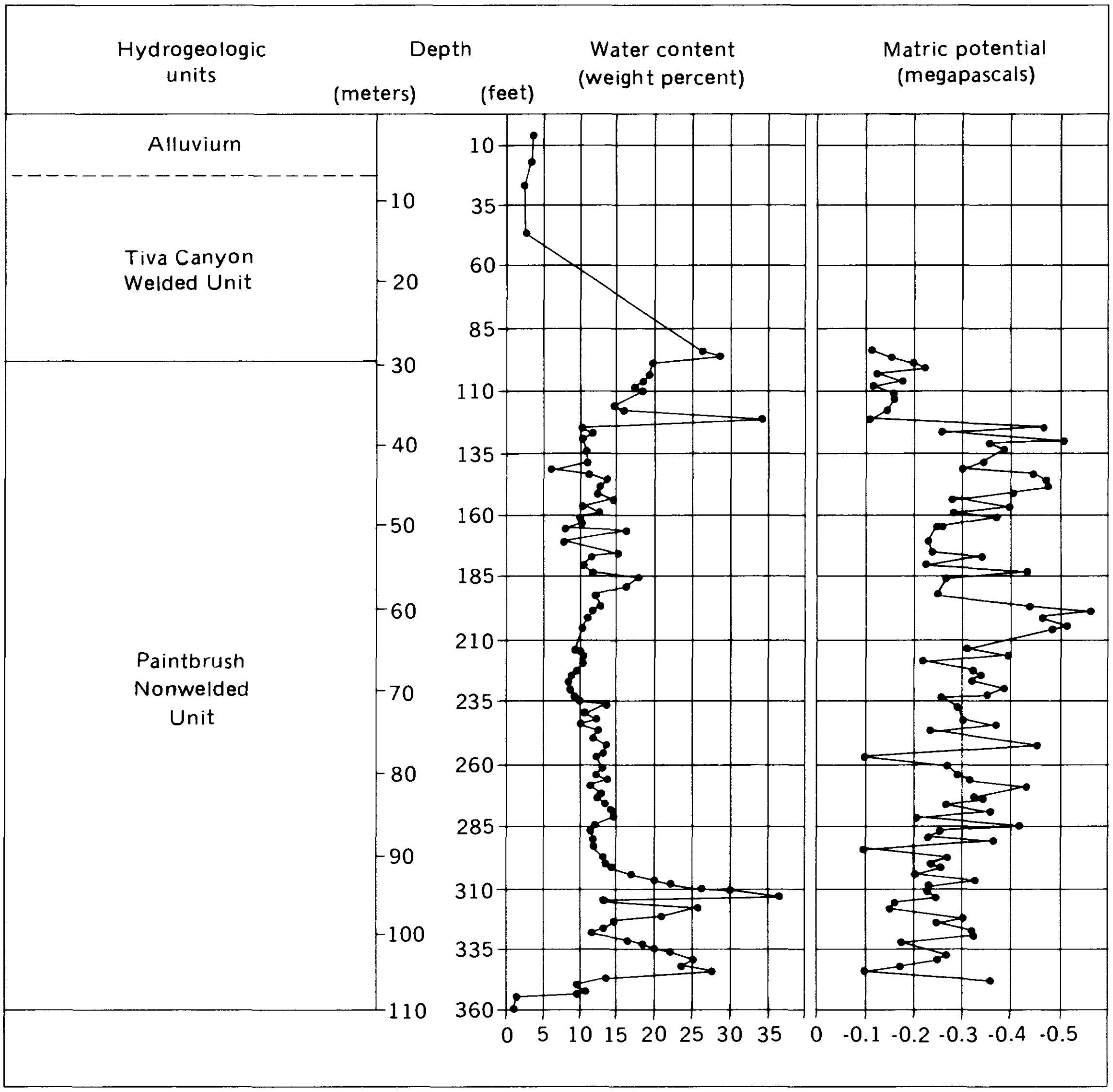

Figure 16.--Hydrogeologic-unit divisions and physical-property data from drill hole UE-25 UZ #5.

Table 3.--*Chemical composition of extracted pore water*

[Depth is distance from land surface to top of core-sample interval; --, data not available; <, less than]

Sample number (depth in meters)	Stress (megapascals)		Major ions (milligrams per liter)							Minor ions (micrograms per liter)			
	Axial	Confining	Ca	Mg	Na	K	Si	Cl	SO_4	Fe	Mn	Sr	Zn
UZ5-TP-4	83	62	56	12	38	12	97	--	--	118	37	546	26
(31.6)	117	62	58	12	33	9	99	34	39	74	20	559	34
(Trial #10)	138	62	61	12	30	15	99	--	--	127	21	585	140
UZ5-TP-1 and -3	76	59	36	7	28	7	72	42	41	<3	7	--	--
(30)	125	62	48	10	29	7	88	45	41	24	11	--	--
(Trial #41)													
UZ5-TP-6 and -5	90	62	27	5	26	6	100	41	37	100	10	--	--
(36)	152	62	27	6	35	8	97	43	47	22	15	--	--
(Trial #56 & #58)													
UZ5-TP-9 and -8	76	59	78	16	61	--	89	89	--	18	43	--	--
(94)	128	62	36	7	39	--	94	51	41	<.1	.3	.5	48
(Trial #15 & #38)													
UZ5-TP-14 and -15	97	62	49	11	58	5	92	83	90	35	4	--	--
(97)	152	62	63	13	54	--	89	--	--	5	21	--	--
(Trial #31 & #35)													
UZ4-TP-1	62	52	116	19	60	13	82	91	155	6	35	1,357	17
(91.6)	83	59	108	19	64	10	87	90	154	11	13	1,366	<3
(Trial #16)	138	62	116	19	64	13	89	92	154	9	62	1,399	14
	[1]178	64	100	19	70	14	90	101	161	11	17	1,325	9
UZ4-TP-2	62	52	127	21	65	15	88	105	174	5	57	1,504	25
(91.3)	138	59	122	20	69	16	88	106	172	5	73	1,502	18
(Trial #17)	[1]178	64	100	19	70	14	90	101	161	11	17	1,325	9
UZ4-TP-3	48	41	123	20	60	14	82	100	164	6	69	1,409	15
(91.4)	138	62	122	20	64	16	92	97	163	4	50	1,450	9
(Trial #18)	[1]178	64	100	19	70	14	90	101	161	11	17	1,325	9

Table 3.--*Chemical composition of extracted pore water*--Continued

Sample number (depth in meters)	Stress (megapascals)		Major ions (milligrams per liter)							Minor ions (micrograms per liter)			
	Axial	Confining	Ca	Mg	Na	K	Si	Cl	SO_4	Fe	Mn	Sr	Zn
UZ4-TP-4	41	34	105	18	64	15	83	84	146	6	56	1,248	3
(91.5)	110	59	107	18	68	16	93	87	149	11	65	1,302	19
(Trial #19)	[1]138	59	101	18	70	14	96	91	151	5	29	1,276	4
UZ4-TP-5	83	59	67	12	43	14	86	78	123	85	13	863	9
(95.3)	[1]117	66	71	13	40	14	85	92	147	86	21	892	71
(Trial #21)													
UZ4-TP-6	83	59	74	13	47	15	83	99	127	60	24	931	107
(95.6)	[1]117	66	71	13	40	14	85	92	147	86	21	892	71
(Trial #22)													

[1]Two or three water samples (from the same stress level) were combined to provide sufficient water volume for chemical analysis.

NOTE: Core from drill hole UE-25 UZ #4 may have been exposed to evaporation; chemical concentrations may be increased.

Table 4.--*Physical properties of the tuff collected from drill holes*

[Porosity calculated from bulk density and grain density]

Depth (meters)	Bulk density (grams per cubic centimeter)	Grain density (grams per cubic centimeter)	Porosity (percent)	Permeability (meter per day)
		UE-25 UZ #4		
73.0	1.42	2.37	40	6.4×10^{-4}
84.5	1.25	2.37	47	3.8×10^{-2}
93.9	1.64	2.28	28	2.2×10^{-2}
101.7	1.46	2.27	36	3.4×10^{-4}
		UE-25 UZ #5		
32.3	1.40	2.31	39	1.0×10^{-2}
34.3	1.38	2.35	41	8.2×10^{-2}
38.4	1.34	2.33	42	8.7×10^{-2}
42.4	1.56	2.26	31	4.1×10^{-3}
70.6	1.18	2.25	47	1.5×10^{-2}
79.7	1.28	2.34	45	1.3×10^{-2}
96.8	1.53	2.33	34	3.4×10^{-4}
105.6	1.54	2.23	31	1.4×10^{-1}

Deformation

Two distinct types of deformation of the nonwelded tuff were observed. Most of the core samples deformed in a ductile manner under triaxial compression. This deformation is interpreted to be the result of progressive pore collapse during compaction of the sample. Brittleness of the tuff also was observed in a few samples that seemed to be partially silicified. These samples either resisted substantial compaction or suddenly failed in a brittle manner under moderate stress. The degree of brittleness seemed to be related to the extent of silicification of the core sample.

Nonsilicified Tuff

Nonsilicified-tuff samples deformed in a gradual ductile manner under triaxial compression; this may be the result of progressive pore collapse of the tuff. Volumes of air and water collected in the syringes during compression may indicate the collapse of the pore network of the tuff. Data were not collected to calculate the decrease in sample volume because additional equipment for measuring lateral strain was not available.

A graph illustrating the volumes of air and water extracted from a typical nonsilicified sample during three levels of increasing triaxial compression is shown in figure 17. In these extractions, most of the air and water was forced from the sample during the first level of triaxial compression. Approximately 70 percent of the total volume of extracted air and water occurred within the first 40 minutes of compression and at an axial stress of 76 MPa and confining stress of 59 MPa. After this point, the rate of water and air extraction rapidly decreased. Only 5 percent of the total air and water volume collected in the syringes was extracted during the last hour of compression, under an axial stress of about 152 MPa and confining stress of 62 MPa. The test samples had water contents of 23 percent and were not silicified.

Silicified Samples

Silicified core samples were collected from two depths from drill hole UE-25 UZ #5 (near 95.4-m depth and 103-m depth) and also from one depth from drill hole UE-25 UZ #4 (near 91.7-m depth). The silicified tuff is located directly beneath zones that have large moisture contents and that may impede the percolation of water. Silicified samples do not show the large initial pore-compaction characteristic of nonsilicified samples. This difference in behavior may be the result of additional structural strength imparted by the silica.

A graph illustrating volumes of air and water extracted from a partially silicified sample during triaxial compression is shown in figure 18. A total of 15.5 mL of air and water were extracted from this sample. In contrast, 58 mL of air and water were extracted at a lower stress from the nonsilicified sample illustrated in figure 17. The water content of the sample illustrated in figure 18 was 20 percent.

One silicified sample (extraction trial no. 33) suddenly failed along a single fracture plane after being compressed for 5 minutes at an axial stress of 152 MPa and a confining stress of 62 MPa. This sudden failure ruptured the membrane of the triaxial cell. Because of the small volume of water generally recovered from greatly silicified samples and the risk of sudden brittle failure, pore-water extraction by triaxial compression may not be applicable for silicified samples.

Chemistry of Extracted Water

Currently (1988), chemical analysis has been completed only on part of the samples. Interpretations made from available chemical data are preliminary. Additional work is needed to confirm the chemical trends presented below.

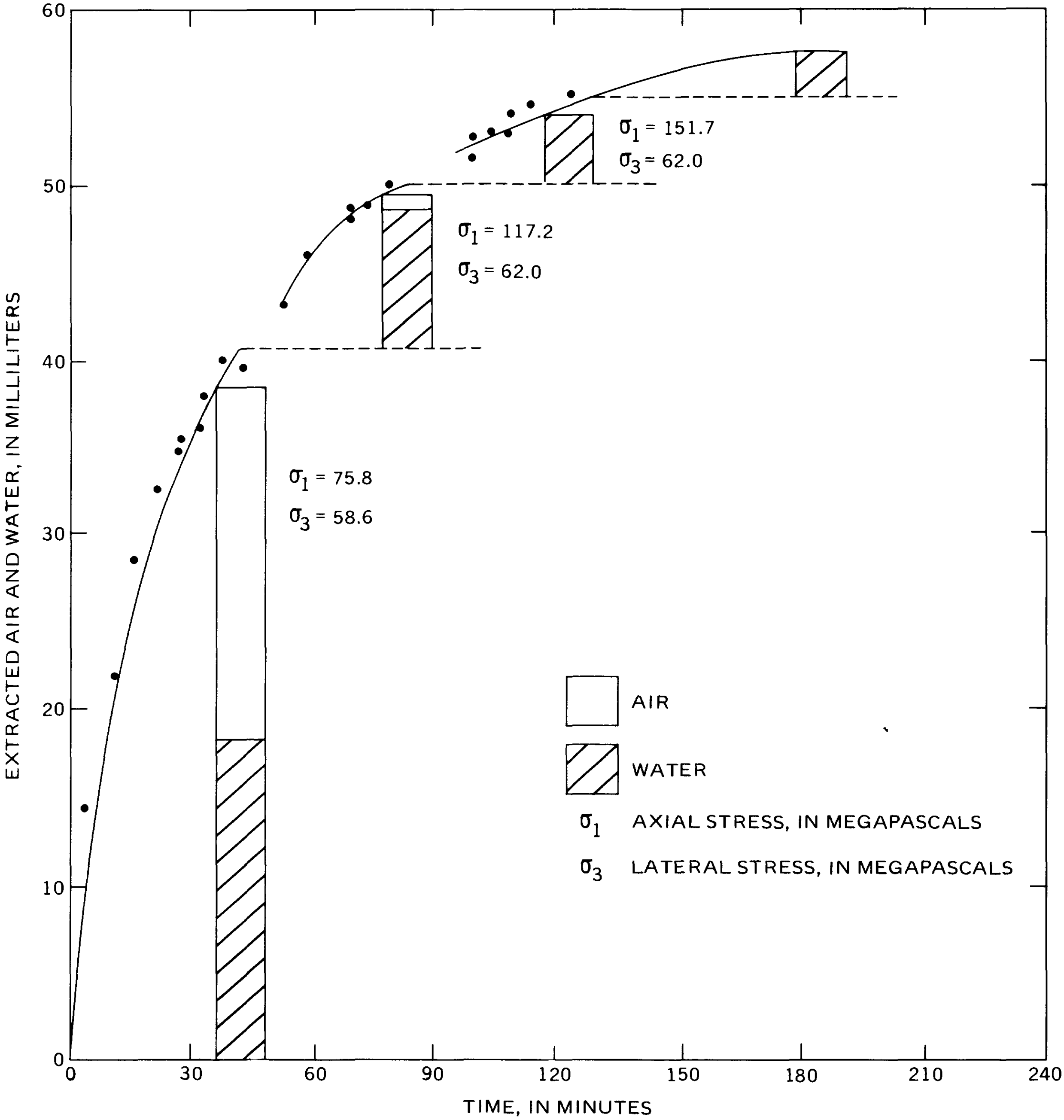

Figure 17.--Volumes of air and water collected in syringes from nonsilicified samples (extraction trial nos. 37 and 38).

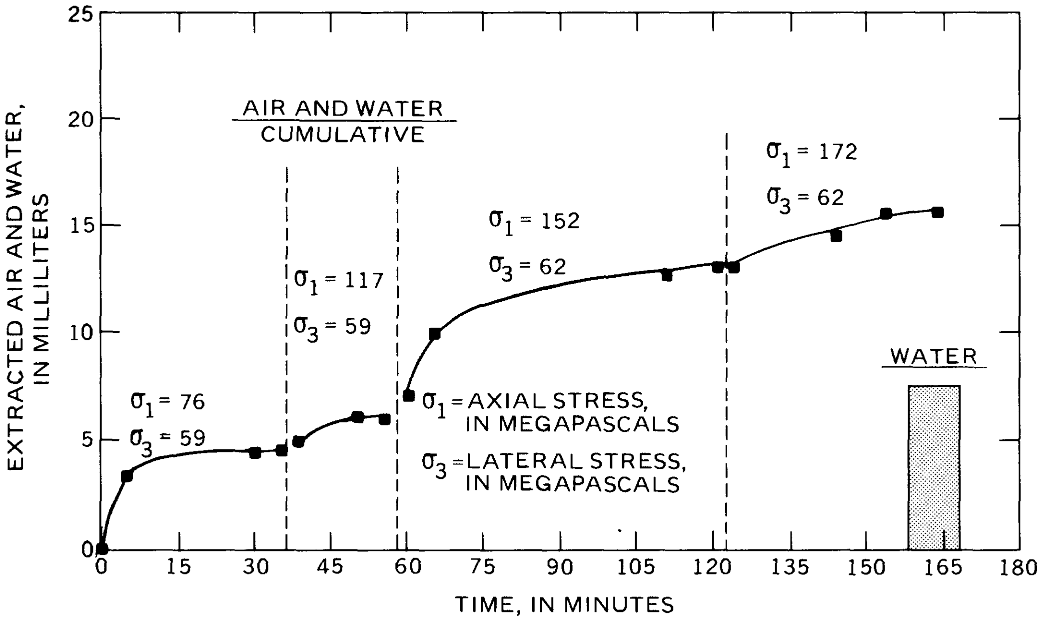

Figure 18.--Volumes of air and water collected in syringes from a partially silicified sample (extraction trial no. 32).

The chemical composition of extracted water has been determined to change with increasing stress. Chemical data for 28 water samples are listed in table 3. To demonstrate the affect of increasing extractive stress on cation and anion concentrations, ion concentrations analyzed for four samples have been plotted against increasing axial stress (figs. 19, 20, 21, and 22). The tuff samples were collected from drill hole UE-25 UZ #4 at a depth of 91.6 m and UE-25 UZ #5 at a depth of 31.6 m. Experimental error is ±5 percent for all the major ions except sulfate, which is ±10 percent. The chemical data for these samples may not necessarily apply to other intervals of the unsaturated zone that have different mineralogies.

As can be observed from the plots of major cation and anion concentrations versus axial stress (figs. 19 and 20), the general trend is for ion concentration to slowly increase with increasing stress. Concentrations of magnesium and potassium changed minimally with increasing stress; sulfate and chloride concentrations seemed to increase only at axial stress greater than 140 MPa; other ion concentrations such as silica and sodium indicate a larger degree of stress dependence from 40 MPa to 180 MPa axial stress. Opposite trends occurred in concentrations of calcium and sodium between samples

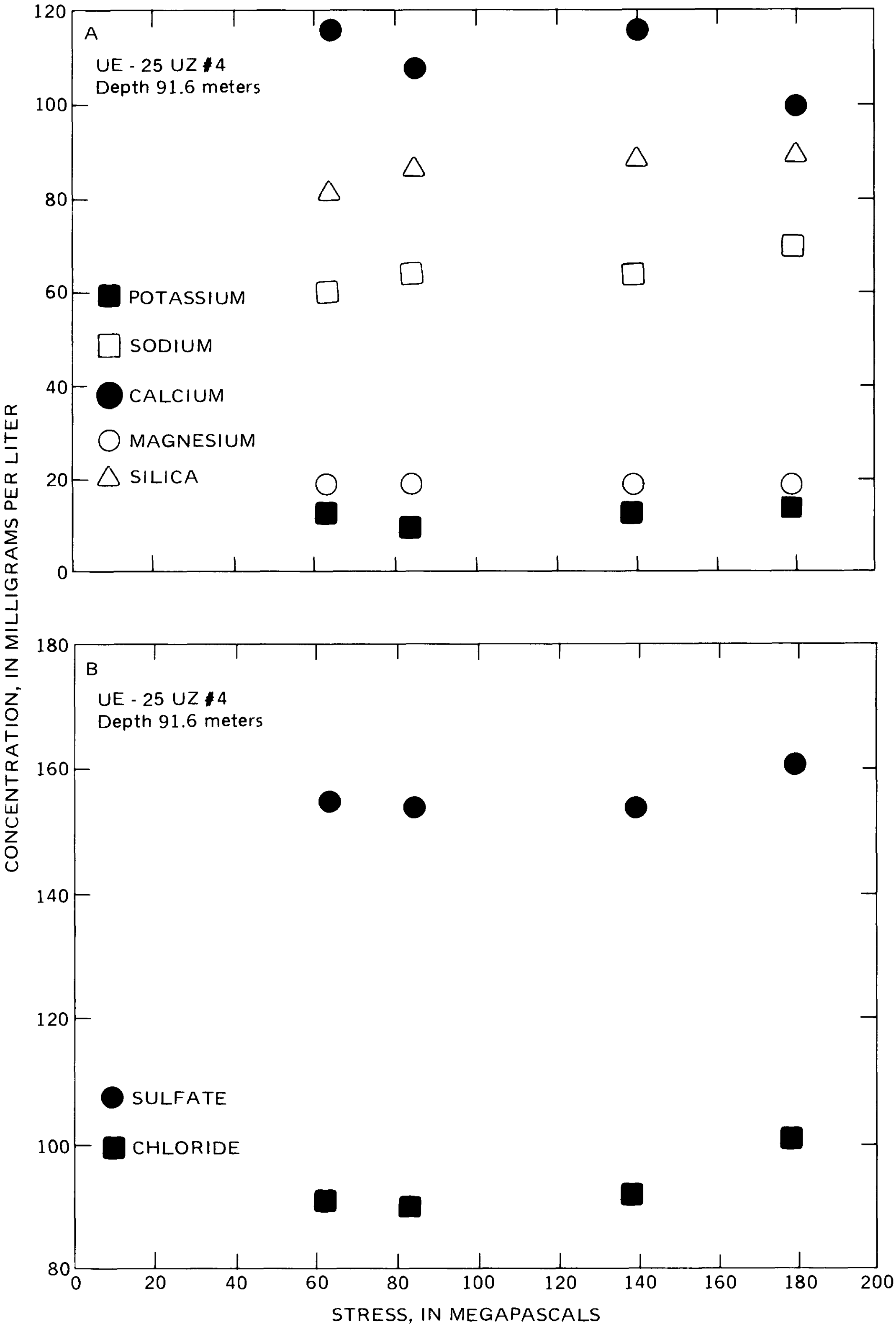

Figure 19.--The affect of increasing axial stress on major cation (*A*), and anion (*B*) concentrations in sample UZ4-TP-1 collected from drill hole UE-25 UZ #4. Lateral stress was increased from 52 to 64 megapascals.

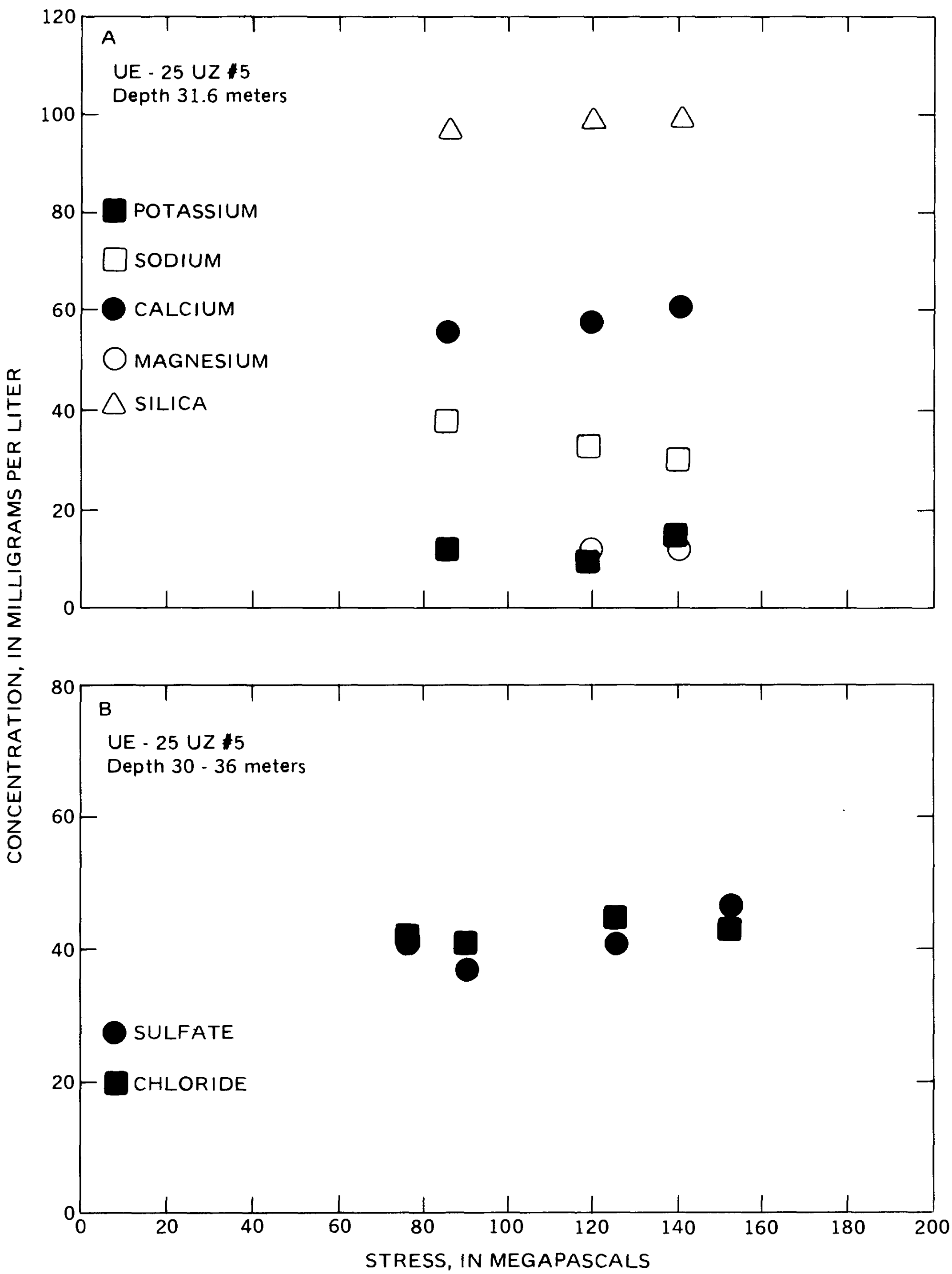

Figure 20.--The affect of increasing axial stress on major cation (*A*) and anion (*B*) concentrations in samples collected from drill hole UE-25 UZ #5. (Major cation values correspond to sample UZ5-TP-4; anion values are composite from UZ5-TP-1, 3, 5, and 6.) Lateral stress was increased from 76 to 152 megapascals.

collected from UE-25 UZ #4 and UE-25 UZ #5 (opposite in the sense that concentrations are increasing on one plot and decreasing on the other). Plots of minor-cation concentration versus axial stress (figs. 21 and 22) also indicate that concentrations slowly increase with stress; however, since the measurement error for the minor cations is larger, the validity of the trend is questioned. In the future, more data will be collected to better establish the validity of the concentration versus stress trends.

The trend of decreasing calcium concentrations and increasing sodium concentrations in the sample collected from UE-25 UZ #4 (fig. 19) may indicate that cation exchange occurred on clays within the sample. Under normal stresses, divalent calcium will replace monovalent sodium on clays (Yong and Warkentin, 1975). This result also might be expected under increased stress because a large-volume decrease is obtained from a small calcium ion replacing two large sodium ions. This volume decrease may be increasingly favored at large axial stress. This trend is reversed for the UE-25 UZ #5 (fig. 20) sample and may indicate that other mineralogical factors are important, and that the calcium and sodium concentrations are related more complexly.

No threshold stress levels reflected by an abrupt change in ion concentration were documented conclusively by the available chemical results. Further experimentation, using a larger number of water samples from cores collected more closely together to decrease mineralogical variation, will be needed to determine relations of ion concentration and axial stress.

In general, the pore-water chemical concentrations obtained by the triaxial-compression method are comparable to pore water recovered using the high-speed centrifugation method (U.S. Geological Survey, written commun., 1988).

Stress-Path Selection

The initial water content of a core sample affects the selection of an appropriate duration for compression. Efficient extraction of pore water from tuff samples that have water contents greater than 15 percent by weight has been achieved in a few hours at axial stresses less than 152 MPa and confining stresses less than 62 MPa. However, for samples that have a water content of 13 percent by weight, the duration of compression must be increased substantially to extract water. No water has been extracted from tuff samples that have water contents of less than 13 percent by weight. The quantity of water extracted is not only dependent upon the moisture content of the tuff but also may be related to its matric potential. The process of water extraction may be energy related. A preliminary relation between water content and matric potential is listed in table 5. Matric potential is a function of pore-size distribution and may reflect more accurately the extractability of pore water. Further study is necessary to establish the relation between water content and matric potential.

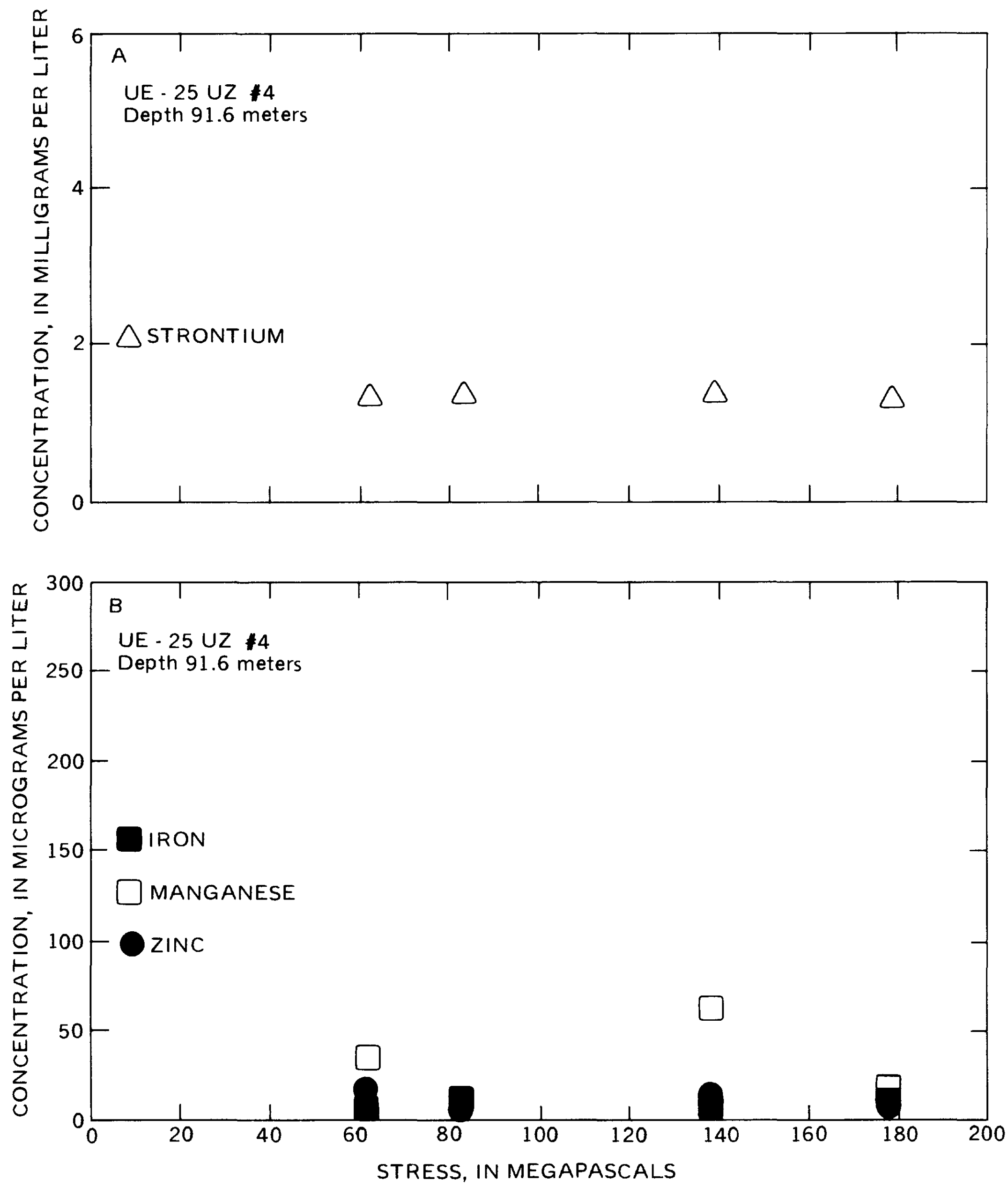

Figure 21.--The affect of increasing axial stress on minor cation concentrations in sample UZ4-TP-1 collected from drill hole UE-25 UZ #4.

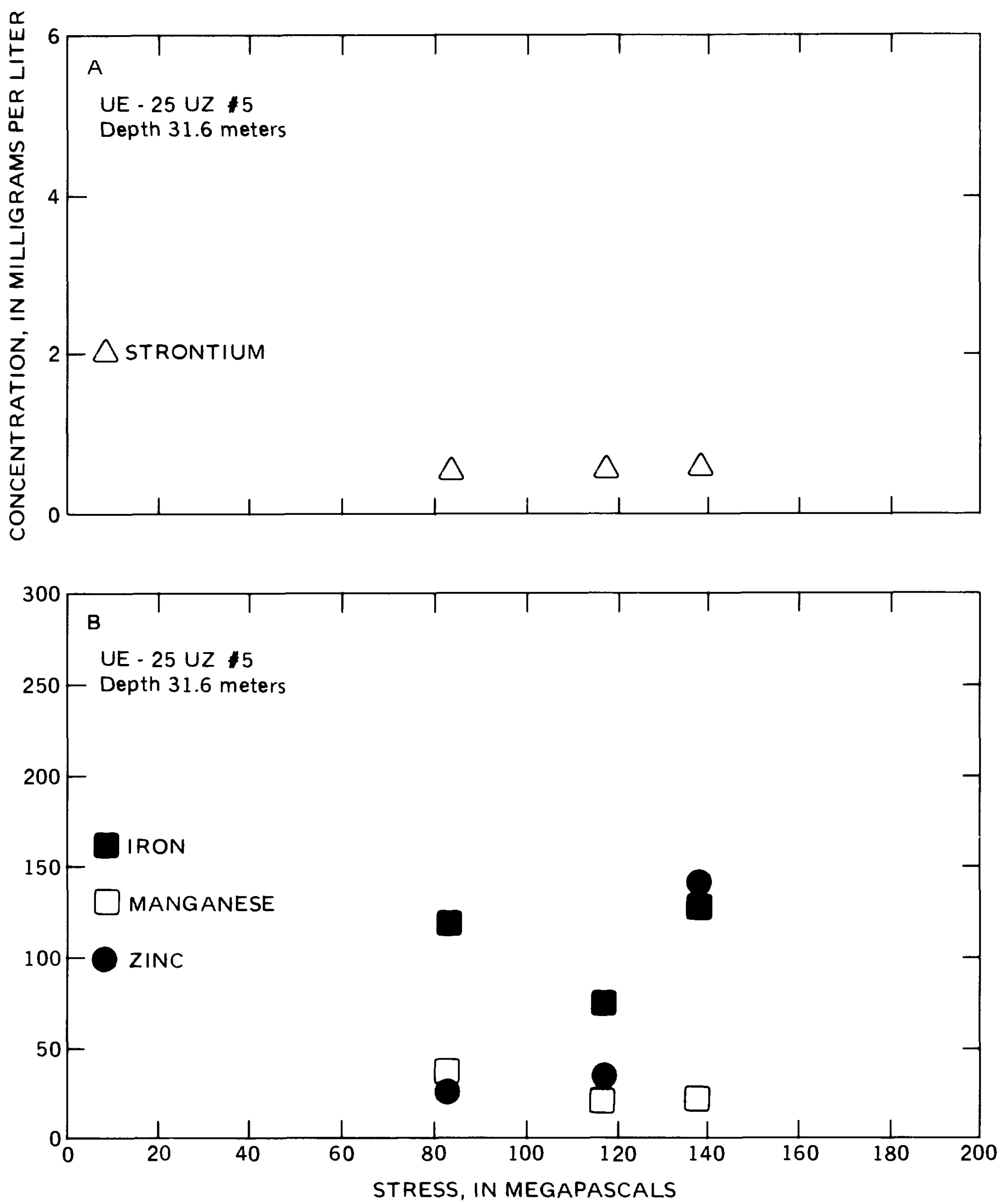

Figure 22.--The affect of increasing axial stress on minor cation concentrations in sample UZ5-TP-4 collected from drill hole UE-25 UZ #5.

Water-content determinations done on tuff samples have confirmed that 13 percent water by weight generally is retained by the tuff. In samples where water contents are greater than 13 percent, a linear relation between the initial water content of the tuff sample and the total volume of water extracted by triaxial compression exists (fig. 23). This relation may be used to predict the approximate quantity of water that can be extracted from a nonsilicified tuff sample that has a length of 105 mm and a diameter of 60 mm:

$$\text{Extracted water (milliliters)} = [2.5 \times \text{Water content (percent by weight)}] - 30.$$

Table 5.--*Preliminary relation between water content and matric potential*

[<, less than]

Water content (percent by weight)	Matric potential (megapascals)
NONWELDED TUFF	
0	<-100
5	-2
10	-.25
11	-.15
12	-.10
13	-.06
14	-.04
15	-.03
20	-.005
WELDED TUFF	
0	-30
1	-3
2	-.5
3	-.06
4	-.001

NOTE:
1. Data obtained from figure 11 in Montazer and Wilson (1984).

2. Average bulk densities assumed: nonwelded = 1.42 grams per cubic centimeter; welded = 2.3 grams per cubic centimeter.

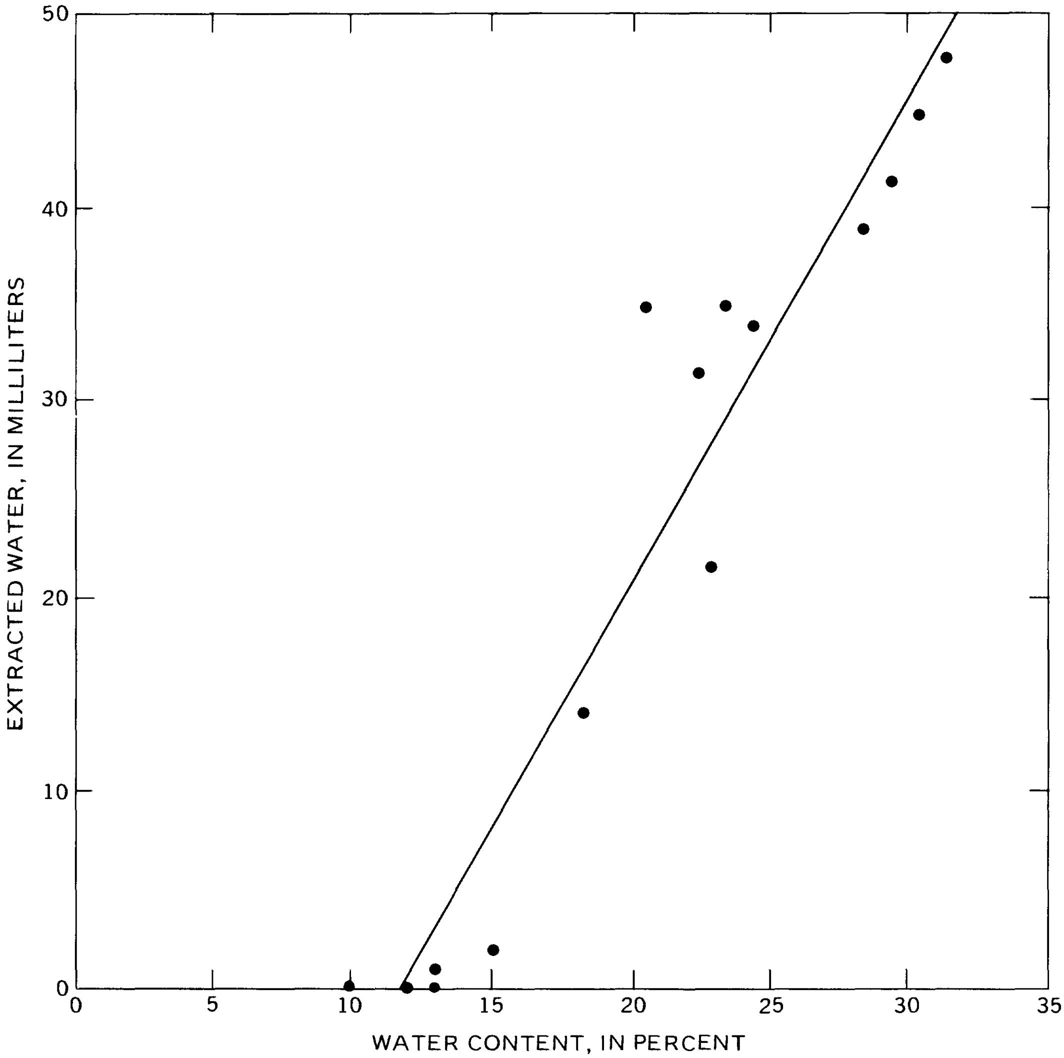

Figure 23.--Total volume of water extracted from tuff samples of various water content; average core sample was 105 millimeters long with a diameter of 60 millimeters.

Long-compressive-duration and large-stress triaxial tests were done on tuff samples that had a water content of 13 percent to establish that a water content of 13 percent was the lower limit for successful water extraction (extraction trial nos. 12 and 13). During extraction trial no. 13, only 3 mL of water was extracted after 15 hours of compression, with an average axial stress of 155 MPa and a confining stress of 59 MPa. One milliliter of water was extracted in trial no. 12, which lasted 1.5 hours, with a peak axial stress of 190 MPa and a confining stress of 69 MPa.

Long-compressive-duration and large-stress triaxial tests also were done on tuff samples that have larger water contents. These tests demonstrated the limited benefit of extending stress paths to large stress levels for long periods of time.

In extraction trial no. 18, a tuff sample that had an initial water content of 29 percent was subjected to four levels of increasing triaxial stress (fig. 24). At the first stress level, 15 mL of water was extracted in 15 minutes with an axial stress of 48 MPa and confining stress of 41 MPa. An additional 22 mL of water was extracted at the second stress level in one hour with an axial stress of 138 MPa and confining stress of 62 MPa. The third stress level yielded no water after one-half hour with the axial stress increased to 158 MPa. Only 4 mL of water was extracted at the last stress level after one-half hour with the axial stress increased to 172 MPa. This extraction trial indicated that about 90 percent of the available water was extracted when an axial stress of 138 MPa and a confining stress of 62 MPa were maintained for one hour. Rapid, initial pore collapse may be responsible for forcing most of the water out of the sample at smaller stresses.

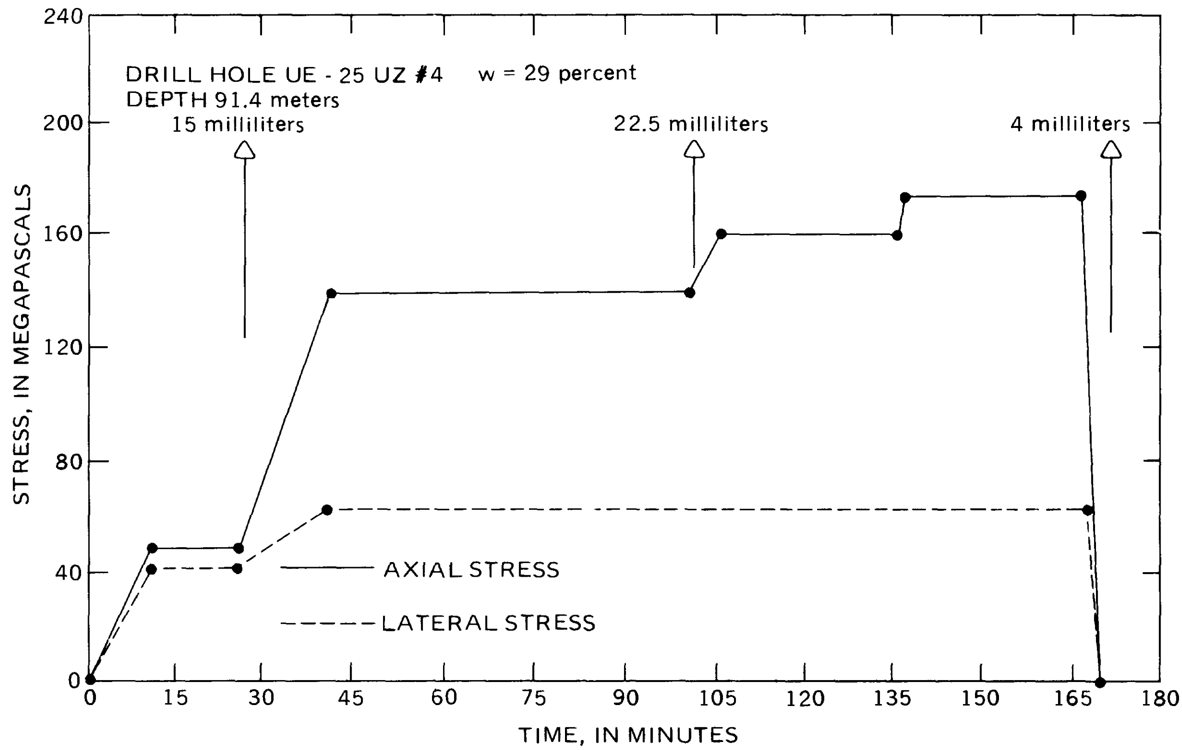

Figure 24.--Stress path for extraction trial no. 18. Arrows indicate the volume of water extracted at the end of each stress level.

Extraction trial no. 22 demonstrated that pore water can be extracted efficiently in a few hours under moderate stresses. The initial water content of the tuff sample of 22 percent was decreased to 13 percent in 2 hours, using axial stresses ranging from 83 MPa to 124 MPa and lateral stresses ranging from 59 MPa to 66 MPa. A final water content of 13 percent matches the lower water-content limit for successful water extraction; this indicates that very little water was left in the tuff that would be recoverable by triaxial compression.

Data from other extraction trials indicate that limited water extraction results from maintaining the final stress for more than one hour, if the axial stress is greater than 139 MPa. Data gathered from extraction trials nos. 37 and 38 indicate that only 3 mL of water was gained by extending the third and final stress level (axial stress = 152 MPa; confining stress = 62 MPa) from 30 minutes to 90 minutes. In extraction trial no. 10, only 4 mL of water was collected after maintaining the final stress level (average axial stress = 134 MPa; confining stress = 63 MPa) for 15 hours.

Long-compression durations should be limited to avoid rust formation on the pore-pressure platens. Rust has formed on the platens when pore water remained in contact with the metal surface for more than 15 hours. Short-compression tests have the advantage of decreasing the reaction time between pore water and new mineral surfaces exposed during compaction of the tuff. These interactions may alter the apparent chemical composition of the extracted water.

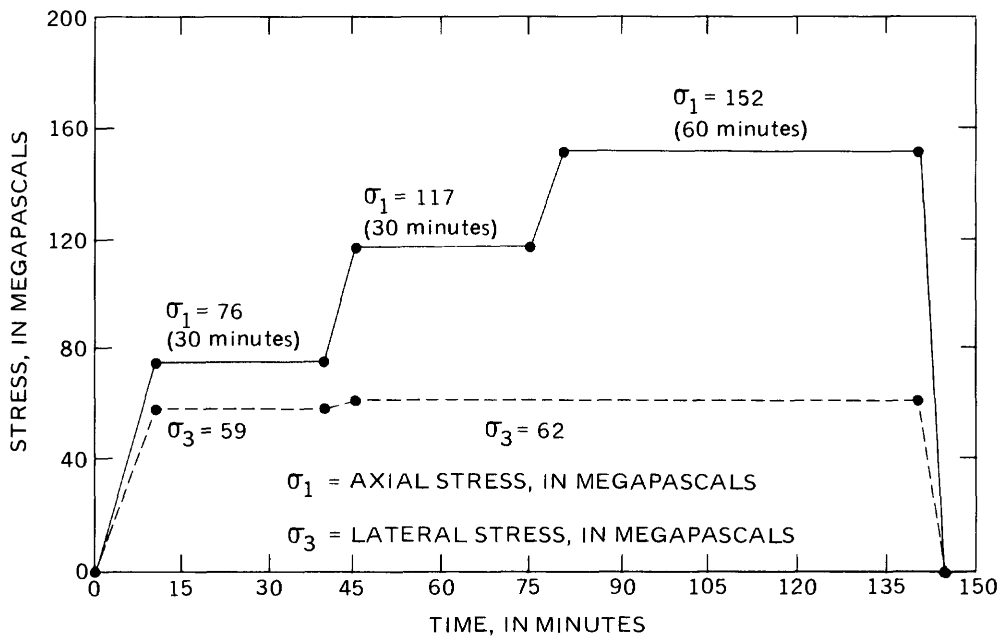

Figure 25.--Suggested stress path for water extraction from tuff samples that have water contents greater than 15 percent.

Based on experimental results, an optimal stress path for tuff samples that have water contents greater than 15 percent has been developed. This stress path consists of three successive stress levels as shown in figure 25. The total suggested compression is approximately 2.5 hours. Tuff samples that have water contents only slightly greater than 15 percent may not yield water during the first two stress levels. To expedite extraction, either or both of the first two stress levels need to be terminated after 5 minutes if no water has been collected in the attached syringes. To avoid developing excessive pore-water pressures, tuff samples should not be loaded in a rapid manner directly from atmospheric pressure to the third stress level.

The suggested stress path for tuff samples that have water contents of 13 to 15 percent is similar to that described previously. The only difference is that the third stress level may be maintained for a longer time as determined by the desired minimum volume of pore water from a specific core interval.

CONCLUSIONS

Definition of flow paths and rates of ground-water flux in the unsaturated zone beneath Yucca Mountain at the NTS requires the extraction of uncontaminated water samples from the nonwelded tuff. To provide pore water for chemical analysis, a method of extracting pore water from nonwelded tuff was developed and refined with a series of 40 experimental extractions.

Emphasis was placed on using the smallest possible stresses and shortest durations consistent with collecting adequate volumes of extracted water. An efficient pore-water collection system is required to help minimize the necessary stress levels and duration of compression. Short compressions have the advantage of decreasing the reaction time between pore water and new mineral surfaces exposed during compaction, while the use of small stress levels diminishes the opportunity of extracting bound water from smectite clay and zeolite. A new triaxial cell was developed using a standard Hoek-Franklin triaxial cell. This system is designed to handle core samples that have a length of 108 mm and a diameter of 60 mm.

Trial extractions indicated that most pore water was extracted quickly from samples at small to moderate stresses. This probably was the result of rapid initial pore collapse that forced water from the core sample. Tests demonstrated that efficient extraction of pore water was achieved using axial stresses less than 152 MPa and confining stresses less than 62 MPa.

Two types of deformation were displayed by the samples. Most tuff samples exhibited macroscopic ductile behavior under triaxial compression. Brittle behavior also was observed in a few partially silicified samples. These samples did not display the large initial pore-collapse characteristic of nonsilicified samples. Because of the small volumes of water generally extracted from silicified samples, and the risk of sudden brittle failure, such samples should be avoided for water extraction by triaxial compression.

The initial water content of a sample affects the potential of extracting pore water and the appropriate duration of compression. Pore water was extracted only from tuff samples that had water contents greater than 13 percent. Efficient extraction of pore water from core samples that had water contents greater than 15 percent is likely to be achieved over 2.5 hours, by applying axial stress from 76 MPa to 152 MPa and confining stress from 59 MPa to 62 MPa. The same stress levels are applicable for tuff samples that have water contents from 13 to 15 percent; however, the larger stresses should be maintained for several additional hours until water extraction becomes negligible. To avoid developing excessive pore-water pressures, tuff samples should not be loaded rapidly to the largest stress.

The chemical composition of extracted water was determined to change under increasing stress. While interpretations based on the available chemical data are preliminary, a few distinct trends in water composition were observed. As axial stress was increased from 40 MPa to 180 MPa, the concentration of silica and sodium in extracted water increased by approximately 5 mg/L. Calcium concentrations seemed to decrease. There was no substantial change in concentrations of magnesium and potassium for this stress range. Sulfate and chloride concentrations seemed to increase at axial stresses greater than 140 MPa. Data scatter was too broad to recognize any conclusive trends for concentrations of manganese, iron, strontium, and zinc.

The parallel decrease in calcium concentration and increase in sodium concentration, observed as compressive stresses were increased, may be the result of cation exchange on a clay component of the tuff. These changes in pore-water chemistry could be explained if sodium was replaced by calcium along the surfaces of clay particles during sample compaction.

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SUPPLEMENTAL INFORMATION

Stress-Path Diagrams

The following stress-path diagrams provide sets of data for each extraction trial. These data indicate the experimental compression conditions under which each pore-water sample was collected. The original reference to the figures following was in the "Experimental Data" section of the text.

The following is an explanation of the symbols in figures 26-55:

D_t = depth from the land surface to the top of the core-sample interval, in meters;
L = length of core sample, in centimeters;
E = total axial strain, in percent;
w = initial water content of the core sample, percent by weight;
w_f = water content of the core sample after compression, in percent by weight;
_____ = axial-stress curve;
--- = lateral-stress curve;
* = volume of water may be too small; the test was ended because of an equipment malfunction; and
XX mL = volume of pore water collected at the end of a given stress level, in milliliters.

Additional Triaxial Tests

Three trial extractions (nos. 1A, 5, and 20) were done on 102-mm-diameter core from drill hole UE-25c #2. These samples were collected from a depth of 402.6-404.7 m. The samples of welded tuff failed in a brittle manner upon initial loading at hydrostatic stresses less than 41 MPa.

Because of equipment malfunction and subsequent loss of confining stress during initial compression, no useful data were collected for extraction trials nos. 9, 14, 34, and 36. The equipment problems were caused by poorly designed triaxial-cell end caps and by worn confining-pressure sleeves. These problems were solved by replacing the defective end caps and using new confining-pressure sleeves.

Core samples for extraction trials nos. 24 through 29 were used for tests of the triaxial cell when equipped with the new, modified end caps. Measurements indicated that this sample interval (UE-25 UZ #4 44.8-46.3 m) initially had a water content of 20 percent. Subsequent water-content measurements, made at Denver indicated that the moisture content had decreased to 9 percent. These samples were sealed in PVC tubes rather than with aluminum foil and wax; this packaging method may have allowed the moisture loss.

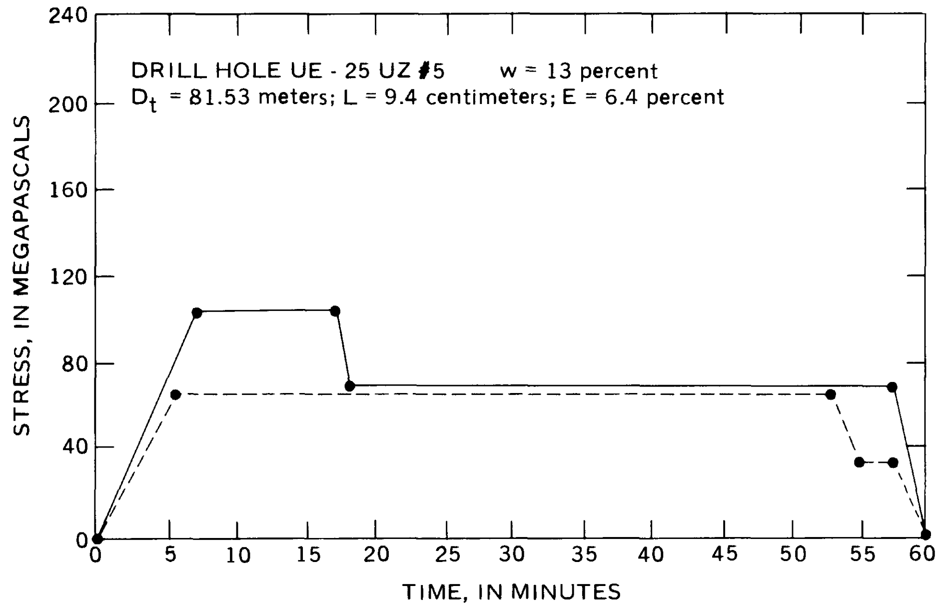


Figure 26.--Extraction trial no. 1.

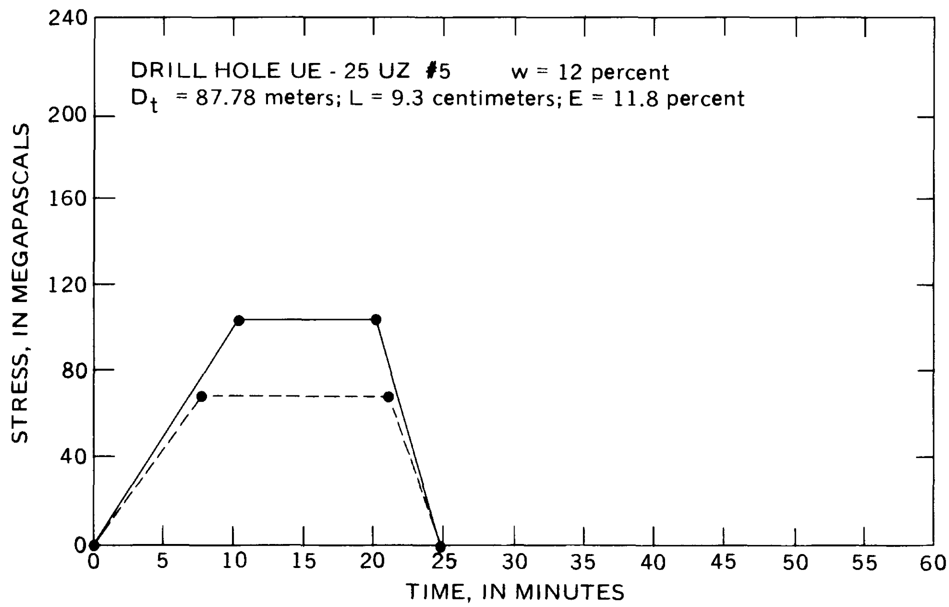


Figure 27.--Extraction trial no. 2.

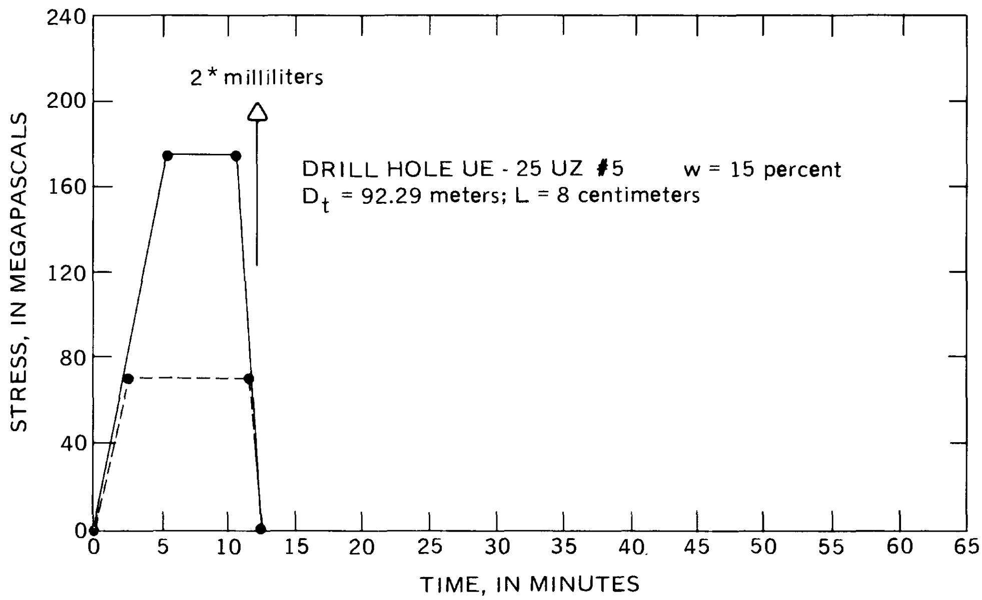


Figure 28.--Extraction trial no. 3.

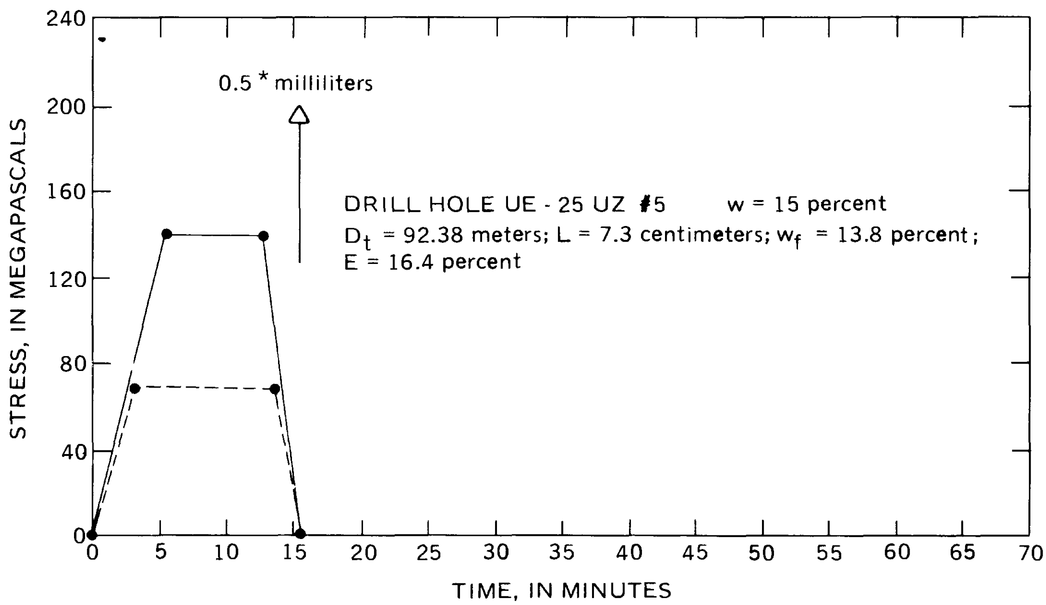


Figure 29.--Extraction trial no. 4.

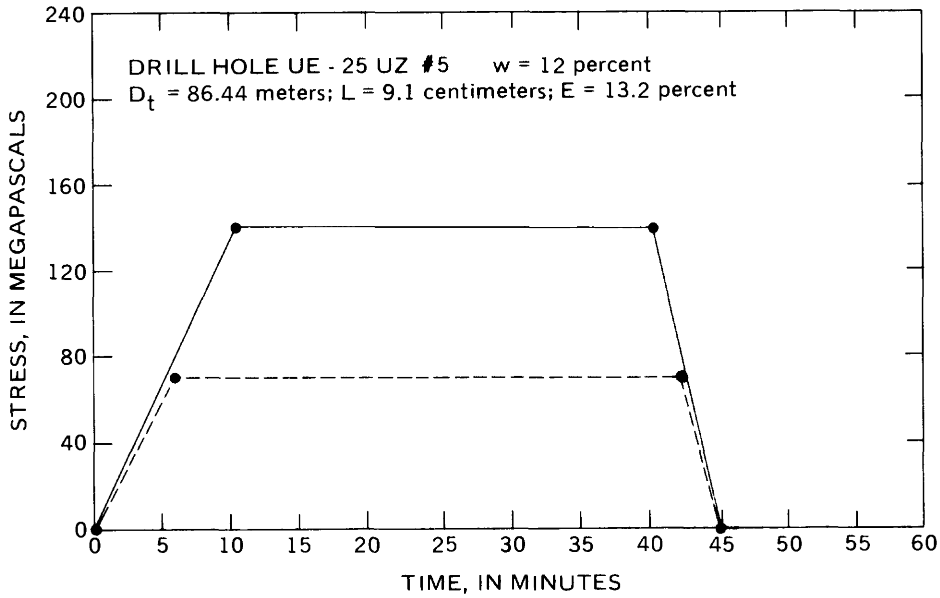


Figure 30.--Extraction trial no. 6.

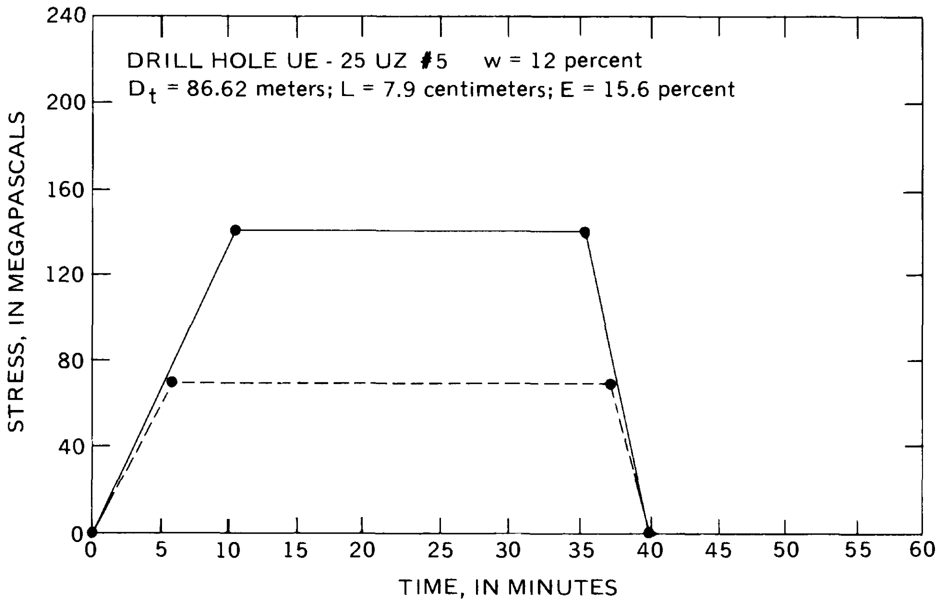


Figure 31.--Extraction trial no. 7.

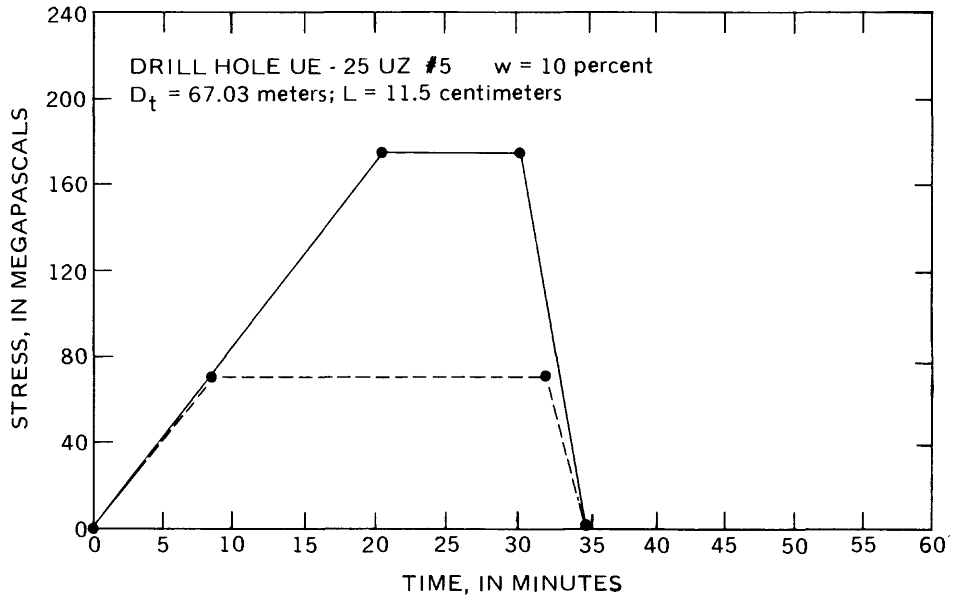


Figure 32.--Extraction trial no. 8.

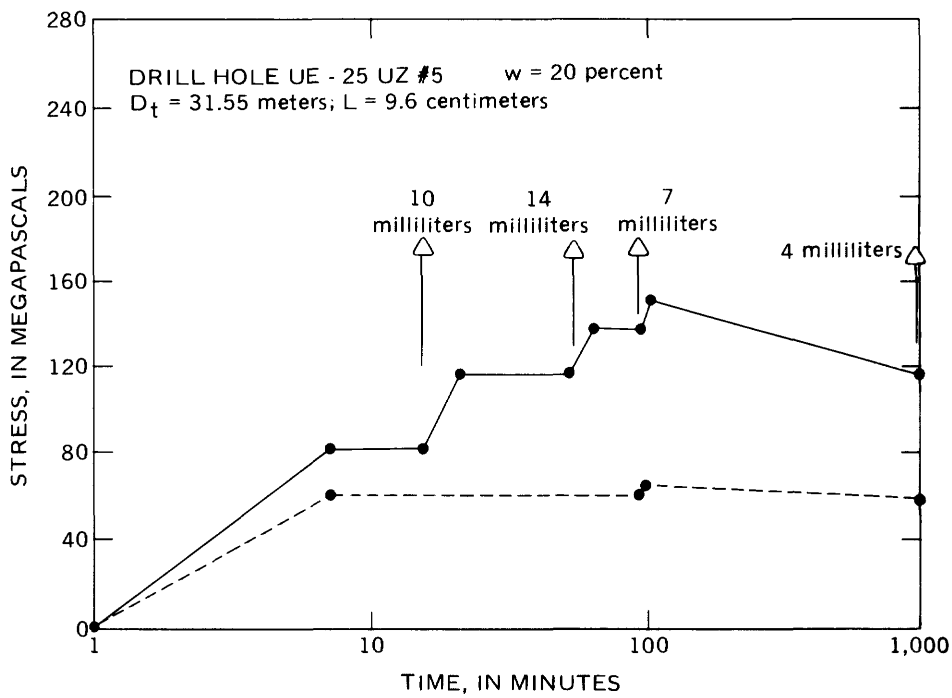


Figure 33.--Extraction trial no. 10.

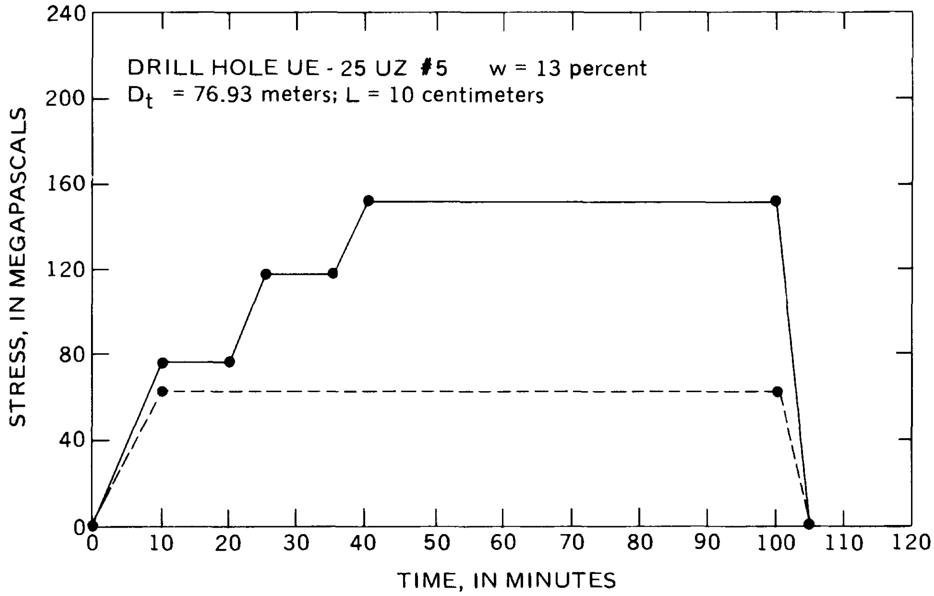


Figure 34.--Extraction trial no. 11.

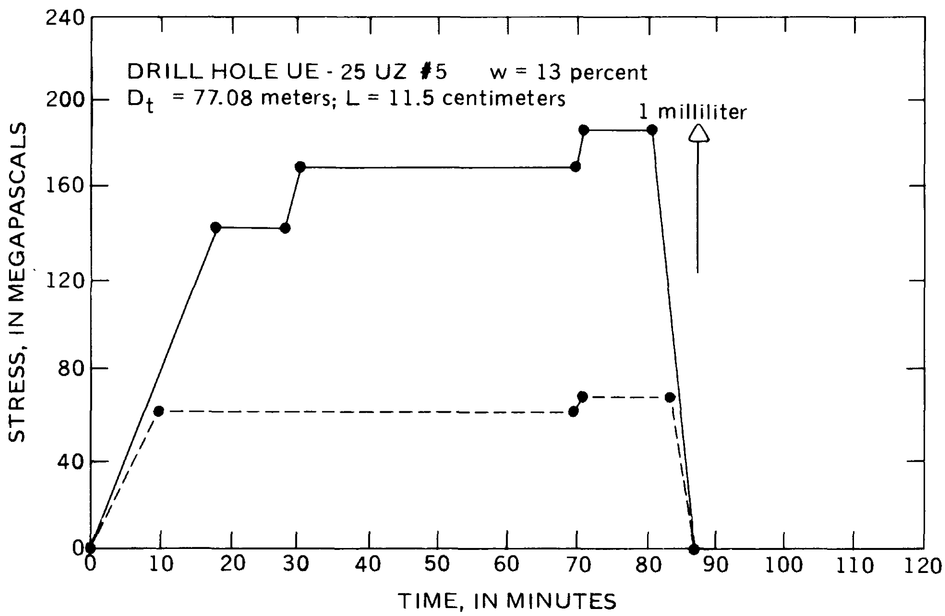


Figure 35.--Extraction trial no. 12.

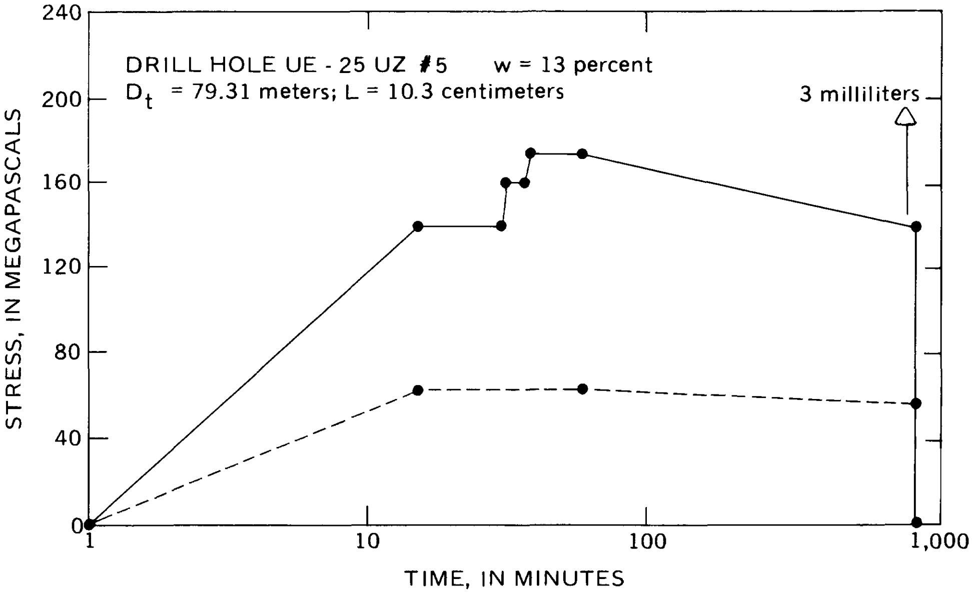


Figure 36.--Extraction trial no. 13.

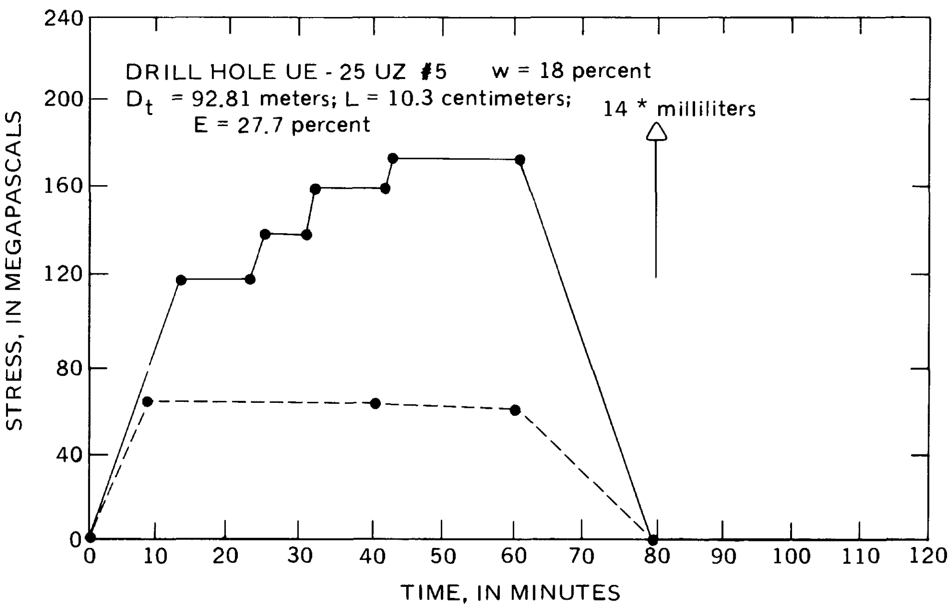


Figure 37.--Extraction trial no. 15.

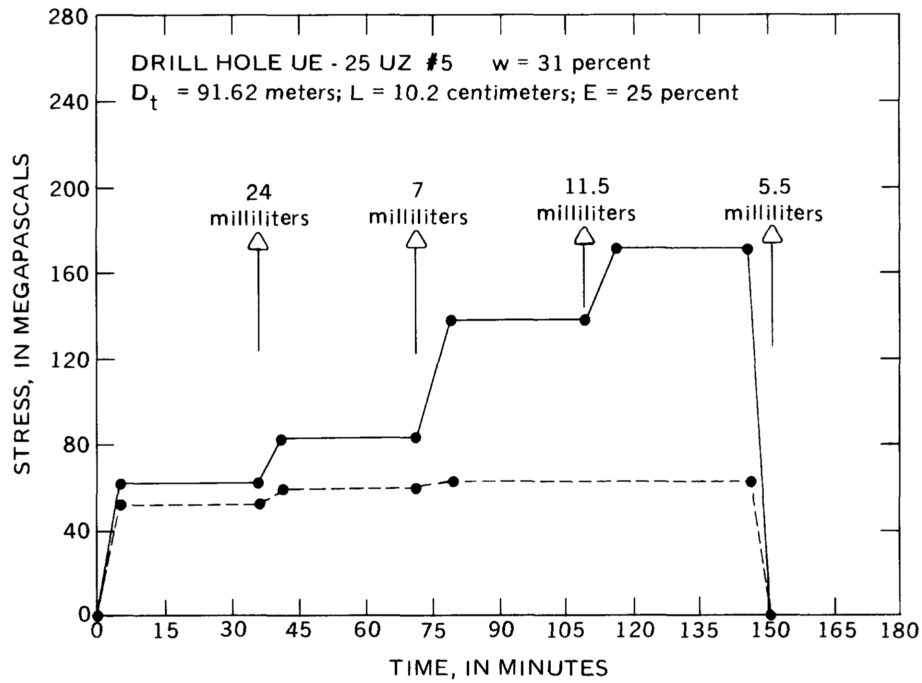


Figure 38.--Extraction trial no. 16.

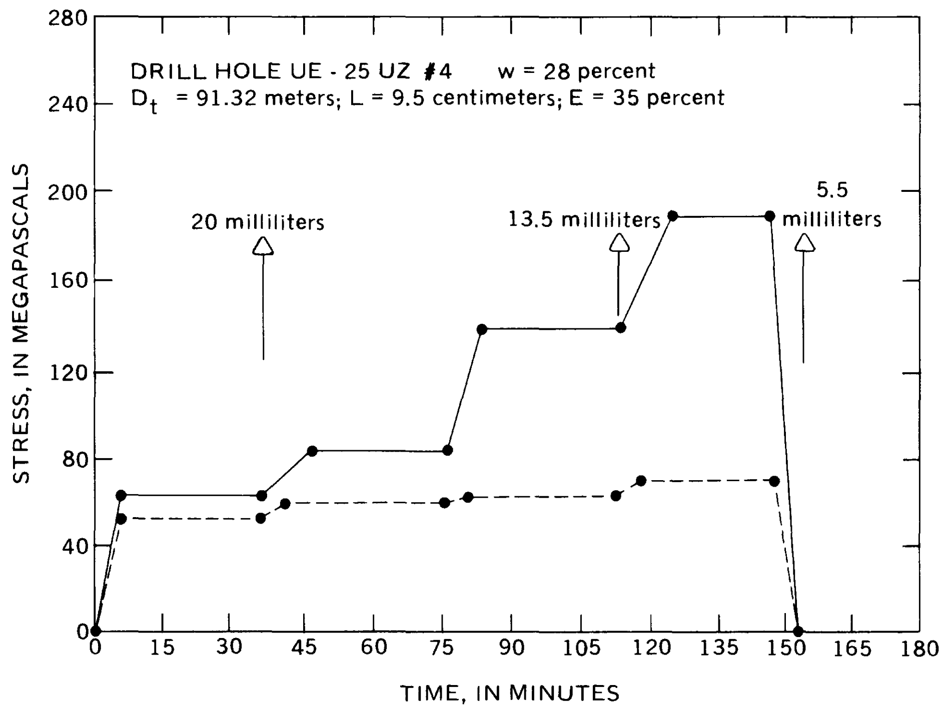


Figure 39.--Extraction trial no. 17.

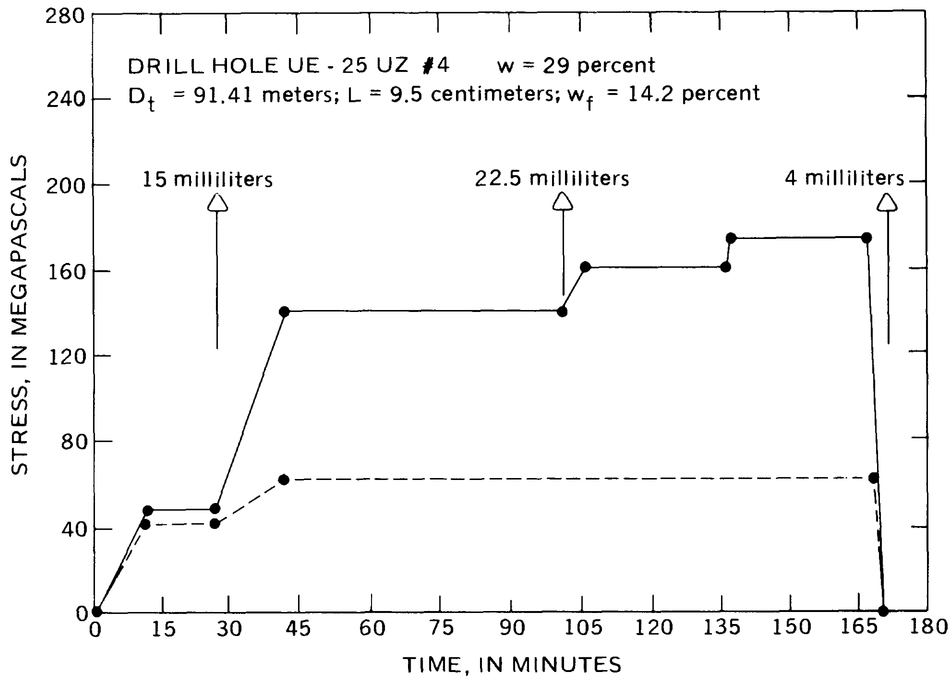


Figure 40.--Extraction trial no. 18.

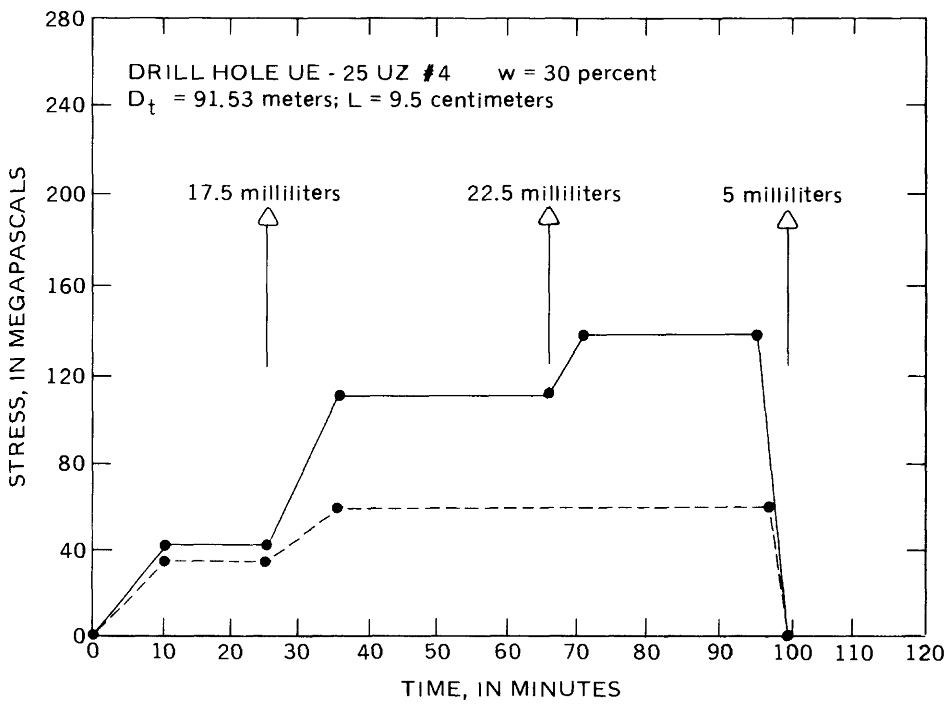


Figure 41.--Extraction trial no. 19.

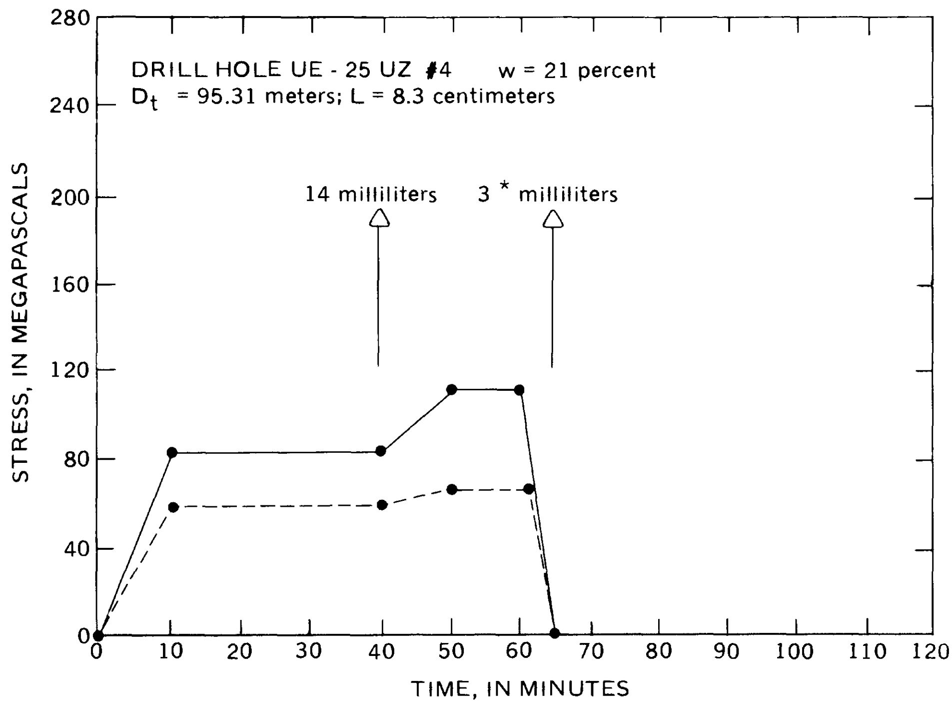


Figure 42.--Extraction trial no. 21.

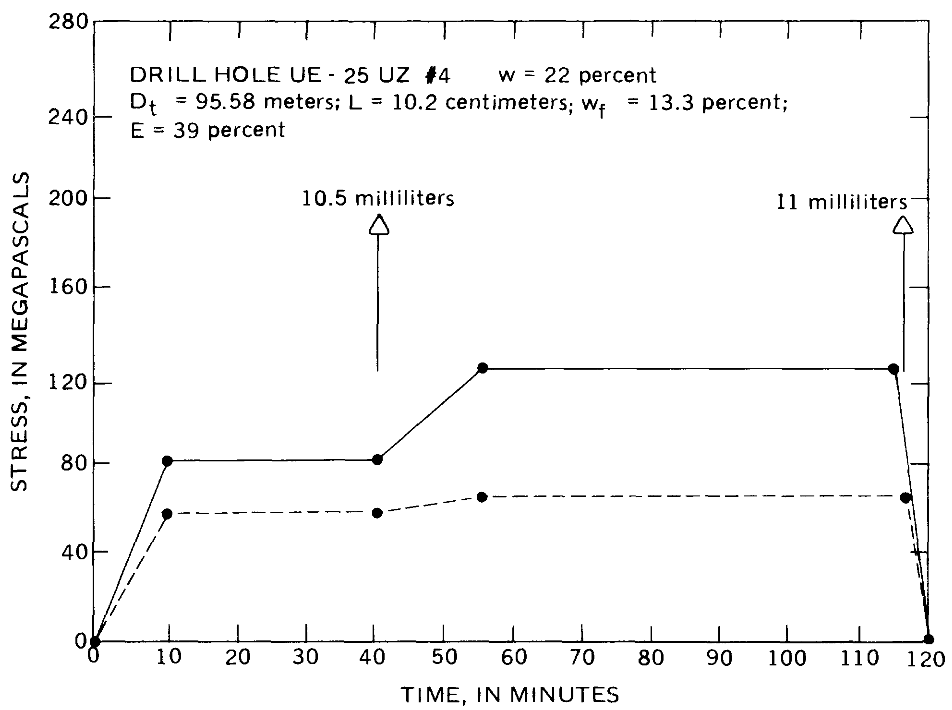


Figure 43.--Extraction trial no. 22.

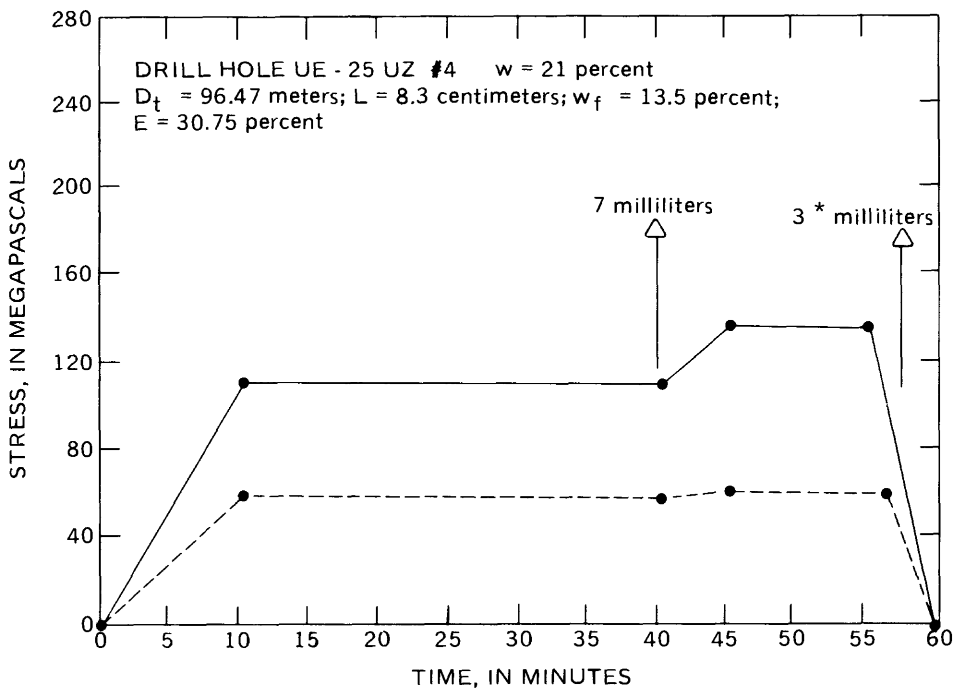


Figure 44.--Extraction trial no. 23.

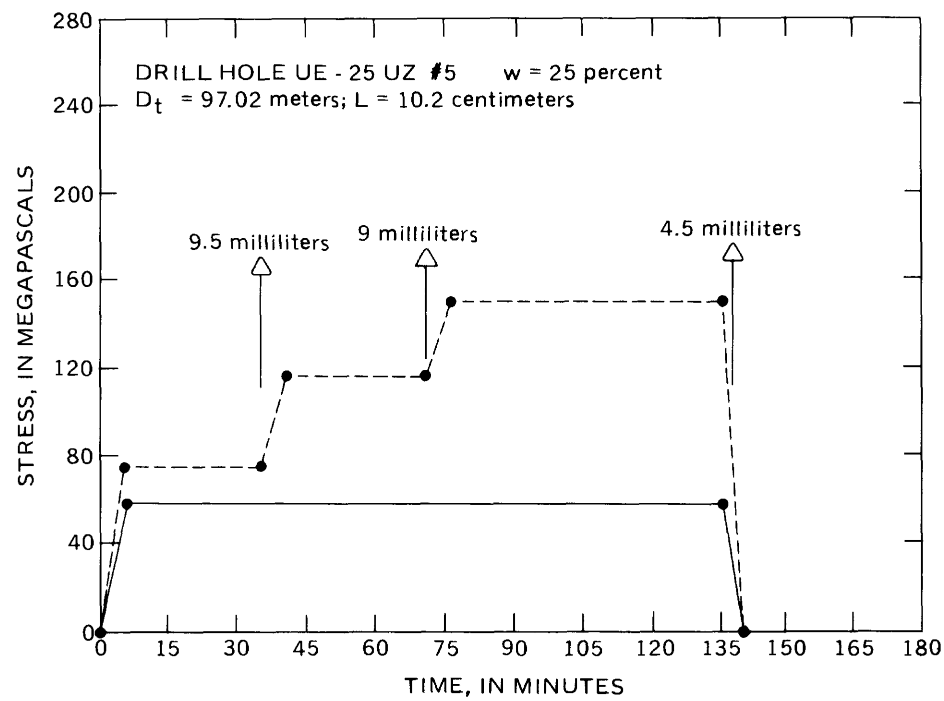


Figure 45.--Extraction trial no. 30.

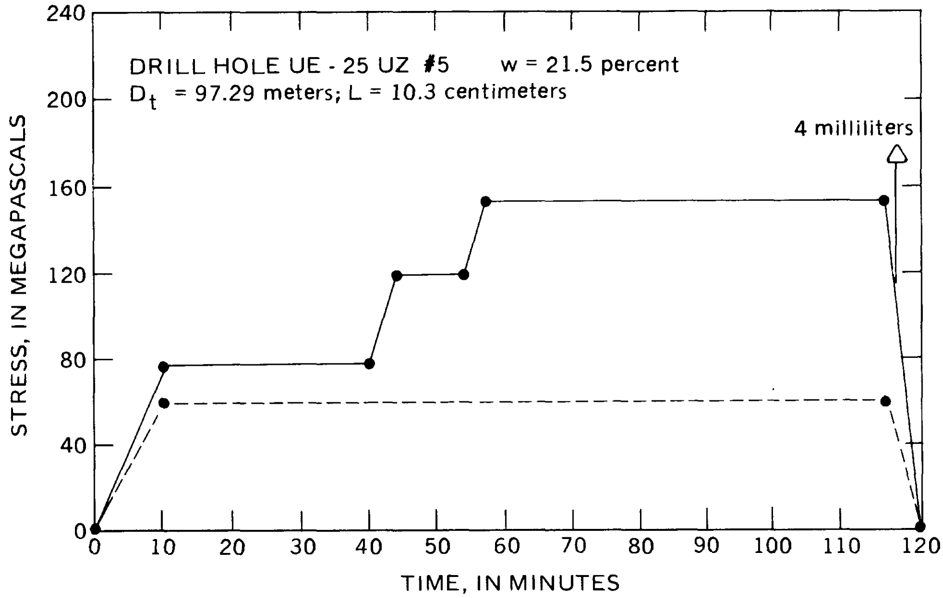


Figure 46.--Extraction trial no. 31.

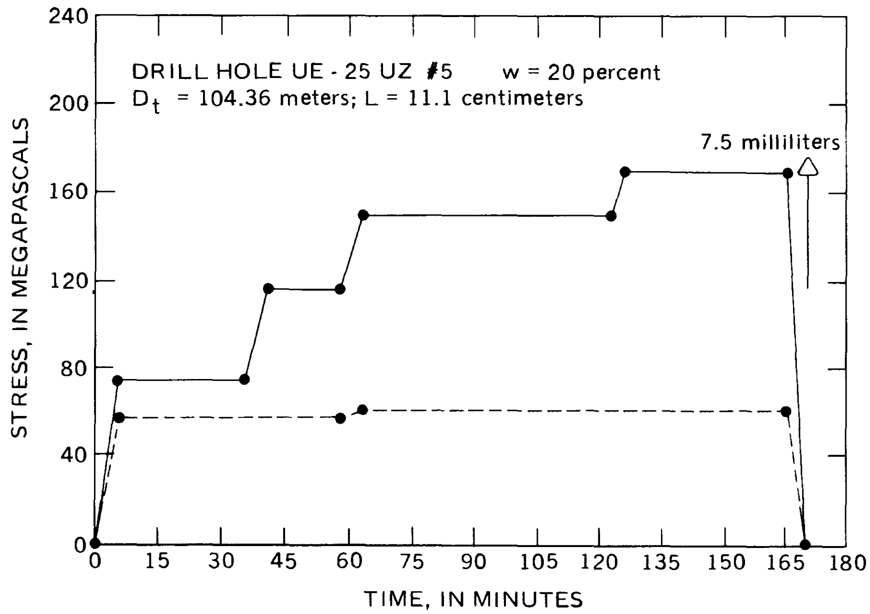


Figure 47.--Extraction trial no. 32.

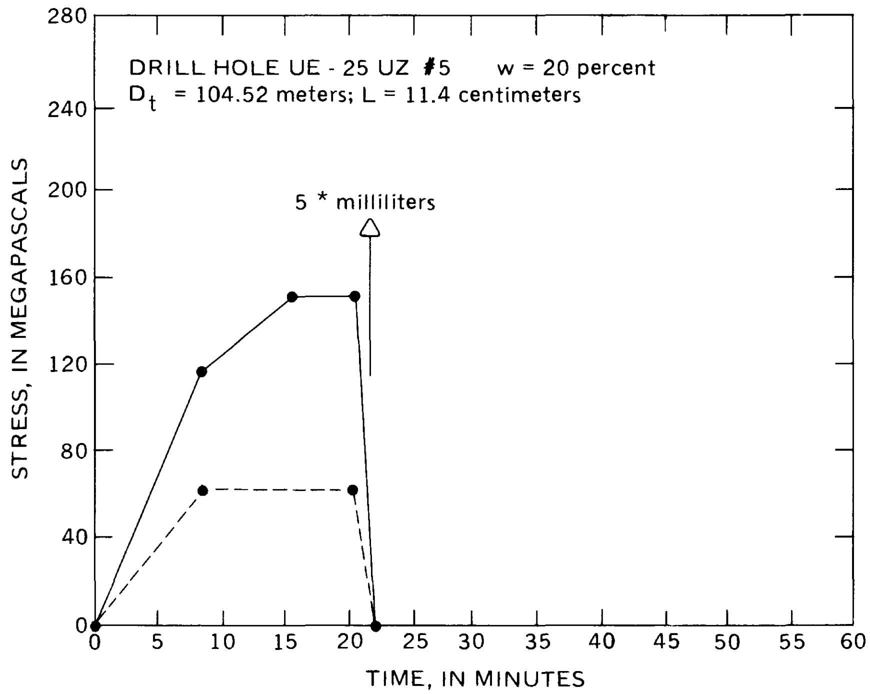


Figure 48.--Extraction trial no. 33.

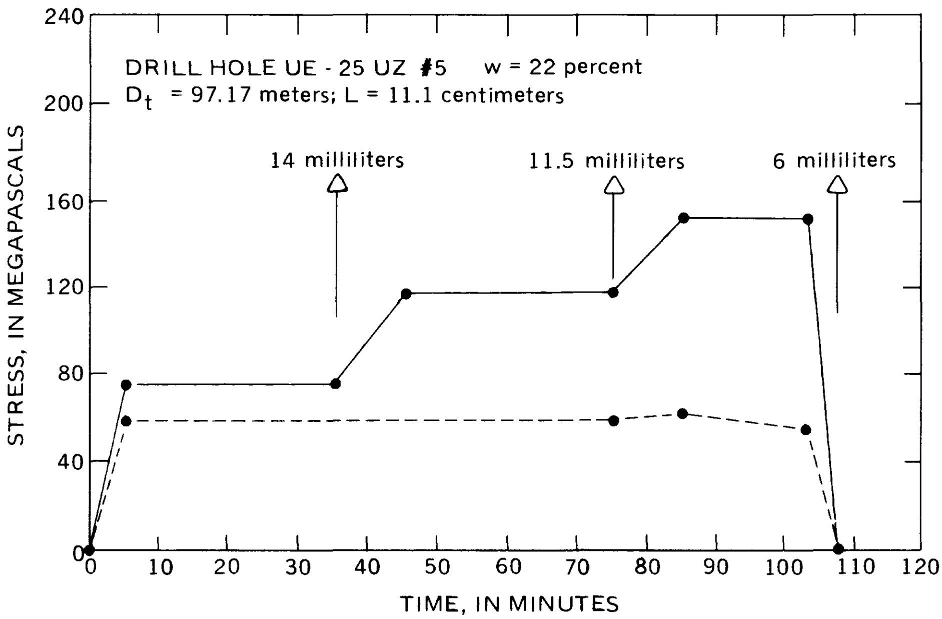


Figure 49.--Extraction trial no. 35.

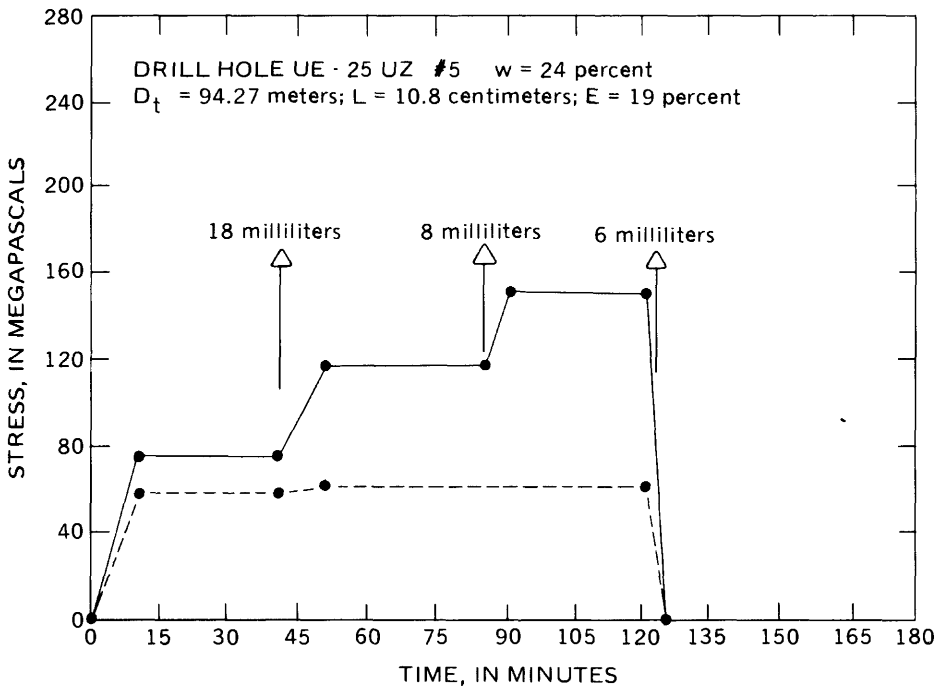


Figure 50.--Extraction trial no. 37.

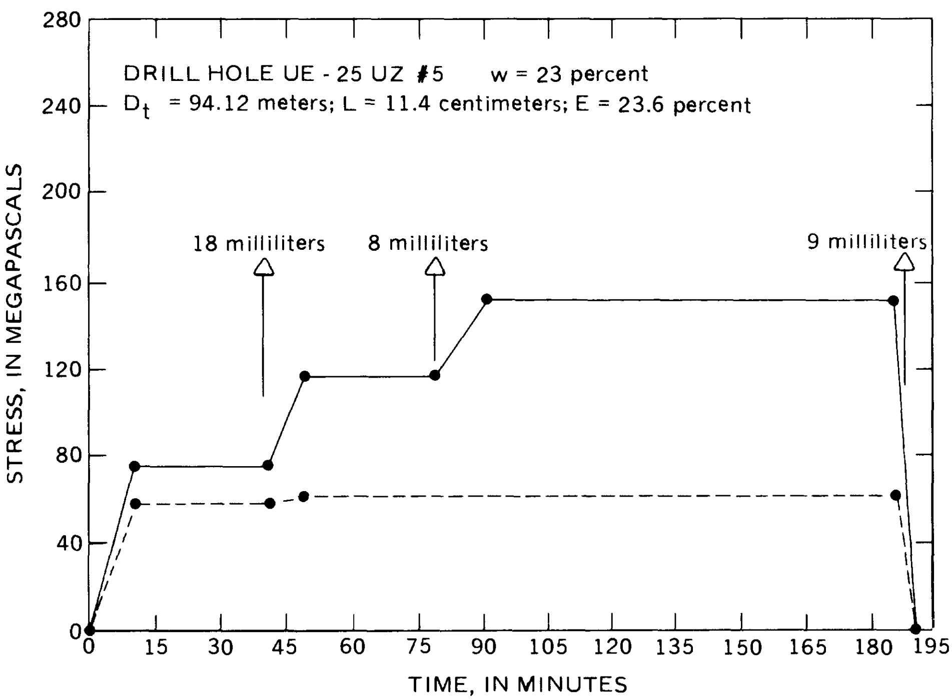


Figure 51.--Extraction trial no. 38.

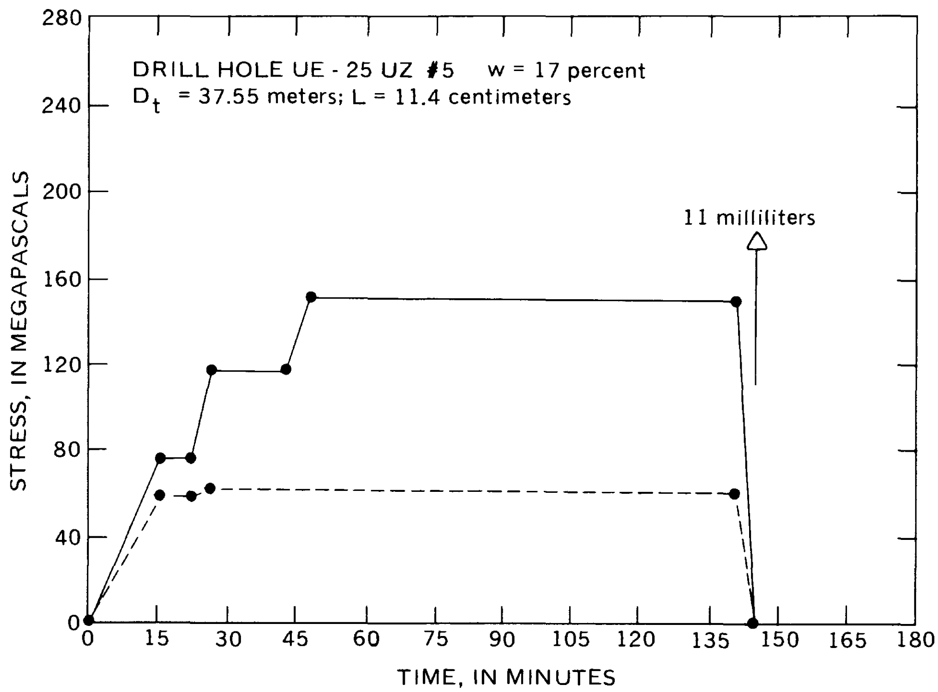
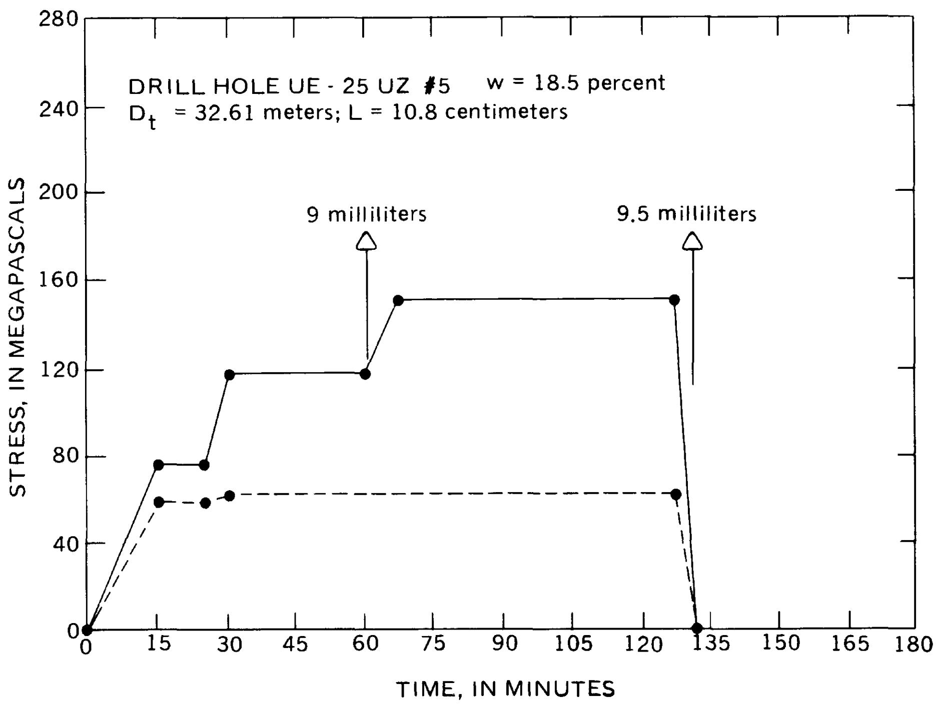


Figure 52.--Extraction trial no. 39.



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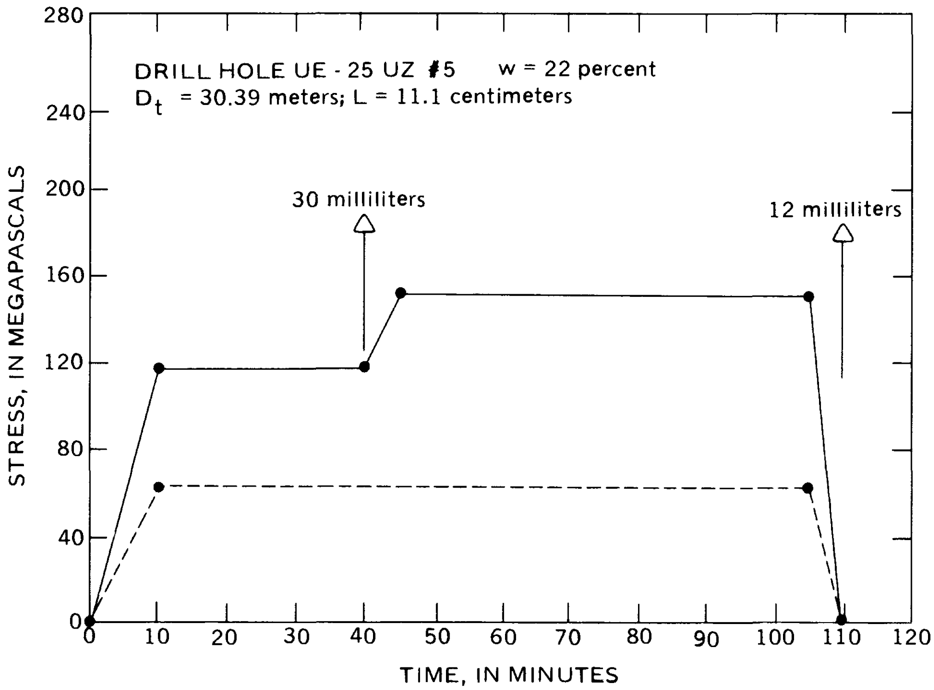

Figure 54.--Extraction trial no. 41.

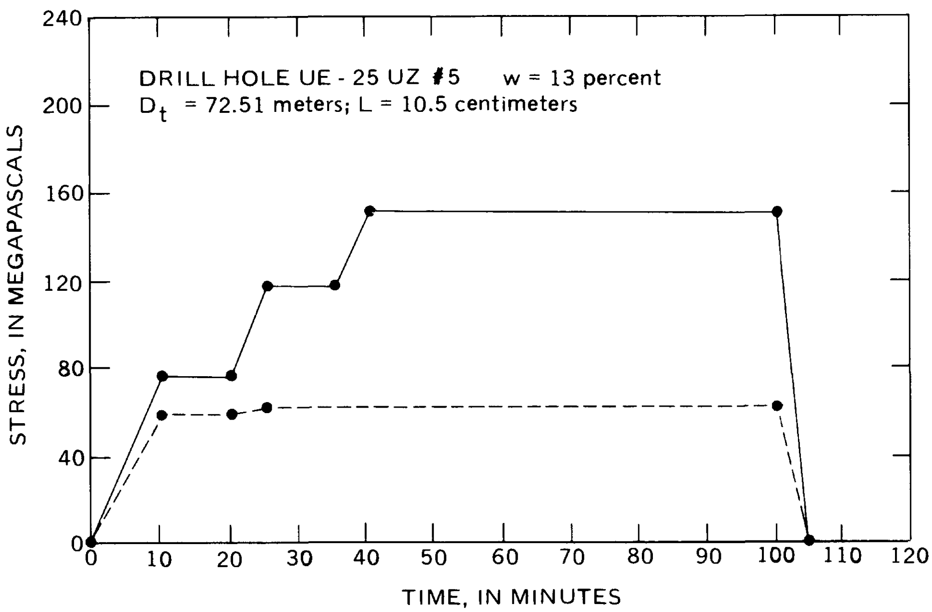

Figure 55.--Extraction trial no. 42.

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