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Comparison and correlation of lithostratigraphic and hydrostratigraphic units of southwest area 20, Pahute Mesa, Nevada test site

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COMPARISON AND CORRELATION OF LITHOSTRATIGRAPHIC AND HYDROSTRATIGRAPHIC UNITS OF SOUTHWEST AREA 20, PAHUTE MESA, NEVADA TEST SITE

by

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ABSTRACT

Traditionally, the boundaries of hydrogeologic units are restricted to the lithologic boundaries of the rock in which the hydrogeologic unit is recognized. This type of identification places emphasis on the composition and lithic characteristic of the unit rather than the material properties of the rock that affect potential ground-water flow. Hydrostratigraphic units represent an improved method of defining potential ground-water flow by identifying and grouping hydrologic units based upon the porosity and permeability of the rocks -- not on geologic contacts, thus removing the limitations of presently defined lithostratigraphic boundaries.

Six major and four minor hydrostratigraphic units were identified in and correlated between exploratory wells UE-20f and UE-20d located in Pahute Mesa of the Nevada Test Site based upon relative changes in porosity and permeability as recorded by geophysical logs. A comparison of hydrostratigraphic and lithostratigraphic units within these wells revealed sufficient variation in the unit-boundary locations to justify separation of these two types in future hydrogeologic investigations.

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INTRODUCTION

In hydrologic studies, an established practice consists of delineating hydrogeologic units based upon the contacts of lithostratigraphic units. The material properties of the rock which influence the hydrologic capabilities are assumed to remain constant throughout the interval of the lithostratigraphic unit. This practice ignores changes in the porosity and permeability of the lithostratigraphic units which could affect the rock's potential flow capabilities and requires hydrogeologic units to follow changes in other geologic formations.

Modeling hydrologic systems based upon the boundaries of lithostratigraphic units constrains potential flow units within the systems to conform to the parameters of the lithostratigraphic units. This method does not permit the possibility of separate, adjacent rock units forming joint flow systems by transmitting water equally even though the units are of different age, genesis, or lithology. Conversely, hydrostratigraphic units define potential flow systems based upon the porosity and permeability of the rocks.

The theory of hydrostratigraphic units was originally introduced by Maxey (1964, p. 126) and defined as ". . . bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system". Hydrostratigraphic units were intended by Maxey to aid ground-water investigations by recognizing and delineating distinct hydrogeologic units into similar groups based on the physical properties of the rocks. These units were proposed as viable counterparts in ground-water studies to formations in lithostratigraphic studies (Seaber, 1988). The concept of hydrostratigraphic units, as defined by Maxey (1964), was not embraced by the North American Commission on Stratigraphic Nomenclature since the definition included hydrologic components and was not restricted to the material properties of the rocks (North American Commission on Stratigraphic Nomenclature, 1983; Seaber, 1988).

Seaber (1988, p. 13) redefined hydrostratigraphic units as ". . . a body of rock distinguished and characterized by its porosity and permeability". This definition is based on the interstices of the geologic materials, therefore, the criteria for hydrostratigraphic units are limited to only the material properties of the rock and does not incorporate any ground-water-flow parameters (Seaber, 1982, 1986, 1988).

In hydrologic investigations, the recognition of hydrostratigraphic units is valuable if the boundaries of these units vary from the boundaries of the lithostratigraphic units. In this study, geophysical logs were used in an attempt to identify hydrostratigraphic units as defined by their porosity and permeability in two exploratory wells (UE-20f and UE-20d) located within the Nevada Test Site (NTS). Once the units were identified, the boundaries of the hydrostratigraphic units as defined by the geophysical data were compared to the boundaries of the lithostratigraphic units. The amount of variation found in this study between the boundaries of these two types of units validates the importance of hydrostratigraphic units in hydrologic investigations and emphasizes the importance of hydrostratigraphic units in defining potential flow systems in ground-water modeling.

The NTS in Nye County, Nevada was selected as the research area for this project due to the potential problem of radionuclide migration in ground water. The NTS has been the most active nuclear testing region within the United States. This area was selected as the testing grounds for the detonation of nuclear devices by the Energy Research and Development Administration in December, 1950. Surface and aerial nuclear testing began on January 27, 1951 and continued until 1957 when fear of atmospheric fallout prompted a change to underground testing. From the first event in 1951 until the present, there have been over 600 announced detonations at this site (Max Bennett (NTS), oral communication, 1992) most of which were conducted underground resulting in the emplacement of large quantities of radioactive material (Borg and others, 1976).

PURPOSE AND SCOPE

The purpose of this study is to determine whether hydrostratigraphic units can be distinguished and correlated by relative changes in the porosity and permeability of siliceous volcanic rocks as indicated by limited geophysical data. If delineation is successful, the boundaries of the hydrostratigraphic units as compared to the boundaries of the lithostratigraphic units will determine the validity of distinguishing these two types of units as separate entities.

The research wells used in this study, UE-20f and UE-20d, are located 2.7 km apart in Pahute Mesa of the Nevada Test Site. Geologic units within the zone of investigation consist of relatively flat-lying siliceous Miocene volcanic rocks located within the saturated zone between static water level (555 to 632 m) to 1370 m below land surface. In order to observe correlations between the two wells, the depth of study (1370 m) coincides with the total depth of the shallower well UE-20d.

OBJECTIVES

The objectives of this investigation are to:

(1) Correlate the lithostratigraphic units of drill holes UE-20f and UE-20d.

(2) Identify and distinguish hydrostratigraphic units from lithostratigraphic units in wells UE-20f and UE-20d based upon the relative porosity and permeability of the rocks.

(3) Determine if enough variation between lithostratigraphic contacts verses hydrostratigraphic contacts identified in UE-20f and UE-20d exists to warrant application of hydrostratigraphic units in future hydrogeologic investigations.

(4) Determine if hydrostratigraphic units identified in UE-20f and UE-20d are correlable.

ASSUMPTIONS

Utilizing geophysical logs to identify hydrostratigraphic units in volcanic rocks require (as in most hydrologic investigations) certain assumptions concerning the physical characteristics of these rocks and subsurface conditions. The assumptions held in this project are:

(1) Where matrix porosity exists, most of the storage capacity in the unit is within the interstitial voids rather than in the fractures.

(2) Regardless of a rock's primary porosity, it is the interconnected fractures within the rock (secondary porosity) through which most of the ground water flows.

(3) Porosity (primary) decreases as a result of increased welding.

(4) Fracturing is much greater within competent units (units containing less primary porosity and increased welding).

(5) Welded rocks and other competent units (i.e. rhyolite and densely-welded tuff) contain mostly interconnected fractures as compared to less competent units (units containing mostly primary porosity and a small degree of welding).

(6) The physical properties of the lithostratigraphic units (i.e. amount of fracturing and degree of welding) are continuous within and between the two exploratory wells.

In summary, this study assumes the dense (low primary/high secondary), highly-fractured lithostratigraphic units in Pahute Mesa maintain the greatest potential of yielding large quantities of ground water, and, that the properties of the lithostratigraphic units remain constant between wells which is comparable with assumptions made in previous studies in this region (Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

BACKGROUND

POROSITY AND PERMEABILITY DEFINED

Porosity is a physical property of rock which is defined as the amount of void (interstitial) space contained within the sample relative to the total volume of the sample. This ratio, expressed as a percent, is a measure of the maximum amount of fluid a rock is capable of holding. Primary porosity, also referred to as matrix or interstitial porosity, is formed contemporaneously with rock deposition. Primary porosity can be affected after deposition by processes that result in fracturing or solution of the original material producing additional voids referred to as secondary porosity. The total porosity of a unit incorporates primary and secondary porosity regardless of origin. Although a specific rock may have the capability of storing large quantities of fluid through large void space to total volume ratio, the rock may not necessarily readily yield such fluids. The ability to transmit and yield fluids is controlled by the rock's effective porosity which is a function of the degree of interconnectiveness between void spaces and is, therefore, a measure of the rock's permeability.

Permeability, in qualitative terms, describes the ability of a porous medium to transmit a fluid and is dependent upon the degree of interconnectedness of the pore spaces (Domenico and Schwartz, 1990). Intrinsic permeability represents the properties of the medium only and is independent of the properties of the fluid. Hydraulic conductivity describes the rate at which fluids move through a porous medium and is related to intrinsic permeability. Even though these terms have specific definitions, permeability is often used interchangeably with hydraulic conductivity (Keys and MacCary, 1971) and intrinsic permeability (Jorgensen, 1989, 1991).

STUDY AREA

The NTS, encompassing an area of approximately 3500 km^2, is located in south-central Nevada (lat 36°36' and 37°24' N. and long 115°56' and 116°35' W.) within Nye County approximately 120 km northwest of the city of Las Vegas (fig. 1). This region consists of predominantly north-south trending mountains with peak elevations up to 2743 m separated by alluvial valleys lying 914 m to 1372 m above sea level. The NTS and adjacent areas receive annually 8 cm to 15 cm of rain on the valleys and generally less than 25 cm on the ridges (except at peak altitudes) making this region one of the most arid in the United States (Winograd and Thordarson, 1975).

The NTS and adjacent areas are located within the miogeoclinal belt of

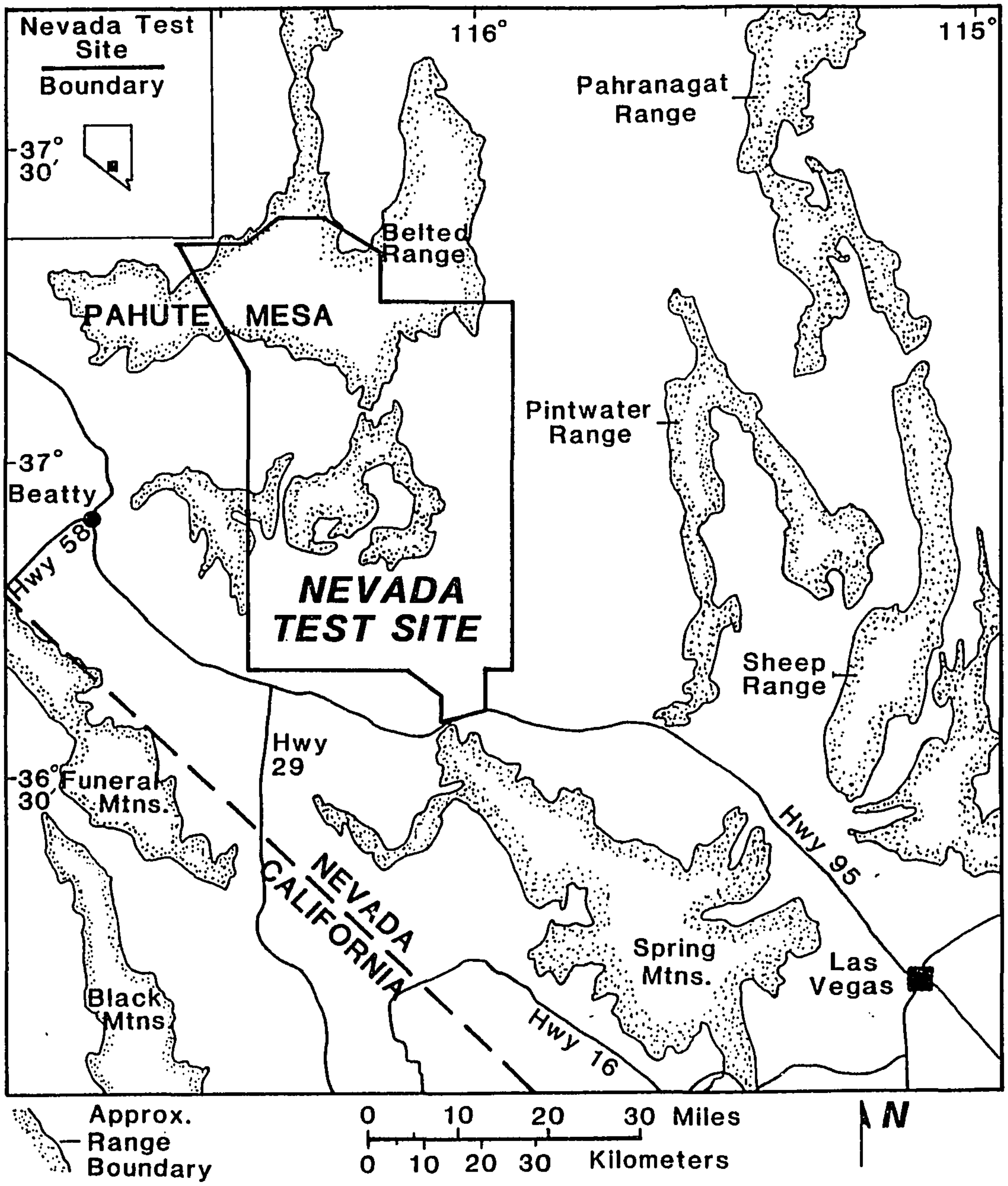

Figure 1. Location map of Nevada Test Site and vicinity (modified from Winograd and Thordarson, 1975).

the Cordilleran geosyncline and are part of the Basin and Range physiographic province. This area contains over 11-km-thick marine sediments deposited during the Precambrian and Paleozoic time with the NTS lying near the thickest miogeoclinal deposits (Ekren, 1968). The Mesozoic system is represented only by isolated granitoid plutons scattered throughout the area, but Tertiary volcanic and Quaternary detrital deposits are ubiquitous throughout this region (Winograd and Thordarson, 1975).

Pahute Mesa, located within the northwest quadrant of the NTS approximately 210 km from Las Vegas, is an area characterized by deep canyons separating buttes and mesas (fig. 2). This elevated plateau has gentle relief and covers about 520 km^2 with elevations ranging from 1,676 m to 2,134 m above mean sea level (Blankennagel, 1968; Blankennagel and Weir, 1973). Volcanic surficial deposits, emplaced during the Tertiary by the explosive activity of the southwestern Nevada volcanic field (SWNVF), cap this region with thicknesses over 4,171 m in some areas (table 1). The volcanic deposits consist of vitrophyre, rhyolite, ash-fall tuff, and ash-flow tuff ranging from non- to densely-welded (Blankennagel, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

The Tertiary volcanic rocks of Pahute Mesa are mostly flat-lying rocks cut by several north-trending normal faults that are a result of Tertiary-age extensional forces acting on this region (fig. 3)(Noble and others, 1968; Orkild and others, 1968, 1969). These faults, striking from N 20° W to N 20° E, have vertical displacements averaging 31 m although vertical offsets of 0.6 m to over 183 m occur. Reactivation of these faults within Pahute Mesa commonly occurs due to nuclear testing that began in this area in 1966 (Covington, 1987).

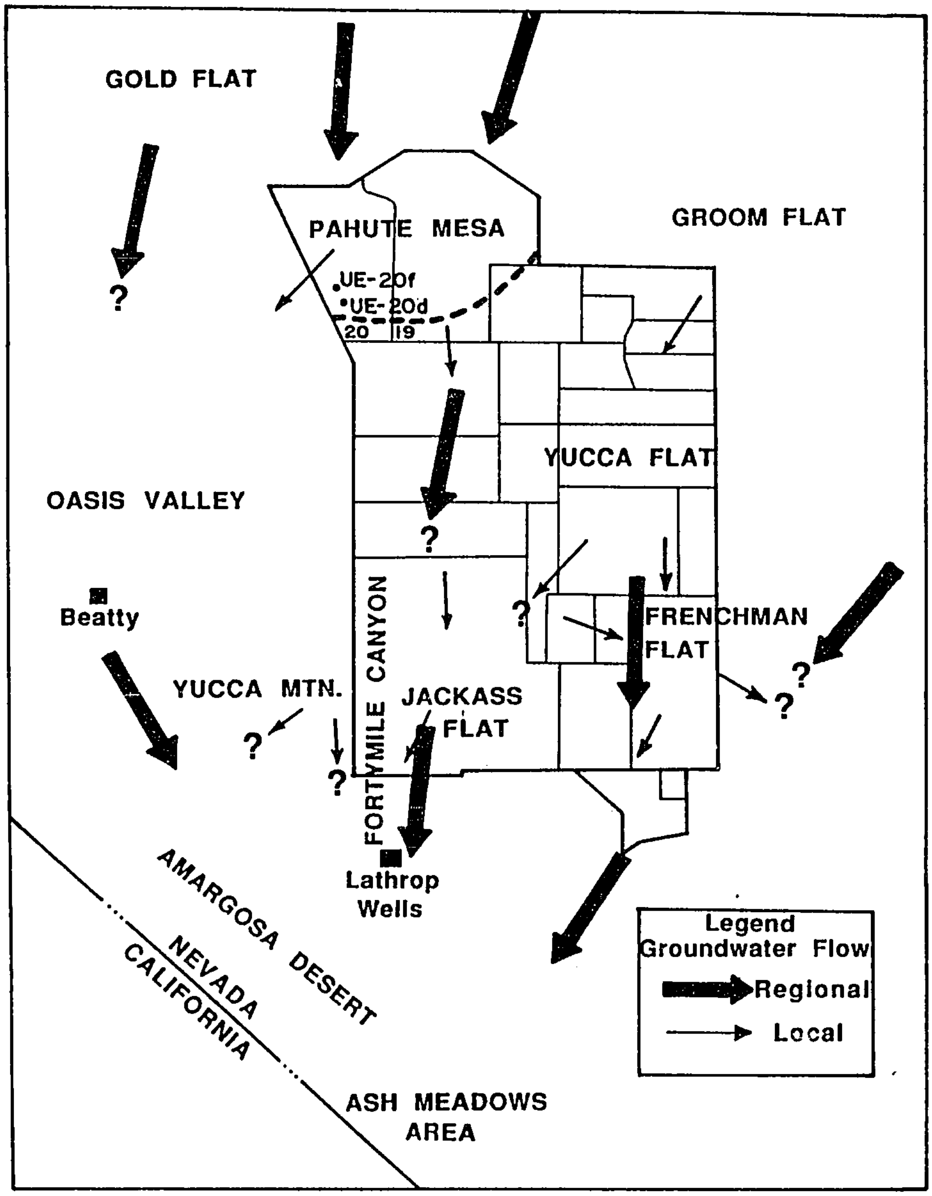

Figure 2. Location map of Pahute Mesa, exploratory wells UE-20f and UE-20d, and direction of regional/local ground-water movement (modified from R. Jacobson, Desert Research Institute, unpub. data, 1992).

The Silent Canyon caldera underlies most of Pahute Mesa. This caldera is a deep, elliptically-shaped structural basin measuring approximately 18 km by 23 km with a greatest axis trending north-northeast

Table 1. General stratigraphy of Pahute Mesa pertinent to this study (modified from C. Russell, Desert Research Institute, unpub. data, 1992).

Stratigraphy of Pahute Mesa

GROUP	Caldera	FORMATION	MEMBER, UNIT/SUBUNIT	SYMBOL	LITH	K-AR
Thirsty Canyon Group (Tt)	Black Mountain Caldera	Trail Ridge Tuff (Ttt)		Ttt	a,b	7.5
		Pahute Mesa Tuff (Ttp)		Ttp	a,b	7.7
		Rocket Wash Tuff (Ttr)		Ttr	a	7.8
		Comendite of Ribbon Cliff (Ttc)	Upper (Ttcu)	Ttcu	1,b	8.9
			Middle (Ttcm)	Ttcm	1,b	8.9
			Lower (Ttcl)	Ttcl	1,b	8.9
		Tuff of Scotch (Ttl)		Ttl	b	
Volcanic of Fortymile Canyon (Tf)	Timber Mountain Caldera	Beatty Wash Formation (Tfb)	Tuff of Cutoff Road (Tfbc)	Tfbc	b	9.9
			Rhyolite of Beatty Wash Formation (Tfbw)	Tfbw	b	
Timber Mountain Group (Tm)	Timber Mountain Caldera	Ammonia Tanks Tuff (Tma)	mafic-rich Ammonia Tanks Tuff (Tmar)	Tmar	a	11.4
			mafic-poor Ammonia Tanks Tuff (Tmap)	Tmap	a,b	11.4
			Bedded Ammonia Tanks Tuff (Tmab)	Tmab	b	
		Rainier Mesa Tuff (Tmr)	mafic-rich Rainier Mesa Tuff (Tmrr)	Tmrr	a,b	11.4
			mafic-poor Rainier Mesa Tuff (Tmrp)	Tmrp	a	11.4
			andesite tephra of Rainier Mesa Tuff (Tmra)	Tmra	b	11.4
			dacite tephra of Rainier Mesa Tuff(Tmrd)	Tmrd	b	11.4
		Rhyolite of "pre-Rainier Mesa" (Tmrl)		Tmrl	b	11.6
		Tuff of Holmes Road (Tmrh)		Tmrh	a,b	
		Basalt of Tierra (Tmt)		Tmt	1	
		Rhyolite of Windy Wash (Tmw)		Tmw	1,b	12.7
Paintbrush Group (Tp)	Claim Mountain Caldera	Rhyolite of Benham (Tpb)		Tpb	1,b	
		Rhyolite of Scrugham Peak (Tps)		Tps	1,b,a	
		Tuff of Pinyon Pass (Tpcy)		Tpcy	a,b	
		Tiva Canyon Tuff (Tpc)	Tiva Canyon Tuff, Pahute Mesa Lobe (Tpcm)	Tpcm	a	12.8
		Rhyolite of Delirium Canyon (Tpd)		Tpd	1,b,a	12.6
		Rhyolite of Echo Peak (Tpe)		Tpe	1,a,b	
		Rhyolite of Silent Canyon (Tpr)		Tpr	1,b	
		Topopah Spring Tuff, (Tpt)	Topopah Spring Tuff, Pahute Mesa Lobe (Tptm)	Tptm	a,b	13.3
Volcanics of Area 20 (Ta)	Silent Canyon Caldera	Calico Hills Formation (Tac)	mafic-poor Calico Hills Formation (Tacp)	Tacp	1,b,a	13.8
			mafic-rich Calico Hills Formation (Tacr)	Tacr	1,b,a	13.8
		Tuff of Pool (Tap)		Tap	b	
		Rhyolite of Inlet (Tai)		Tia	1,b,a	

(fig. 4)(Orkild and others, 1968; Blankennagel and Weir, 1973; Sawyer and Sargent, 1989). The amount of subsidence within the caldera ranges from

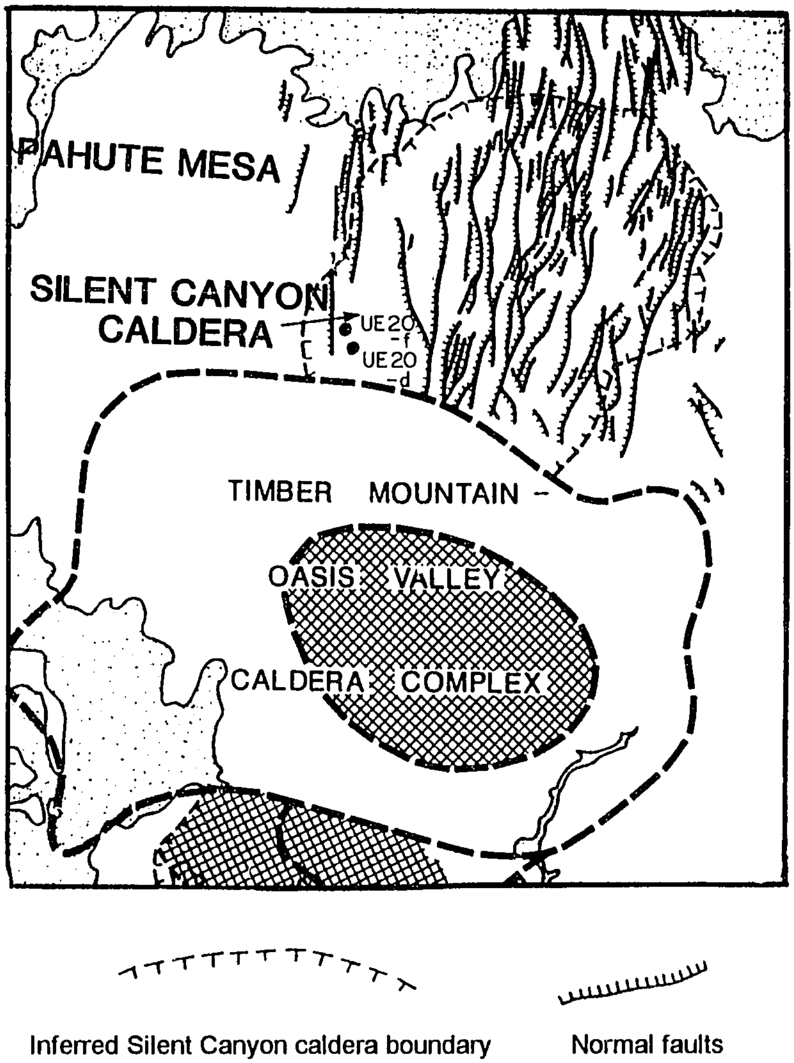

Figure 3. Location map of normal faults within Pahute Mesa (modified from Carr, 1990).

1,524 m on the northeast side to 2,134 m on the west with collapse occurring simultaneously with regional faulting (Blankennagel and Weir, 1973).

The existence of the Silent Canyon caldera was first inferred from data collected from gravity surveys and surface mapping, but the existence of the

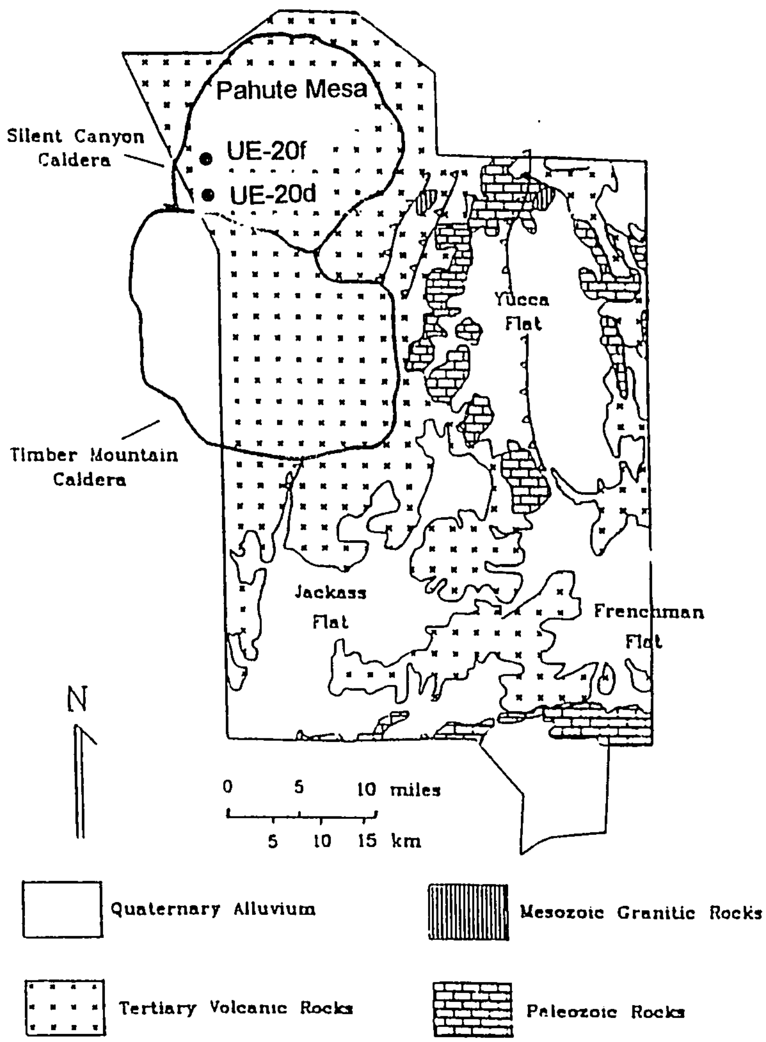

Figure 4. Map illustrating the regional geology and locations of the Silent Canyon and Timber Mountain calderas at the Nevada Test Site. (R. Jacobson, Desert Research Institute, unpub. data, 1992).

caldera was not documented until exploratory drilling was performed in Pahute Mesa (Orkild and others, 1968; Blankennagel and Weir, 1973). Rocks associated with the formation of this caldera (Belted Range Group) are mostly obscured by younger units erupted from nearby volcanic centers (Black Mountain, Timber Mountain, Claim Mountain) except on the eastern side of the caldera where a few outcrops of caldera-associated rocks occur (Orkild and others, 1968; Blankennagel and Weir, 1973). Although the actual thicknesses of Tertiary volcanic deposits in this area is unknown, drilling in the moat area of the Silent Canyon caldera in southwest Pahute Mesa penetrated deposits over 4,170 m thick. Due to variations in the areal extent of volcanic deposits, a detailed description of the units pertinent to this research is provided in the appendix.

The most detailed study into the hydrogeology of Pahute Mesa was published by Blankennagel and Weir in 1973. Similar to the hydrogeologic units identified at the NTS by Winograd and Thordarson (1975), Blankennagel and Weir evaluated the hydrologic importance of the geologic systems in Pahute Mesa and delineated these hydrogeologic units based on geologic contacts.

Ground-water flow beneath Pahute Mesa is concentrated within relatively dense rock with movement primarily through interconnected fault and joint systems (Blankennagel and Weir, 1973). The fractured rhyolite and welded tuff of the Deadhorse Flat Formation constitute the major aquifers in eastern Pahute Mesa (Blankennagel and Weir, 1973). In the western and central portions of the mesa, the significant aquifers are within the fractured and faulted tuffs and rhyolites of Area 20 (Blankennagel and Weir, 1973). Even though the permeability of the fractured-rock aquifers will vary depending on the percentage of open and interconnected fractures, the more dense rocks usually transmit water in greater quantities than non-welded tuffs and ash-fall units illustrating the importance of secondary porosity over primary porosity within certain volcanic rocks (Blankennagel, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

Aquifer tests conducted in exploratory wells within Pahute Mesa found the average depth to water from land surface to be approximately 600 m in the west and 720 m in the eastern portion of the mesa (Blankennagel and Weir, 1973). Ground water in this region is of the sodium-potassium type with an average velocity of flow ranging from 0.004 m/day to 0.21m/day (Blankennagel and Weir, 1973). Aquifer tests also provided values of transmissivity through the volcanic rocks of Pahute Mesa that ranged from 17 to 1739 m^2/day (Blankennagel and Weir, 1973). Data collected from geophysical logs and aquifer tests recognized two main aquifers, the upper (postcaldera rocks) and the lower (intracaldera rocks) in which the lower aquifer has much greater permeability (Blankennagel, 1968). The lower aquifer exhibits a head 12.8 m lower than the upper aquifer suggesting a downward movement of ground water from the upper to the lower aquifer (Blankennagel, 1968).

Drill cores from Pahute Mesa exhibit fracture densities in dense rocks (rhyolitic flows and welded tuffs) ranging from 0 to 14 fractures per meter (Blankennagel and Weir, 1973). Most of the fractures are believed to be a result of shrinkage during cooling although the location relative to faults and/or manner in which the volcanic rocks were emplaced can also promote fracturing (Blankennagel and Weir, 1973). Vertical fractures, which can be produced during cooling, may also be a result of tectonic activity causing extensional and shear failure of the rocks (Thordarson and others, 1985) or by stress induced by drilling. Surface faulting in Pahute Mesa ranges from 0 to 26 faults per km^2 with these faults commonly open and contributing to the overall permeability, especially vertical permeability, of the units (Blankennagel and Weir, 1973).

The direction of ground-water movement within Pahute Mesa is south and southwest with discharge occurring in the Oasis Valley-Fortymile Canyon basin, a tributary to the northwest and central Amargosa Desert (fig. 2). This direction is controlled, in part, by the Silent Canyon caldera which acts as a subsurface barrier (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). Ground water within Pahute Mesa discharges at an estimated rate as high as 16,899 m^3/day with the estimated annual recharge from precipitation and perched or semiperched water to be up to 27,036 m^3/day (Blankennagel and Weir, 1973). The complex flow pattern of ground water in Pahute Mesa is attributed to the occurrence of fractures, faults, subsurface barriers, and complex geologic structures.

METHOD

To delineate hydrostratigraphic units within wells UE-20f and UE-20d, suites of geophysical logs are viewed simultaneously for responses indicating significant changes in the porosity and potential permeability of the volcanic rocks. The caliper, electric, neutron, temperature, and variable density logs from UE-20f and the caliper, density, electric, variable density, and velocity logs from UE-20d provide the most useful information available for this study.

Primary porosity present in the volcanic rocks within the saturated zone of the NTS and adjacent areas do not contribute significantly to regional ground-water movement, rather, the majority of the water moving within this region is through interconnected joint and fault systems in the more competent rocks which have minimal primary porosity (Blankennagel 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). The neutron, density, and sonic logs, all referred to as porosity logs, provide information on the amount of water present within the formations (Keys and MacCary, 1971; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Asquith and Gibson, 1982; Jorgensen, 1989, 1991). Again, most ground-water movement is due to secondary porosity (fractures) within the more competent units; thus, to identify potential high permeability zones, the variable density, velocity, and caliper logs can be used to determine relative fracture densities. The electric log measurements are used to infer unit lithologies within UE-20f and UE-20d based upon porosity variations which result from differing modes of deposition of the volcanic rocks. Finally, the temperature log in UE-20f provides information on possible water movement and influx further identifying zones of high or low permeability (Blankennagel, 1968). Once hydrostratigraphic units are identified, the importance of recognizing such units will depend on (1) the ability of these units to be correlated between the two wells, and (2) the location of the hydrostratigraphic contacts as compared to the lithostratigraphic boundaries.

An attempt to correlate the hydrostratigraphic units delineated separately in UE-20f and UE-20d involves joining units possessing similar relative porosity and permeability values as inferred from the geophysical logs. These units must also occur at similar depths in both wells (relative to each other) for horizontal ground-water flow to be possible. Once correlated, the material properties of the hydrostratigraphic units are assumed to remain uniform within and between UE-20f and UE-20d.

The significance of identifying hydrostratigraphic units as separate entities from lithostratigraphic units lay in the variation of the two separate boundaries. Significant variation in the locations of the hydrostratigraphic boundaries as compared to the lithostratigraphic contacts justify separation of these two types in future hydrogeologic investigations. Therefore, hydrostratigraphic units identified in, and correlated between UE-20f and UE-20d are compared to the lithostratigraphic units within both wells.

SELECTED WELLS

The two wells used in this study, UE-20f and UE-20d, are located 2.7 km apart in the southwest section of Area 20 on Pahute Mesa of the NTS (fig. 5). The letters "UE" in the well names classify these wells as exploratory holes drilled to determine the suitability of the location for underground nuclear testing. The number "20" identifies these wells as boreholes located within Area 20 of the NTS, and the letters "f" and "d" distinguish the separate wells.

The selection of UE-20f and UE-20d as the research wells in this study was preceded by consideration of the objectives of the Ground Water Characterization Project (GCP). The GCP is an effort by the U.S. Department of Energy (DOE) to aid research involving the possible migration of radionuclides in ground water by defining the hydrogeologic framework of the NTS and adjacent areas. Analyses of the geologic and hydrogeologic systems in this region will assist in ground-water-flow modeling and possibly govern future environmental restoration efforts.

The criteria used to select the area and wells in this study consisted of the direction of regional ground-water movement, the availability of

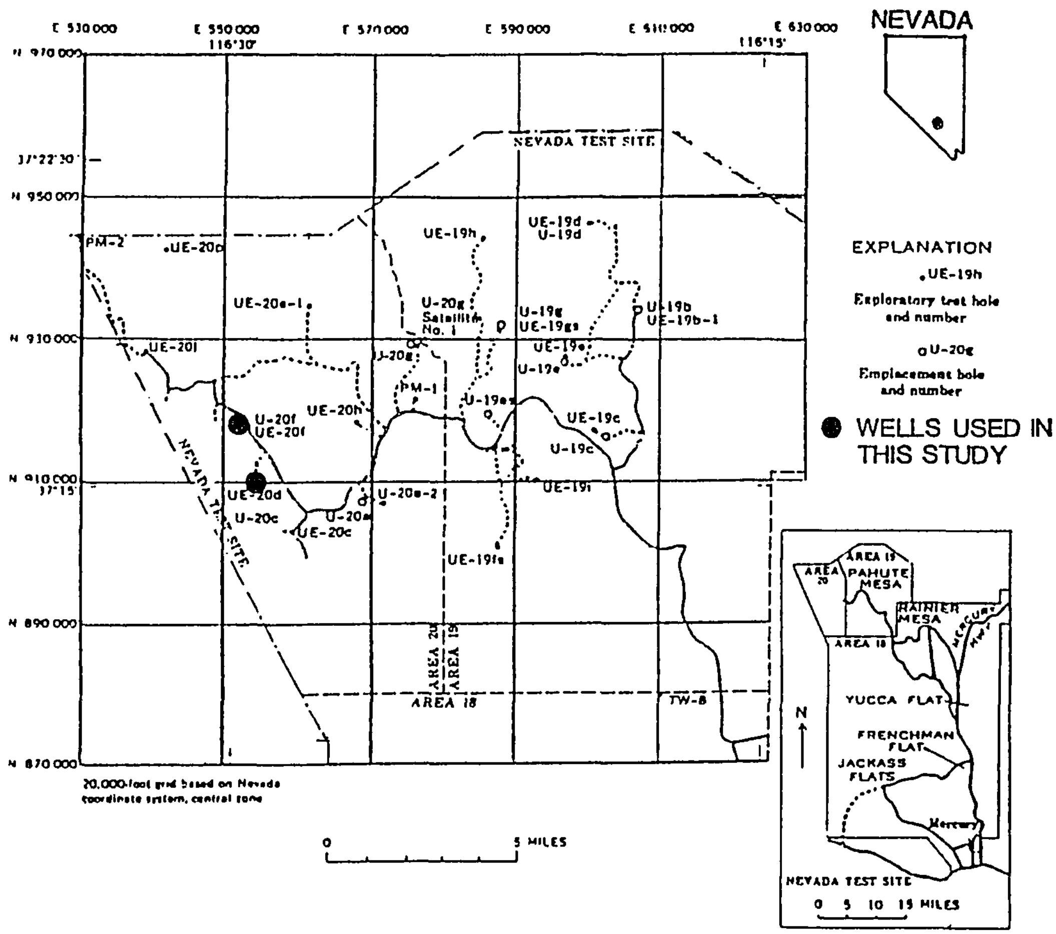

Figure 5. Location map of UE-20f, UE-20d, and other wells within Pahute Mesa, Area 20, Nevada Test Site (Blankennagel and Weir, 1973).

geophysical well data, the proximity to the NTS boundary, the greatest density of hydrologic data, and the location of wells within the same structural zone. After examination of the available data on wells within Pahute Mesa that would fulfill the above requirements and an extensive literature search for all material pertinent to this investigation, wells UE-20f and UE-20d were selected for study.

Both wells were drilled in 1964 reaching a total depth (TD) of 4,171 m in UE-20f and 1,369 m in UE-20d below the respective well heads. Upon completion of aquifer tests, geophysical logging, and sampling, the wells were cemented to the surface (UE-20f in 1975, UE-20d in 1977) (E. Clark, NTS, personal communication, 1992).

GEOPHYSICAL WELL LOGGING

Geophysical well logging is a technique for subsurface exploration which involves lowering sensing devices down a borehole to measure and record the physical properties of the rocks, formation fluids, and /or drillhole. This technique, also referred to as borehole geophysics, began almost a century ago with simple temperature measuring devices and has developed into a technical field using sophisticated tools that can measure a wide array of in-situ conditions (Keys and MacCary, 1971).

The original suite of geophysical logs run in UE-20f and UE-20d consisted of the caliper, salinometer, induction, radioactive survey, electric, density, 3-D velocity, nuclear (neutron), trace injector and spinner survey, and temperature logs (E. Clark, NTS, personal communication, 1992). Of these logs, table 2 lists the logs used in this study considered most able of providing useful and accurate geophysical information concerning the material properties of the rocks. A brief description of the geophysical logs used in this study is presented below.

Table 2. Geophysical logs used to identify hydrostratigraphic units in exploratory wells UE-20f and UE-20d, Pahute Mesa, Nevada Test Site.

Log Type	Logs Available		Logged Interval (meters)		Type of Information Inferred From Logs
	UE-20f	UE-20d	UE-20f	UE-20d	
Density	NA	X		732-1354	Porosity
Neutron	X	NA	0-1378		Porosity
Velocity	NA	X		741-1369	Porosity, Fracturing, Unit Competency
Variable Density	X	X	579-1379	732-1367	Porosity, Fracturing, Unit Competency
Caliper	X	X	220-1372	732-1368	Borehole rugosity, Washed-out zones, Fracturing
Electric	X	X	597-1380	738-1368	Lithology
Temperature	X	NA	427-1378		Zones of water movement and influx

NA = Not Available

CALIPER

Caliper tools are geophysical devices which measure the diameter of boreholes. Changes in the diameter can be due to fractured intervals, roughening of the borehole, or washed-out zones attesting to incompetent or weakened units.

DENSITY

Density logs, also called gamma-gamma logs, measure the electron density of a formation which are correlable with the bulk density of the unit. Bulk density is defined as the total weight of a substance divided by the total volume and is dependent upon the density of the formation material, formation porosity, and fluid density within the pores of the rocks (Schlumberger, 1992).

Density tools contain a radioactive source within the sonde that emits gamma rays into the adjacent formation. As the gamma rays penetrate the formation, collisions occur with the electrons present causing a decrease in the gamma ray's initial energy. These collisions are directly related to the number of electrons present in the formation which can represent the bulk density of the rocks (Asquith and Gibson, 1982; Schlumberger, 1989, 1992). Saturated rocks containing a small percentage of matrix porosity (therefore a small amount of water) will register as zones of decreased gamma ray detection due to the expenditure of energy during collisions. Fractured-rock intervals within the saturated zone could be detected as regions of low porosity (low water content) due to the larger amount of rock material relative to the fractured area even though the fractured area is transmitting large quantities of water.

ELECTRIC (RESISTIVITY)

Electric (resistivity) logs measure the amount of resistance of a formation to an electric current. Since most minerals have zero conductivity (high resistivity), an electrical current dispatched into the borehole is transmitted by ions within the interstitial fluids and not by the rocks; therefore, an increase in measured resistivity indicates a decrease in the volume of interstitial fluids (Muller and Kibler, 1984, 1985; Schlumberger, 1989). Based on known values of resistivity measurements provided by previous studies, electric log responses are extremely useful as lithologic indicators (Blankennagel, 1968; Snyder, 1968; Keys and MacCary, 1971; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

The resistivity of rocks in a drillhole can be measured by either transmitting or inducing a current from a probe into the adjacent formation. One type of probe passes a known current through the formation using contacting electrodes which in turn detects the resulting potential through an electrode arrangement. The other type of probe induces a current by use of a transmitting coil which produces an electromagnetic field in the formation that is detected by receiving coils (Muller and Kibler, 1984, 1985).

The electric log measurements are recorded utilizing two separate scales. One scale measures resistivity values from 0 to 10 chart divisions (500 ohm-meters), and the second measures from 10 to 20 chart divisions (5000 ohm-meters), however, the increments between the 500 and 5000 ohm-meters are not the same. As a resistivity value higher than 500 ohm-meters is recorded, the recorder "jumps" scale returning to the beginning of the scale and proceeds to measure resistivity values as 500 instead of 50 ohm-meters per chart division.

NEUTRON

Neutron logs contain a radioactive source which provides millions of electric volts of initial energy to neutrons and then emits the neutrons into the adjacent formations. The neutrons beamed into the formation collide with the formation's nuclei losing part of their initial energy (Schlumberger, 1989, 1992). The greatest loss of energy occurs when neutrons collide with nuclei of nearly identical mass (e.g. hydrogen) which causes the neutrons to greatly reduce their speed. At this slower velocity, surrounding atoms "capture" the slowed neutrons (Schlumberger, 1989, 1992). An increase in the hydrogen ratio within a formation will result in an increased "capture" rate with less neutrons left to be detected by the tool; therefore, the count rates of the detectors decrease with increased hydrogen concentration (Schlumberger, 1989, 1992).

The response of the neutron log in fractured terrain can indicate zones of low water content (porosity) that are actually high water-yielding intervals. This anomaly is due to the difference in water volume contained within the fractures verses the amount of water within the matrix. Generally, the volume of water contained within the pore spaces is greater than the amount of water within the fractures because the volume of rock containing the matrix porosity is much greater. However, water moving within the fractured zones generally has a much greater volume as compared to water movement within the matrix.

TEMPERATURE

Temperature logs provide a continuous measurement of the thermal gradient of the fluid surrounding the sensor as it descends in the borehole. To obtain an accurate temperature for a given depth, the borehole fluid must reach thermal equilibrium with the surrounding rock and all effects from drilling must be eliminated (Keys and MacCary, 1971). Temperature logs have been used to indicate zones of water movement and influx by investigating temperature variations within the borehole (Blankennagel, 1968; Keys and MacCary, 1971). Zones experiencing an increase or decrease from normal thermal gradients can indicate permeable regions that are accepting water from other permeable zones, and temperatures that become constant with increasing depths generally indicate interaquifer circulation (Blankennagel, 1968).

VELOCITY

The velocity log, also known as the sonic or acoustic log, utilizes transmitters that emit sound waves into the adjacent formations and receivers which detect and record the sound waves as they travel past the receivers (Schlumberger, 1989, 1992). The amount of time required for the sound wave to be emitted by the transmitter, travel a known distance parallel to the borehole within the adjacent formation, and be detected at the receivers is termed the interval transit time of the formation (Keys and MacCary, 1971; Asquith and Gibson, 1982; Muller and Kibler, 1985; Schlumberger, 1989, 1992). This interval transit time is measured from the arrival of the sound wave at the first receiver until the arrival of the sound wave at the second receiver. The travel time is a function of the lithology and porosity of the formation. An accelerated interval transit time in volcanic rocks is indicative of a "tighter" formation (less porosity resulting in increased competency). The travel time, however, can be affected by cavities or washouts in the borehole, thus, the sonic log measurements should be verified by comparing responses of this log with the caliper log (Keys and MacCary, 1971).

The velocity log can also be used to indicate zones of fracturing by exhibiting "cycle skipping". This phenomenon occurs as fractures cause the pulse from the transmitter(s) to be attenuated below the level of detection of the receivers. The following signals not weakened to that level are regarded as the first arrival time resulting in an arrival time that appears very slow. Therefore, sudden decreases in the arrival time of a sonic signal that occurs over a small depth interval should be investigated with the caliper and 3-D velocity logs for possible fracture identification.

VARIABLE DENSITY LOG

Another form of sonic/acoustic logging, the variable density or 3-D velocity log, utilizes the full-wave form of the sonic pulse in detecting the matrix porosity of the rock unit (Carroll, 1968; Rush and others, 1984; Thordarson and others, 1985). The 3-D log operates in the same manner as the sonic log, however, the sonic log records the first arrival of the sonic signal while the 3-D log records the full wave train for a period of time following the first arrival (Carroll, 1968). Changes in the relative "tightness" of the units are recorded by the 3-D velocity log as a decrease in the arrival times of the full-wave forms with a corresponding decrease in the matrix porosity of the rocks. Also, the amount of relative fracturing over the length of borehole is identified with this tool as breaks or intervals of no response due to the attenuation of the pulses below the detection limits of the tool. Thus, the variable density log can aid in identifying changes in lithology, matrix porosity and fracturing when interpreted along with the proper suite of geophysical logs.

GEOPHYSICAL LOG RESPONSE

In an attempt to delineate hydrostratigraphic units, the individual suites of geophysical logs from UE-20f and UE-20d are viewed simultaneously for responses indicative (to this study) of significant changes in the porosity and permeability of the lithostratigraphic units. For the responses to be considered valid representations of varying degrees of porosity and permeability, thus delineating hydrostratigraphic units, the appropriate log responses must occur in each log at similar depths in the well. A brief summary of the log responses used to delineate hydrostratigraphic units is presented below.

An increase or decrease in radiation counts of 10 chart divisions detected by the density log and the neutron log is considered to be representative of major changes in the hydrogeologic properties of the lithostratigraphic units (fig. 6). A change of 10 chart divisions is midway on the log scale which permits changes in the material properties of the rocks to be distinguished from fluctuations due to extraneous effects. The scale used to record the count rates for the density log in UE-20d was apparently set at a sensitivity level inappropriate for the rocks within Pahute Mesa which resulted in measurements occurring "off-scale". The measurements on the density log represent 2000 counts per minute per log division, and to record the large variation in count rates detected within the volcanic rocks, the scale was "shifted" towards the center of the paper log resulting in very high count rates registering off scale. Fortunately, the setting still allows for qualitative evaluation of the rocks based on relative changes in the count rates that tend to portray large differences between permeable and impermeable zones.

Similar to the density and neutron logs, an increase or decrease of 10 chart divisions in the velocity log response is considered to be representative of major changes in the hydrogeologic properties of the rocks (fig. 6). Responses measuring within the first 10 chart divisions (indicating a more rapid velocity) are considered to be zones of dense, competent rocks (e.g.

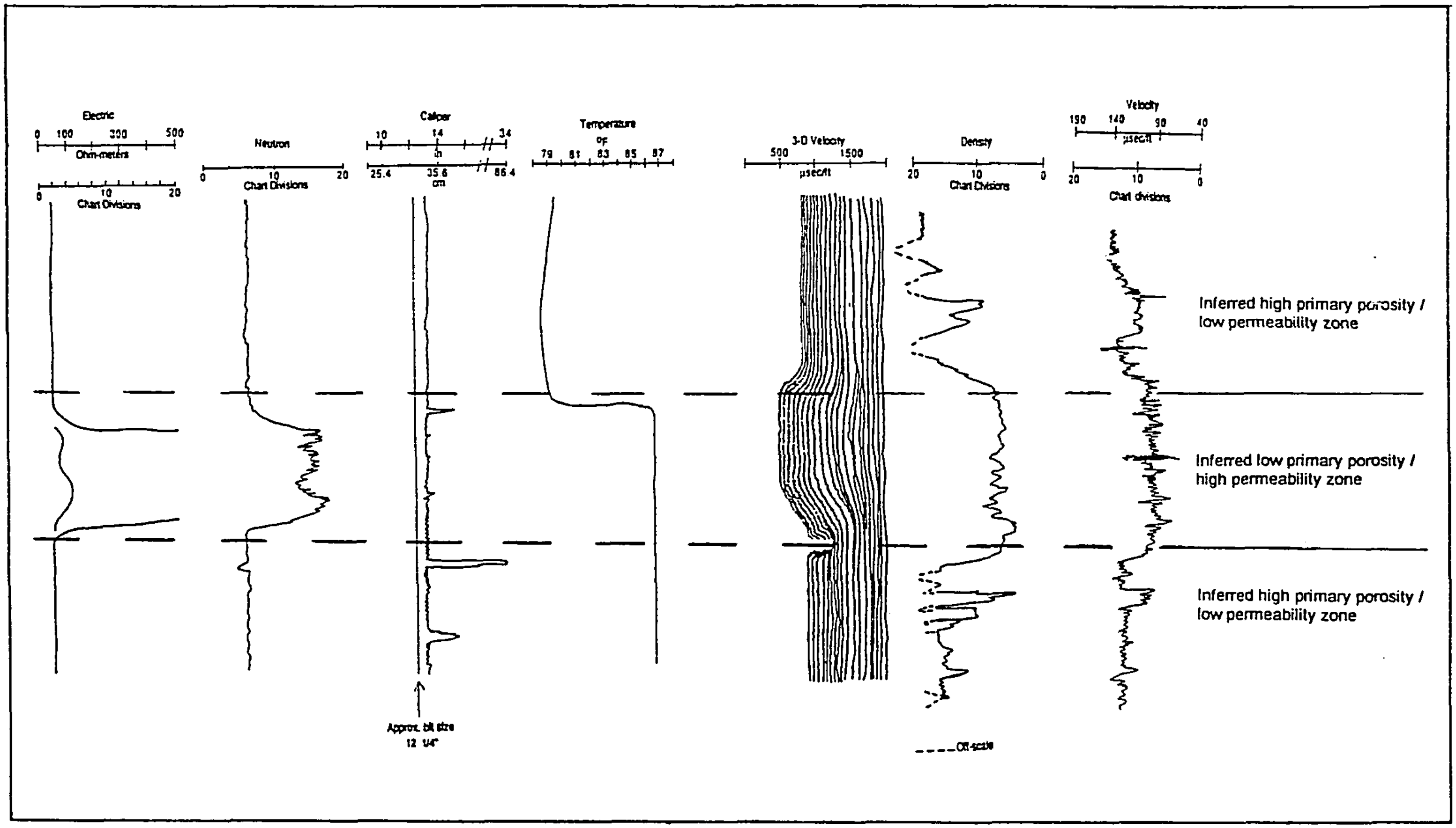

Figure 6. An example of geophysical log responses to zones of high/low porosity and permeability based upon criteria set in this study.

rhyolite); therefore, responses within the first half of the velocity log should represent zones capable of having high permeability (J. Corbett, Schlumberger Wireline and Testing, written communication, 1993). Again, a change of 10 chart divisions (midway of scale) permits changes in the material properties of the rocks to be distinguished from fluctuations due to extraneous effects.

A measurement of 225 ohm-meters (4.5 chart divisions) by the 16" normal curve of the electric log is used as the cut-off point for segregation of the rock types into groups of less permeable and more permeable units (fig. 6). Previous studies at the NTS found relatively impermeable zeolitized tuffs generally register a resistivity measurement below 100 ohm-meters, and bedded ash-fall tuffs, tuffaceous sediments, and non-welded and partly welded ash-flow tuffs usually result in measurements not exceeding 225 ohm-meters (Blankennagel, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). Resistivity readings greater than 225 ohm-meters are usually found in the more densely welded tuffs, vitrophyres and rhyolitic lava flows (Blankennagel, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). Most ground-water movement in Pahute Mesa is believed to occur within fractured zones, and it is the more competent rocks (densely welded tuff, vitrophyre and rhyolitic lava flow) that experience the greater fracturing, therefore, a resistivity reading of more than 225 ohm-meters should indicate a relatively permeable region provided the remaining log responses are concordant.

The temperature log from UE-20f is used to indicate zones of probable water influx corresponding to more permeable units (Blankennagel, 1968; Keys and MacCary, 1971) (fig. 6). Fluctuations in temperature often occur above or below zones of permeability as the temperature adjusts to "normal" subsurface temperatures at that depth. Also, regions experiencing crossflow between permeable zones often maintain a relatively stable temperature due to mixing of the ground waters.

The 3-D velocity log provided information on the relative fracturing, relative matrix porosity, and the "tightness" of zones within UE-20f and UE-20d (fig. 6). To delineate the relative fracturing between the various hydrostratigraphic units, a relative fracture index was developed in this study for each well that assigned a number from one to four for each zone displaying a significant change in either arrival times of the full wave train or changes in the "strength" of the signal. The fracture index compares the amount of fracturing within the rocks penetrated by one drillhole only, and the assigned number for each unit does not represent the fractures quantitatively. Higher index numbers correspond to less fracturing of the units, therefore, a zone designated as "4" on the fracture index contains few, if any, fractures.

The caliper log is used in this study to document the overall stability of the drillhole and aids in identifying both fracture and washed-out intervals.

LITHOSTRATIGRAPHIC UNITS AND CORRELATION OF WELLS UE-20F AND UE-20D

Lithostratigraphic columns for wells UE-20f (fig. 7) and UE-20d (fig. 8) were constructed based on petrographic descriptions of well cores and cuttings (table 3)(R. Warren, Los Alamos National Laboratory (LANL), unpub. data, 1992). Included within the lithostratigraphic columns are the textural characteristics of the geologic units also provided by Warren (R. Warren, LANL, unpub. data, 1992). The textural features (bedded, densely-welded,

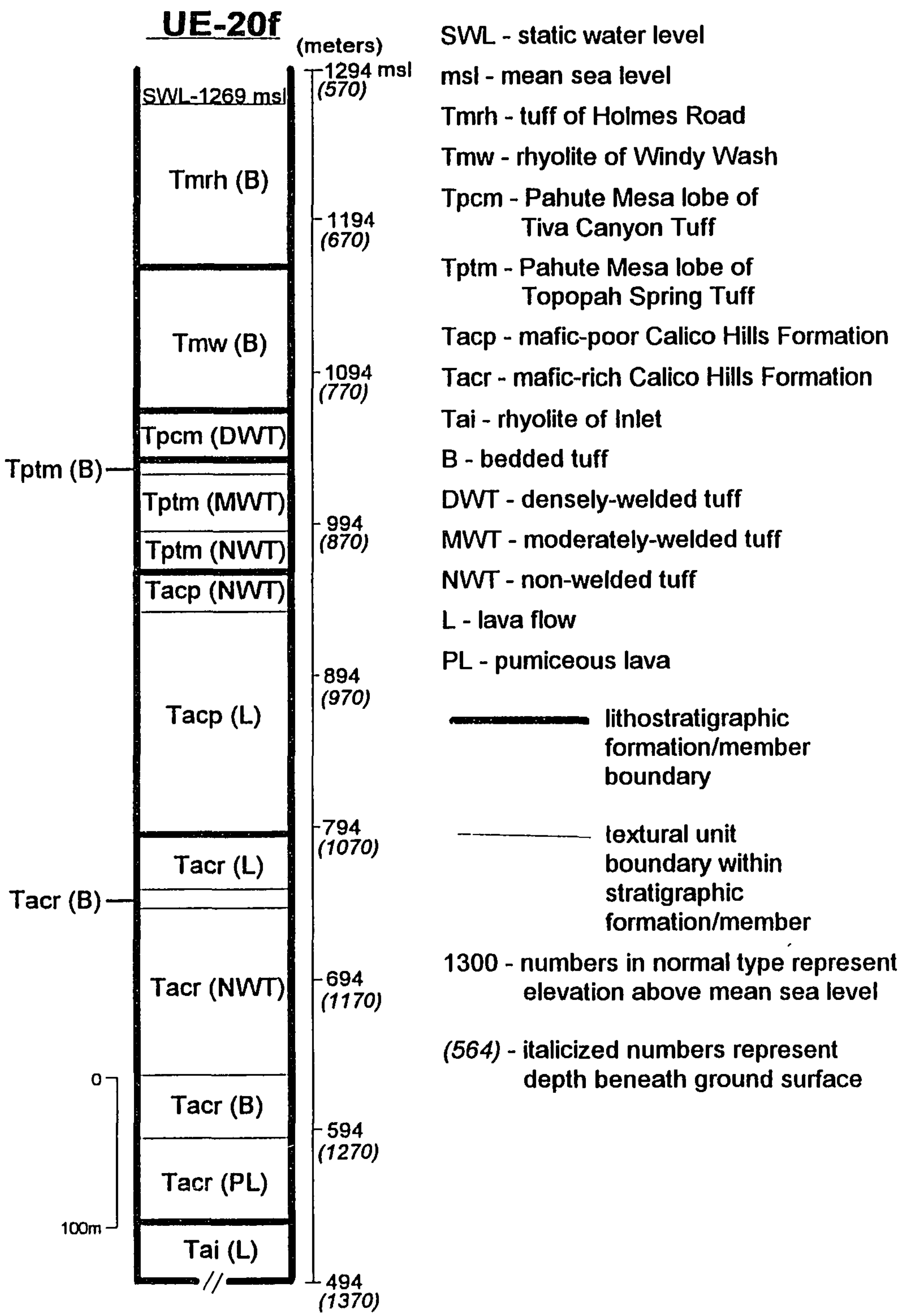

Figure 7. Lithostratigraphic column of exploratory well UE-20f in Pahute Mesa, Nevada Test Site (R. Warren, LANL, unpub. data, 1992).

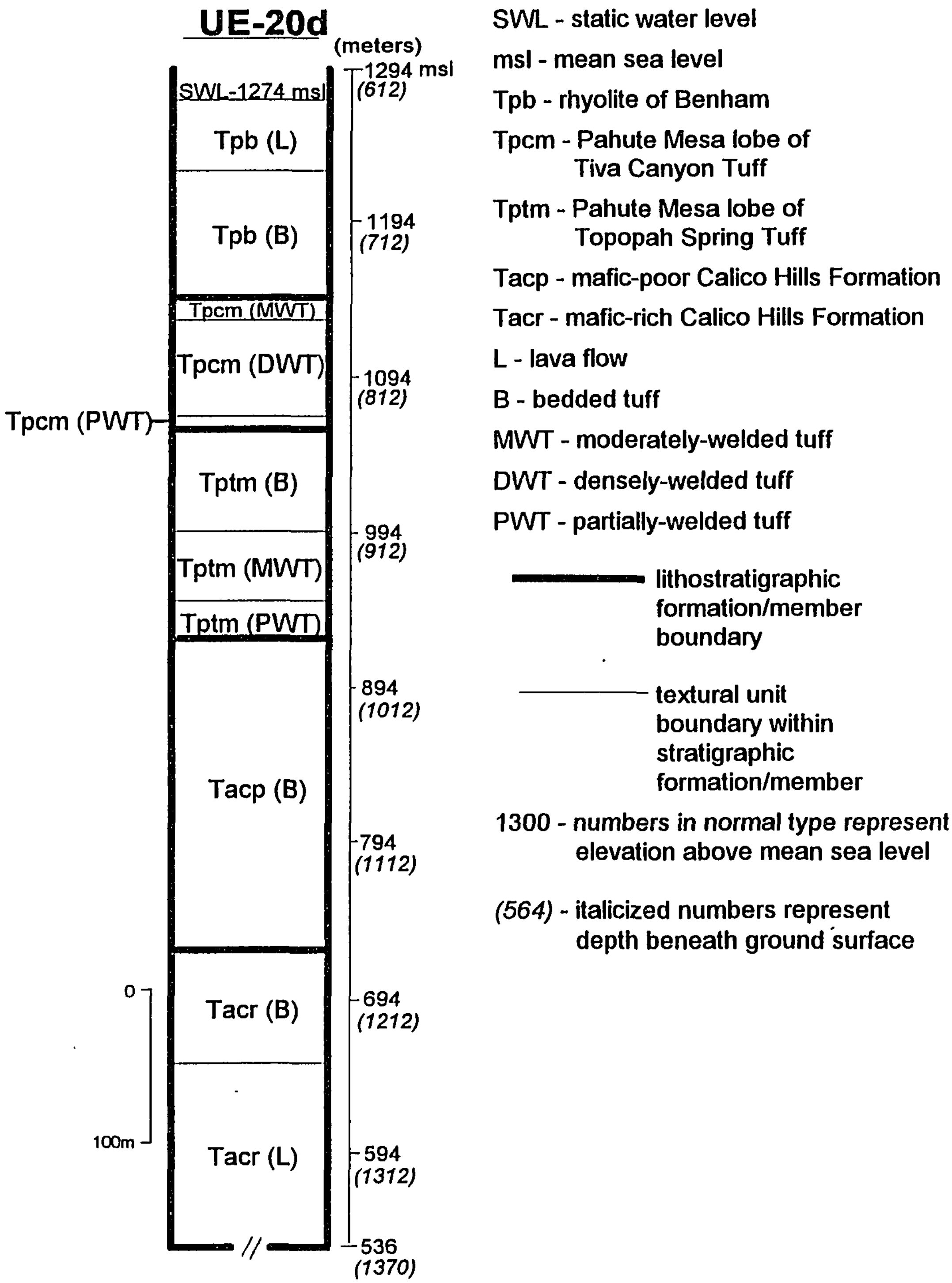

Figure 8. Lithostratigraphic column of exploratory well UE-20d in Pahute Mesa, Nevada Test Site (R. Warren, LANL, unpub. data, 1992).

Table 3. Unit depths and descriptions for UE-20d and UE-20f (R. Warren, LANL, unpub. data, 1992)

UE-20d			
Depth Interval (meters)	Unit	Depth Interval (meters)	Depositional Unit
577.29 - 759.56	Tpb	577.29 - 676.66	L - Lava Flow
759.56 - 836.68	Tpcm	676.66 - 759.56	B - Bedded Tuff
836.68 - 968.65	Tptm	759.56 - 774.19	MWT - Moderately-Welded Tuff
968.65 - 1170.43	Tacp	774.19 - 832.10	DWT - Densely-Welded Tuff
1170.43 - 1369.16	Tacr	832.10 - 836.68	PWT - Partially-Welded Tuff
		836.68 - 902.21	B - Bedded Tuff
		902.21 - 946.40	MWT - Moderately-Welded Tuff
		946.40 - 968.65	PWT - Partially-Welded Tuff
		968.65 - 1244.80	B - Bedded Tuff
		1244.80 - 1369.16	L - Lava Flow

UE-20f			
Depth Interval (meters)	Unit	Depth Interval (meters)	Depositional Unit
588.26 - 701.04	Tmrh	588.26 - 795.53	B - Bedded Tuff
701.04 - 795.53	Tmw	795.53 - 827.53	DWT - Densely-Welded Tuff
795.53 - 827.53	Tpcm	827.53 - 835.46	B - Bedded Tuff
827.53 - 899.16	Tptm	835.46 - 870.51	MWT - Moderately - Welded Tuff
899.16 - 1071.37	Tacp	870.51 - 924.76	NWT - Non-welded Tuff
1071.37 - 1323.75	Tacr	924.76 - 1106.42	L - Lava Flow
1323.75 - 1704.75	Tai	1106.42 - 1116.48	B - Bedded Tuff
		1116.48 - 1226.82	NWT - Non-welded Tuff
		1226.82 - 1267.97	B - Bedded Tuff
		1267.97 - 1323.75	PL - Pumiceous-Lava Flow

etc.) infer the depositional and cooling history of the rock, both of which greatly affect the rock's primary porosity.

To illustrate the relationship between the geologic units of UE-20f and UE-20d, the lithostratigraphic columns produced for each well were correlated in two separate ways. First, a correlation between the two wells based upon lithostratigraphic boundaries was performed to illustrate the occurrence and relative depth of the geologic units within each well (fig. 9). Secondly, the lithostratigraphic boundaries of the units were ignored and correlations between the two wells were based upon similar depositional units (fig. 10). This type of correlation emphasizes the mode of deposition and the cooling history of the rock, therefore, theoretically joining units containing similar primary porosity.

INTERPRETATION OF GEOPHYSICAL LOGS / DELINEATION OF HYDROSTRATIGRAPHIC UNITS

Hydrostratigraphic units were delineated within exploratory wells UE-20f and UE-20d by simultaneously interpreting specific suites of geophysical logs as to changes in the relative porosity and permeability of the units. Before delineation of these units, the geophysical logs listed in table 2 were examined to determine if the logs were "on-depth". This condition ("on-depth") refers to the depth of the casing (a known value) and the depth of the logs' response to the casing occurring at equal depths. This calibration insures the accuracy of the depth for a given log response. Measured logs run in UE-20f (temperature, electric, 3-D velocity, neutron, and caliper) were found to be "on-depth" and placed at equal depths to one another. The measured logs run in UE-20d (electric, density, velocity, 3-D velocity, and

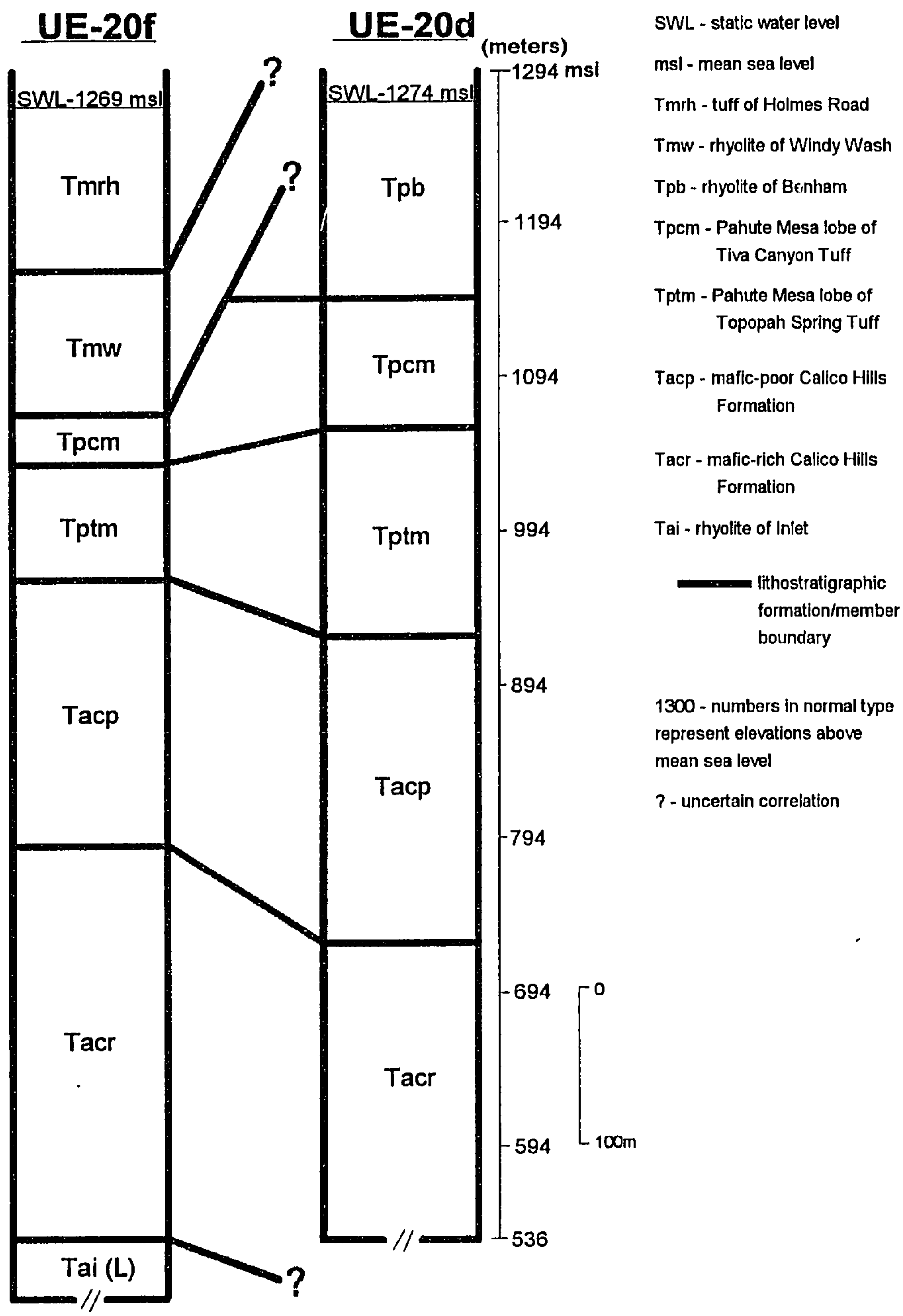

Figure 9. Correlation between units in UE-20f and UE-20d based upon lithostratigraphic formation/member boundaries.

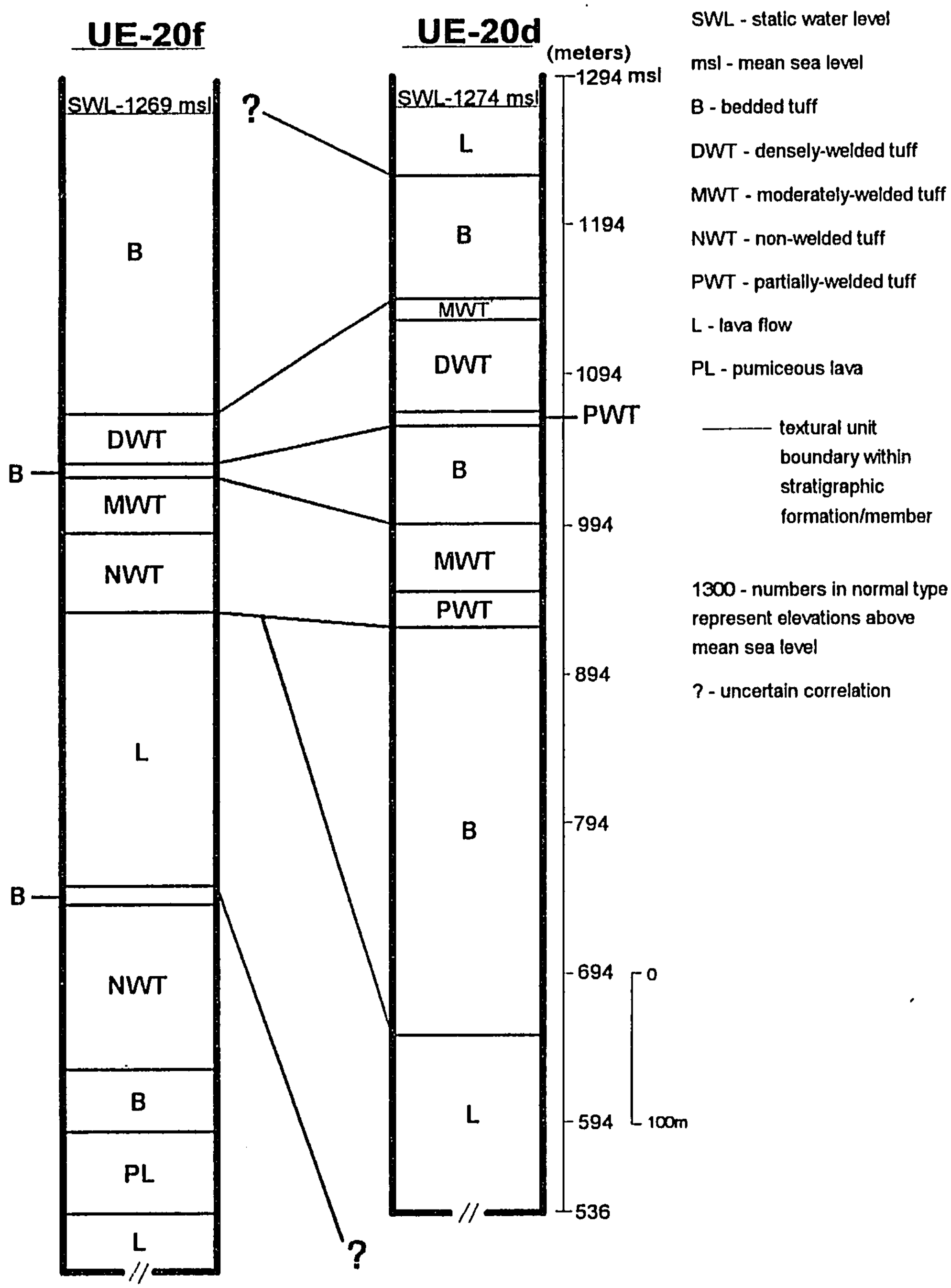

Figure 10. Correlation between units in UE-20f and UE-20d based upon textural unit boundaries within stratigraphic formations/members.

caliper) were discovered to be off-depth requiring adjustments to bring the responses at a recorded depth into agreement with true depth. Once the depth irregularities in UE-20d were calculated, the logs were placed at appropriate levels to one another. For clarification and reference purposes, the interpretation of the geophysical data, thus the delineation of separate hydrostratigraphic units, will be presented first followed by the description of the log responses within each identified interval.

The research interval in well UE-20f (SWL = 595 m - 1370 m depth) and UE-20d (SWL = 632 m - 1370 m depth) contains six major and four minor (localized) hydrostratigraphic units (fig. 11) (tables 4, 5). Of the six major units in UE-20f and UE-20d, H.U. #1, H.U. #3 and H.U. #5 are recognized as relatively less permeable than the remaining major units based upon geophysical log responses. The minor hydrostratigraphic units, H.U. #5fa, H.U. #5fb, H.U. #3d and H.U. #5d, are potential flow systems found to possess a relatively higher permeability than the adjacent units; however, the minor units are restricted to the individual wells and may not contribute to regional ground-water flow. The minor hydrostratigraphic units are identified by the number of the major hydrostratigraphic unit (e.g. #5) followed by the alphabetical letter of the well (e.g. #5f) in which it is found. In the event of two or more minor units occurring within the same major hydrostratigraphic unit of the same well, an alphabet letter accompanies the well number and letter (e.g. #5fa). Therefore, H.U. #5fa identifies one of the minor hydrostratigraphic units contained within H.U. #5 in exploratory well UE-20f.

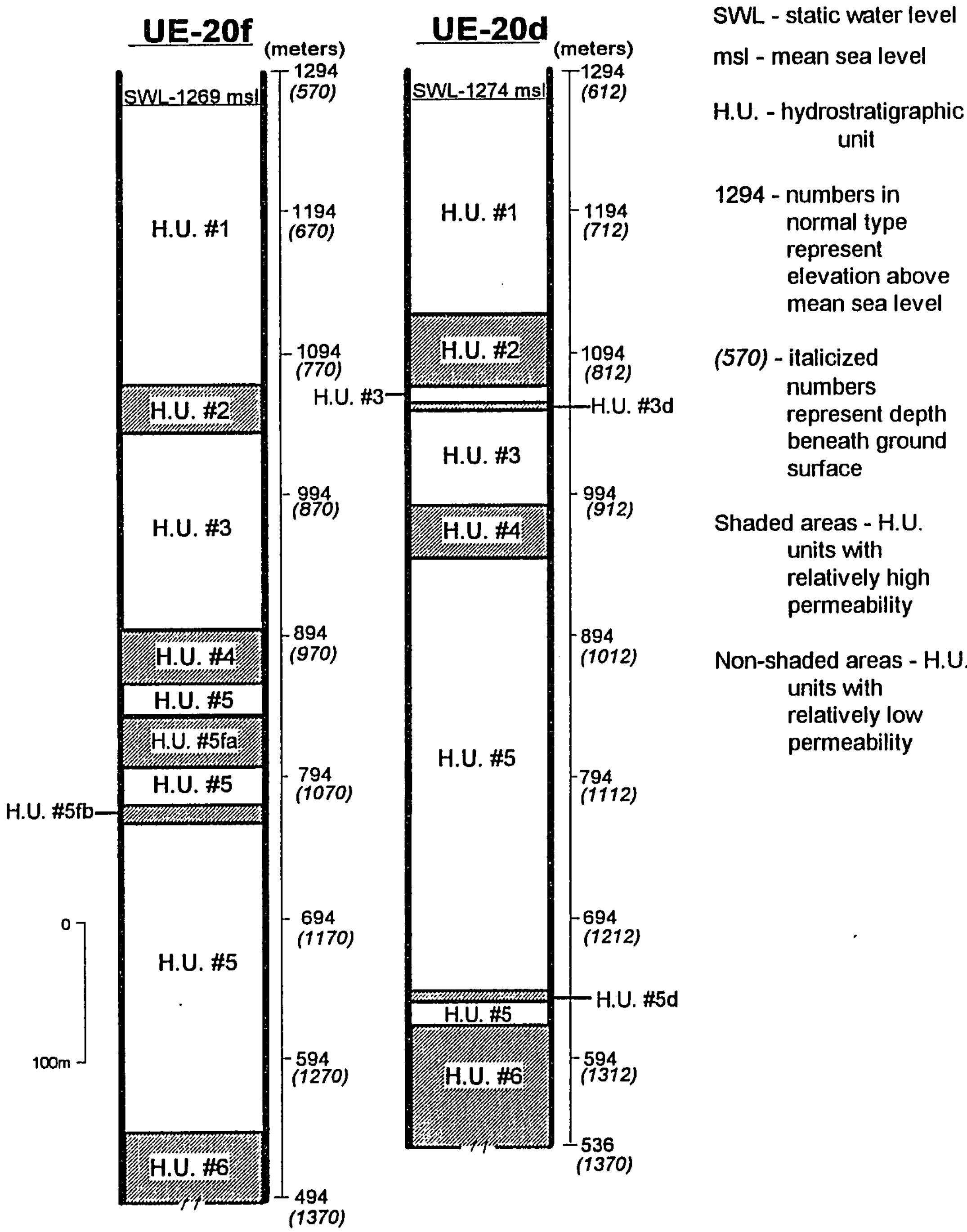

Figure 11. Hydrostratigraphic units delineated from geophysical log responses in UE-20f and UE-20d.

Table 4. Hydrostratigraphic unit depth intervals and relative permeabilities in UE-20f.

Hydrostratigraphic Unit	Depth Interval (meters)	Relative Permeability
H.U. #1	SWL-796	Low
H.U. #2	796-830	High
H.U. #3	830-968	Low
H.U. #4	968-1005	High
H.U. #5	1005-1325	Low
H.U. #5fa	1029-1067	High
H.U. #5fb	1093-1106	High
H.U. #6	1325-1370	High

SWL = static water level

Table 5. Hydrostratigraphic unit depth intervals and relative permeabilities in UE-20d.

Hydrostratigraphic Unit	Depth Interval (meters)	Relative Permeability
H.U. #1	(?)-784	Low
H.U. #2	784-834	High
H.U. #3	834-911	Low
H.U. #3d	842-846	High
H.U. #4	911-947	High
H.U. #5	947-1270	Low
H.U. #5d	1257-1260	High
H.U. #6	1270-1370	High

EXPLORATORY WELL UE-20F

HYDROSTRATIGRAPHIC UNIT #1 (H.U. #1)

The first hydrostratigraphic unit, H.U. #1 (fig. 11), is considered to be a low permeability unit, and geophysical log responses within the interval of H.U. #1 correspond to values previously identified in low permeability volcanic rocks at the NTS (Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). The electric log measurements are 50 ohm-meters or less (1 chart division) obtained from the 16-inch normal curve which is in accordance with resistivity readings previously established in bedded tuffs of low permeability (fig. 12)(Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). The fracture index for H.U. #1 (as evaluated from the 3-D velocity log) ranks this interval as a 4 indicating little- to no-fracturing (table 6), and the caliper log indicates a stable borehole with only small, isolated wash-outs that do not appear to affect the overall relative measurements. The neutron log maintains an average value of 6 chart divisions indicating a steady volume of water within the matrix of the non-fractured tuffs. The lack of secondary porosity within these units suggests negligible permeability based on the assumption that most ground-water movement beneath Pahute Mesa occurs through fractures (Blankennagel, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Rush and others, 1984; Thordarson and others, 1985).

The temperature log from UE-20f exhibits a steady decrease in temperature with depth of 1.3 ^{o}C (81.2 ^{o}F to 78.8 ^{o}F) for the first 165 m of the saturated zone (fig. 12). Temperature within the borehole stabilized at

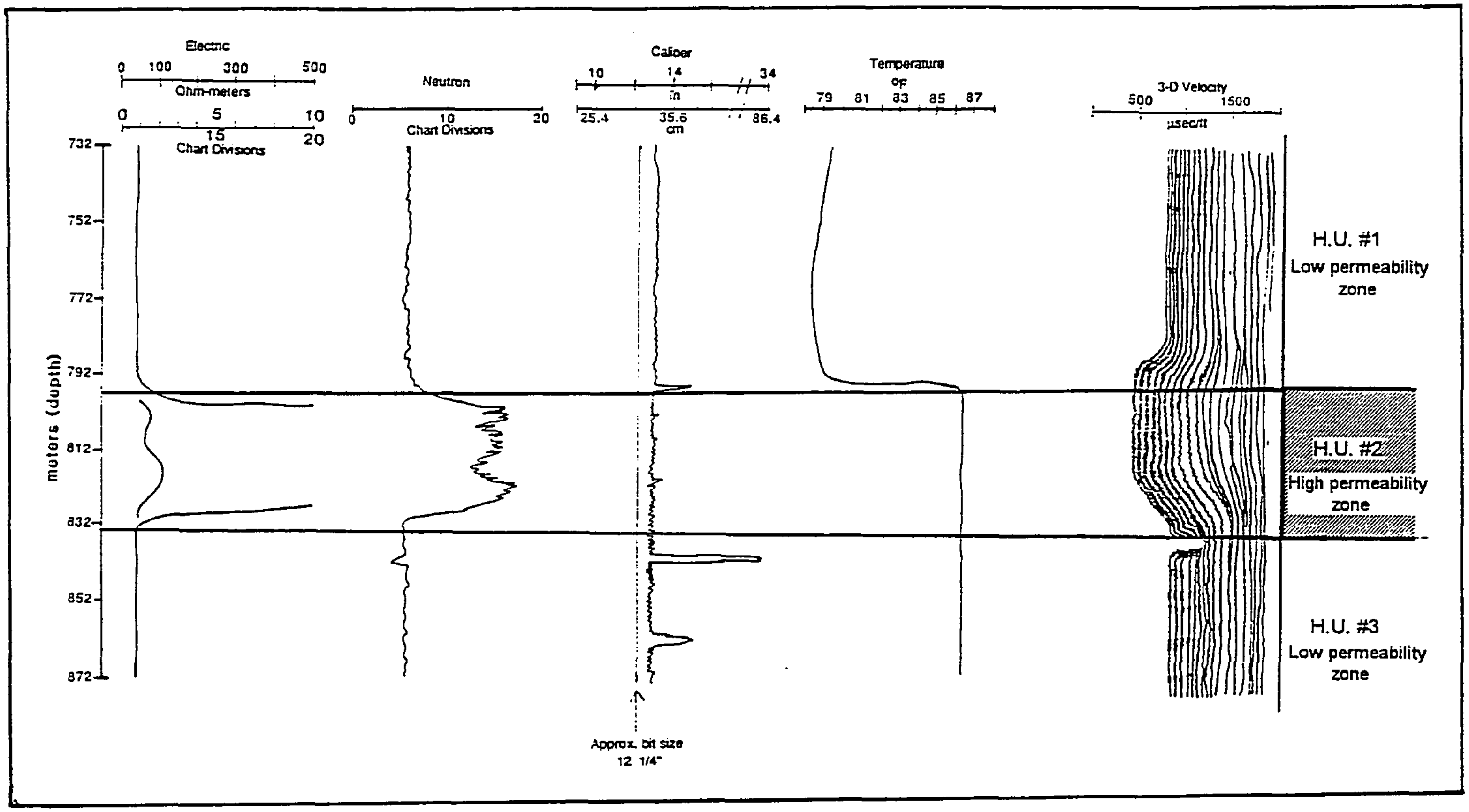

Figure 12. Generalized geophysical log responses to H.U. #1, H.U. #2, and H.U. #3 in UE-20f.

Table 6. Relative fracture index for major hydrostratigraphic units as determined from 3-D velocity logs in UE-20f and UE-20d.

Well #	Relative Fracture Index[1]					
	H.U. #1	H.U. #2	H.U. #3	H.U. #4	H.U. #5	H.U. #6
UE-20f	4	2	3	2	3	3
UE-20d	NR	2	NR	1	3.5	3

([1]Lower numbers represent relatively higher fracturing; NR = No response)

about 26 °C (78.8 °F) for 18 m between the interval of 762 m depth and 780 m depth followed by a gradual increase near the contact between H.U. #1 and H.U. #2. The lack of a radical increase or decrease in temperature within H.U. # 1 indicates a normal geothermal gradient within the shallow subsurface and the lack of water movement into, or out of, this zone suggesting low permeability within these units (Blankennagel, 1968).

HYDROSTRATIGRAPHIC UNIT #2 (H.U. #2)

The second hydrostratigraphic unit, H.U. #2 (fig. 11), is considered a relatively high permeability zone, and the geophysical data within this interval corresponds to values previously identified in high permeability rock. A resistivity measurement of over 12 chart divisions (1000 ohm-meters) is recorded within H.U. #2 as compared to less than 1 chart division (50 ohm-meters) in H.U. #1 (fig. 12). This increase in resistivity signifies lower porosity and more rock matrix in H.U. #2 as compared to H.U. #1. This resistivity measurement is in accordance with previous measurements of densely-welded tuffs and other competent volcanic rocks found within the NTS (Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

The 3-D velocity log records faster arrival times of the wave train within H.U. #2 than in the adjacent units indicating more competent rock within H.U. #2 (fig. 12). This interval is a 2 on the relative fracture index (table 6) based on the 3-D velocity log. The increased fracturing is more common in the denser lava flows and welded-tuffs (and is more likely to remain open) than in the less competent non-welded flows and ash-fall tuffs that are found within Pahute Mesa (Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Rush and others, 1984). Borehole rugosity and minimal borehole enlargement is recorded in H.U. #2 by the caliper log as a result of fracturing in the densely-welded tuff.

The neutron log measures an increase in count rates from approximately 6 chart intervals in H.U. #1 to an average of 14 chart intervals within H.U. #2 (fig. 12). Within this zone, the neutron log is not detecting as much water per volume of rock as in the low permeability zones, however, due to the assumptions made in this study and previous hydrologic investigations at the NTS, it is the dense, fractured zones that have the greater potential for ground-water movement.

The temperature log supports the classification of H.U. #2 as a relatively higher permeability zone (fig. 12). A decrease in temperature from 30 ^{o}C (86 ^{o}F) to 26 ^{o}C (79 ^{o}F) was measured in a 3 meter interval at the boundary between H.U. #1 and H.U. #2 indicating the transition from a permeable to a less permeable zone. This transition causes a rapid increase or decrease in the temperature within the borehole as the temperature adjusts to normal thermal gradients (due to the lack of influx) for that particular depth (Blankennagel, 1968).

HYDROSTRATIGRAPHIC UNIT #3 (H.U. #3)

Similar to H.U. #1, H.U. #3 is inferred to be a low permeability zone with geophysical log responses indicative of low permeability volcanic rock (fig. 11). A resistivity value of approximately 50 ohm-meters (1 chart division) is registered (as in H.U. #1) within H.U. #3 (fig. 12) (Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). A temperature increase of 0.4 ^{0}C within H.U. #3 is noted by the temperature log supporting the theory of little ground-water movement within this interval. Blankennagel (1968) explains this lack of temperature change as an indication of low permeability rock allowing little movement of water into, or out of, this region.

Hydrostratigraphic unit #3 contains few fractures over most of the interval, but the relative fracture density increases toward the base of H.U. #3 resulting in a fracture index of 3 for the entire section (fig. 12) (table 6). The neutron log measurements average 6 - 7 chart divisions which is similar to the neutron measurements in H.U. #1.

HYDROSTRATIGRAPHIC UNIT #4 (H.U. #4)

The fourth hydrostratigraphic unit, H.U. #4 (fig. 11), is inferred to be a relatively high permeability zone. Geophysical log responses in this interval include an increase in resistivity from 1 chart division (50 ohm-meters) registered in the overlying H.U. #3 to over 12 chart divisions (1000 ohm-meters) in H.U. #4 (fig. 13). This increase in the electric log response is accompanied by an increase in the count rates detected by the neutron tool from slightly less than 10 chart divisions in H.U. #3 to 19 chart divisions in H.U. #4. The 3-D velocity log records this unit as relatively more dense with

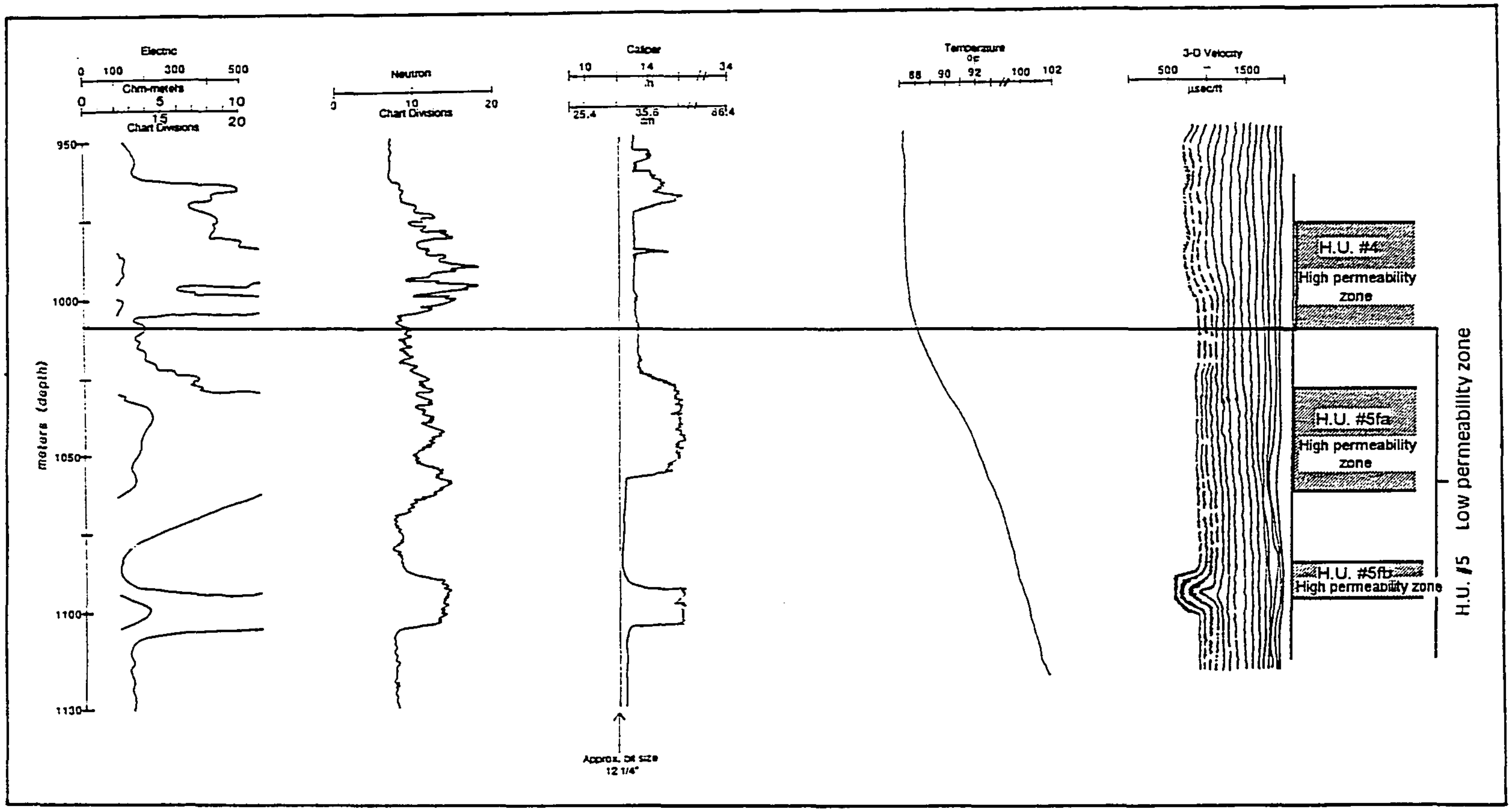

Figure 13. Generalized geophysical log responses to H.U. #4 and H.U. #5 in UE-20f.

an increase in fracturing (2 on the fracture index) (table 6) as compared to H.U. #3, and borehole rugosity continues in H.U. #4 but with a slight overall decrease as compared to H.U. #3 as measured with the caliper log.

The temperature log within UE-20f supports the concept of H.U. #4 as a permeable unit (fig. 13). The minor change of 0.2 ^{0}C with depth that occurs over the interval of H.U. #4 signifies the cross-flow of water within the borehole between the permeable intervals of H.U. #2 and H.U. #4 (Blankennagel, 1968). Also, a rapid temperature increase (with depth) begins at the lower boundary of H.U. #4 indicating an adjustment to normal geothermal gradients (for that depth) which has been observed by Blankennagel (1968) to occur above and/or below permeable zones.

HYDROSTRATIGRAPHIC UNIT #5 (H.U. #5)

Hydrostratigraphic unit #5 (fig. 11) is the lowermost low permeability unit delineated within UE-20f. The resistivity reading within H.U. #5 averages approximately 2.5 chart divisions (~125 ohm-meters) for the first 18 m to 21 m (fig. 13). This average is higher than previous resistivity measurements in UE-20f. This higher reading is probably due to the rock type (lava flow) that occurs within this zone, but this value is not as high as average values typically seen in competent rocks (i.e. lava flows) (Blankennagel, 1968; Snyder, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). One possible reason for the lower resistivity readings within the lava flow is alteration (i.e. zeolitization, argillization) that tends to increase the ion content in the interstitial fluids causing a decrease in the resistivity (Snyder, 1968). No correlation has been established between porosity and the degree of alteration (Blankennagel and Weir, 1973); therefore, by interpreting logs simultaneously, lower resistivity readings that may be due to alteration within the rocks should not affect this study. Information concerning alteration in both UE-20f and UE-20d was not available. Consequently, a correlation between alteration and resistivity values is not possible and alteration can only be assumed as a possible explanation for lower resistivity values. Most of the remaining interval of H.U. #5 exhibits an average resistivity value below 2 chart divisions (100 ohm-meters), however, fluctuations (not exceeding 3 chart divisions) occur sporadically possibly due to varying degrees of welding within isolated zones of the bedded and non-welded tuffs.

Neutron count rates in H.U. #5 range from approximately 7 to 10 chart intervals with some areas remaining only slightly below the boundary between low and high permeability rocks (10 chart intervals) (fig. 13). The upper portion of this unit contains an increase in fracturing especially in the upper half within the lava units as indicated by the 3-D velocity and caliper logs resulting in an average relative fracture index of 3 (table 6). The increase in fracturing could account for the higher water content identified by the neutron log and also the increase in the borehole roughness recorded by the caliper log. After 1106 m depth, the caliper log indicates borehole stability until the lower boundary of H.U. #5.

The temperature log increases from 31 ^{o}C (88 ^{o}F) to 44 ^{o}C (111 ^{o}F) in the 320 m span of H.U. #5 (fig. 13). The temperature increases more rapidly with depth within this zone than previously measured which also supports the interpretation that this unit is a low permeability zone. Areas of little or no water movement located above or below permeable zones often exhibit a rapid increase or decrease in temperature to adjust to the normal subsurface temperature of that depth (Blankennagel, 1968).

Two minor zones of high permeability (H.U. #5fa and H.U. #5fb) were identified within the low permeability interval of H.U. #5 (fig. 11). Most of the geophysical log responses for these minor units are similar to the previous measurements recorded in intervals delineated as zones of relatively high permeability.

The electric log measurements recorded in H.U. #5fa and H.U. #5fb increase from the average reading of 2 - 2.5 chart divisions in H.U. #5 to about 14 chart divisions (2000 ohm-meters)(fig. 13). This fluctuation in resistivity measurements may be due to varying degrees of alteration within the lava flow, however, the higher readings are typical in tightly-welded rock and other competent units (i.e. lava flow) as verified in previous studies (Blankennagel, 1968; Snyder, 1968; Carroll, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

The neutron log count rate within H.U. #5fa and H.U. #5fb averages 10.5 - 11 chart divisions which is identical to that of denser-rock types (containing less matrix porosity) within UE-20f. The 3-D velocity log maintains a relatively constant arrival time with a slight increase in fracturing in H.U. #5fa as compared to H.U. #5, but the interval of H.U. #5fb appears to contain fewer fractures than H.U. #5fa. The minor unit, H.U. #5fb, transmits the 3-D velocity signal much faster than either H.U. #5 or H.U. #5fa indicating a relatively "tighter" section of the lava flow (fig. 13).

The temperature log within H.U. #5 does not vary its response in the intervals of the minor hydrostratigraphic units. This lack of response appears to indicate that no influx or movement of ground water is occurring between any high permeability zone and H.U. #5 although isolated intervals (H.U. #5fa and H.U. #5fb) are capable of relatively higher permeability.

HYDROSTRATIGRAPHIC UNIT #6 (H.U. #6)

The lowermost hydrostratigraphic unit identified in UE-20f is a relatively high permeability zone designated H.U. #6 (fig. 11). Values from the electric log show an initial increase in resistivity from 1 to 5 chart intervals (50 to 250 ohm-meters) in H.U. #6 as compared to H.U. #5 (fig. 14). This increase, however, does not remain constant throughout the interval -- instead, the resistivity values fluctuate between 1 to 1.5 chart intervals below the 225 ohm-meter (4.5 chart division) boundary. Normally, this low resistivity would prevent the classification of this unit as a relatively more permeable zone, but the lithology and the remaining log values indicate that this zone is of higher permeability than the adjacent rocks.

As discussed previously, lava-flow units that have undergone alteration (zeolitization or argillization) have been observed to result in lower than normal resistivity values (Snyder, 1968). A possible explanation for the fluctuations in the resistivity values in H.U. #6 is an alternating pattern of vitrification/devitrification within this lava unit (H. Covington, USGS, written communication, 1993). Again, no correlation has been established between porosity and the degree of alteration (Blankennagel and Weir, 1973); therefore, although alteration processes may affect the electric log responses, it should not affect the porosity or the outcome of this study.

The count rates detected by the neutron log increase to approximately 11 chart intervals within H.U. #6, and the 3-D velocity log indicates a competent rock unit containing enough fractures to be ranked a 3 on the relative fracture index (fig. 14)(table 6). The borehole remains stable throughout this interval with only minor fracturing recorded by the caliper log.

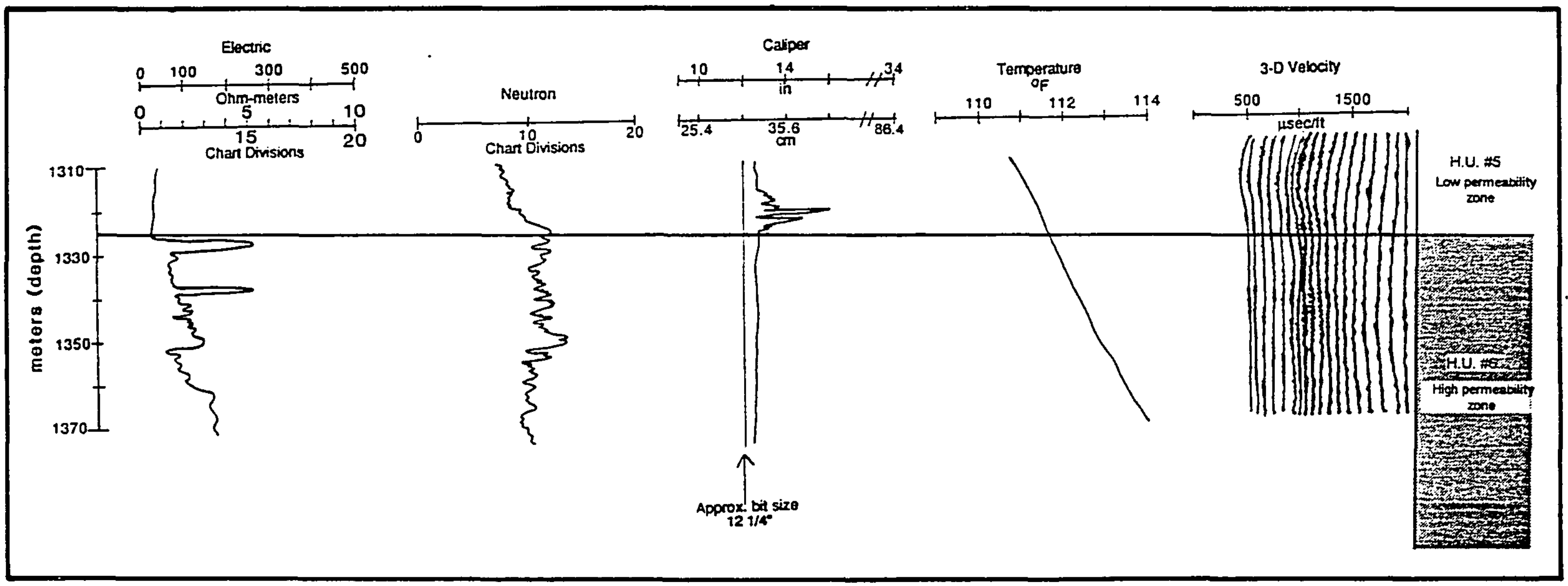

Figure 14. Generalized geophysical log responses to H.U. #6 in UE-20f.

EXPLORATORY WELL UE-20D

HYDROSTRATIGRAPHIC UNIT #1 (H.U. #1)

Hydrostratigraphic unit #1 is delineated as a relatively low permeability unit (fig. 11). Although the upper limit of the research interval in both UE-20f and UE-20d is the static-water level (this study only considers units within the saturated zone), the specific units contained within H.U. #1 in this well are not known due to the lack of data needed to identify the upper limit of this hydrostratigraphic unit. The suite of geophysical logs used to evaluate UE-20d have a top logged depth 100 m below the static-water level at approximately 732 m below ground surface. Within this 100 m interval (between static-water level and the depth of the logs used in this study), density, temperature, caliper, electric, and 3-D velocity measurements were taken, but the results are not used in this study due to the following factors: (1) the interval of the density log (205 m - 744 m) does not include the casing depth necessary to determine if the density readings are on-depth, (2) the paper copy that records the measurements of the density tool was not positioned properly, therefore, many of the measurements extend beyond the boundaries of the paper, (3) the temperature log was run within the same day as drilling in the well (well temperature was not stabilized), (4) a caliper log within this interval is of no value to this research without additional logs, (5) the electric log does not include the casing depth necessary to determine if the resistivity readings are on depth, (6) some responses of the electric log appear to be drawn by hand, and (7) the 3-D velocity log within this interval is not legible. Therefore, only the units below 732 m depth are known to be included within H.U. #1.

The resistivity readings in H.U. #1 maintain an approximate measurement of 1 chart division until 756 m (actual corrected depth of 760 m) at which time the resistivity values increase to an average of 3 - 3.5 chart divisions (100-175 ohm-meters) (fig. 15). This increase in resistivity is due to the change in lithology from a bedded tuff to a moderately-welded tuff accompanied by a decrease in matrix porosity (R. Warren, LANL, unpub. data, 1992).

Borehole problems in UE-20d within H.U. #1 prevent the assignment of a relative fracture index to this zone (table 6). The caliper log records large washed-out intervals (which increases the well diameter up to 38 cm in some areas) occurring within this interval that results in "no-response" from the 3-D velocity log (fig. 15). The velocity (sonic) log detects one 3 m zone of possible fracturing by exhibiting "cycle skipping" at a depth of 773 m to 776 m, but the density log does not show a decrease in count rates to a level designated in this study as indicative of a zone of relatively high permeability.

HYDROSTRATIGRAPHIC UNIT #2 (H.U. #2)

Geophysical log responses identify H.U. #2 as a relatively high permeability zone (fig. 11). The electric log measurements within this unit increase from an approximate value of 3 - 3.5 chart divisions (100-175 ohm-meters) to over 20 chart intervals (5000 ohm-meters) towards the base of H.U. #2 indicating a decrease in matrix porosity (fig. 15).

The caliper log, while still recording borehole rugosity and washed-out zones, recorded the interval of H.U. #2 as one of the most stable regions in UE-20d. This borehole stability enabled the 3-D velocity log to identify this unit as relatively competent and to record enough measurements to assign

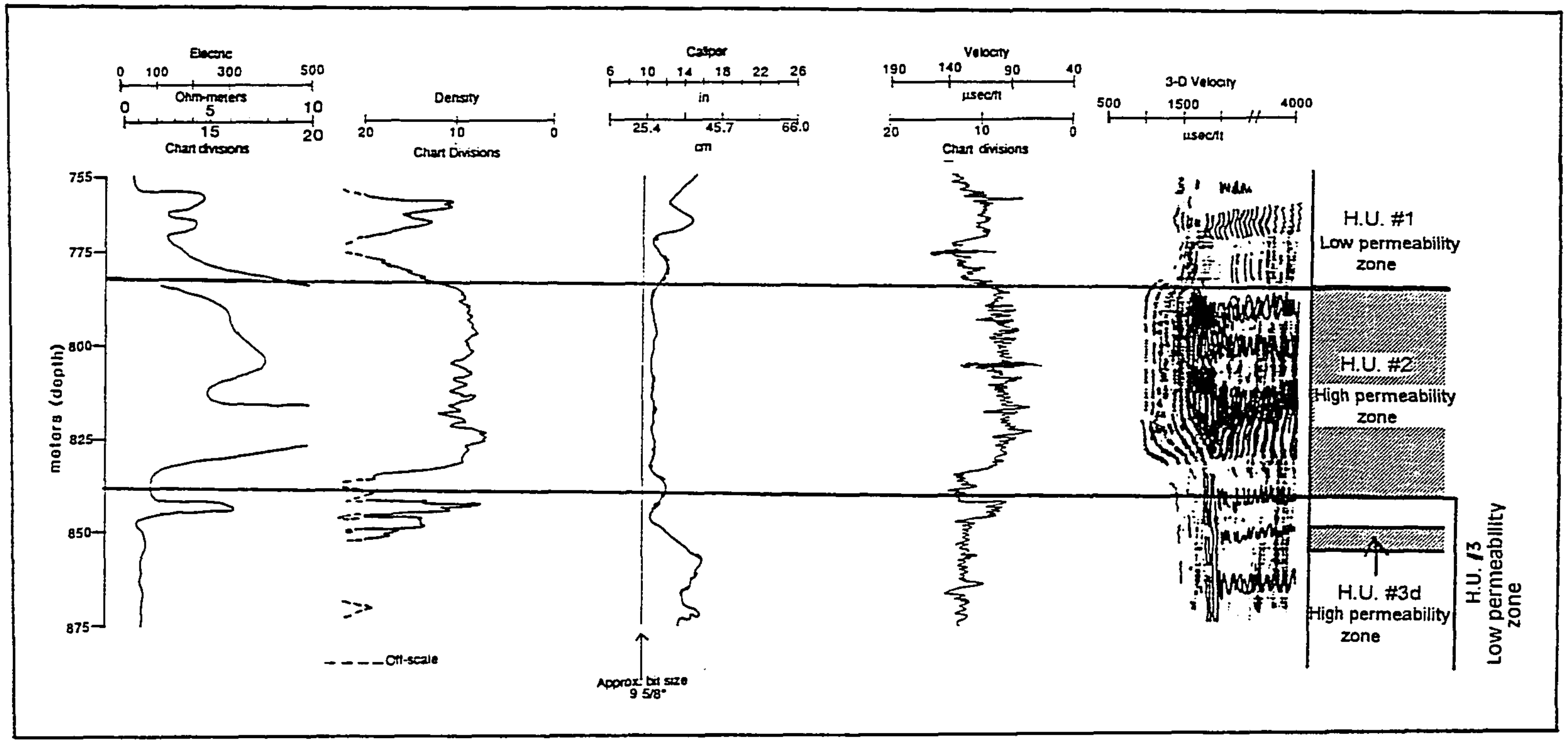

Figure 15. Generalized geophysical log responses to H.U. #1, H.U. #2, and H.U. #3 in UE-20d.

this tuff a value of 2 on the relative fracture index (table 6). The interval transit time of the velocity log decreases in the interval of H.U. #2 to approximately 6 chart divisions indicating a very competent unit. The density log registers a decrease in the count rates below 10 chart divisions also representing a decrease in porosity, yet an increase in permeability, per volume of rock.

HYDROSTRATIGRAPHIC UNIT #3 (H.U. #3)

Hydrostratigraphic unit #3 is delineated as a low permeability unit with geophysical log responses similar to other inferred low permeability zones within this study (fig. 11). A resistivity reading of 1.5 chart divisions (75 ohm-meters) or less is recorded in the interval of H.U. #3 by the 16-inch normal curve (fig. 15). The count rates detected by the density log increase well above 10 chart divisions indicating an increase in the porosity of the rocks, and the interval transit time of the velocity log increases indicating less competent units. The borehole within the interval of H.U. #3 increases from approximately 25 cm to 41 cm in some areas resulting in another "no response" from the 3-D velocity log. This precludes the relative classification of the fracture density within H.U. #3; however, the velocity log does not indicate any zones of fracturing by its lack of "cycle skipping" (fig. 15).

One minor hydrostratigraphic unit, H.U. #3d, is located within the upper portion of the low permeability interval of H.U. #3 (fig. 11). This 4 m minor unit exhibits log responses, like the minor units in UE-20f, similar to measurements recorded in UE-20d in intervals delineated as relatively high permeability zones.

The electric log measurements increase from the average reading of 2 chart divisions or less in H.U. #3 to 6 chart divisions in H.U. #3d (fig. 15). This variation in resistivity is possibly due to an increase in welding of the bedded tuff within this minor interval. The count rates detected by the density log decreased to about 10 chart intervals within H.U. #3d signifying less matrix porosity than H.U. #3, and the arrival time for the velocity log decreased indicating a relatively competent unit similar to H.U. #2. Although the borehole was relatively stable within the interval of H.U. #3d, the 3-D velocity log still registered (as in the entire interval of H.U. #3) a "no response" for the relative fracture index. Therefore, H.U. #3d is considered more permeable relative to the rest of H.U. #3, but it is not considered a participant in regional ground-water movement due to its lack of apparent areal extent (cannot be distinguished in UE-20d).

HYDROSTRATIGRAPHIC UNIT #4 (H.U. #4)

The fourth hydrostratigraphic unit, H.U. #4 (fig. 11), is considered more permeable than adjacent units and is characterized by an electric log response similar to hydrostratigraphic units in UE-20d believed to be of comparable permeability . This hydrostratigraphic unit displays an increase of 15 chart divisions (2500 ohm-meters) over H.U. #3 and demonstrates the variation in resistivity readings between competent and incompetent rocks (fig. 16).

The density log experiences a decrease to an average of 9 chart divisions in the count rates recorded within the interval of H.U. #4 (fig. 16). The decrease in the count rate corresponds to an increase in the bulk density of the tuff as a result of a decrease in the porosity per volume of rock material. The velocity log also registers a decrease in the transit time of the signal

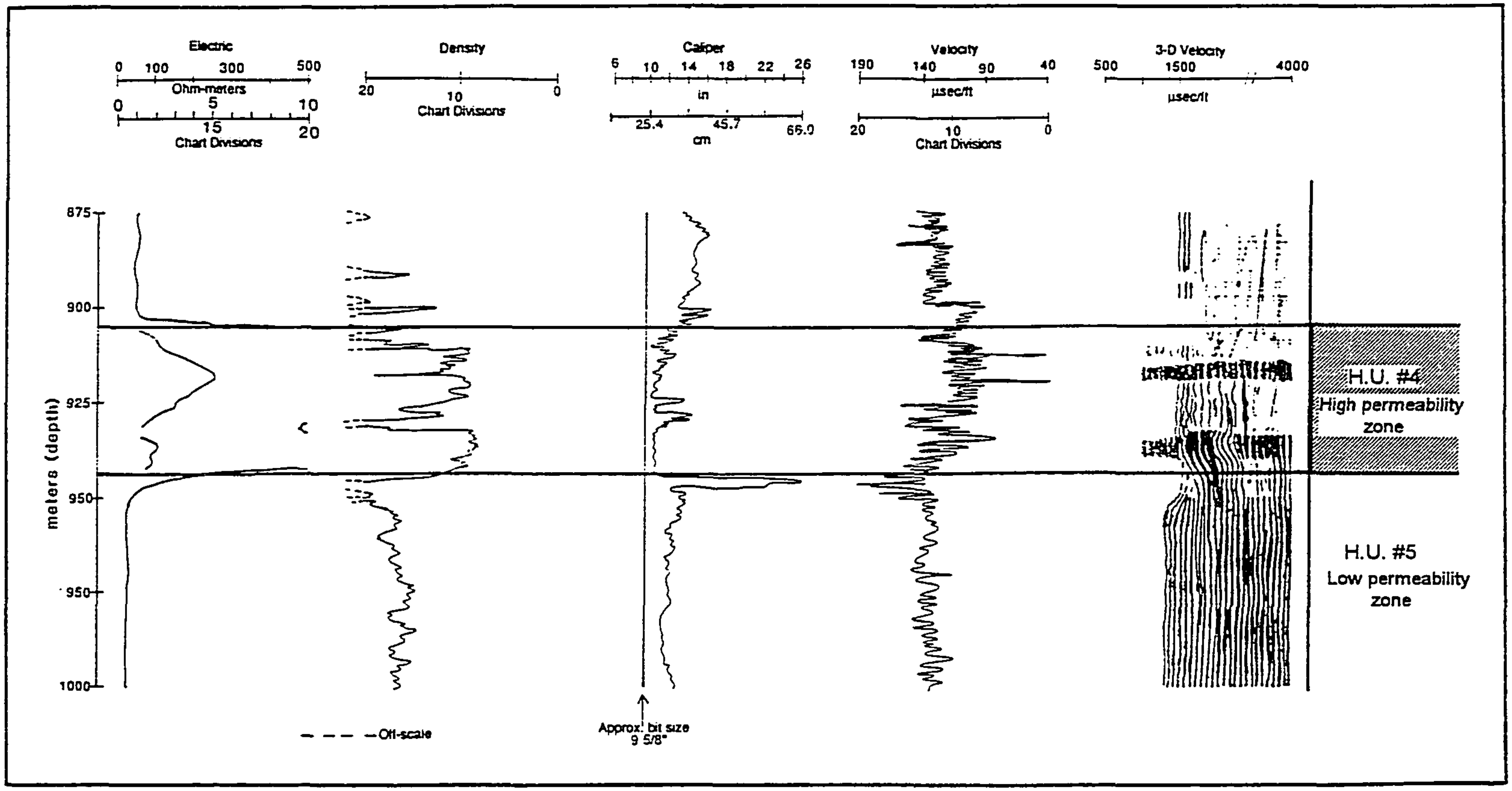

Figure 16. Generalized geophysical log responses to H.U. #4 and H.U. #5 in UE-20d.

which parallels the increase in rock volume. An increase in fracturing is recorded within this interval by the velocity log in the form of "cycle skipping" and by the attenuation of the signal from the 3-D velocity log. The borehole contains washed-out zones as a result of the fracturing within H.U. #4 particularly at the contact between H.U. #4 and H.U. #5. The effect does not prevent a comparison of the fracturing within UE-20d and the assignment of a 1 to H.U. #4 on the relative fracture index (table 6).

HYDROSTRATIGRAPHIC UNIT #5 (H.U. #5)

Hydrostratigraphic unit #5 is considered to be a relatively low permeability unit (fig. 11). The average resistivity measurement within H.U. #5 is approximately 1 chart division (50 ohm-meters) with the exception of one 31 m section around 1187 m depth (corresponding to the contact between the two bedded tuffs - not shown) with a resistivity of up to 2 chart divisions (fig. 16).

The borehole contains a fairly uniform enlargement averaging 5 cm over the length of the interval of H.U. #5 as recorded by the caliper log. A fracture index of 3.5 is assigned to this interval due to isolated fracture zones within the relatively unfractured hydrostratigraphic unit (table 6). Values from the velocity log remain above 10 chart divisions for most of H.U. #5, however, small zones within the units designated as mafic-poor bedded tuff, and the majority of the mafic-rich bedded tuff, register below 10 chart divisions. This decrease is possibly due to an increase in welding resulting in faster arrival times of the sound waves sonic signal.

One minor hydrostratigraphic unit of relatively high permeability, H.U. #5d, was delineated within H.U. #5 (fig. 11). This small, isolated interval maintains geophysical log responses that are generally seen in high secondary/low matrix porosity units. The electric log increases from 1 to about 6 chart divisions, and the caliper log records relative stability within the borehole (fig. 17). The velocity log decreases from 10 to an average of 2 chart divisions while the 3-D velocity log simultaneously registers a relatively competent unit. A slight increase in fracturing is detected by both the 3-D velocity and velocity log in the interval of H.U. #5d. As with the previously mentioned minor hydrostratigraphic units in both UE-20f and UE-20d, H.U. #5d apparently is not present in UE-20f indicating (to this study) limited geographic extent. As a result, this unit most likely does not contribute to regional ground-water movement.

HYDROSTRATIGRAPHIC UNIT #6 (H.U. #6)

The lowermost hydrostratigraphic unit, H.U. #6 (fig. 11), is delineated as a relatively high permeability unit exhibiting geophysical log responses similar to other inferred high permeability zones. The unit yields an electric log response similar to the electric response within H.U. #6 in UE-20f by exhibiting resistivity values below average in several regions with some (although less than in UE-20f) periods of fluctuations (fig. 17). However, these erratic measurements occur less frequently than in UE-20f, and below 1286 m depth, the resistivity readings (except for 1 brief interval) remain above 4.5 chart intervals (225 ohm-meters). If alteration and vitrification/devitrification processes are responsible for the irregular resistivity readings in both UE-20f and UE-20d, then it appears that rocks within UE-20d have undergone less alteration than rocks within UE-20f.

The density log recorded a decrease in its count rate from to below 10

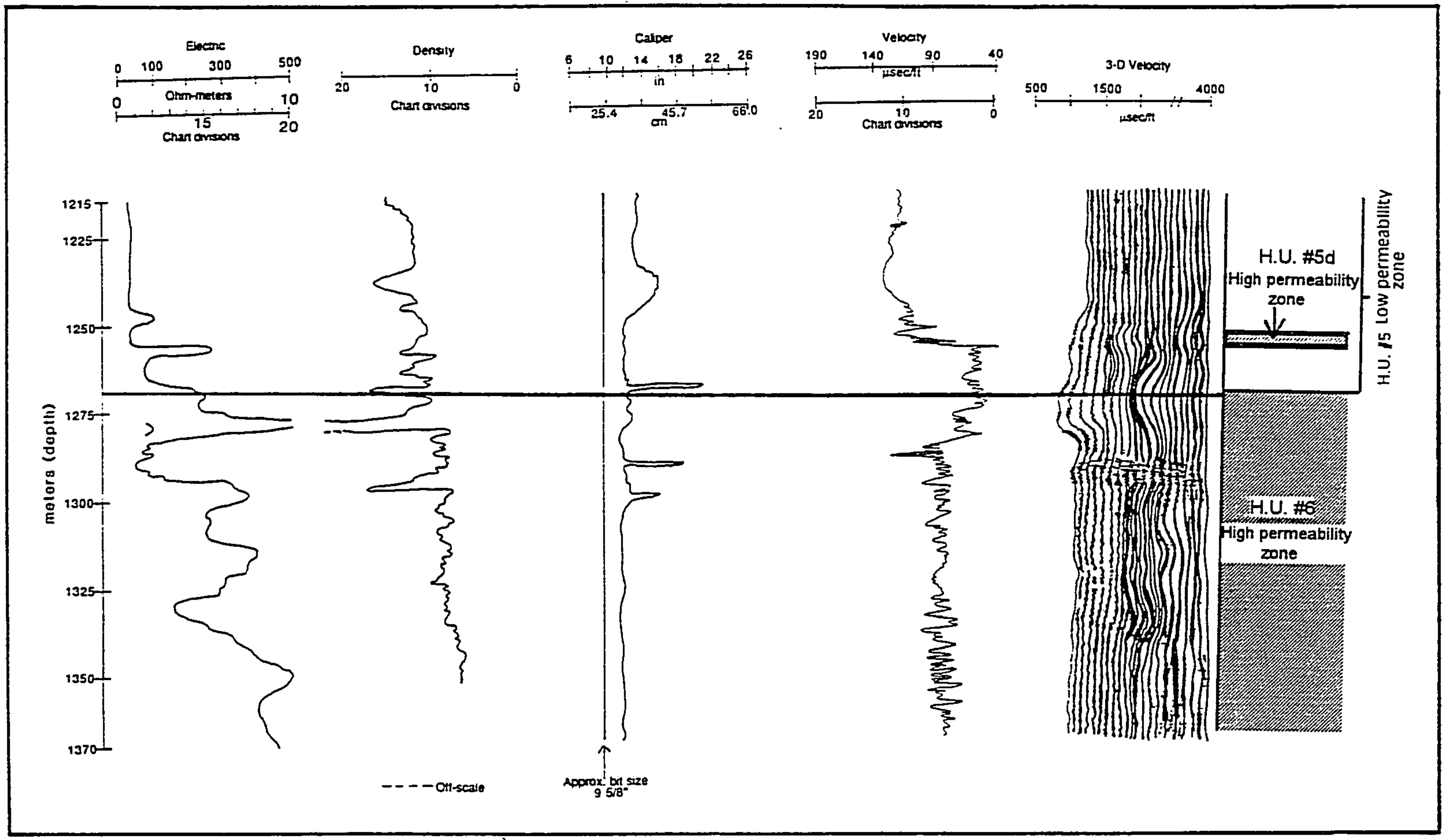

Figure 17. Generalized geophysical log responses to H.U. #5 and H.U. #6 in UE-20d.

chart divisions within H.U. #6 signifying less porosity (more bulk density) per volume of rock (fig. 17). Also, a decrease in the arrival times of both the velocity and 3-D velocity log identifies the lava flow as a competent unit containing low matrix porosity. Fracturing within H.U. #6 (as recorded with the 3-D log) is not extensive, and a relative fracture index of 3 is assigned to this unit (table 6). Only two minor episodes of "cycle skipping" are recorded by the velocity log suggesting only minor fracturing in H.U. #6. The caliper log records a fairly stable borehole with only few areas of wash-outs and enlargements.

CORRELATION OF HYDROSTRATIGRAPHIC UNITS DELINEATED IN UE-20F AND UE-20D

Hydrostratigraphic units delineated in exploratory wells UE-20f and UE-20d are correlated based upon similar porosity and permeability values as interpreted from geophysical logs (fig. 18). The approach used in this study (hydrostratigraphic units) distinguishes potential flow systems based upon significant changes in the physical properties of the rock resulting in hydrostratigraphic columns with an alternating pattern of low and high permeability zones. Beginning with the first significant change in the material properties of the rock located within the saturated zone of both UE-20f and UE-20d, the alternating pattern of potential low/high permeability zones is established within each well.

Correlation of hydrostratigraphic units between the two wells was based on zones of comparable porosity and permeability values. The sequence of these zones assumes that rock properties are continuous

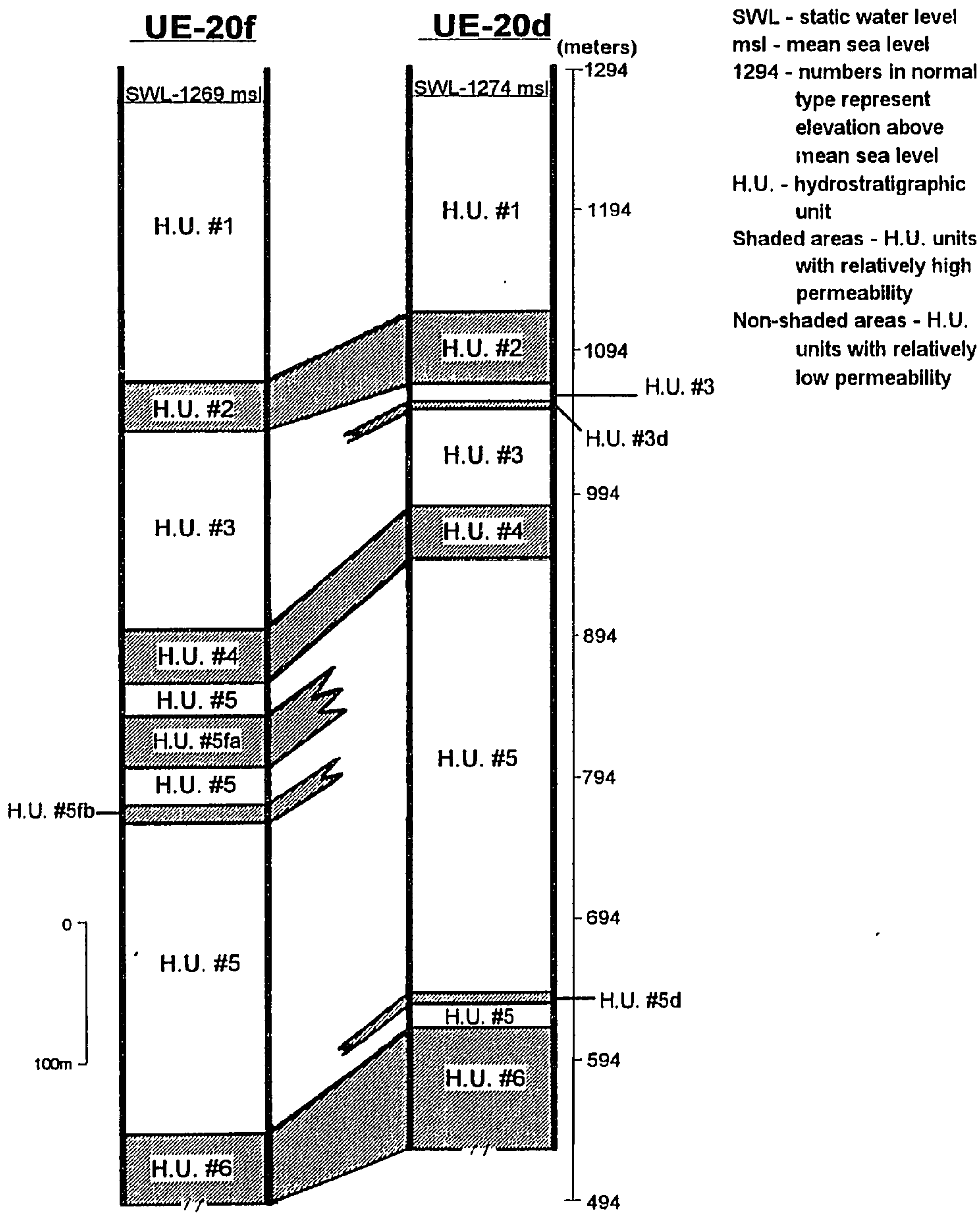

Figure 18. Correlation of hydrostratigraphic units delineated in UE-20f and UE-20d.

between the two wells. The relative position (depth) of the correlated units must be consistent with potential ground-water flow, and after considering the direction of local ground-water movement and the distance between the two wells, ground-water flow between the hydrostratigraphic units correlated between UE-20f and UE-20d is inferred.

The minor hydrostratigraphic units delineated in this study, H.U. #5fa, H.U. #5fb, H.U. #3d, and H.U. #5d, are geographically-limited potential-flow systems that are recognized only in the well in which it is located. The minor units do not extend to adjacent wells thus cannot be correlated between UE-20f and UE-20d. The minor units do not contribute to regional ground-water flow.

COMPARISON OF HYDROSTRATIGRAPHIC AND LITHOSTRATIGRAPHIC UNITS

One of the main objectives of this study is to determine whether enough variation exists between hydrostratigraphic and lithostratigraphic contacts to warrant the application of hydrostratigraphic units in future hydrogeologic investigations. A comparison of the lithostratigraphic boundaries (as provided by R. Warren, LANL, unpub. data, 1992) and the hydrostratigraphic boundaries delineated in this study in UE-20f and UE-20d illustrates the usefulness of utilizing hydrostratigraphic units in saturated-zone environments.

Many of the boundaries of the major hydrostratigraphic units in both UE-20f (fig. 19) and UE-20d (fig. 20) coincide with lithostratigraphic contacts. The contact between H.U. #1 and H.U. #2, between H.U. #2 and H.U. #3, and between H.U. #5 and H.U. #6 in UE-20f, and the contact between H.U. #1 and

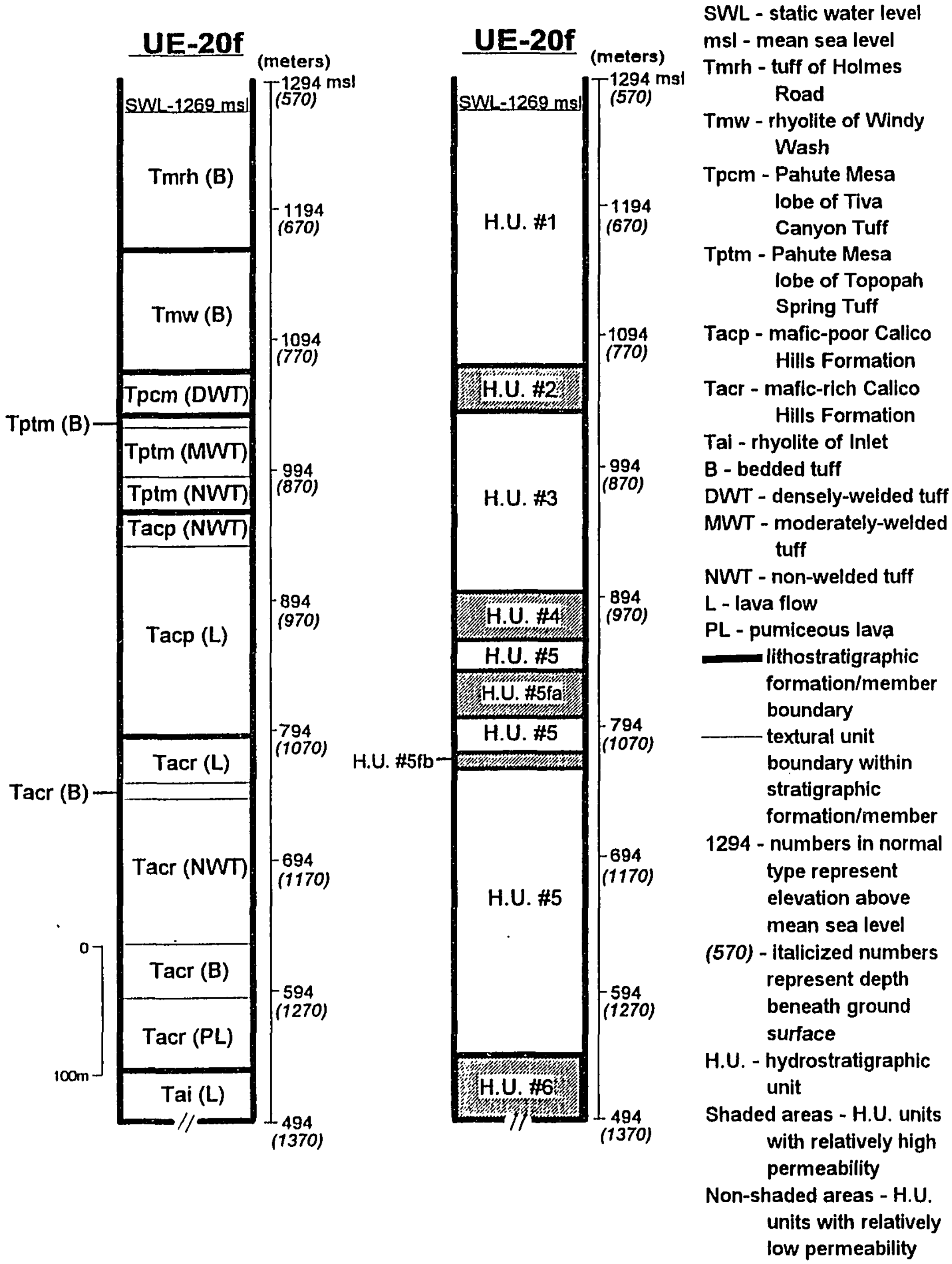

Figure 19. Lithostratigraphic units based upon preexisting information (R. Warren, LANL, unpub. data, 1992) and hydrostratigraphic units delineated in this study in well UE-20f.

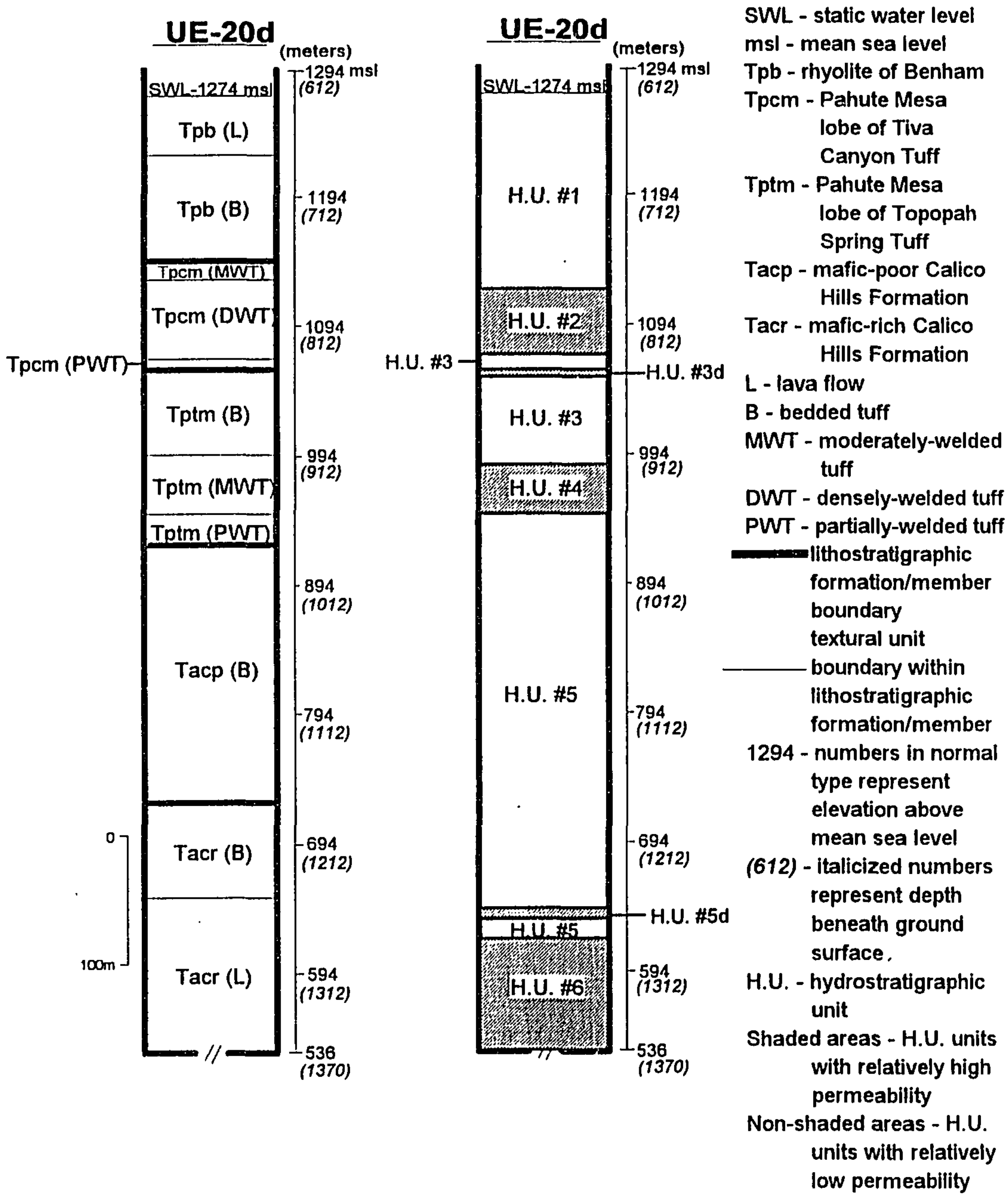

Figure 20. Lithostratigraphic units based upon preexisting information (R. Warren, LANL, unpub. data, 1992) and hydrostratigraphic units delineated in this study in well UE-20d.

H.U. #2, between H.U. #2 and H.U. #3, between H.U. #3 and H.U. #4, and between H.U. #4 and H.U. #5 in UE-20d occurs within close proximity to lithostratigraphic boundaries. This similarity in boundary locations is not unexpected since the criteria used to distinguish hydrostratigraphic units (porosity and permeability) is primarily a result of the rock's mode of deposition which also delineates separate lithostratigraphic units.

An important variation in the location of the lithostratigraphic verses hydrostratigraphic boundary is evident in H.U. #3 and H.U. #5 in UE-20f and in H.U. #1 and H.U. #5 in UE-20d. Contained within the individual hydrostratigraphic units are several lithostratigraphic units of varying rock type that normally contain different values of porosity and permeability. The denser, welded rock is generally assumed to contain less primary porosity and more secondary porosity (fractures) than the less dense and non-welded units, therefore, the potential ability of the different lithostratigraphic units to transmit ground water normally varies with the different rock type. However, the hydrogeologic properties of the lithostratigraphic units as measured by the geophysical logs used in this study indicate similar values of porosity and permeability, and therefore similar ground-water-flow potential resulting in the combination of separate lithostratigraphic units into one hydrostratigraphic unit.

Another important distinction between the boundaries of lithostratigraphic and hydrostratigraphic units is illustrated in H.U. #4 in UE-20f and H.U. #6 in UE-20d. Both hydrostratigraphic units are recognized (in this study) as high permeability zones that are contained within a competent lava flow. Significant variations in the physical properties of the individual lava flows as measured by the geophysical log responses indicate a potential inability of the lava unit to transmit ground water uniformly, thus, the individual lava flows are split into separate hydrostratigraphic units with distinct porosity and permeability values. Thus, as demonstrated by this study, a single hydrostratigraphic unit will incorporate separate lithostratigraphic units or separate a single lithostratigraphic unit into several hydrostratigraphic units depending upon the similarity and/or difference in the physical properties of the host rock(s) regardless of age, lithology, or mode of deposition.

DISCUSSION / CONCLUSIONS

Recognizing hydrogeologic units based strictly upon the lithostratigraphic boundaries of the host rock(s) assumes the ground-water-flow potential of the rock will remain constant throughout the entire unit. This method of delineation overlooks potential variation in the hydrogeologic characteristics of the rock which can cause fluctuations in the hydrogeologic unit's ability to transmit water. Hydrostratigraphic units classify rock based upon its porosity and permeability ignoring boundaries based upon age, lithology, and/or mode of deposition.

In research wells UE-20f and UE-20d, six major and four minor (localized) hydrostratigraphic units were delineated based upon distinct geophysical log responses from caliper, electric, density, neutron, 3-D velocity, temperature, and velocity logs. Based on the findings of this study, three of the major hydrostratigraphic units (H.U. #2, H.U. #4, H.U. #6) are relatively more permeable than the remaining three (H.U. #1, H.U. #3, H.U. #5). The hydrostratigraphic units with potentially high permeability occur within rock containing less primary (matrix) porosity and more secondary porosity (fractures) as determined from the geophysical logs. This inference agrees with previous studies on the volcanic rocks of this region which determined that ground-water movement within Pahute Mesa occurred primarily through fractures within the more competent volcanic rock (Blankennagel, 1968; Winograd and others, 1971; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975).

Hydraulic tests performed in UE-20f, UE-20d, and surrounding wells in Pahute Mesa in the 1960's determined that zones of zeolitized bedded tuff, in general, maintained the lowest permeability while competent units (i.e. welded tuff, rhyolitic lava flow) were major water-yielding zones (Blankennagel and Weir, 1973). Some of the water-yielding units identified by Blankennagel and Weir (1973) included rhyolitic lava flow, vitrophyre and welded tuff of the Volcanics of Area 20, welded tuff of the Paintbrush Group, and welded tuff of the Timber Mountain Group. The hydrostratigraphic units delineated in this study as zones of relatively high permeability occur within the rock-types identified in the 1973 study as major water-yielding units.

The permeability of the competent units depends on the amount of fracturing present within the relatively dense rock. The range in fracture densities within selected wells in Pahute Mesa (based on drill core) is recorded as 0 to 14 fractures per meter located primarily within rhyolitic lava flow, vitrophyre, and welded tuff (Blankennagel and Weir, 1973); but, an accurate depiction of the amount of fracturing within a unit is difficult to determine from core samples due to the low recovery in such intervals. In this study, the 3-D velocity log provides information on the relative amount of fracturing within units in UE-20f and UE-20d from which a relative fracture index was prepared for both wells. This type of geophysical log has been confirmed in previous studies as a valuable indicator of fractured-rock intervals (Carroll, 1968; Blankennagel and Weir, 1973). Based upon the 3-D velocity log, the highest degree of fracturing occurs within densely-welded tuff and rhyolitic lava in both UE-20f and UE-20d which agrees with previous fracture studies in volcanic rock (Blankennagel, 1968; Carroll, 1968; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Wood and Fernandez, 1988)(fig. 21). Cores obtained during drilling of UE-20f and UE-20d were physically inspected during this study and compared (when possible) to zones delineated by the 3-D velocity log as intervals of increased/decreased fracturing. Physical inspection of the drill cores agreed with fractured-zone intervals delineated by the 3-D velocity log.

Hydrostratigraphic units, unlike traditional hydrogeologic units, group rocks possessing similar porosity and permeability values without regard to lithostratigraphic contacts. The hydrostratigraphic units recognized in this study crossed both lithostratigraphic-formation/member boundaries and textural-unit contacts illustrating the change in emphasis from age, lithology, or mode of deposition to the material properties of the rock when identifying lithostratigraphic verses hydrostratigraphic parameters. The variation in boundary locations of the lithostratigraphic and hydrostratigraphic units, as illustrated in this study, demonstrates the need for applying the concept of hydrostratigraphic units for an accurate representation of potential ground-water flow in future hydrologic investigations.

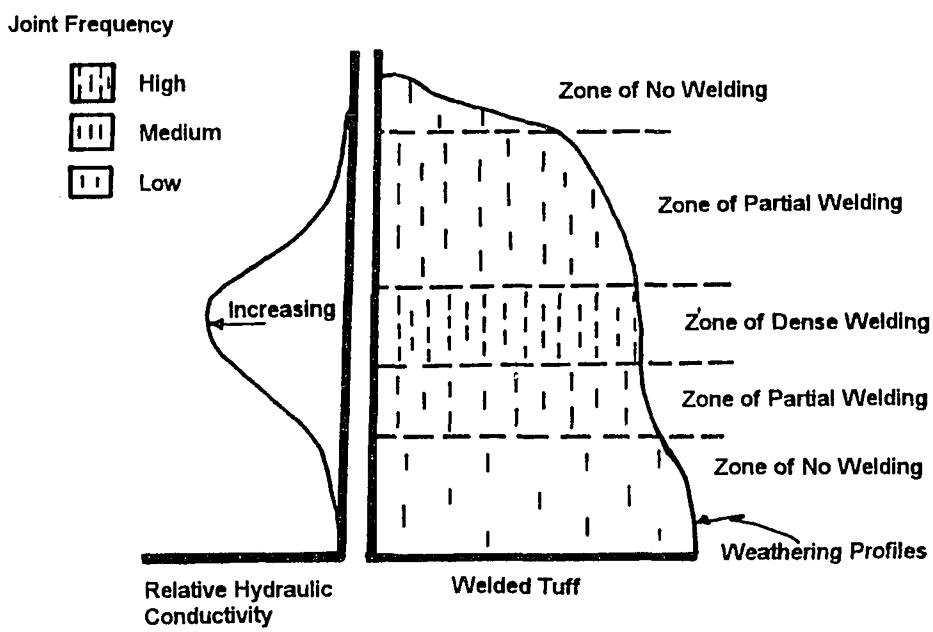

Figure 21. Comparison of joint frequency and hydraulic conductivity in a welded tuff (modified from Wood and Fernandez, 1988).

FUTURE WORK INTERESTS

This graduate research assistant is considering additional research with hydrostratigraphic units in UE-20f. Supplementary studies will possibly include attempts to place numerical ranges of both porosity and permeability within the hydrostratigraphic units identified in this study based upon existing data (i.e. core samples, limited hydraulic test data, geophysical logs, selected measured values from cores) and additional laboratory tests which was not possible during this limited study.

RECOMMENDATIONS

The delineation of hydrostratigraphic units in UE-20f and UE-20d was dependent upon data obtained in these wells approximately thirty years ago. The 1964 techniques, while not as sophisticated as techniques employed today, provide data that is now impossible to reproduce due to plugging of these wells. Present and future data collection (i.e. logging and coring) should go beyond data collection that only fulfills current needs, to the acquisition of as much information as possible for future investigations. It is recommended that a standard suite of geophysical logs be run in every hole drilled at the NTS including, but not restricted to, logs providing information on the resistivity, temperature, porosity and fracture density of the units. Also, coring the entire borehole to provide a continuous record of lithologic and textural changes in the rock units is an ideal practice, but unrealistic due to the high cost. For the benefit of present and future research, it is recommended that the predetermined coring interval be limited to a maximum distance of 46 m with additional core samples taken at every suspected lithostratigraphic contact. Finally, for a cost-effective method of performing an initial investigation into the hydrogeologic framework of the NTS, and in areas limited to existing data, it is recommended that hydrostratigraphic units be identified using geophysical logs as performed in this study.

APPENDIX

UNIT DESCRIPTIONS

(R. Warren, LANL, unpub. data, 1992)

Timber Mountain Group (Tm)

This calc-alkaline assemblage is distinctive by a generally high content of quartz phenocrysts in rhyolitic units. The upper part of the Timber Mountain Group consists of two petrochemically zoned large-volume ash-flow sheets and associated units erupted from the Timber Mountain caldera at 11.4 and 11.6 Ma. The lower part of the Timber Mountain Group is the Transition subassemblage (Tn), erupted 12.4 Ma, probably within the Claim Canyon caldera.

tuff of Holmes Road (Tmrh)

Widespread, lithologically distinctive rhyolitic bedded tuff; each bed has a base of pink, pumice-rich tuff that grades upwards into massive brown tuff. Scarce to common felsic phenocrysts are sanidine, plagioclase, and quartz. Distinctive tiny mafic and accessory minerals are scarce to rare hornblende, lesser biotite, rare clinopyroxene and scarce sphene. Brown tuffs are generally more mafic-and plagioclase-rich and pink tuffs very mafic-poor and quartz-rich.

rhyolite of Windy Wash (Tmw)

Rhyolitic flows and related breccia envelopes. Distinctive petrographic features are similar to those of underlying rhyolite of Water Pipe Butte: abundant felsic phenocrysts of sanidine, plagioclase, and quartz, common mafics of biotite and rare hornblende, and very abundant sphene.

Paintbrush Group (Tp)

This calc-alkaline assemblage is distinctive by a general absence or rarity of quartz phenocrysts in rhyolitic units and presence of sphene, with the exception of units in the lowest part of the Group. In addition to biotite, rhyolitic units in the upper part of the Paintbrush Group generally contain hornblende whereas units in the lower part generally contain clinopyroxene. Large-volume, zoned ash-flow sheets of the Topopah Spring (Tpt) and Tiva Canyon (Tpc) tuffs occupy the base and middle of the group, respectively; small-volume welded tuff and lava units occupy the remainder. The large-volume sheets probably erupted from calderas approximately coincident with the Timber Mountain caldera 12.7 - 12.8 Ma, perhaps displaced slightly to the south, and most of the small-volume units probably erupted within these calderas.

rhyolite of Benham (Tpb)

Rhyolitic flows and related breccia and tephra envelopes. Scarce to common felsic phenocrysts are sanidine, plagioclase, and rare quartz. Scarce to common mafics are biotite and rare hornblende, and sphene is present.

Pahute Mesa lobe of Tiva Canyon Tuff (Tpcm)

Zoned and strongly welded rhyolitic ash-flow tuff. Scarce felsic phenocrysts of sanidine and minor plagioclase, scarce to common mafics of biotite and clinopyroxene, and common sphene.

bedded Topopah Spring Tuff (Tptb)

Post-ignimbrite tephra immediately above Topopah Spring Tuff. Zoned like Topopah Spring Tuff. Near to top, scarce to common felsic phenocrysts of sanidine and plagioclase, and common to abundant mafics of biotite and rare clinopyroxene. Near base, scarce to rare felsic phenocrysts of plagioclase and lesser sanidine and quartz, and scarce to rare mafics of hornblende, biotite, and lesser clinopyroxene and orthopyroxene.

Pahute Mesa lobe of Topopah Spring Tuff (Tptm)

Zoned and strongly welded rhyolitic ash-flow tuff. Scarce felsic phenocrysts of sanidine, plagioclase, and minor quartz, and scarce biotite.

Volcanics of Area 20 (Ta)

This calc-alkaline assemblage is characterized by relatively large-volume rhyolitic lavas and related breccia and tephra envelopes. Quartz phenocrysts are abundant in all units, including mafic-rich ones. The volcanics of Area 20 erupted 12.9 Ma within the Area 20 caldera of the Silent Canyon caldera complex north of Timber Mountain, and south of Timber Mountain within an unknown structure.

mafic-poor Calico Hills Formation (Tacp)

Rhyolitic flows and related breccia and tephra envelopes, and associated non-welded ash-flow tuff. Tuff facies is much more prevalent than for most units that are not primarily welded tuff, and constitutes about half the volume of the mafic-poor Calico Hills Formation. Petrographically very distinctive, with rare biotite and scarce to rare felsic phenocrysts of quartz, sanidine, and lesser plagioclase.

mafic-rich Calico Hills Formation (Tacr)

Rhyolitic flows and related breccia and tephra envelopes, and associated non-welded ash-flow tuff. Petrographically very distinctive, with scarce to common biotite and felsic phenocrysts of quartz, plagioclase, and sanidine.

rhyolite of Inlet (Tai)

Thick rhyolitic flows and minor related breccia and tephra envelopes, known only in Pahute Mesa subsurface. Petrographically very similar to rhyolite of Prospectors Pass: common to abundant felsic phenocrysts of plagioclase, sanidine, and lesser quartz, and abundant mafics of biotite and lesser hornblende.

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