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Mr. Jeff Pohle
Division of Waste Management
Mail Stop SS-623
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

RE: NTS

Dear Jeff:

I am enclosing our conceptual model paper entitled "Conceptual Models of Groundwater Flow in the Saturated and Unsaturated Zones in the Vicinity of Yucca Mountain, Nevada." If you have any questions, please call.

Sincerely,

James L. Osiensky /sl

James L. Osiensky

JLO:sl

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LPDR ✓ (B, N, S)

Distribution:
J Pohle

(Return to WM, 623-SS) Sac

CONCEPTUAL MODELS OF GROUNDWATER FLOW IN THE SATURATED AND UNSATURATED ZONES IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

1 Introduction

Conceptual models of saturated groundwater flow as discussed herein refer to regional and local scales as described in the SOW. Our descriptions of "regional" and "local" groundwater flow systems refer more to scale rather than to the more restrictive definitions for these terms as coined by Toth (1963). Toth's definitions are generally accepted in the hydrogeological community. Toth defines "regional, intermediate and local" groundwater flow systems as follows: A regional groundwater flow system is defined as one that receives recharge at the basin divide and discharges at the bottom of the basin (fig. 1). A local groundwater flow system is defined as one that receives recharge at a topographic high and discharges at an adjacent topographic low. Toth considers topographic highs and lows to be synonymous with groundwater divides. An intermediate groundwater flow system receives recharge at a topographic high but has one or more topographic highs and lows (local flow systems) between its recharge area and its discharge area. The data base in the vicinity of Yucca Mountain does not permit us to adhere strictly to these definitions during our ensuing discussion of conceptual models. Consequently we are forced to address conceptual models more in terms of scale rather than in terms of the locations of groundwater divides as Toth did.

Conceptual models of flow in the unsaturated zone described herein are limited to the immediate vicinity of the potential Yucca Mountain repository. Our discussion of these conceptual models is presented under the heading "Conceptual Models of Groundwater Flow in the Vicinity of Yucca Mountain."

2 Conceptual Models of Regional Groundwater Flow

2.1 Hydrostratigraphic Units

Current USGS conceptual models of groundwater flow in the vicinity of Yucca Mountain are based primarily on conceptual models proposed originally by Winograd and Thordarson (1975). The conceptual models of Winograd and Thordarson have been modified to include data that were not available during development of the original conceptual models. Wherever appropriate we have pointed out deficiencies of proposed models; we also have identified deficiencies in the data base that introduces weaknesses into the proposed models.

Regional groundwater flow in the vicinity of the Nevada Test Site occurs within the Death Valley groundwater basin. Figure 2 shows the approximate topographic boundary of the regional groundwater flow system. Based on

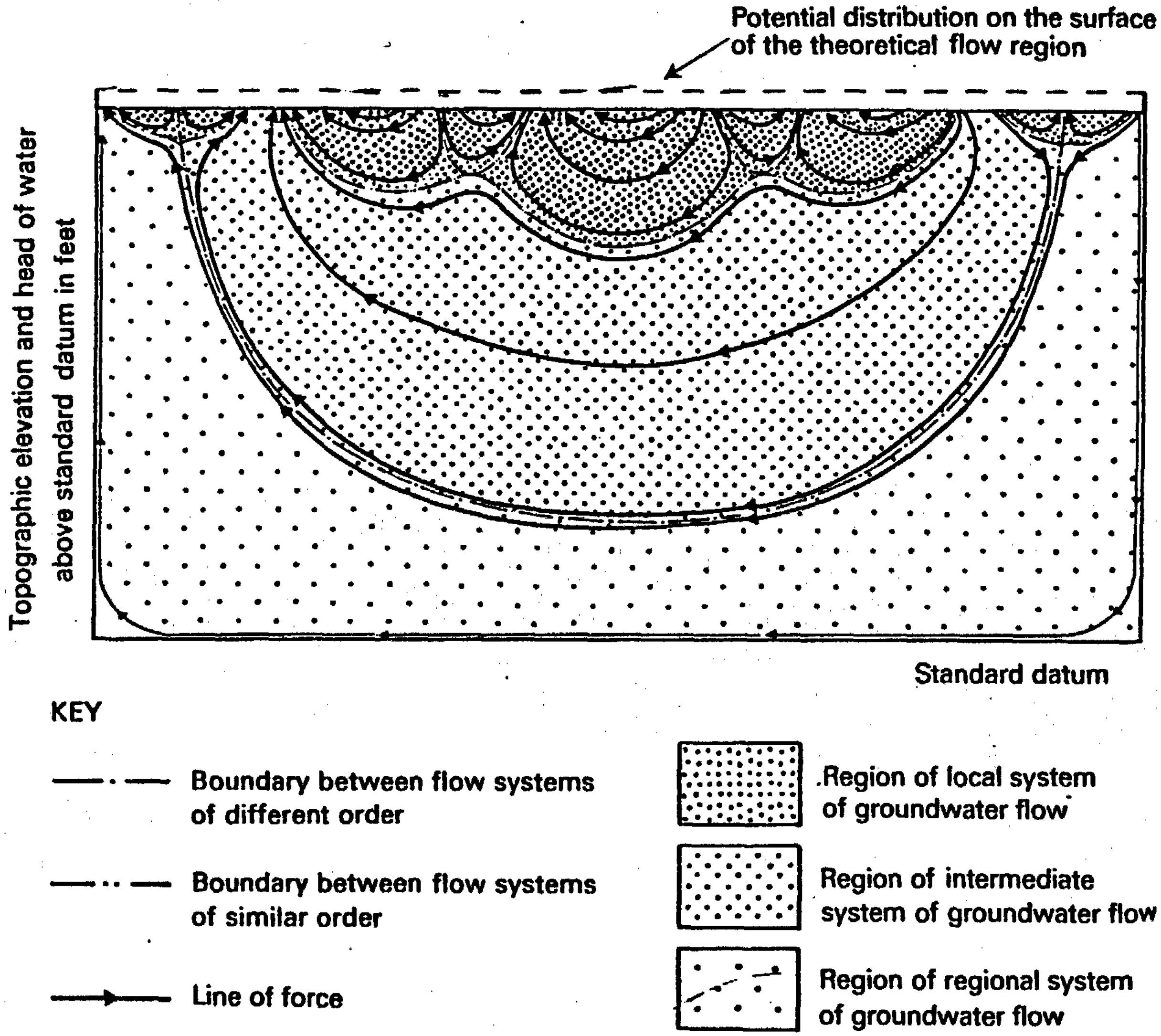


Figure 1. Theoretical flow pattern and boundaries between different flow systems (after Toth, 1963).

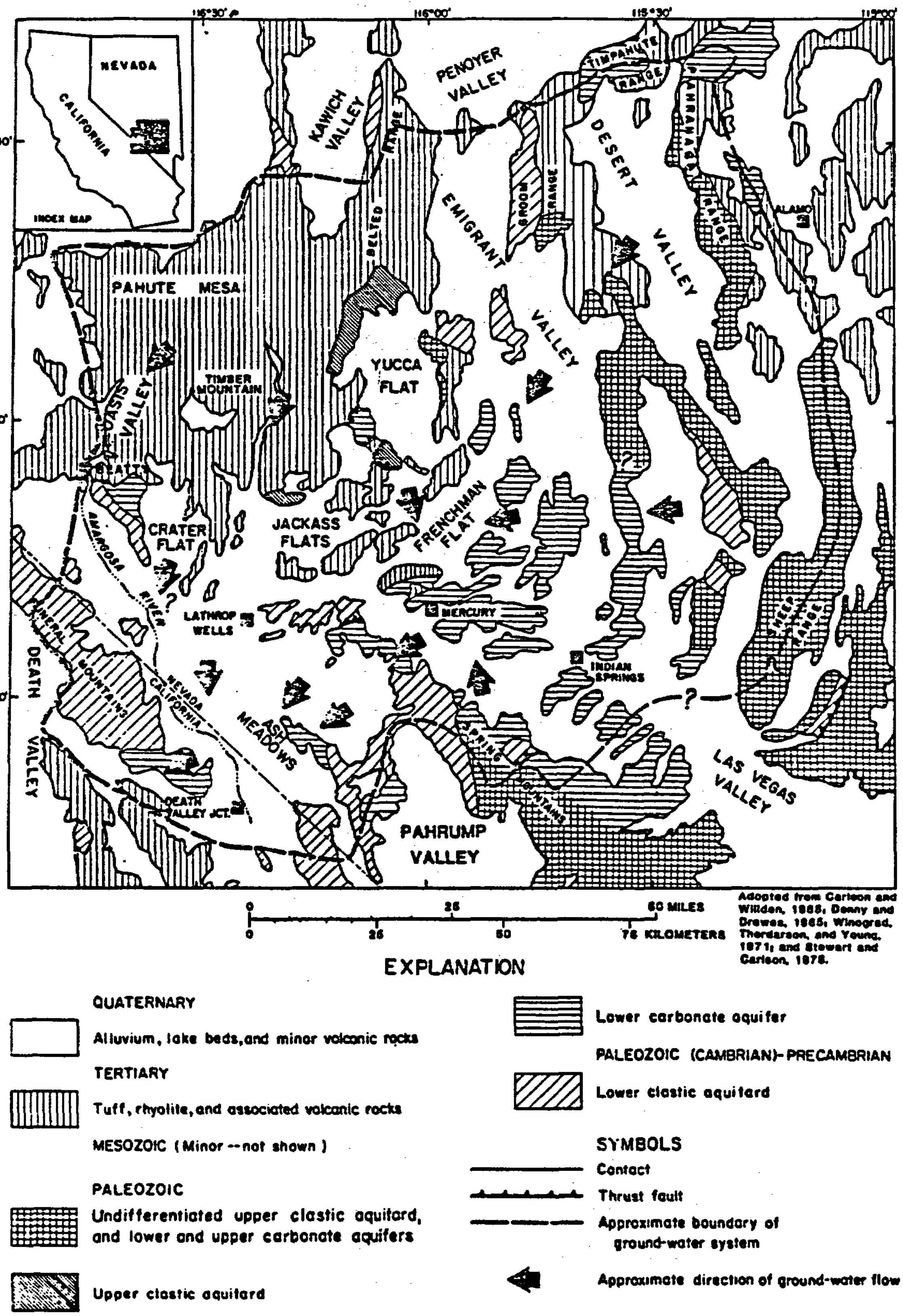


Figure 2. Generalized geology (after Waddell, 1982).

topography, probable groundwater recharge areas (identified primarily as synonymous with relatively high precipitation areas), and observed groundwater discharge areas, the Death Valley groundwater basin has been divided into three subbasins. These subbasins are: Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek Ranch subbasins (fig. 3). According to the principles of Toth (1963), groundwater flow within these subbasins consists of local and intermediate groundwater flow systems. These flow systems are interpreted to be superimposed upon the regional groundwater flow system that exists within the upper and lower carbonate aquifers. The upper and lower carbonate aquifers are separated by a hydrostratigraphic unit called the upper clastic aquitard. The lower carbonate aquifer is underlain by a unit called the lower clastic aquitard. Figure 4 shows the general stratigraphic relationships among the hydrostratigraphic units in the vicinity of Yucca Mountain. Figure 5 shows the general geographic distributions of hydrostratigraphic units.

According to Winograd and Thordarson (1975), the lower clastic aquitard is composed of quartzites and shales of the Johnnie, Stirling, Wood Canyon, and Carrara Formations. According to Waddell and others (1984) the transmissivity of the lower clastic aquitard is approximately 10 m^2/d (meters squared per day) but essentially no field data exist; because of this relatively low hydraulic conductivity, the lower clastic aquitard is considered to have a significant effect on the distribution of hydraulic potential in the locations of groundwater discharge areas. Total thickness of the lower clastic aquitard is approximately 2,700 m (meters). The lower carbonate aquifer consists of limestones and dolomites of Cambrian, Ordovician, Silurian, and Devonian Ages. Total thickness of this unit exceeds 4,700 m; transmissivities range from 10 to 10,000 m^2/d (Waddell and others, 1984). Consequently, the entire section clearly is not an aquifer. The lower carbonate aquifer is considered to be the major groundwater aquifer in the vicinity of the Nevada Test Site. Data are not available that would facilitate division of this aquifer into more detailed hydrostratigraphic units (aquifers and aquitards).

The upper clastic aquitard consists primarily of argillite, with minor quartzite and limestone strata, of the Eleana Formation. The maximum thickness of this unit is approximately 2,400 m; transmissivity is estimated to be 5 m^2/d or less (Waddell and others, 1984). But no field data are available for the Eleana Formation in the vicinity of Yucca Mountain.

The upper carbonate aquifer consists of the Tippipah Limestone of Pennsylvanian and Permian Age. The maximum thickness of the upper carbonate aquifer exceeds 1,000 m; however, it is considered to be of minor regional hydrogeologic significance because it is saturated only under the western portion of Yucca Flat (Waddell and others, 1984). The upper carbonate aquifer and the lower carbonate aquifer form a single hydrogeologic unit in the eastern part of the candidate area due to the absence of the upper clastic aquitard (fig. 4). According to Waddell and others (1984), the transmissivity of the upper carbonate aquifer ranges from about 10 to 1,250 m^2/d. It has not been differentiated into more detailed hydrostratigraphic

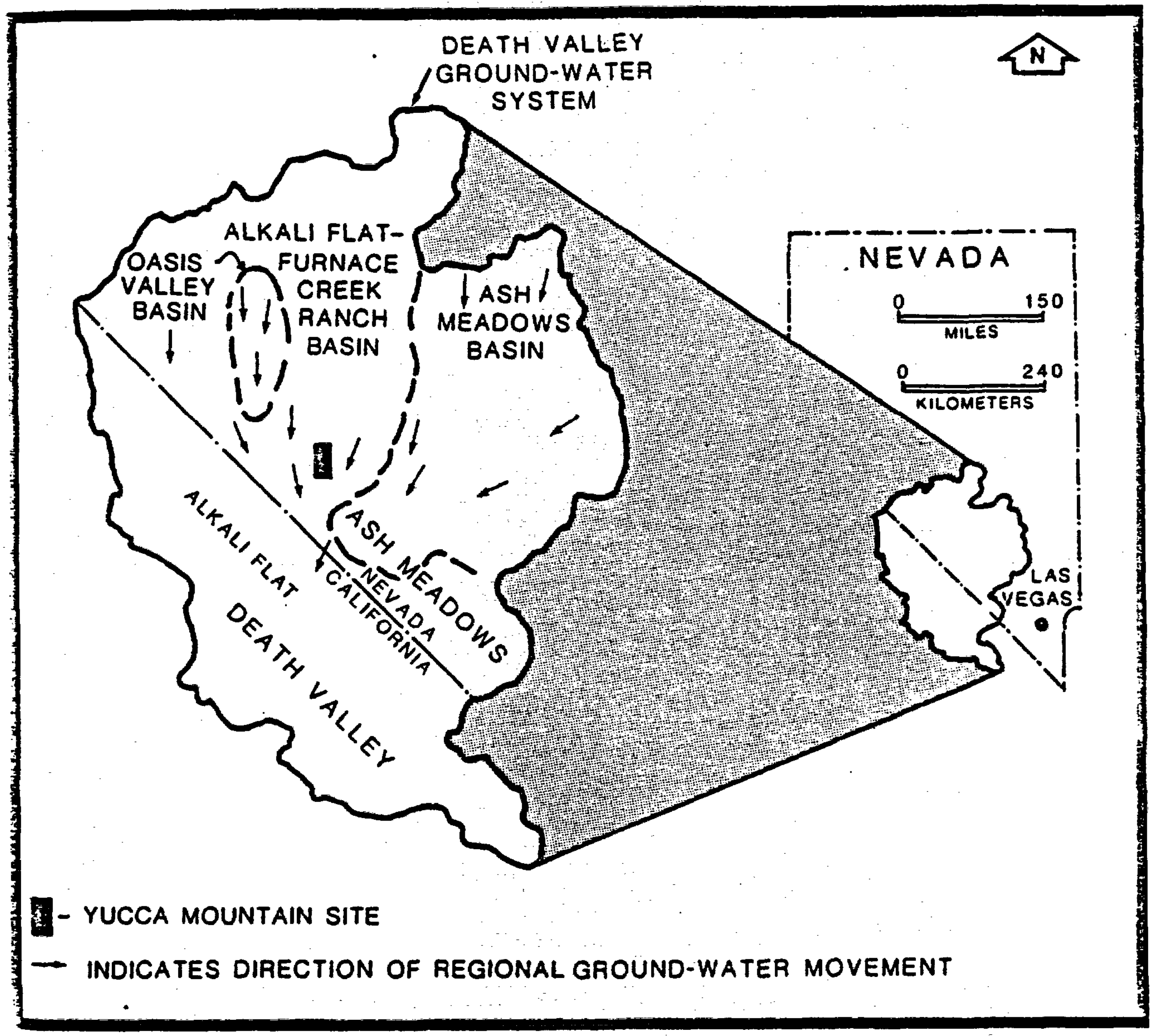


Figure 3. Location of Yucca Mountain site with respect to the basins of the Death Valley groundwater system (modified from Waddell, 1982).

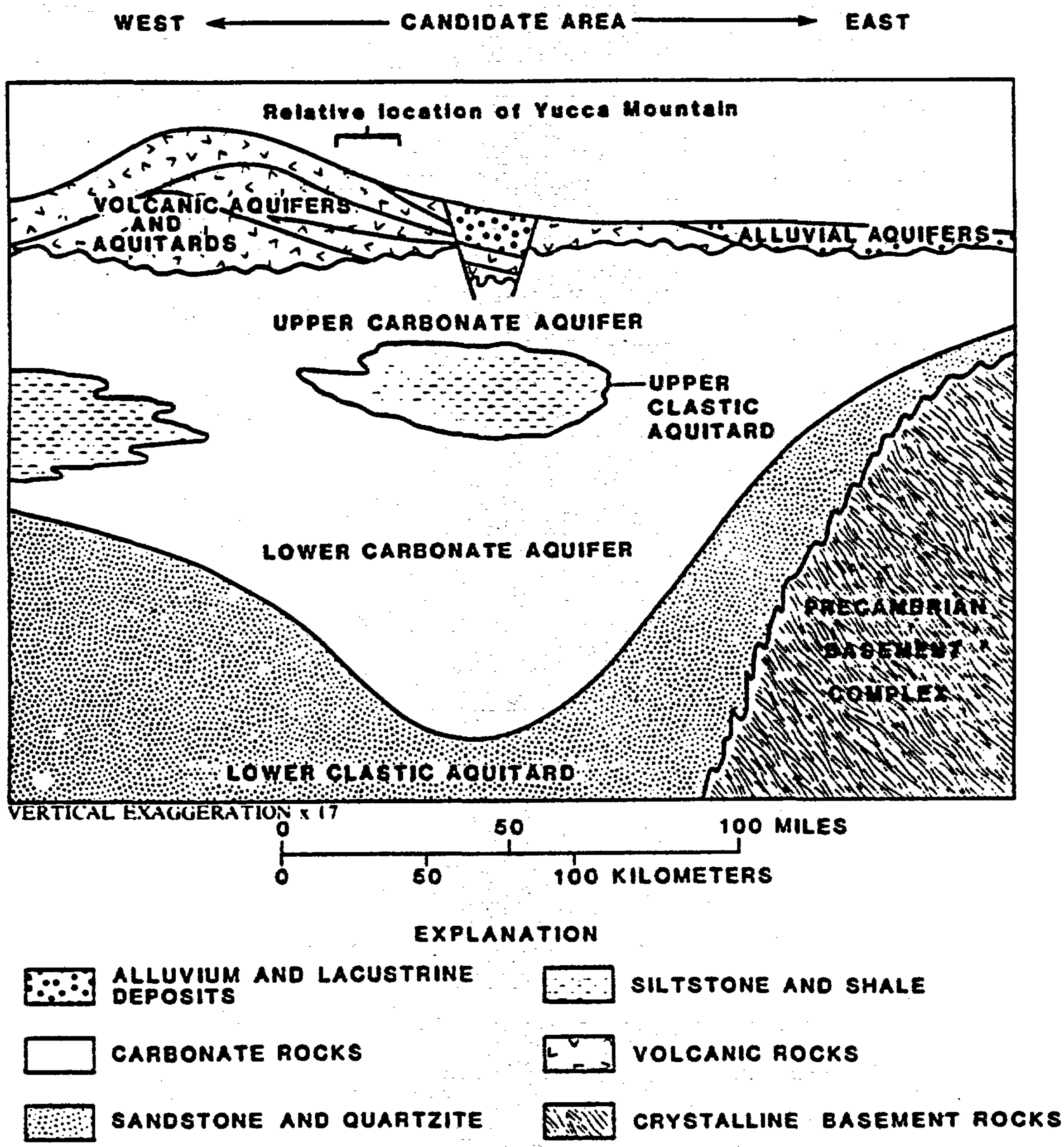


Figure 4. Stratigraphic relationships among hydrostratigraphic units in the Candidate Area (after Waddell and others, 1984).

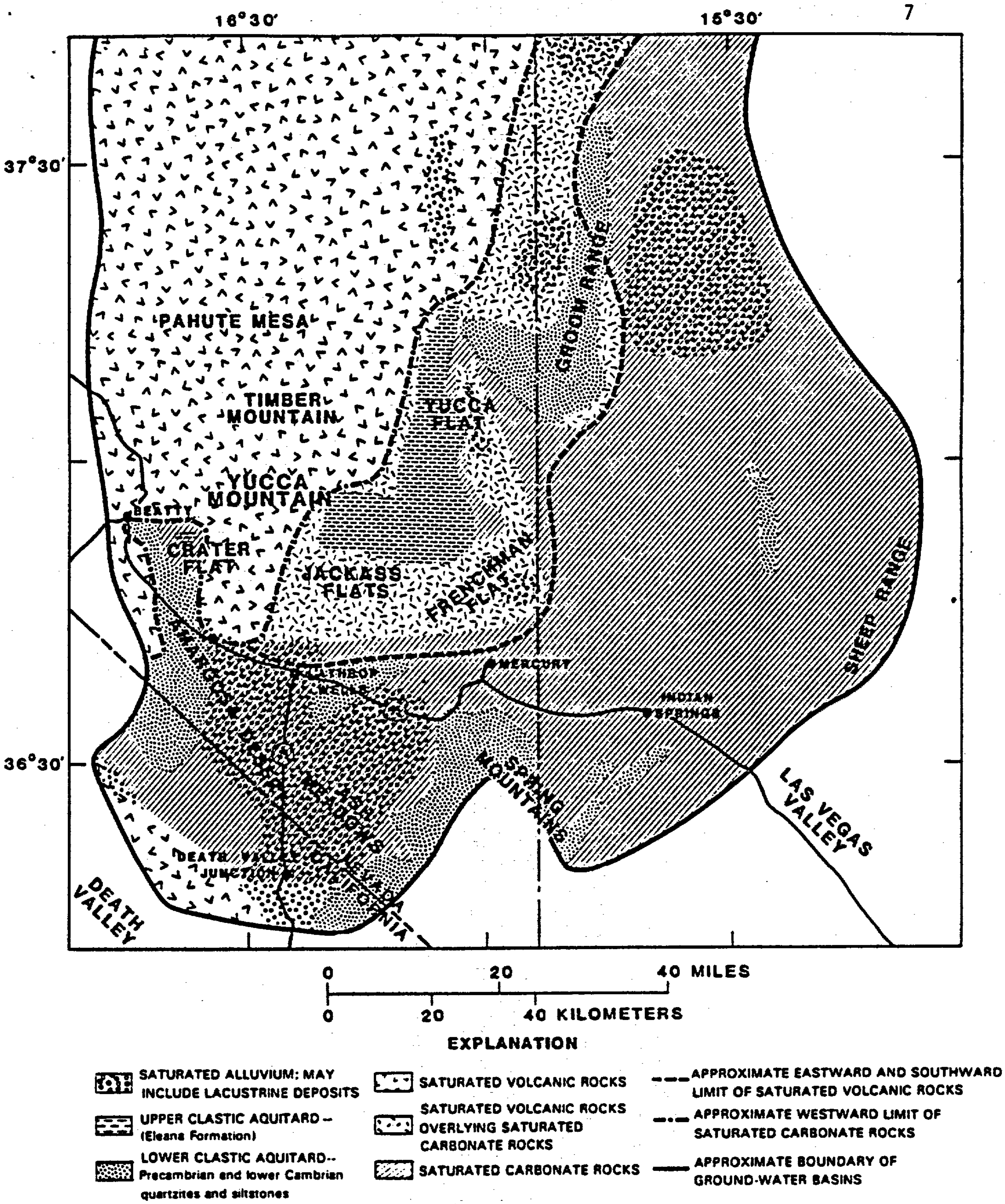


Figure 5. General geographic distribution of hydrostratigraphic units (after Waddell and others, 1984).

units (aquifers and aquitards). Presumably all conceptual models of both carbonate aquifers assume permeability to be fracture controlled.

2.2 Recharge to the Lower Carbonate Aquifer

According to the conceptual model implied by Winograd and Thordarson (1975), recharge to the lower carbonate aquifer (regional groundwater flow system) occurs principally in areas of high precipitation and favorable rock type (location of its outcrop areas) and secondarily by downward leakage of water from the Cenozoic hydrogeologic units. According to Winograd and Thordarson (1975), this conceptual model also assumes that underflow into the basin from the northeast may constitute a major source of recharge. The word underflow is used in the context of water moving through the deeper portions of a regional groundwater flow system as discussed above. It should be noted that the approximate boundary of the groundwater system for this conceptual model as shown on figure 2 is not the groundwater divide at the boundary of the Death Valley groundwater basin. Apparently the location of the basin divide has not been delineated; consequently this inconsistency.

According to Winograd and Thordarson (1975), this conceptual model assumes that recharge to the lower carbonate aquifer from precipitation occurs in the Sheep Range, northwestern Spring Mountains, southern Pahranagat Range, and to a lesser extent beneath the Pintwater Range, the Desert Range, and the Spotted Range. The data bases for this assumption are very limited; consequently this assumption is somewhat speculative. But the conceptual model is defensible at the existing stage of data development.

Based on the deuterium content of groundwater in Pahranagat Valley, along the flanks of the Spring Mountains and the Sheep Range, and at Ash Meadows (fig. 2), Winograd and Thordarson (1975) suggest that as much as 35 percent of the groundwater discharge that occurs in Ash Meadows may enter the basin from the northeast as underflow through the deep portion of a regional groundwater flow system.

Winograd and Thordarson (1975) suggest also that the quantity of recharge entering the lower carbonate aquifer on the northwest side of the basin probably is only a few percent of the total discharge measured at Ash Meadows. In addition, Winograd and Thordarson (1975) consider downward leakage of groundwater from the Cenozoic rocks into the lower carbonate aquifer to be a minor source of recharge. The data base that supports this portion of the aforementioned conceptual model also is very limited.

Regional groundwater flow in the lower carbonate aquifer is influenced by geologic structure and erosion surfaces within the aquifer. According to Winograd and Thordarson (1975), several thousand feet of the carbonate rocks occur within the zone of saturation throughout most of the study area. If in fact a continuous permeable or semipermeable section of the lower carbonate aquifer exists between the recharge area along the basin divide and the discharge area at the bottom of the basin it is probable that a regional groundwater flow system as defined by Toth (1963) exists in the lower carbonate aquifer. However, the hydraulic head boundaries of the regional groundwater flow system have not been delineated by a sound data base.

The prevalent conceptual model of the regional groundwater flow system portrays the system as extending from a recharge area along the basin divide to its discharge area within the Oasis Valley subbasin, Alkali Flat-Furnace Creek Ranch subbasin, and/or the Ash Meadows subbasin. A prominent line of springs occurs in the southeastern and east-central part of the Amargosa Desert (fig. 6). The spring line is roughly parallel to the Gravity Fault (fig. 7). According to Claassen (1983), the proximity of the potentiometric high to the Gravity Fault near its intersection with the Spector Range thrust fault indicates the possibility of a breach of the confining properties of the Gravity Fault observed to the southeast along the Ash Meadow spring line (fig. 6). According to Claassen (1983), the potentiometric surface in the valley fill is about 10 m lower than that in the underlying carbonates: This difference provides a fluid potential gradient for upward leakage. The groundwater quality data presented in Claassen (1983) cannot be interpreted uniquely to determine the sources of water in the valley fill east of the Gravity Fault. However, Claassen (1983) suggests that the water in the valley fill is a mixture of recharge that has moved downward and upward leakage.

According to Winograd and Thordarson (1975, p. 79),

> One group of springs at point of rocks emerges directly from the lower carbonate aquifer. This spring discharges less than 20 gpm and is the only one emerging directly from the lower carbonate aquifer in the Ash Meadows discharge area. However, groundwater also occurs in the lower carbonate aquifer in Devil's Hole, where the water table is about 50 ft below land surface...
>
> Head gradients, temperature of water, and chemical quality of water suggest that water emerging from the pool springs is derived by upward leakage from the lower carbonate aquifer, which flanks and underlies the Quaternary strata at the spring line.
>
> The potentiometric surface in the carbonate aquifer at Devil's Hole is 14 to 159 ft higher than the orifice altitudes at the spring pools (fig. 6). Thus a positive head gradient exists for moving water upward from the carbonate aquifer into the overlying sedimentary deposit and to land surface, provided an avenue of permeability is available...
>
> A comparison of water temperature in the lower carbonate aquifer, at the pool springs, and in the Quaternary strata suggests that the springs are fed by the carbonate aquifer.

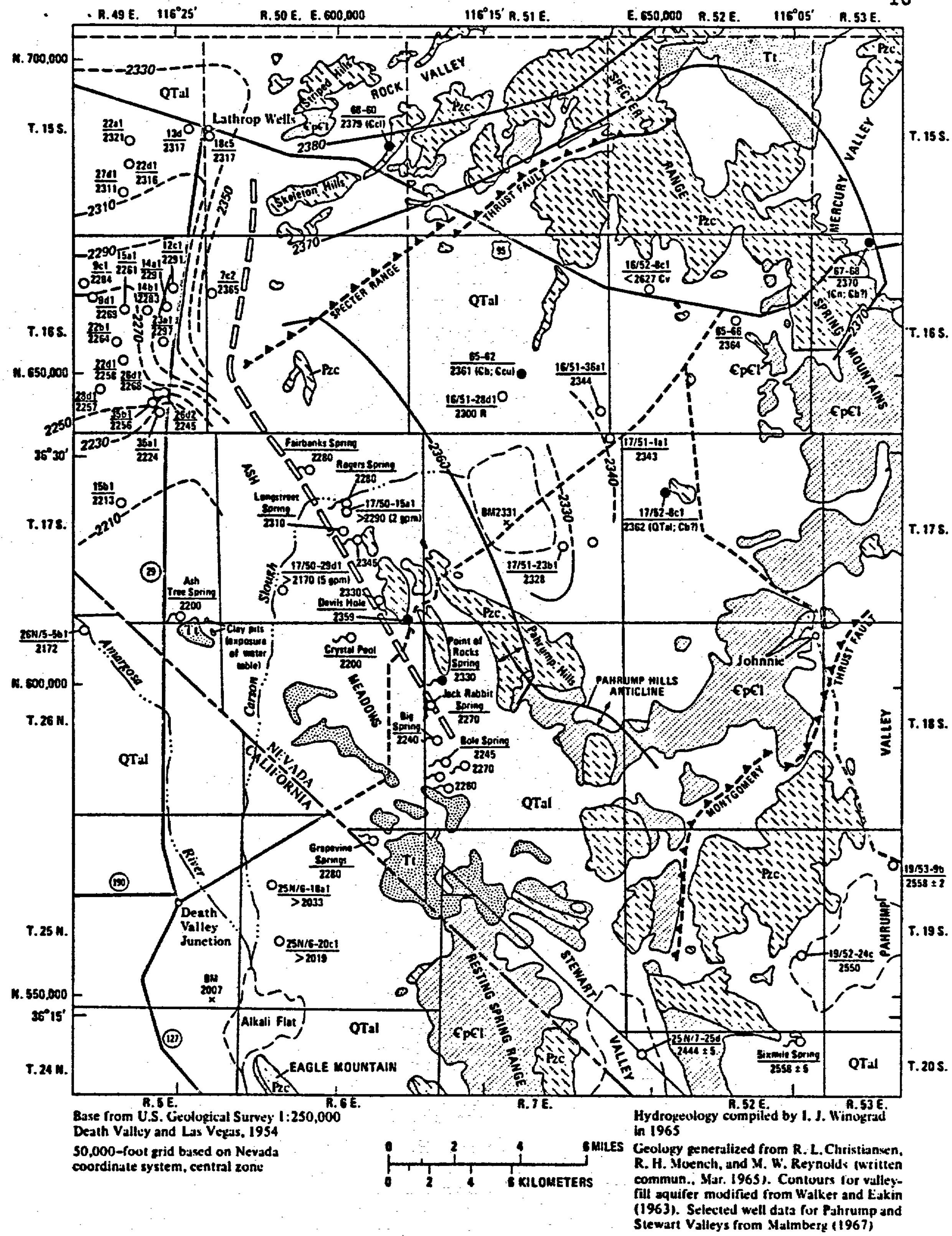


Figure 6. Hydrogeology of southeastern Amargosa Desert (after Winograd and Thordarson, 1975).

EXPLANATION

QTal — TERTIARY AND QUATERNARY

Valley-fill aquifer
Alluvial fan, fluvial, fanglomerate, mudflow, playa, lake, and spring deposits; an aquitard in Ash Meadows

Tt — TERTIARY

Tuff aquitard
Tuffaceous, fluvial, and lacustrine strata; Rocks of Pavits Spring and the Horse Spring Formation in north-northeastern part of map; sandstone, claystone, conglomerate, and tuff in southern part of map

Pzc — CAMBRIAN TO DEVONIAN

Lower carbonate aquifer
Dolomite and limestone; minor shale and quartzite

pЄЄl — PRECAMBRIAN AND CAMBRIAN

Lower clastic aquitard
Quartzite, siltstone, shale, and minor limestone

Contact

Anticline

Thrust fault
Sawteeth on upper plate; dashed where inferred

HYDROGEOLOGIC AND GEOLOGIC UNITS

SYMBOL	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT
Єn	Nopah Formation	Lower carbonate aquifer
Єb	Bonanza King Formation	Lower carbonate aquifer
Єcu	Carrara Formation, upper part	Lower carbonate aquifer
Єcl	Carrara Formation, lower part	Lower clastic aquitard

HYDRAULIC SYMBOLS

NOTE: All altitudes and contours in feet; datum is mean sea level. Areas of significant evapotranspiration are at Ash Meadows and at Alkali Flat and vicinity

67-68 / 2370 (Єn; Єb?)

Test well
Well tapping pre-Tertiary hydrogeologic units; upper number is well number; lower number is altitude of static water level; symbols in parentheses are formations tapped

17/52-8c1 / 2362 (QTal; Єb?)

Water well
Well tapping valley-fill aquifer and lower carbonate aquifer; upper number is well number; lower number is altitude of composite static water level of both hydrogeologic units; symbols in parentheses are formations tapped

17/50-29d1 / >2170 (5 gpm)

Water well
Well tapping valley-fill aquifer; upper number is well number; lower number is altitude of static water level; R, reported water level; Cv, caved well; symbol > denotes well was flowing; flow rate is in parentheses

Devils Hole / 2359

Spring or cavern
Spring or cavern in lower carbonate aquifer (Bonanza King Formation); number is altitude of spring or of water level in cavern

Crystal Pool / 2200

Spring
Spring in Quaternary lake beds and travertine deposits; number is altitude of spring

2380

Potentiometric contour, inferred
Shows altitude of potentiometric surface in lower carbonate aquifer and lower clastic aquitard; contour interval, 10 feet

2330

Potentiometric contour
Shows altitude of potentiometric surface in valley-fill aquifer; dashed where inferred; contour interval, 20 feet; contours for southwest quadrant given on plate 1

Inferred ground-water barrier
Width of symbol not intended to represent width of hydraulic barrier, which may range from several tens to a few thousand feet

Dry lakebed

BM × 2007

BM, bench mark, showing altitude of land surface

Figure 6. Continued.

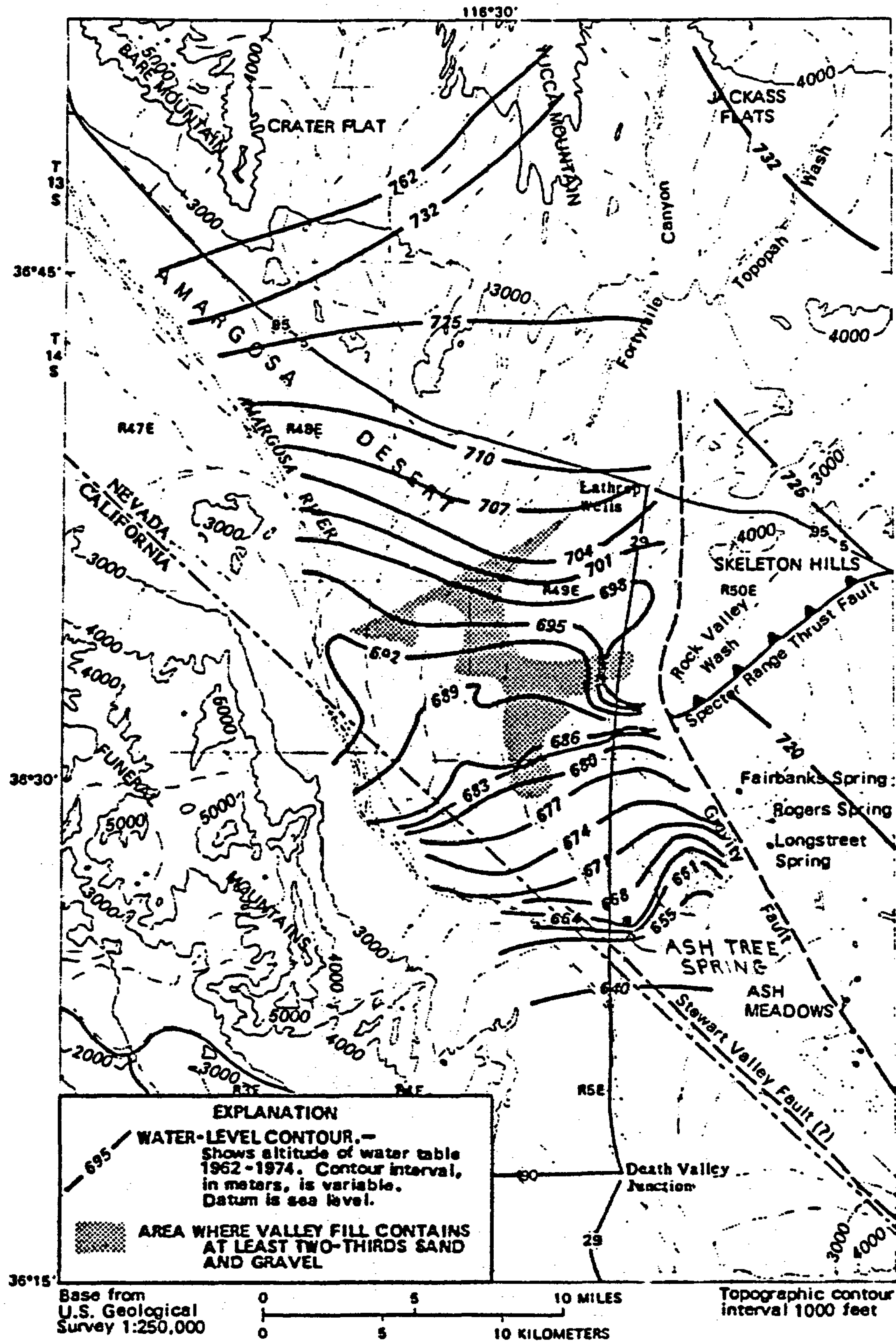


Figure 7. Water level altitudes (modified from Walker and Eakin, 1963).

Claassen (1983) suggests that the absence of potentiometric discontinuities west of the Gravity Fault and north of the Ash Tree Spring (fig. 6) and the presence of the Ash Meadows spring line just east of the fault indicate that the carbonate aquifer does not extend west of the Gravity Fault into the west-central Amargosa Desert.

In summary, the actual boundaries of the conceptualized regional groundwater flow system are not defined by a reliable data base. However, a generalized conceptual model of the regional groundwater flow system has been developed and supported by limited hydraulic head data and groundwater geochemistry data; permeability data essentially are non-existent. Recharge to the regional groundwater flow system is along the basin divide where precipitation is greatest and where the lower carbonate aquifer crops out. The most probable sources of recharge to the conceptualized regional flow system are believed to be the Timpahute Range, Pahranagat Range, Sheep Range, and the Spring Mountains (fig. 2).

Limited groundwater potential (hydraulic head) data in the lower carbonate aquifer (deep portion of the conceptualized regional flow system) indicate that the regional hydraulic gradient is relatively flat towards the Ash Meadows discharge area to the southwest. Groundwater potential data for the lower carbonate aquifer, the tuff aquifers, and the valley fill aquifers indicate that a downward directed fluid potential gradient exists through the hydrostratigraphic units throughout most of the area to the east and northeast of the Ash Meadows spring line. Groundwater potential data suggest that an upward directed potential gradient exists from the lower carbonate aquifer into the Tertiary and/or valley fill aquifers in the Amargosa Desert and north toward Yucca Mountain.

3 Intermediate and Local Groundwater Flow Systems

3.1 Hydrogeologic Units

Volcanic rocks of Tertiary and Quaternary Ages occur in the western and central parts of the candidate area. These volcanic rocks consist of ash flow and ash fall tuffs (nonwelded to welded) and basalt and rhyolite flows. Some of these units form aquifers and others form aquitards. Figure 5 shows the geographic distributions of the hydrostratigraphic units. These units form the groundwater flow pathways for the prevalent conceptual model that corresponds to Toth's (1963) intermediate and local flow systems.

Valley fill aquifers of Tertiary and Quaternary Ages are composed of alluvial fan, fluvial, fanglomerate, lake bed, and mudflow deposits. According to Waddell and others (1984), valley fill material generally is saturated only beneath the structurally deepest parts of the flats in the candidate area, and where present in, and upgradient from, discharge areas. Alluvium is the principal aquifer beneath most of the Amargosa Desert. The alluvium in the Amargosa Desert constitutes the shallowest hydrostratigraphic unit in the discharge area for both intermediate and local conceptualized flow models.

3.2 Groundwater Flow

Conceptual models of local and intermediate groundwater flow systems are based primarily on the definitions presented by Toth (1963) except, as explained above, scale is a primary factor. Local and intermediate groundwater flow systems are superimposed upon the deeper regional groundwater flow system in the carbonate aquifer. Because of the complex structural setting of the candidate area and the lack of data, conceptual models of local and intermediate groundwater flow systems cannot be broken down into hydrostratigraphic units.

Various investigators have divided the Death Valley groundwater basin into subbasins [Winograd and Thordarson (1975); Waddell and others (1984); Czarnecki and Waddell (1984); Waddell (1982); Czarnecki (1984); Rice (1984)]. These subbasins can be viewed as synonymous with conceptualized intermediate and local groundwater flow systems.

According to Waddell and others (1984), the groundwater flow in the candidate area is influenced by parts of three such subbasins or flow systems: Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek Ranch. If more data were available these subbasins undoubtedly could be subdivided further into smaller flow systems. As defined by Waddell and others (1984), a subbasin consists of recharge areas and flowpaths to a major discharge area. The boundaries of these subbasins have been based primarily on topography and geology; but they are not well defined in terms of hydraulic head measurements. The actual locations of groundwater divides (boundaries) between the subbasins are not known. Delineation of the sources (recharge areas) of the groundwater that discharges from these three subbasins is difficult because of the complex structural geology of the area. The complex structural geology of the area also complicates the interpretation of groundwater chemistry data collected within each subbasin.

4 Conceptual Models of Groundwater Flow in the Vicinity of Yucca Mountain

4.1 Introduction

In our opinion, insufficient data are available currently to characterize the hydrogeologic system accurately in the vicinity of Yucca Mountain. However, generalizing conceptual models of groundwater flow in the saturated and unsaturated zones have been proposed. The conceptual model of groundwater flow in the saturated zone that has been developed by the USGS as presented below appears to be one defensible interpretation. Homogeneity within segments of the conceptual model is tacitly assumed. Fault zones are not isolated out as inhomogeneous. Deficiencies in the data base of the saturated zone have been noted clearly in reports that discuss conceptual models. Deficiencies in the data base of the unsaturated zone are not nearly as identifiable. Conflicting data do exist. In addition, portions of the conceptual model for the unsaturated zone presented by the USGS are unsupported by data.

4.2 Conceptual Model of Saturated Groundwater Flow

Yucca Mountain is located within the Alkali Flat-Furnace Creek subbasin as proposed by Waddell and others (1984). Figure 8 is a geologic section through the subbasin that extends from Pahute Mesa to Alkali Flat and Eagle Mountain. The northern part of the subbasin is underlain by rocks associated with the Silent Canyon Caldera, the Timber Mountain Caldera, and the Claim Canyon Caldera. The southern part of the subbasin, in the vicinity of the Amargosa Desert and Alkali Flat, is underlain primarily by unconsolidated terrestrial deposits (hereinafter called alluvium). According to Waddell and others (1984), from approximately 10 km (kilometers) north of Amargosa Valley (formerly Lathrop Wells) southward past Alkali Flat, the saturated zone extends into the alluvium. Aeromagnetic data presented by Greenhaus and Zablocki (1982) show that volcanic rocks are scarce beneath the Amargosa Desert.

A local groundwater flow system originating at Yucca Mountain is superimposed onto an intermediate groundwater flow system that is conceptualized as receiving recharge in the vicinity of Pahute Mesa. This intermediate flow system extends beneath Yucca Mountain to its discharge area somewhere in the vicinity of the Amargosa Desert.

Potentiometric data collected from wells in the vicinity of Yucca Mountain indicate that the general direction of groundwater flow is southward from Yucca Mountain to the Amargosa Desert (figs. 9 and 10). The intermediate groundwater flow system is conceptualized as extending from Pahute Mesa to the Amargosa Desert; but local groundwater flow systems that receive recharge at topographic highs such as Yucca Mountain or beneath washes during runoff events are recognized also. Recharge at Yucca Mountain is not well understood. Groundwater geochemical data collected by Claassen (1983) indicate that local groundwater recharge has occurred within Forty-Mile Canyon during approximately the last 4,000 years. Insufficient potentiometric data are available to delineate the effects of local recharge on the direction of groundwater flow in the vicinity of Yucca Mountain.

Potentiometric data available currently are not adequate to define the vertical head gradient(s) in the vicinity of Yucca Mountain. Temperature logs have been used to estimate flow directions and rates of flow in boreholes. However, according to Waddell and others (1984), these data cannot be interpreted uniquely because of the following:

1) Transient effects from drilling and pumping or injecting water still may be present at the time of the survey.

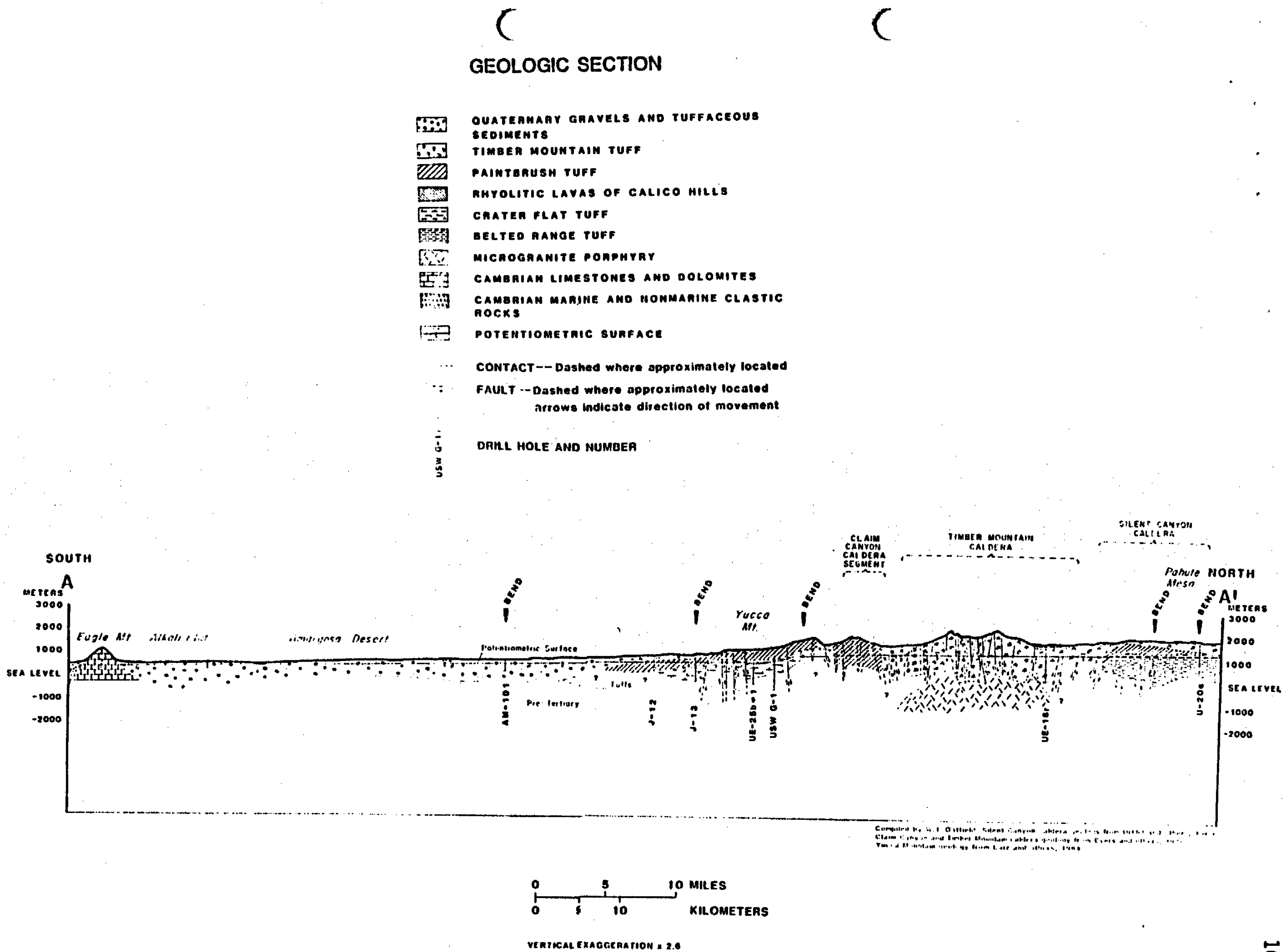


Figure 8. South-north geologic section through the Alkali Flat-Furnace Creek subbasin (after Waddell and others, 1984).

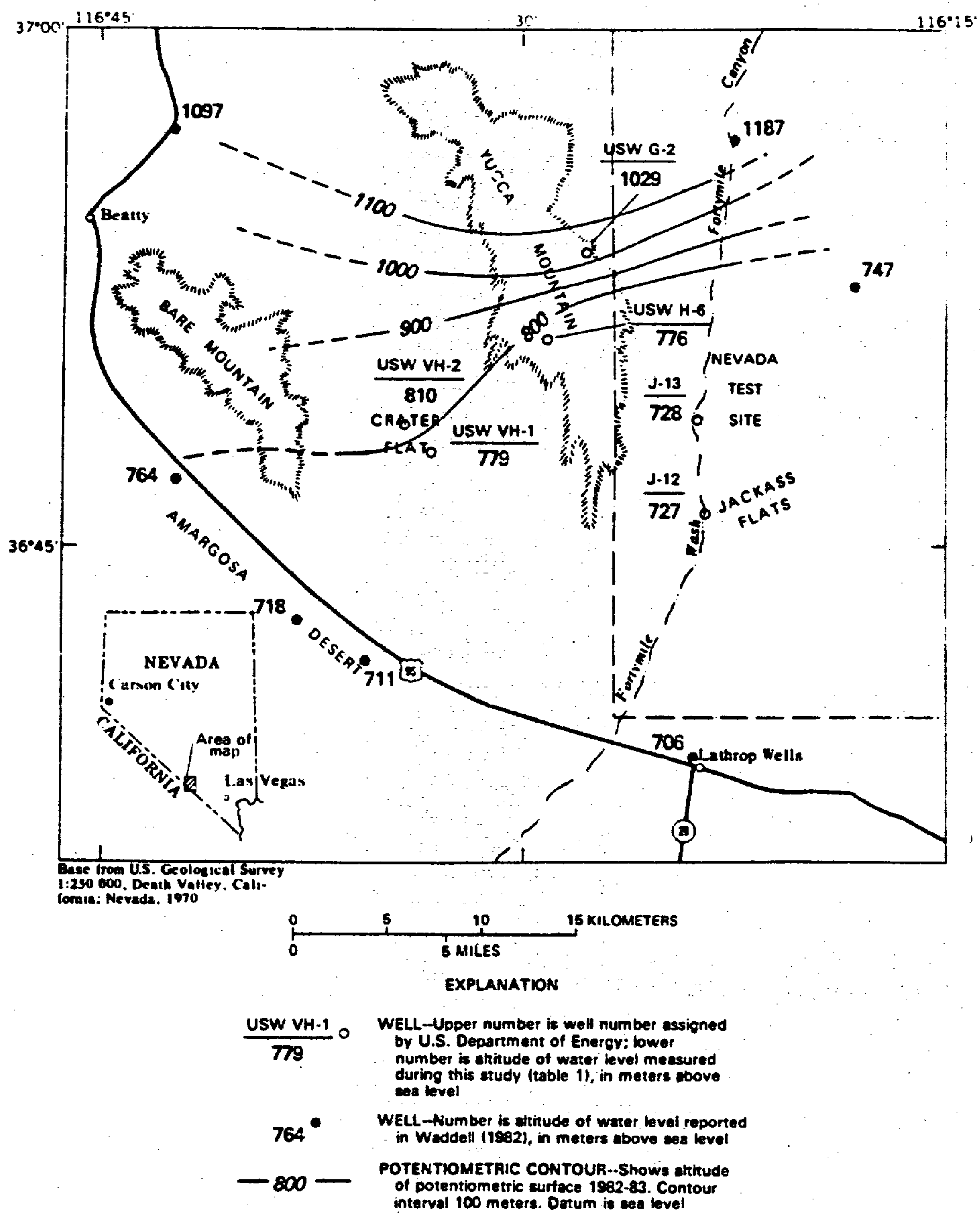
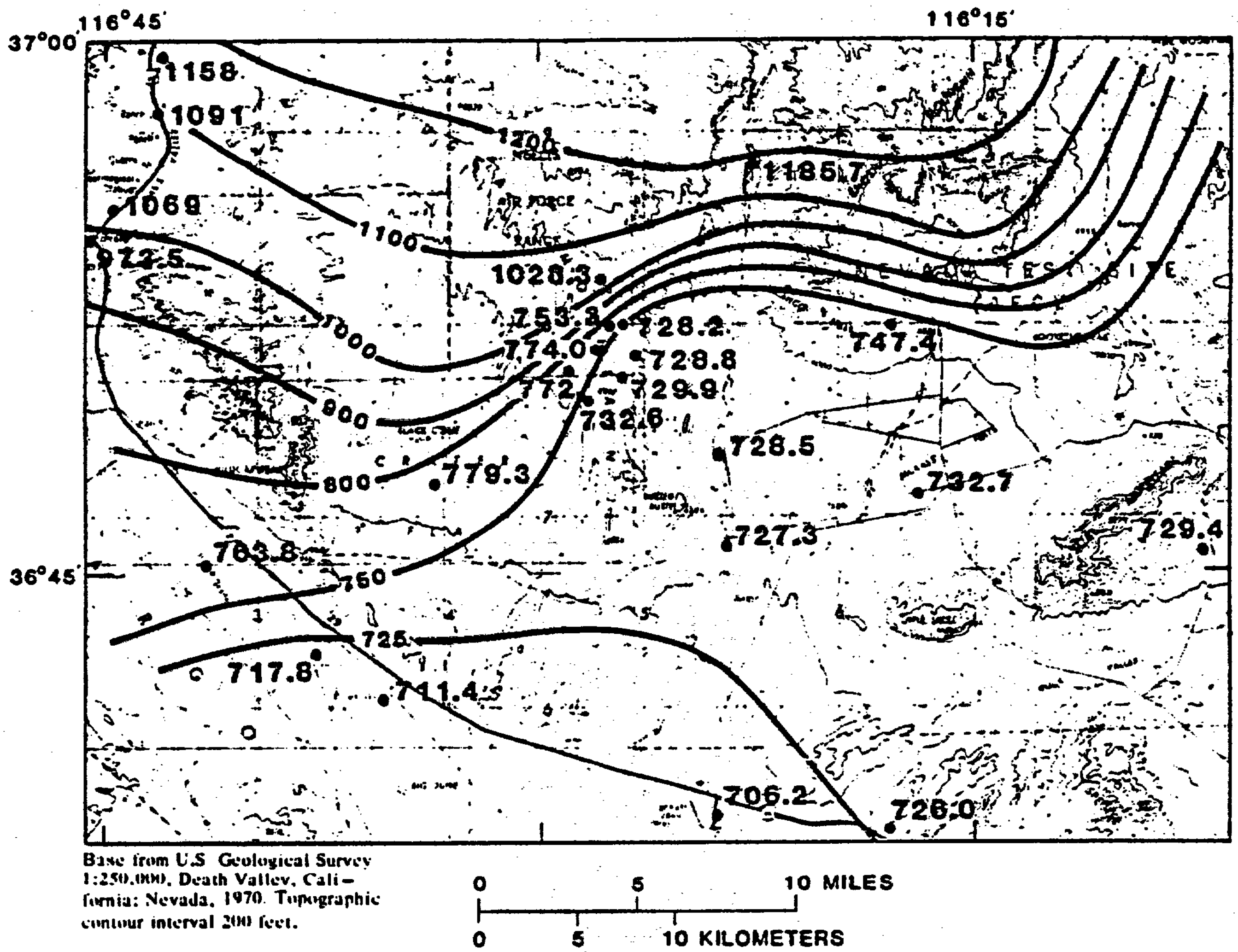


Figure 9. Preliminary potentiometric-surface map, Yucca Mountain and vicinity (after Robison, 1984).



EXPLANATION

—800— **POTENTIOMETRIC CONTOUR--** Shows altitude of potentiometric surface, 19--. Contour interval, in meters, is variable. Datum is sea level.

•747.4 **TEST HOLE--** Number is measured composite water level, in meters above sea level.

Figure 10. Preliminary potentiometric surface of site vicinity (after Waddell and others, 1984).

2) Most procedures assume that heat moves only vertically. This assumption is not valid if there is a horizontal component of groundwater flow, which appears to be the case at Yucca Mountain.

3) Calculated flow rates may be erroneous due to the very high hydraulic conductivity within the boreholes.

According to Waddell and others (1984), hydraulic head data for test well USW H-1 and test well UE-25p#1 indicate that an upward hydraulic gradient from the Pre-Tertiary carbonate rocks into the overlying Tertiary rocks exists in the vicinity of Yucca Mountain. However, these data are preliminary.

4.3 Flow Paths From Yucca Mountain to Natural Discharge Areas

Figure 11 presents a preliminary potentiometric surface map of Yucca Mountain. The potentiometric contours indicate that the general direction of groundwater flow beneath Yucca Mountain is toward the southeast into the Forty Mile Wash area. Additional potentiometric data (fig. 10) indicate that the groundwater flow direction then turns to the south toward the Amargosa Desert and Alkali Flat areas. It should be noted, however, that the actual flowpath that a particle of water from Yucca Mountain will take cannot be determined from this potentiometric map. The actual flowpath a particle of water will take is controlled by inhomogeneities such as permeable fractures and possible gouge along faults and by anisotropy (Waddell and others, 1984). According to the conceptual model of Waddell and others (1984), most groundwater flowing beneath Yucca Mountain would discharge at Alkali Flat; but some may discharge at Furnace Creek Ranch. The data base available currently does not allow reliable delineation of the discharge area for water flowing beneath Yucca Mountain. The current interpretation by the USGS is predetermined by the unauthenticated boundary conditions assumed in the conceptual models described above.

4.4 Hydrogeologic Controls of Groundwater Flow in Saturated Tuffs

Groundwater flow in saturated tuff occurs both as matrix flow and flow through discontinuities such as fault zones and joints. According to Waddell and others (1984), preliminary interpretations indicate that conductivities of fractures are several orders of magnitude greater than matrix conductivities. These interpretations are supported by measurements on cores, and by pumping tests on packed off nonproductive parts of drill holes. Such tests indicate that the hydraulic conductivity of the matrix is much lower than the productive parts of the drill holes (see Williams, 1985). In addition, productive zones as determined by borehole flow and temperature surveys performed during pumping tests correlate with fracture zones identified from televiewer and caliper logs. These data indicate clearly that secondary porosity caused by fracturing of the tuffs produced

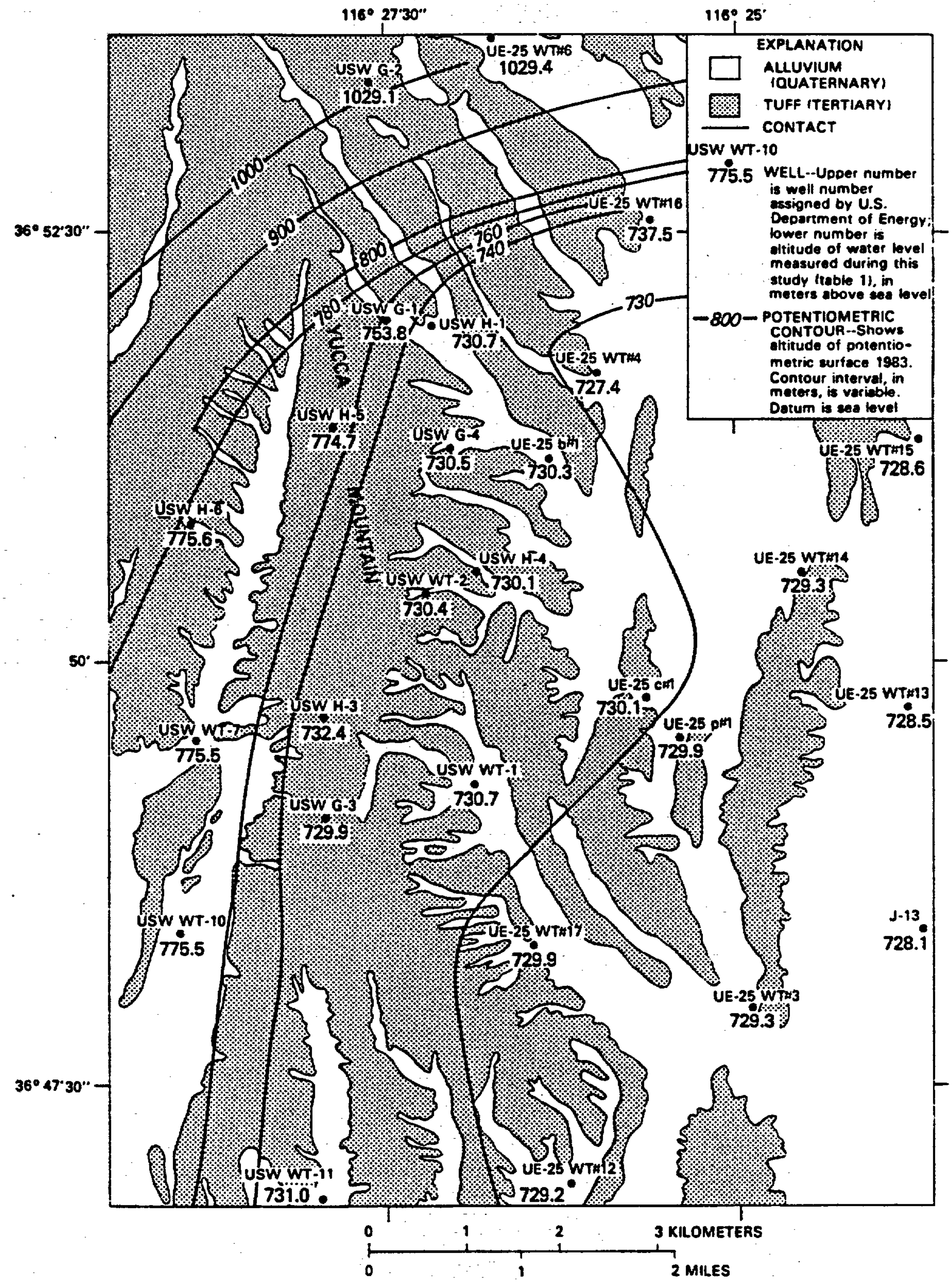


Figure 11. Preliminary potentiometric-surface map, Yucca Mountain (after Robison, 1984).

significant secondary hydraulic conductivity. Fractures are considered to exert the primary control over the movement of groundwater in welded tuff. But the nature of this control has not been conceptualized.

Two theoretical approaches have been used to estimate the hydraulic properties of the fractured tuff aquifers in the vicinity of Yucca Mountain. The two approaches require the assumption of two very different conceptual models. Most analyses of aquifer test data have used the equivalent porous medium approach. However, aquifer test data for test well UE-25b#1 (pumped well) and test well UE-25a#1 (observation well) were analyzed by the continuum approach (Moench, 1984). Williams (1985) has reviewed the latter approach in detail.

The equivalent porous medium approach involves treating the conceptual model for fractured rock as an equivalent porous medium. This analogy is possible if the intact blocks of rock are essentially impermeable so that fluid flow occurs through the fractures only. According to Long and others (1982), a fractured rock is considered to behave hydraulically like an equivalent porous medium when 1) there is an insignificant change in the value of the equivalent hydraulic conductivity with a small change in the size of the test volume, and 2) an equivalent hydraulic conductivity tensor exists which will predict the correct flux within the representative elementary volume when the direction of a constant gradient is changed.

The equivalent porous medium conceptual model is based on the assumption that average values for the hydrogeologic characteristics such as porosity, specific storage, and hydraulic conductivity can be ascertained for a large volume of rock containing numerous fractures. The representative elementary volume (REV) (macroscopic scale) over which the average values are obtained must be assumed to be homogeneous (Evans and others, 1983). This requirement constitutes a major limitation of the approach because fractured rocks are heterogeneous by definition. Freeze (1975), Smith and Freeze (1979a, b), and Smith (1978) have concluded that it may not be possible to define equivalent homogeneous properties for every heterogeneous system. As discontinuity spacing becomes larger and larger the scale of investigation constrained by the diameters and spacings of drill holes becomes a limiting factor.

Theoretical and experimental work by Snow (1969) suggests that the hydraulic conductivity of fractured rocks vary in magnitude in relation to the size of the sample. This work implies that the characterization of a sample of rock may continue to change as the size of the sample changes (Long and others, 1982). Another limitation of the approach is that no well-defined method exists for estimating the gross porous medium parameters, which are scale dependent, from details about the fractures; in addition, the equivalent permeability tensor may be dependent on the boundary conditions of a particular REV, so that the equivalent permeability ceases to be a property of the material only (Evans and others, 1983).

The continuum approach treats the network of fractures as a fictitious continuum. Permeable rock blocks are represented by another continuum which overlaps and interacts with the fracture continuum (Hsieh and others, 1983). Two (or more) different sets of values for pressure, porosity, specific discharge, hydraulic conductivity, and specific storage can be defined at each point in the flow region. One set is defined for the fracture continuum and one set is defined for the rock continuum (Hsieh and others, 1983). This "double-porosity" approach is a mathematical approximation and a convenience; its physics is ill defined because two (or more) different sets of values for the aforementioned hydraulic properties cannot be related to actual physical measurements at the location (Evans and others, 1983).

Moench (1984) proposed a modified double-porosity conceptual model which helps minimize the aforementioned limitations of the double-porosity approach. Moench's model incorporates the effects of a thin layer of low permeability mineral coating or fracture skin at the fracture-block interfaces. The fracture skin is assumed to have a hydraulic conductivity that is less than the rock matrix. Thus the fracture skin is assumed to impede the interchange of fluid between the fractures and the blocks. The skin in effect behaves as a "confining layer" between two other segments of the porous medium, the fracture segment and the rock matrix segment.

Both conceptual models have significant limitations. However, insufficient data are available currently to prove or disprove the validity of either conceptual model for analyzing specific aquifer pumping test data from the Nevada Test Site. In addition, other conceptual models also are defensible.

In the context of the issues presented in NRC draft Site Technical Position 1.0 (August, 1984) the conceptual models discussed above leave many questions unanswered. For example, Issue 1.1.1.1 asks what are the hydrogeologic limits of groundwater flow systems. To date the boundaries have been defined on the basis of topography because insufficient hydraulic head and hydraulic property measurements have been conducted to permit the use of any other approach. Issue 1.1.2.6.2 addresses the three-dimensional distribution of hydrogeologic parameters in the saturated zone beneath Yucca Mountain. The defensibility of any conceptual model requires the answer to this question. The information available to date requires a conceptual model that accommodates a data base which shows that only a few discrete zones tens or hundreds of meters apart vertically produce all the water derived from any given drill hole. At present, however, these zones have not been tested separately; only a few have been tested together. But most importantly no hypothesis has been proposed for relating these vertically isolated "aquifers" among different drillholes. Consequently it is not clear that the conceptual models discussed above, all of which tacitly assume homogeneity of hydrostratigraphic units in three dimensional space, are valid. The limited understanding of the three-dimensional distribution of hydrogeologic parameters and the limited data on flow system boundaries constitute the major weaknesses in the defensibility of the conceptual models that have been proposed.

Some additional conceptual models that can be proposed in the absence of the aforementioned data base are presented in the following section.

4.5 Alternative Conceptual Models for Flow in the Saturated Zone

Alternative conceptual models for groundwater flow in the saturated zone can be developed based on the data available currently. It is recognized that groundwater flow in the saturated zone in the vicinity of Yucca Mountain is fracture controlled. However, the generally accepted conceptual model suggests that the indurated aquifers are homogeneous but anisotropic (i.e., that the hydraulic properties of the aquifers are constant with position within the aquifers but vary with direction in relation to the attitudes of fractures). If it can be assumed safely that the homogeneous and anisotropic conceptual model is applicable to the NTS, the directions of decreasing water level elevations shown on figures 7, 9, 10 and 11 can be used to indicate the general directions of groundwater flow at least under steady state conditions.

An alternative conceptual model also may be presented to explain the conditions observed to exist in the vicinity of the NTS. Since fractured rocks are heterogeneous by definition, it is reasonable to assume that geological heterogeneity would have a profound effect on groundwater flow in the structurally complex setting of the NTS. Sharp breaks in the observed piezometric surface support this hypothesis. Heterogeneity can have a significant effect on the locations of groundwater recharge and discharge areas. Figure 12 illustrates some of the effects of heterogeneity on the locations of recharge and discharge areas. Figure 12d in particular illustrates the presence of a groundwater discharge area (center of figure) that could not occur under purely topographic control (Freeze and Cherry, 1979).

If it is assumed that the aquifers in the candidate area predominately are heterogeneous, the homogeneous, anisotropic conceptual model clearly may be inadequate to characterize the conditions of groundwater flow. Many heterogeneous, conceptual models could be presented to explain the locations of groundwater discharge areas in the Amargosa Desert (fig. 12). For example, it may be reasonable to assume that groundwater flow occurs predominantly through interconnected discrete fault zones due to the complex structural setting of the NTS. It is probable that several potential configurations of interconnected, permeable fault zones could be modeled mathematically to simulate springs known to exist in the vicinity of the NTS. Permeable fracture zones that occur in several boreholes could be used as evidence to support this type of conceptual model.

Another factor that should be taken into account is the potential misidentification of the locations of primary groundwater recharge areas. The locations of primary groundwater recharge areas have been based on precipitation rates and surficial geology (i.e., outcrops of aquifers). However, as illustrated in figure 12, the locations of groundwater recharge

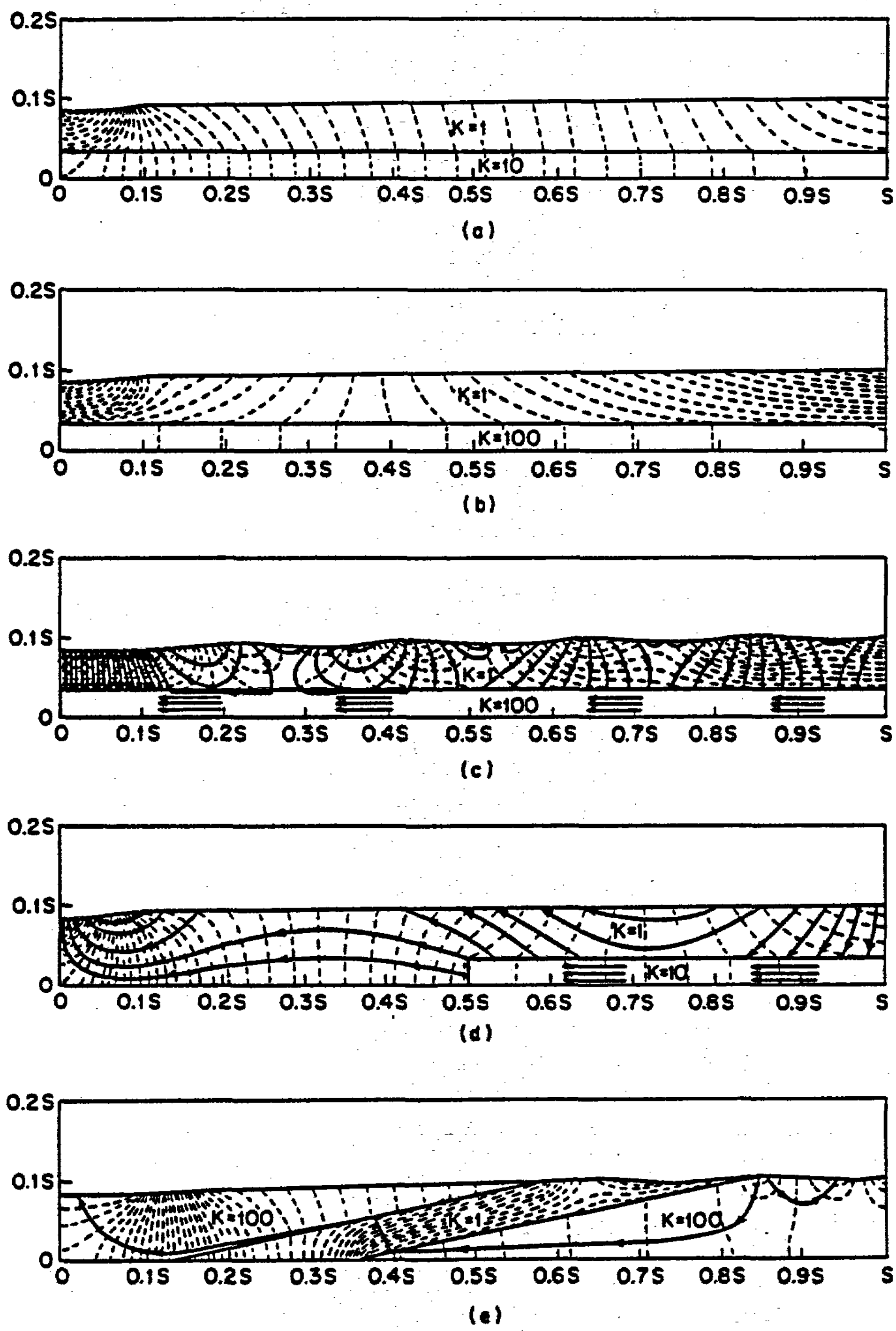


Figure 12. Effect of geology on regional groundwater flow patterns (after Freeze and Witherspoon, 1967).

areas may be controlled by subsurface geological heterogeneity. Thus, it is possible that recharge to the aquifers in the candidate area occurs in areas other than those that have been identified. Such a change in the distribution of recharge areas would have a significant effect on the directions of groundwater flow and the lengths of the flow paths.

4.6 Conceptual Model for Flow in the Unsaturated Zone

The most simplistic conceptual model for Yucca Mountain incorporates steady downward flow under partially saturated conditions at low moisture content. This condition is in fact specified as the most favorable condition in 10CFR960. In addition negligible movement of air and water vapor would be desirable. The formulation for such a conceptual model can be divided into three parts.

1. The physical processes governing flow in a fractured porous medium under unsaturated conditions.

2. The relationships of these physical flow processes to the natural conditions in Yucca Mountain.

3. The effect on the natural flow regime by the disruption caused by the repository.

4.6.1 Physical Flow Processes

The mechanisms which govern the occurrence and flow of water in porous media under partially saturated conditions are based on surface chemistry in terms of the attraction of solid particles for water. In a system such as that which occurs in the vadose zone, water is a wetting fluid and air is a non-wetting fluid. The solid particles are wet with water by strong adhesive forces that produce curved interfaces between the water phase and the air phase. A pressure discontinuity (capillary pressure) occurs across the interfaces with the higher pressure on the concave or air side of the interface. The pressure difference is inversely related to the radius of curvature of the interface. Consequently at large pressure differences water will occur only in small pore spaces; however, at small pressure differences (water pressure near atmospheric) water will occur in all but the largest pores.

In the case of welded tuff, where fractures may be several orders of magnitude larger than the pore spaces, a tendency would develop for water to move out of the fractures and into the porous matrix. It must be recognized that the fractures themselves have dimensions which approach zero at points of contact. Therefore, water will occur in the fractures at points of contact even if the pressure of the water is considerably less than atmospheric. Wang and Narasimhan (1984) have used this idea in the development of a conceptual model for fractured porous media. They note that under unsaturated conditions (water pressure less than atmospheric) flow would occur across the fractures into adjacent porous blocks rather than parallel to the fractures. At higher water pressures, (small pressure difference) the films around the points of contact would increase in thickness and flow could occur more readily perpendicular to the fracture. Thus for unsaturated conditions, fractured porous media can be viewed as porous media with abrupt changes in the capillary pressure-saturation and capillary pressure-conductivity relationships.

Two factors may influence the above discussion.

1. The occurrence of materials on the surfaces of fractures which resist wetting to water or which seal the surfaces.

2. The occurrence of entrapped air within the porous blocks.

It is unlikely that any surfaces in the volcanic tuff are completely water repellent because wetting by water is a time dependent process; over geologic time it is relatively certain that all particles will have developed a water film. A possibility exists, however, that materials could have been deposited on the fracture walls that have sealed the pores so that water could not move into the pores. This change of hydraulic properties of the fracture walls would produce a conceptual model for the unsaturated zone that would not include flow in the matrix pore spaces.

Entrapped air in the blocks possibly could prevent movement of water into the pores. This condition should be investigated in-situ at the Yucca Mountain site; its existence also would produce a different conceptual model.

4.6.2 Flow Processes Under Natural Conditions in Yucca Mountain

The flow process through the unsaturated zone at Yucca Mountain is believed to be a downward movement from the ground surface to the water table. The basic objective in producing a conceptual model is to evaluate the probable magnitude of the downward movement rate. The mathematics of the model for steady downward flow under unsaturated conditions through layered materials of varying conductivities is presented in Bear (1972) and Corey (1977). The analysis has been verified experimentally many times. The analysis shows that for steady unsaturated downward flow, the effective conductivity in each layer will be equal to the flux rate; the hydraulic gradient through each layer will be equal to one. At the interface between any two layers of different permeability, the gradient may be greater than or less than one depending on the capillary pressures in the two materials. The theory also shows that the transition zone for the capillary pressure distribution always occurs in the upper material.

Sufficient data required for an initial application of this model to Yucca Mountain are available in Peters and others (1984). The data consist of representative values of saturated conductivity, capillary pressure-saturation values, porosity and residual saturation. These data were derived from laboratory tests on 48 core samples from boreholes G-4 and GU-3; the samples sources were distributed vertically throughout the entire profile of Yucca Mountain. Average in-situ values of saturation for the various formations also are available (Montazer and Wilson, 1984).

The Brooks-Corey method (Brooks and Corey, 1964) may be used with the capillary pressure-saturation data to determine the displacement pressure, ψ_d, and pore size distribution index, λ, for each of the representative cores from each formation. These calculated values are shown in table 1.

Table 1. Hydraulic characteristics of cores.

Sample No.	Formation	Porosity	Saturated Hydraulic Conductivity (mm/yr)	ψ_d (m)	λ
G4-1	Tiva Canyon	.09	.31	125	.97
GU3-7	Paintbrush	.37	12,000.00	45	1.49
G4-6	Topapah Spring	.11	.60	225	1.19
G4-11	Calico Hills	.28	.63 to .00076	3.40	.55

Application of the aforementioned analysis to Yucca Mountain requires assuming a value of downward flux and then determining whether the resulting calculated capillary pressures and saturations compare favorably with measured in-situ values. Reliable measured downward flux values are not available.

We will assume that the downward flux (q) is 0.5 mm/yr. Since the saturated matrix conductivity of the Tiva Canyon Member is only 0.31 mm/yr a portion of the flow would occur in the fractures of the formation. Applying the Brooks-Corey equation

$$q = K\left(\frac{\psi_d}{\psi}\right)^{2+3\lambda}$$

for the Paintbrush Tuff and solving for the capillary pressure, ψ, we find that $\psi = 213$ m. Using this value with figure 13 to obtain the degree of saturation we obtain a value of 0.30. This value is about one half the average saturation value presented by Montazer and Wilson (1984). The capillary pressure in the Topapah Spring Member is calculated similarly as

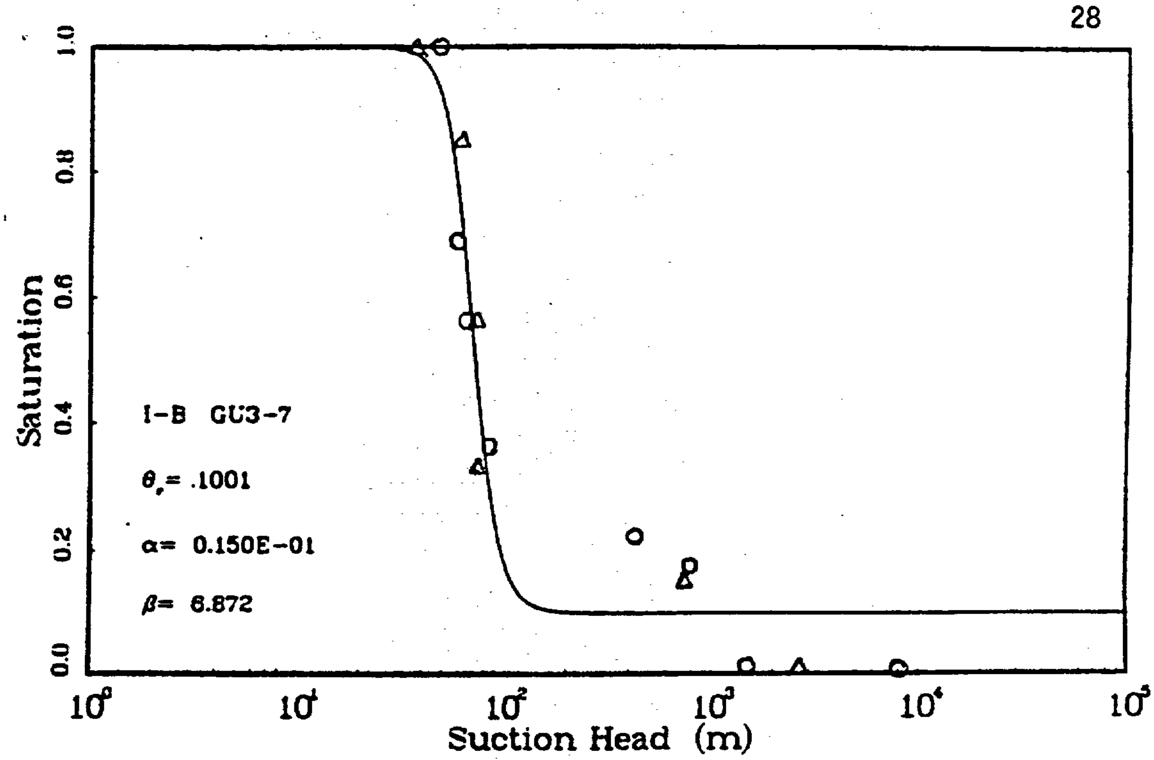


Figure 13. Capillary pressure saturation curve for Paintbrush Tuff.

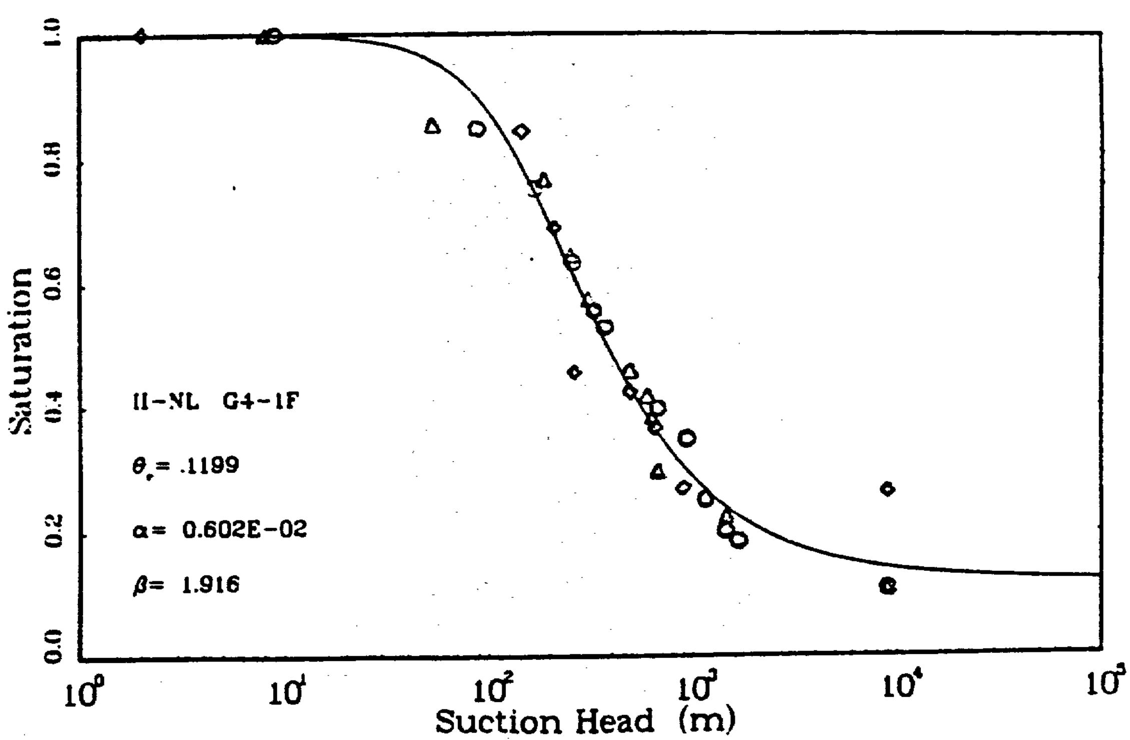


Figure 14. Capillary pressure saturation curve for Topapah Spring Member.

232.7 m. Using this value with figure 14, the calculated saturation level is 0.65. The average value of saturation presented by Montazer and Wilson (1984) is 0.65. Applying the same process to the tuffaceous beds of the Calico Hills (Calico Hills) yields a capillary pressure of 362 m, whereupon the saturation value is 0.78. However, the water table is approximately 250 to 300 m below the top of the Calico Hills which would prevent the occurrence of a capillary pressure of 362 m. The pressure distribution in the Calico Hills essentially would be hydrostatic throughout. The degree of saturation would be 1.0 at the water table and would decrease with distance above the water table. The value of saturation from Montazer and Wilson (1984) is 0.90 which agrees with our analysis.

Although the above analysis is very simplistic, it appears to match the available field data fairly well; however only one sample from each formation was used for the hydraulic property data. It must be realized that considerable spatial variation of material properties can be expected. Consequently locations may exist from which the data would not fit our analysis.

The above analysis also assumes that the layered formations are nearly downdip, however, this would not be expected to be significant unless saturated conditions occurred above a relatively impermeable layer.

The term capillary barrier has been used in many of the discussions of flow in Yucca Mountain. This concept is completely invalid in the case of steady flow. The reason for the invalidity is that if a very coarse material underlies a fine material, the saturation level in the fine material will increase to the point that will allow water to move into the coarse material. The only alternative to this is to assume that the saturation increases, a horizontal gradient develops and the water moves around the coarse material. Montazer and Wilson (1984) suggest that water would move laterally until it reaches a fracture through which it would move under completely saturated conditions. However, we believe that water would move from fine material into underlying coarse material at a lower saturation level than would be required for water to move into fractures. Due to heterogeneities known to exist in Yucca Mountain it may be possible that small regions of nearly saturated, downward flow exist whereas other regions exist that have lower saturation levels. Montazer and Wilson's (1984) model perhaps would be more appropriate if the formations were steeply dipping.

Film flow down the fractures also has been proposed in some of the conceptual models. We do not believe that film flow occurs because the fracture apertures are estimated to be at most .05 mm in width. Under these conditions, water films would thicken and completely fill the fracture if it did not move into the matrix pore spaces as described above.

Flow into fractures from high intensity rainfall events has been of concern because flow into the fractures presumably could move down through the profile much faster than has been hypothesized for flow in the porous matrix. It should be noted that in order for fractures to conduct water in this way they need to be open at the ground surface and be in direct contact with ponded water. If a soil mantle exists over the entrance to the fractures, then water flow into the fractures under saturated conditions would be improbable. However it is possible that open fractures may be exposed to saturated conditions beneath the stream channels during high runoff events. A study of the fracture characteristics of the outcrops on Yucca Mountain would shed light on this conceptual model.

4.5.3 Flow Conditions With Repository In Place

Two factors must be considered with a repository in place.

1. The flow paths for downward flow will be interrupted.

2. The possibility exists that vapor movement may occur due to heating of rocks around the repository.

The first of these factors should be reasonably easy to predict. A three-dimensional unsaturated flow model could be used to examine the extent of flow around the repository and whether water would move into the repository. Some papers have referred to placing a capillary barrier around the backfill material such that the water does not move in. We repeat that a capillary barrier would act only temporarily until the saturation level of the material above the barrier reached the point at which flow would occur into the barrier. This saturation level would be dependent on the horizontal extent of the repository, and on the cross-sectional area of the rock not excavated but available for flow. It seems improbable that it would be possible to design a barrier that would not allow water movement through the repository during a period of 1,000 to 10,000 years. It may be possible however, that the drifts of the repository are spaced such that there are sufficient undisturbed rocks between the drifts to conduct the water downward. Such spacing would be highly dependent on the magnitude of downward flux; this condition could be investigated by numerical modeling as stated above.

A conceptual model developed by Montazer and Wilson (1984) hypothesizes flow as occurring rapidly through the Tiva Canyon fractures and then moving very slowly into the Paintbrush unit because of entrapped air. The air entrapment is said to cause some of the flux to move laterally so as to decrease flow into the Paintbrush unit. In our opinion such a conceptual model is very questionable. No explanation is presented as to why the air would be trapped nor why a decrease of flux into the Paintbrush unit would occur. This process effectively would produce a perched zone. The authors point out correctly that no evidence of authentic perched zones has been discovered.

The concept of entrapped air is a transient phenomenon that would influence the flow only near the ground surface if rapid infiltration from the ground surface occurred. Entrapped air ultimately would be dissolved in the water and would either be carried out by moving water or diffused through the water to the atmosphere (Adams, Bloomsburg and Corey, 1969). The concept of air entrapment producing barriers to downward flow should be rejected because no reason is presented that it should occur and no evidence is presented that it does occur.

The conceptual model that envisions circulating vapor flow around the heat source of the repository is very intriging. Basically this conceptual model anticipates that water would be evaporated near the heat source, then move in the vapor phase to some distance from the repository where it would condense. Due to the capillary pressure gradient and the change of the saturation level of the liquid phase, the liquid water would then move back toward the repository. This concept would produce a recirculating system wherein no water would even move into the repository nor leave the area. However, it must be recognized that the temperature of the repository would drop after several hundred years, whereupon water would move into and through the repository. Consequently, on a long term basis this conceptual model would not be functional.

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