UNITED STATES

DEPARTMENT OF THE INTERIOR

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PALEOHYDROLOGY OF THE SOUTHERN GREAT BASIN, WITH SPECIAL REFERENCE TO WATER TABLE FLUCTUATIONS BENEATH THE NEVADA TEST SITE DURING THE LATE(?) PLEISTOCENE

By

Isaac J. Winograd and Gene C. Doty

Open-file Report 80-569

Prepared in cooperation with the U.S. Department of Energy

Reston, Virginia

1980

UNITED STATES DEPARTMENT OF THE INTERIOR

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ABSTRACT

Knowledge of the magnitude of water table rise during Pleistocene pluvial climates, and of the resultant shortening of ground-water flow path and reduction in unsaturated zone thickness, is mandatory for a technical evaluation of the Nevada Test Site (NTS) or other arid zone sites as repositories for high-level or transuranic element radioactive wastes. The distribution of calcitic veins in alluvium and lakebeds, and of tufa deposits, between the Ash Meadows spring discharge area and the Nevada Test Site suggests that discharge from the regional Paleozoic carbonate aquifer during the Late(?) Pleistocene occurred at distances as much as 14 kilometers northeast of Ash Meadows and at altitudes up to 50 meters higher than at present. Use of the underflow equation (relating discharge to transmissivity, aquifer width, and hydraulic gradient), and various assumptions regarding pluvial recharge, transmissivity, and altitude of ground-water base level, suggest possible rises in potentiometric level in the carbonate aquifer of 6-90 meters beneath central Frenchman Flat, 58 kilometers northeast of Ash Meadows. During Wisconsin time the rise probably did not exceed 30 meters. Water-level rises beneath Frenchman Flat during future pluvials are unlikely to exceed 30 meters, and future levels might even be 10 meters lower than the modern one, 210 meters beneath the center of the valley.

Neither the cited rise in potentiometric level in the regional carbonate aquifer, nor the shortened flow path during the Late(?) Pleistocene preclude utilization of the NTS as a repository for high-level or transuranic-element radioactive wastes provided other requisite conditions are met at this site. Deep water tables, attendant thick (up to several hundred meter) unsaturated zones, and ground-water flow paths tens of kilometers in length characterized the region during Wisconsin time and possibly throughout the Pleistocene, and are likely to so characterize it during future pluvial climates.

INTRODUCTION

The valleys at the Nevada Test Site (NTS) and surrounding parts of the southern Great Basin are characterized by aridity, very deep water tables (as deep as 600 meters), low hydraulic gradients in the principal aquifers, ground-water flow paths tens of kilometers in length, and by tuffaceous rocks with relatively high sorptive capacity for radionuclides. These characteristics are among some of the perceived technical attributes of the NTS (Fig. 1) as a potential repository for the disposal of high-level (HLW) or transuranic contaminated (TRU) radioactive wastes.

However, it has been well documented in the paleoecologic and paleoclimatologic literature that the climate of the region was significantly wetter during the Pleistocene Epoch approximately 10,000 to 1.8 million years ago. Specifically, between 40,000 and 10,000 years ago during the middle-to-late Wisconsin time of the Pleistocene some of the topographically closed basins of the Nevada Test Site region intermittently had lakes and woodland plants; for example, Juniper grew at altitudes as much as 600 meters (m) lower than today. These conditions reflected some combination of increased rainfall and reduced temperature. (Broecker and Kaufman, 1965; Mehringer, 1965, 1967; Miller, 1948; Ore and Warren, 1971; Smith, 1968, 1979; Spaulding, 1977, 1980; Wells and Berger, 1967; Wells, 1979; Snyder and Langbein, 1962; Van Devender, 1977; Van Devender and Spaulding, 1979; Weide and Weide, 1977). The impact of these wetter periods, called pluvials, on the altitude of the water table, and on the geographic location of ground-water discharge areas, that is, on flow-path length, is unknown. Yet, such information is required

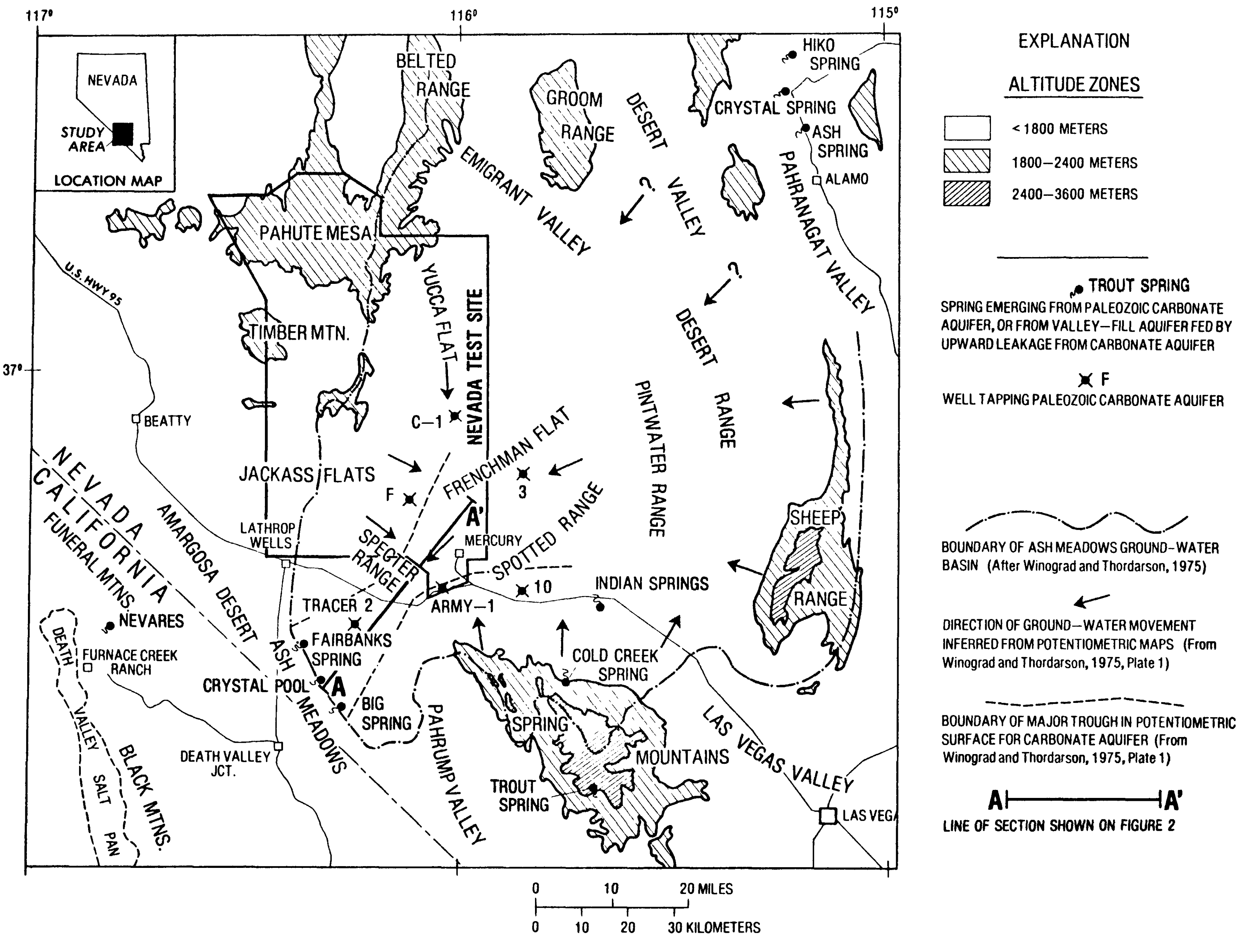

Figure 1.--Index map of the Nevada Test Site and vicinity showing generalized hydrogeology and boundary of the Ash Meadows ground-water basin, Nevada

for a rigorous evaluation of the NTS as a site for the disposal of HLW and TRU wastes; such wastes must remain isolated from the hydrosphere and biosphere for not less than several hundreds of years and conceivably for periods on the order of tens to hundreds of thousands of years depending upon the radionuclide release scenarios envisioned (Bredehoeft and others, 1978; p. 9-12; Interagency Review Group, 1978, p. 8-13).

The purposes of this report are twofold: (a) to demonstrate why a knowledge of the altitude of past water-tables is important for a critical evaluation of the Nevada Test Site (NTS) as a potential repository for HLW and TRU wastes; and (b) to present and discuss the results of a reconnaissance of modern and fossil spring deposits which, coupled with hydrogeologic considerations, provide evidence pertinent to the magnitude of water-table rises and changes in length of ground-water flow path during the Pleistocene, and particularly during Wisconsin time.

A brief overview of the hydrogeologic setting follows to provide the background necessary for the remainder of the report. The reader is referred to Winograd and Thordarson (1975), Dudley and Larson (1976), Winograd and Friedman (1972), and Winograd and Pearson (1976) for detailed descriptions of the hydrogeology and hydrogeochemistry of the Ash Meadows ground-water basin.

Hydrogeologic Setting

Figure 1 shows the outline of the Ash Meadows ground-water basin to which the eastern one-half of the NTS is tributary. Ground-water flow in this basin is controlled principally by the presence of a thick (several hundred to a few thousand meter) sequence of dense and highly fractured Paleozoic carbonate rocks, termed the lower carbonate aquifer by Winograd and Thordarson (1975). The presence of this aquifer beneath ridges and valleys permits the regional movement of ground water beneath the prominent topographic divides separating the intermontane valleys of the area. In this fashion ground-water flow beneath a minimum of 10 intermontane valleys is integrated into a single ground-water basin, the Ash Meadows basin. The direction of flow within this ground-water basin is depicted in figure 1. Discharge from the basin occurs along a spring lineament at Ash Meadows 40 kilometers (km) southwest of Mercury, Nevada; the discharge exceeds 40 cubic meters per minute (m^3/min; equivalent to 10,600 gallons per minute or 17,100 acre-feet annually).

The hydraulic gradient in the regional carbonate aquifer between central Frenchman Flat and Ash Meadows is extremely low, 0.11 m/km; the difference in water level in this 58 km distance is about 6 m. This low gradient reflects the very high fracture transmissivity of the lower carbonate aquifer, particularly in the region between the Specter Range and Ash Meadows (fig. 1). Winograd and Thordarson (1975, p. C71-C74) estimated transmissivities in the range of $5x10^4$ to $7x10^4$ m^2/d ($4x10^6$ to $6x10^6$ gallons per day per foot in the older units utilized by Winograd and Thordarson, 1975).

Ground water also occurs in tuff and valley fill aquifers of Cenozoic age beneath the valleys. A thick tuffaceous aquitard (stratum of very low permeability) of Tertiary age separates the Cenozoic and the lower carbonate aquifers.

In much of the eastern third of Nevada and southeastern California major springs emerge at valley level directly from the base of ridges of Paleozoic carbonate rocks, or from alluvium, lake beds, or tufa mounds adjacent to outcrops of these carbonate rocks which comprise the lower carbonate aquifer (Maxey and Mifflin, 1966; Winograd, 1972). The discharge of individual springs ranges up to 29 m^3/min and groups of springs yield as much as 85 m^3/min. This discharge pattern reflects, in part, topographic setting, and, in part, ground-water barriers such as fault zones juxtaposing Paleozoic clastic rocks and the lower carbonate aquifer (Winograd and Thordarson, 1975). A major, and we believe a reasonable, assumption made in this study is that during the Pleistocene, and particularly during pluvial climates of Wisconsin time, 10,000 to 100,000 years ago, the same topographic-structural geologic features controlled ground-water discharge from the lower carbonate aquifer as control this discharge today. Thus with a major regional rise in water level, major pluvial springs would have discharged from topographically higher outcrops of the lower carbonate aquifer in addition to present outlets. A corollary assumption to which we return later is that faulting and erosion have had only minor effects on the regional topography (say less than a few tens of meters) in the last 100,000 years.

In the preceding paragraph we have applied the Law of Uniformitarianism, that is, that the present is a key to the past, and in the next section we imply that the past may be a key to the future. Both matters are fraught with philosophical difficulties some of which have been discussed by the senior author in Bredehoeft, and others (1978, p. 9-12). Briefly, this law applies only to physical processes, not to the magnitude or frequency with which such processes operate. That is, there is no guarantee that future rises in potentiometric level in response to pluvial climate will equal the magnitude of past rises; future water levels might be higher than any past level, or even be lower than modern levels. Yet, knowledge of the maximum credible rise in the past and of the accompanying shortening of flow path is instructive for an analysis of the ability of the NTS to isolate radioactive wastes through long periods of geologic time. We are using the Law of Uniformitarianism only as a qualitative means of putting bounds on possible future changes of the present regional flow system. Such changes, if significant, should be taken into account in predicting the residence time of selected radionuclides emplaced within the ground-water flow system encompassing the NTS.

Effects of Future Pluvial-Related Rise in Water Table on the Suitability of the Nevada Test Site as a Radioactive Waste Repository

The return of a pluvial climate to the Southwest, say a thousand years hence, might affect the isolation of HLW or TRU wastes buried at the NTS in three ways. First, a major rise in water table (more correctly in the potentiometric level) might result in a significantly reduced distance of ground-water flow from the NTS to points of natural discharge. Second, the utility of the unsaturated zone (that is the volume of rock between the land surface and the water table) as a waste disposal environment might be reduced. Third, an increase in recharge during the pluvials would be accompanied by an increase in ground-water velocity, and hence by shorter residence times for any dissolved radionuclides. These matters are discussed in turn below.

The possible effects of water table rise, in response to past (or future) climate, on ground-water path length are illustrated by figure 2. This figure shows diagrammatically the flow of water in the lower carbonate aquifer between Frenchman Flat and the Ash Meadows discharge area and the influence of hypothesized changes of water table altitude. If past (or future) pluvial conditions raised the water table 40 to 50 m, or to an altitude of 760 to 770 m, water could discharge from the lower carbonate aquifer at point A (Fig. 2), about 14 km closer to Frenchman Flat than is Ash Meadows; a past (or future) rise of 150 m, to an altitude of about 870 m, could result in natural discharge from aquifer outcrops at point B, 21 km closer to Frenchman Flat. Not only would such rises in water table result in shortening of the flow path, but the reduced depth to water would increase the likelihood that the lower carbonate aquifer might be tapped for water supply in the future in the region between Ash Meadows and Frenchman Flat.

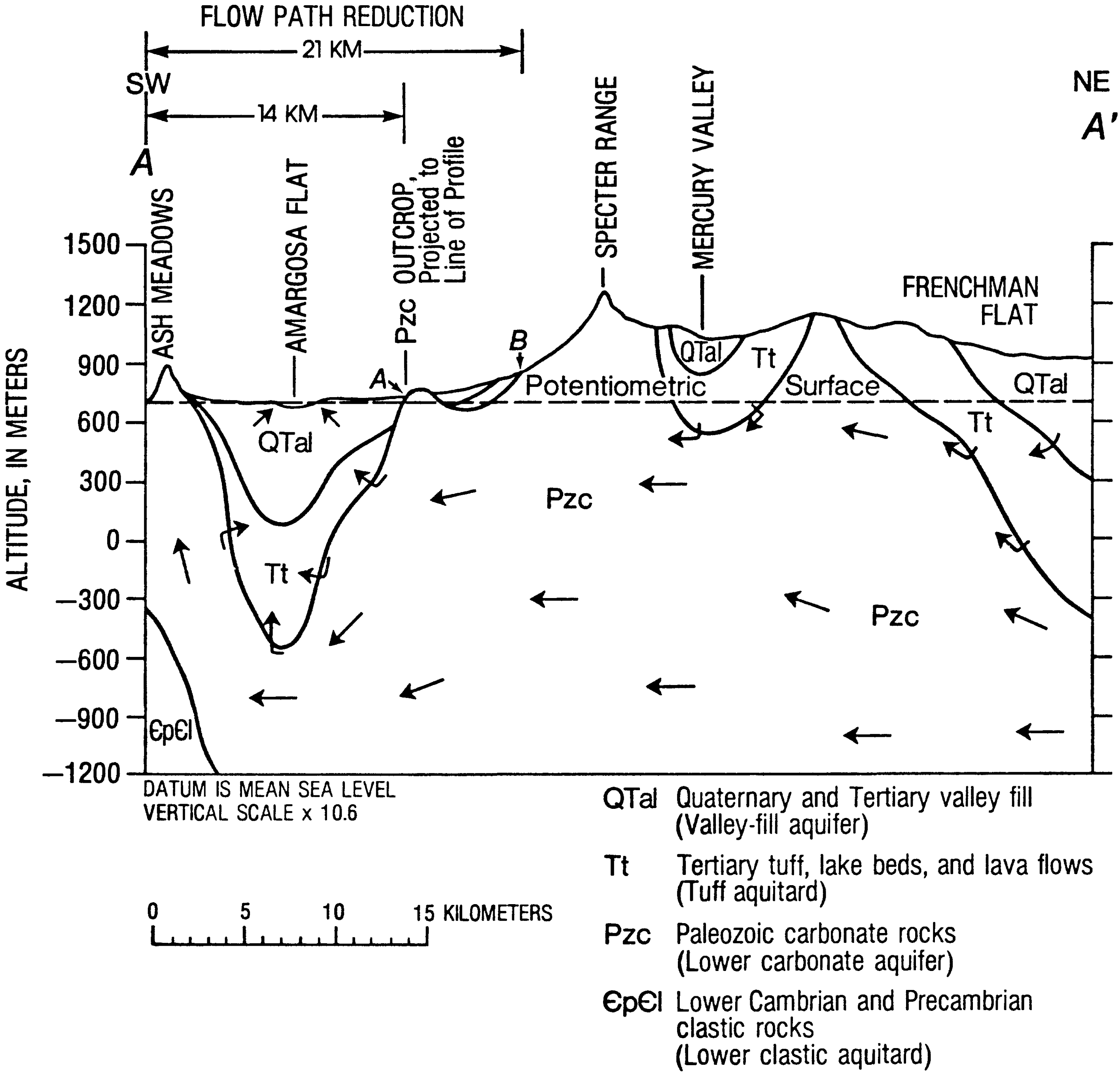

Figure 2.--Diagrammatic section illustrating effects of possible past or future pluvial-related water table rise on length of ground-water flow path from Frenchman Flat to points of natural discharge at Ash Meadows in the Amargosa Desert, Nevada (Line of section is shown on figure 1; water level rises of 40 and 150 m would initiate discharge from the lower carbonate aquifer at points A and B, respectively 14 and 21 Km northeast of modern spring lineament; arrows depict ground-water flow)

A shortening of flow path, even in excess of 21 km, need not necessarily rule out the NTS as a potential repository. The flow path length from north-central Yucca Flat to Ash Meadows is roughly 85 km, and that from central Frenchman Flat is 58 km. More importantly, the suitability of the NTS or any other proposed repository site, depends on several technical factors (for example, rock sorptive properties, ground-water velocity, and waste-form solubility) in addition to flow-path length (Donath, and others, 1978). Nevertheless, an analyses of the migration of radionuclides from a repository at NTS requires knowledge of present as well as possible future hydrologic boundary conditions; hence the need to place a limit on the probable lengths of past, and, by analogy, of future, ground-water flow paths.

The assets and liabilities of disposal of HLW or TRU wastes in thick (600 m) unsaturated zones of the Southwest, including those at the NTS, have been discussed by Winograd (1972, 1974). Evaluation of this concept, which will require perhaps a decade of research, has been endorsed by Angino (1977), the National Academy of Sciences - National Research Council (1976, 1978), Geotechnical Engineers, Inc. (1979) and Krauskopf (1979). Briefly, the unsaturated zone at the NTS appears to provide a major barrier to the movement of radionuclides under present climatic conditions due to the very small flux of water through this zone, coupled with high radionuclide sorptive capacity of valley fill (alluvium) and tuffaceous rocks comprising the zone (Winograd, 1974, 1980). Under future pluvial conditions, however, might a repository constructed near the base of the present unsaturated zone be inundated by a high "water-table stand?" A related question deserving close examination is whether pluvial conditions would result in significantly greater percolation of precipitation through the unsaturated zone beneath the valleys to the water table. The intuitive belief that deep percolation must have been significantly greater during the pluvials may not be correct. Xeric juniper woodland containing cold desert flora occurred at altitudes as low as 1100 m in the NTS region during Wisconsin time (Wells and Berger, 1967). Deep vertical percolation through the unsaturated zone beneath the valleys during the pluvials might not have been significantly greater than today due to the denser vegetative cover. Knowledge of the magnitude of past water table rise and of deep percolation during pluvial climates is obviously needed as part of any evaluation of the unsaturated zones at the NTS, or elsewhere in the Southwest, for radioactive waste disposal (Winograd, 1980).

Ground-water velocity is a direct function of the flux of water through, and an indirect function of the effective porosity of, a given cross-section of any aquifer. Thus, if recharge to the lower carbonate aquifer doubled during pluvial times, the ground-water velocity in this aquifer would double and the residence time of any dissolved radionuclides would be halved. This relationship is correct only if the thickness of the aquifer remains unchanged in response to an increase in flux, a factor not strictly correct for the regional carbonate aquifer as will be shown in this report. Nevertheless, considerations of velocity increase would be of particular importance to plans for disposal of radioactive wastes below the water table in fractured rocks of very low effective porosity such as the lower carbonate aquifer or the Tertiary welded tuff of the region. In this report, our principal concern relates to the first and second of the three listed potential hydrogeologic effects of pluvial climate, namely changes in flow path length and in thickness of the unsaturated zone.

Acknowledgments

The writers are indebted to Industrial Minerals Ventures, Inc., for making available information from their extensive exploration of the Amargosa area for clay minerals. Michael Collins, Richard Baird, and Jack Mayhew of that organization supplied drill-hole data and conducted tours of currently-operated clay pits. We thank Margaret J. Baldwin for serving as our photographer at sites represented by figures 4-16 and 20-23. The review comments of W. J. Carr, R. L. Hay, D. I. Leap, B. F. Jones, W. G. Spaulding, W. C. Swadley, B. J. Szabo, and R. K. Waddell improved the manuscript and are appreciated.

Conversion of Units

The metric system is used throughout this report although most of the original measurements and data were reported in inch-pound units. In a few places in the Introduction certain inch-pound units are also given for convenience of the reader. Conversion of the original data to metric units follows significant figure guidelines outlined by Bishop, and others (1978, p. 197-202). Conversion factors of use to readers of this report are listed below.

Multiply SI metric units	by	To obtain inch-pound units
	Length	
meter (m)	3.281	foot(ft)
kilometers(km)	0.621	mile (mi)
	Area	
square kilometer (km^2)	0.386	square mile (mi^2)
	Flow	
cubic meter per minute(m^3/min)	264.19	gallon per minute (gal/min)
	426.138	acre-foot per year(acre-ft/yr)
	Transmissivity	
square meter per day(m^2/d)	80.5	gallons per day per foot (gal/d ft^{-1})
	10.76	square feet per day (ft^2/d)

METHODS OF INVESTIGATION

Between the NTS and the Ash Meadows discharge area the lower carbonate aquifer occurs alternately under confined ("artesian") conditions beneath the valleys and unconfined (water table) conditions beneath the knolls and ridges (Fig. 2). If the water table was tens to a few hundred meters higher during Wisconsin (or earlier) time than the present highest potentiometric level at Ash Meadows (719 meters), it is probable that springs would have discharged directly from the lower carbonate aquifer at higher altitudes along the base or periphery of the numerous carbonate rock knolls and ridges in the region between Ash Meadows and the NTS (Fig. 2). In designing this study we assumed that had such discharge occurred some evidence of it would remain in the form of spring and spring-related deposits such as those found (and described below) at modern and known fossil springs. This major assumption receives detailed discussion in a subsequent section.

The study involved the following steps. First, all known major springs between Ash Meadows and Death Valley were visited to observe the morphology of modern spring deposits. Fossil tufa mounds adjacent to the modern springs at King Spring in Ash Meadows (fig. 3) and at Nevares Spring in Death Valley (fig. 1) were also studied. Second, fossil spring or tufa deposits, mapped by Denny and Drewes (1965) in the Ash Meadows area but not associated with modern springs, were visited and their morphology observed. Third, valley-level outcrops of the lower carbonate aquifer at altitudes of 720 to 940 meters were examined on foot and from light aircraft for evidence of tufa deposits (fig. 3) and calcitic veins

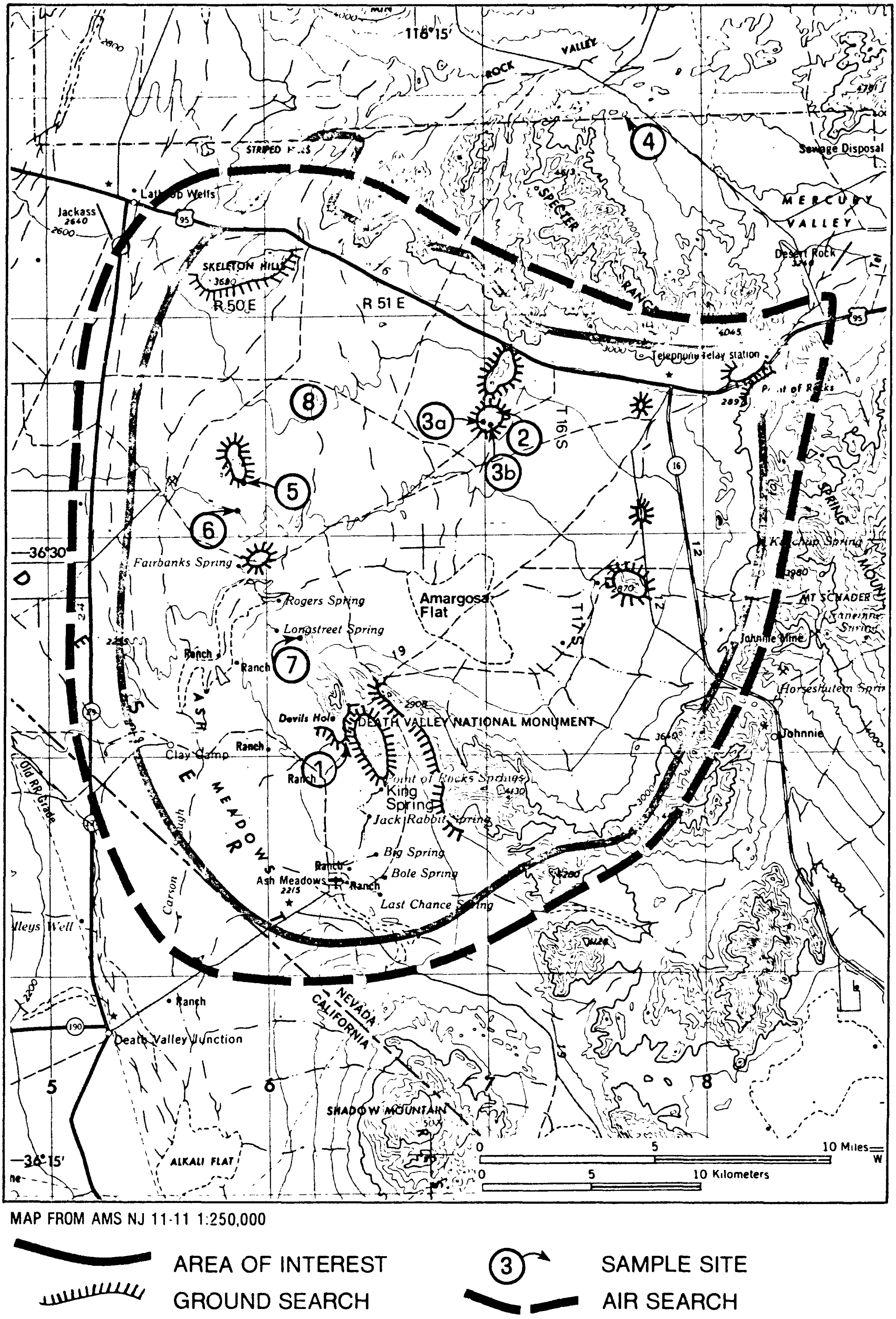

Figure 3. Map showing areas of ground and aircraft survey for pluvial spring deposits, Ash Meadows - Mercury Valley area, Nevada.

marking the conduits of fossil springs. The altitudes of these outcrops ranged up to roughly 220 meters above the present highest potentiometric surface (719 meters) in the lower carbonate aquifer at Ash Meadows. Selected tufa deposits and related calcitic veins were sampled for uranium-disequilibrium dating ($^{234}U/^{238}U$ and $^{230}Th/^{234}U$) and for stable isotopic (oxygen-18 and carbon-13) analyses. The results and interpretation of the uranium-thorium dating and stable isotopic data are the subject matter of other reports in process. Lastly, outcrops of caliche (defined below) were also examined in order to contrast these two broad classes of predominantly calcium carbonate deposits.

Caliche and Tufa Defined

Caliche and tufa are both composed principally of calcium carbonate ($CaCO_3$), both form in more than one environment, and both may display several morphologies even when deposited in a single environment. And, not surprisingly, they may be mistaken for each other. We define these terms before proceeding.

Caliche, in a soil environment, is defined in the Glossary of Geology (American Geological Institute, 1974, p. 101) as "an opaque, reddish brown to buff or white calcareous material of secondary accumulation (in place), commonly found in layers on, near, or within the surface of stoney soils of arid and semi-arid regions, but also occurring as a subsoil deposit in sub-humid climates. It is composed largely of crusts or succession of crusts of soluble calcium salts in addition to impurities such as gravel, sand, silt, and clay. It may occur as a soft, thin, extremely porous and friable horizon within the soil, but more commonly it is a thick (several centimeters to a meter or more), impermeable, and strongly indurated layer near the surface or exposed by erosion; the cementing material is essentially calcium carbonate, but may contain magnesium carbonate, silica, or gypsum. The term has been used for the calcium carbonate cement itself." Calcrete, a synonym of caliche, is defined (American Geological Institute, 1974, p. 100) as "a conglomerate consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution and redeposited through the agency of infiltrating waters, or deposited by the escape of carbon dioxide from vadose water."

Bachman and Machette (1977) consider the term caliche too general a description for calcium carbonate deposits of diverse origins found in the southwestern United States. They prefer the more specific terms calcrete, calcic soils, and pervasively cemented deposits. We agree with these authors, but, in order to expedite discussion in our report, we restrict the term "caliche" to calcium carbonate deposits of pedogenic (or soil) origin and the term "calcrete" to the well-indurated calcium carbonate deposits found in arroyos.

Both caliche, developed in soil or interfluve environments, and calcrete, deposited along the beds and walls of arroyos, occur in the study area. The reader is referred to papers by Gardner (1972), Cooley and others (1973), and Lattman (1973) for detailed description of soil caliche and arroyo bottom calcrete of areas along the periphery of the Nevada Test Site.

Tufa is defined in the Glossary of Geology (American Geological Institute, 1974, p. 759) as "A chemical sedimentary rock composed of calcium carbonate, formed by evaporation as a thin, surficial, soft, spongy, cellular or porous, semifriable incrustation around the mouth of a hot or cold calcareous spring or seep, or along a stream carrying calcium carbonate in solution, and exceptionally as a thick, bulbous, concretionary or compact deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. The hard, dense variety is travertine."

Tufa, as used in the remainder of this report, refers to calcium carbonate deposits which display fossilized vegetative mats similar to those forming at modern springs, or which comprise strata which field relations clearly demonstrate have originated from spring discharge, for example, the draped strata comprising the prominent mounds at King and Nevares Springs.

We acknowledge that the morphology of stratiform tufa deposits which formed in a spring-fed marsh might, if not in proximity to a tufa mound or to a modern spring, be indistinguishable from those formed in a marsh environment bordering a lake. Because of the widespread Pliocene(?) and Pleistocene lake deposits of the region this origin cannot be discounted for some of the tufas of the study area.

The variable morphology of pedogenic caliche has been well described in a voluminous literature (see for example, Reeves, 1976 and Bachman and Machette, 1977, for recent reviews); we cannot justify reviewing this subject matter here. Several major distinctions visible in the field exist, however, between pedogenic caliche and calcrete of the region and the tufa, whose morphology is described in the next section. First, the tufas of the NTS area are usually permeated by fossilized plants or molds of plants, clearly suggesting deposition in a marsh environment; such features are absent in pedogenic caliche or calcrete. Second, some tufas exhibit draped and moundlike forms unlike those described for pedogenic caliche or arroyo bottom calcrete. Third, in pedogenic caliche the "concentration of calcium carbonate decreases progressively downward in the deposit below a carbonate maximum that lies near the top of the calcareous zones" (Bachman and Machette, 1977, p. 21), and different morphologies accompany the decrease in calcium carbonate concentration. Such features are not generally evident in tufas. Fourth, where pedogenic caliche underlies a geomorphic surface "its morphology is relatively persistent and can be traced laterally over extensive areas--possibly tens to hundreds of square kilometers" (Bachman and Machette, 1977, p. 21-22). Most tufas by contrast are restricted to the immediate vicinity of the spring, or in the case of lacustrine tufas, to a paleo-shoreline. Finally, some dense tufas deposited in arroyos may be distinguished from calcrete by limited detrital material above the base of the deposit.

No attempt was made in this reconnaissance to distinguish between tufa, caliche and calcrete deposits on the basis of petrologic, mineralogic, or stable isotopic criteria. Only morphologic distinctions visible in the field were utilized to distinguish between these deposits.

Morphology of the Tufa Deposits

Common macroscale and megascale morphologies displayed by modern and fossil spring deposits of the Ash Meadows and Death Valley region are illustrated by figures 4 through 23. Mats of vegetative matter encrusted with calcium carbonate, sodium(?) carbonate, and other salts and (or) molds of such vegetation constitute reliable macroscale features useful for distinguishing tufa from pedogenic caliche or arroyo-bottom calcrete deposits. Modern vegetative mats at Crystal Pool and Nevares Spring are shown in figures 4 and 5. At Nevares Spring successive stages of fossilization of the vegetative mats is clearly displayed in the upper meter of tufa as shown in figures 6 and 7. At greater depths, the older tufa deposits at this site are denser and the fossilized vegetative mats considerably more difficult to discern (Fig. 8). Nevertheless, many of these older tufas can be distinguished from caliche and calcrete even in the absence of an association with young porous tufa; unlike pedogenic caliche, and regardless of their density, these older tufas exhibit no evidence of the cementation of preexisting valley-fill, or arroyo-bottom sediments.

Figure 4.--Carbonate incrustation of saltgrass (Distichlis spicata) on margins of Crystal Pool by precipitation from spring-fed soil moisture, Ash Meadows, Nev. (SE 1/4, NE 1/4, sec. 3, T18S., R.50E.)

Figure 5.--Minerals precipitating from spring discharge encrust vegetation and rock in stream-marsh environment at Nevares Spring, Death Valley, Calif. (Lower third to half of photograph is of water-filled rill; 3 x 5-inch card serves as scale; SW 1/4, NE 1/4 sec. 36 T.28N., R.1E.)

Figure 6.--Ropy mass of fossilized plant material, southwest side of tufa mound at Nevares Spring, Death Valley, Calif..

Figure 7.--Highly porous fossilized vegetative mats comprising tufa capping mound at Nevares Spring, Death Valley, Calif. (porosity may, in part, reflect dissolution by rain).

Figure 8.--Progressive reduction of tufa porosity, and concomitant obscurement of vegetative mat structure with depth, Nevares Spring, Death Valley, Calif. (Reprecipitation at depth of calcium carbonate dissolved at surface of tufa by rain, or continued mineral precipitation from ground water enroute to spring, may account for reduction in porosity.)

Figure 9 shows planar (stratiform), thin (about one-third meter), and well fossilized vegetative mats overlying lake deposits some 800 m west-southwest of Devils Hole (fig. 3, site 1). These deposits were mapped by Denney and Drewes (1965, plate 1) as spring deposits; they also suggested that a spring once emerged near Devils Hole, a major, near-vertical, cavern within the lower carbonate aquifer. At present the water table is about 15 m below the land surface at Devils Hole.

A spring-fed, or perhaps a lake-fed, marsh origin for the dense calcareous deposits capping the butte (figs. 3 and 10) northeast of Fairbanks Spring is likely. The mapping of these deposits as spring deposits by Denny and Drewes (1965, plate 1) is reasonable for they display morphologies (fig. 11) similar to those described above; nevertheless, an origin along the margins of a lake cannot be ruled out. The presence of these tufas atop a butte, at an elevation approximately 45 m above Fairbanks Spring, may reflect Quaternary faulting and(or) erosion following lowering of base level in the southern Amargosa Desert. The age of these deposits is unknown; but they appear to be no younger than mid-Pleistocene age. Evidence for Quaternary faulting, and that the spring lineament at Ash Meadows is fault-controlled is presented by Winograd and Thordarson (1975, p. C81-C83), Denny and Drewes (1965, pl. 1), and Dudley and Larson (1976).

Figure 9.--Fossilized vegetative mat 800 meters west-southwest of Devils Hole, Ash Meadows, Nev.. (Note triangular cross section (sedges?) of some broken molds. Deposit is planar and mostly less than one third meter in thickness. View from top. NW 1/4,sec.1,T.18S.,R.50E.)

Figure 10.--Butte 800 meters northeast of Fairbanks Spring, Ash Meadows, Nev.. (Dense, calcareous, and siliceous caprock, 2 to 4 meters thick, overlies Pliocene(?) and Pleistocene lake deposits. SW 1/4,sec.3,T.17S.,R50E.)

Figure 11.--Close-up of caprock shown in Figure 10, showing morphology and porosity similar to that displayed by fossilized vegetative mats found elsewhere at Ash Meadows, Nev. and at Nevares Spring, Calif.. View from top.

In the absence of fossilized vegetative mats, several megascale features are also useful to identify fossil spring and spring-related deposits. These features include tufas draped over existing topography and tufa mounds such as those at Nevares Spring and King Spring. About 800 m above the mouth of Furnace Creek Wash, a tufa deposit drapes over the side and extends to the bed of the wash (fig. 12). Hunt and Mabey (1966, p. A-78) noted that this dates the travertine as younger than this part of the canyon of Furnace Creek Wash. The tufas comprising the mounds at Nevares and King Springs dip in all directions from the crest, are locally cavernous, and generally increase in density with depth (figs. 13-16). Subsidiary mounds of relatively small size occur locally on the flanks of the principal mound.

The tufa deposits described to this point are not a complete set of those known to the authors. At Keane Wonder Spring in Death Valley (SE 1/4,sec 1, T.15S.,R.46E.), roughly 24 km north-northwest of Nevares Spring, and also along Furnace Creek Wash 26 km west of Death Valley Junction (fig. 1), dense and well laminated deposits resembling hydrothermally deposited calcite veins are present in association with deposits similar to those described above. The dense tufa along Furnace Creek Wash (fig. 17) is associated with a swarm of nearly vertical, dense, and finely laminated calcite veins (fig. 18).

Figure 12.--Tufa draping over north bank of Furnace Creek Wash, Death Valley, Calif. (about 800 meters above mouth of wash).

Figure 13.--Tufa mound at Nevares Spring, Death Valley, Calif. (View is from the west).

Figure 14.--Cavernous character of tufas capping mound at Nevares Spring, Death Valley, Calif.. (Closeup of these deposits shown by figures 6-8; 3 x 5 card serves as scale.)

Figure 15.--Tufa mound at King Spring, Point of Rocks, Ash Meadows, Nev. (King Spring is at right middle-ground; carbonate rocks of Cambrian age form ridge in background; view is to the east, mounding displayed by arcuate outcrop pattern; SW 1/4,NE 1/4., sec.7,T.18S.,R51E.)

Figure 16.--Cavernous character of tufas capping mound at King Spring, Ash Meadows, Nev. (Carbonate rocks of Cambrian age in background.)

Figure 17.--Dense and well-laminated tufa at calcitic vein swarm, Furnace Creek Wash, Death Valley, Calif. (Camera case provides scale; NE 1/4,sec.18,T.26N.,R.3E.)

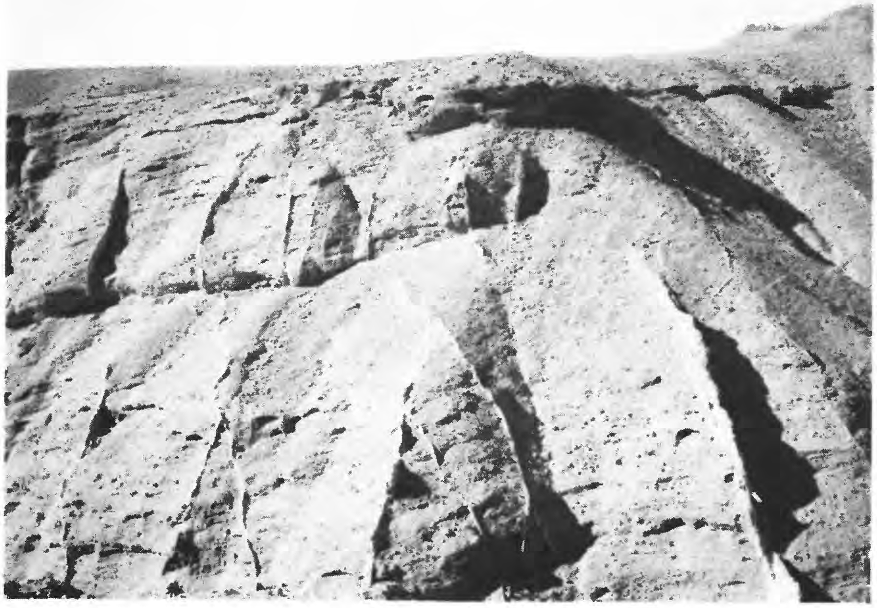

Figure 18.--Calcitic vein swarm in fanglomerate of Funeral Formation, Furnace Creek Wash, Death Valley, Calif. (Relief on the order of 60 meters.)

The highly variable morphology of the tufas reflects at least the following factors: degree of saturation (itself a function of temperature) of the ground water with respect to calcite; rate of discharge; topography, that is whether ground-water discharge and subsequent deposition occurred in channel, marsh, soil, or mound environments; degree of reduction of original porosity by subsequent ground-water flow to the spring and associated precipitation of calcite; alteration of porosity by weathering processes; and type of density of vegetation. Discussion of the effect of these factors on tufa morphology is beyond the scope of this report.

Calcitic Veins and Other Evidence of Fossil Ground-water Flow

In addition to tufa deposits, calcitic veins, and in one location, strandlines marking former water table(s), provided some clues regarding places and altitude of possible pluvial ground-water discharge.

The rocks of the region, particularly the highly fractured Paleozoic carbonate rocks but also Quaternary alluvium and the Pliocene(?) and Pleistocene lakebeds , contain calcite (calcium carbonate) lining or filling fractures. These calcitic veins vary from a millimeter to more than a meter in width, are generally finely banded, dense, and extend over vertical and horizontal distances of meters to hundreds of meters. Field relations at sample sites 1-7 (fig. 3), but particularly at the calcitic vein swarm (figs. 17 and 18) adjacent to Furnace Creek Wash, indicate that these veins mark avenues of fossil ground-water flow. The major evidence--upward bifurcation of the veins and the passage of a vein into a tufa--is visible in the vein swarm area (fig. 18) where erosion has exposed over 60 m of nearly vertical veins in fanglomerate (Funeral Formation of Pliocene and Pleistocene(?) age). In figure 19 we show an example of the innumerable calcitic veins in the Paleozoic carbonate rocks of the study area. Obviously, not all calcitic veins mark the avenues of Late(?) Pleistocene ground water flow and discharge; accordingly, we concentrated our attention in this reconnaissance on those veins filling fractures in Pliocene(?) and Pleistocene lakebeds and Quaternary valley fill.

Figure 19.--Calcitic vein in Paleozoic carbonate rocks, Devils Hole, Ash Meadows, Nev. (Vein fills a N40°E trending fault in the Bonanza King Formation; SW 1/4, SE 1/4, sec. 36,T.17S.,R.50E.)

Figures 20 through 22 illustrate a common type of calcitic deposit coating Paleozoic carbonate rocks along joint and bedding planes. These deposits superficially resemble veins in that they appear to cement debris within joints and bedding planes and are also banded. They resemble tufa by virtue of their draped form (fig. 20) and appearance on weathered surfaces (figs. 21 and 22). We believe these ubiquitous deposits are weathering rinds because in selected specimens they grade into unweathered carbonate rocks. We do not consider them evidence for paleo-ground water flow, particularly flow during the Pleistocene.

Figure 20.--Calcitic deposit draped along bedding plane and joint of Paleozoic carbonate rock, Amargosa Desert, Nev. (Deposit is probably a weathering rind developed along joint and bedding plane openings; NE 1/4,NE 1/4,sec.17,T.16S.,R52E.)

Figure 21.--Closeup (side view) of calcitic deposit of Figure 20. (Note faint banding and weak prismatic structure accentuated by weathering).

Figure 22.--Closeup (top view) of calcitic deposits of figure 20. (Note resemblance to tufa deposits shown in Figures 7,9, and 11)

Direct evidence for higher stands of the water table in the lower carbonate aquifer is available on the walls of Devils Hole (fig. 3). Notches on the east and south walls of this cavern are evidence of water levels as high as 6 m above the 1966 level (altitude 719 m); photographs of these features are given by Winograd and Thordarson (1975, figs. 36 and 37).

RESULTS OF FIELD SEARCH

Figure 3 delineates the region in which low ridges of the Paleozoic carbonate rocks (comprising the lower carbonate aquifer) were examined on foot and (or) from light aircraft for evidence of pluvial tufa and related vein deposits. The reconnaissance was confined to an altitude range of roughly 720 to 940 m based on the following considerations. The highest potentiometric surface in the Ash Meadows discharge area at present--namely, the water level in Devils Hole--was at an altitude of 719 m in 1966, before pumping of the lower carbonate aquifer for irrigation. In view of this, and the possible higher fossil water levels in Devils Hole (discussed above), there seemed to be little reason to search below the 720 m altitude. Conversely, there is no geomorphic evidence to suggest that Frenchman Flat (unlike some closed basins) contained a lake during the pluvial periods (W.W. Dudley, Jr., oral communication, April 24, 1977; Mifflin and Wheat, 1979). Therefore, the altitude of the present playa in Frenchman Flat (about 940m) can be hypothesized to be the highest possible altitude to which water tables might have risen during Wisconsin time.

No tufa mounds or stratiform tufa were found--either at the base of, or in the immediate vicinity (within a few kilometers) of the knolls and low ridges of Paleozoic carbonate rocks--between the altitudes of 760 and 940 m north and northeast of Ash Meadows. Tufa deposits were found, however, between the altitudes of 720 to 760 m, or as much as 40 m above the highest modern water level (719 m) in Devils Hole. The most prominent of the observed fossil tufas is that capping the butte (altitude 742 m) northeast of Fairbanks Spring (figs. 3,10, and 11).

Particularly surprising to us was the absence of tufa along the west side of an unnamed ridge about 6 km due east of Amargosa Flat (fig. 3). Here, Paleozoic carbonate rocks comprising the lower carbonate aquifer crop out at altitudes as low as 740 to 750 m; that is, at altitudes comparable to those having tufa northeast of Ash Meadows. We suggest in a concluding section, that the absence of tufa at this location may reflect differential uplift of Ash Meadows relative to areas to the east.

Dense calcitic veins filling fractures in lakebeds, and (or) alluvium were found between the altitudes of 720 and 770 m north and northeast of Ash Meadows (table 1). Figure 23 shows a calcite vein, at sample site 2 (fig. 3), which fills a fracture in carbonate rock and is also disseminated into overlying alluvium; this vein occurs at an altitude of about 770 m in the southeast corner of section 15, T.16.S.,R.51.E.. Veins at sites 3a and 3b are similar to those at site 2. Calcitic veins in alluvium, lake-beds, and Paleozoic carbonate rocks were found by W.C. Swadley (U.S. Geological Survey, Denver, Colo.) at an altitude of about 760 m at site 5 (table 1). At sample site 6 (fig. 3) several calcitic veins filling fractures in white lakebeds crop out in a north-northeast trending band about 15 m wide by 230 m long; these veins occur at an altitude of 710 to 720 m. R.L. Hay (University of Calif., Berkeley) discovered calcitic vein material in alluvium and lakebeds adjacent to carbonate rocks at an altitude of 740 to 760 m at sample site 7 near the center of section 23, T.17.S., R.50.E..

Table 1. Description of selected calcitic veins sites, Ash Meadows area, Amargosa Desert, Nevada.

Site number (Keyed to figure 3)	Location	Altitude (meters)	Description
1	SW 1/4,SE 1/4, sec.36, T.17S., R.50E.	738 ± 2	Vein fills N.40°E. trending fault zone; visible on southwest wall of Devils Hole; vein extends from land surface to below water level (altitude 719 m) in this cavern developed in Paleozoic carbonate aquifer; see fig. 19.
2	SE 1/4,SE 1/4, sec.15,T.16S., R.51E.	768 ± 2	Vein in Paleozoic carbonate rock and overlying valley fill; see figure 23.
3a,3b	SE 1/4,NE 1/4, sec.22,T.16S., R.51E.	765 ± 3	Veins similar to those at site 2
4	701,600 N 653,400 E (Nevada State, 10,000 foot grid)	1,140 ± 6	Veins occur along faulted margins of Paleozoic carbonate rock hill in in Mercury Valley; faults trend N.30°-50°E.
5	SE 1/4,SW 1/4, sec.27,T.16S., R.50E.	756 ± 9	Veins in valley fill, lakebeds, and Paleozoic carbonate rocks
6	NE 1/4,NE 1/4, SE 1/4,sec.33., T.16S,R.50E.	716±3	North-northeast trending veins in Pliocene(?) and Pleistocene lakebeds
7	NE 1/4,SW 1/4, sec.23,T.17S., R.50E.	750 ± 6	Northeast-trending vein in colluvium and lakebeds adjacent to ridge of Paleozoic carbonate rocks
8	NE 1/4,NW 1/4, sec. 13,T.16S., R.50E.	790 ± 3	Dense travertine float; source unknown, but size of blocks (some over 1 meter in largest dimension) suggests proximity of parent vein

Figure 23.--Calcitic vein at sample site 2, Amargosa Desert, Nev.. Rock on the lower left is Paleozoic carbonate; vein overturns and calcitic material is disseminated into alluvium at right side of photograph. (3 x 5 inch card serves as scale; SE 1/4,SE 1/4,sec.15,T.16S.,R.51E.)

In addition to the veins in alluvium and lakebeds found at sites 2, 3a, 3b, and 5-7, W.C. Swadley has found dense travertine float at altitudes as high as 790 m in the NE 1/4, NW 1/4, section 13, T.16.S.R.50.E. (station 8, fig. 3). A source for this float has not been found nor has the float been dated (W.C. Swadley, personal communication, May 1979), but some of the blocks are large (over 1 m in diameter) and cannot have moved very far from their source. We do not know if the vein(s) comprising this float filled fractures in alluvium, lakebeds, or Paleozoic carbonate rocks; hence we cannot evaluate them as indicators of possible ground-water discharge during the Pleistocene.

Two sites (1 and 4 of fig. 3) at which calcitic veins occur only in Paleozoic carbonate rocks are also listed in table 1; these sites receive special discussion in subsequent sections.

DISCUSSION

Over a period of hundreds of thousands of years, the disposition of radioactive wastes buried at the NTS may be influenced by tectonism, and erosion related to tectonism, as well as by major climatic changes. The present difference in altitude between the Ash Meadows discharge area and Frenchman Flat, for example, might have changed several tens to perhaps a hundred meters over a period of several hundred thousand to a million years. In the discussion below we focus on possible hydrogeologic effects of climatic change during approximately the last 100,000 years of the Pleistocene, that is during Wisconsin time. We assume that erosion or tectonic activity have not changed the regional topography significantly (say more than 30m) during this time. We are specifically concerned about the difference of altitude between Frenchman Flat and Ash Meadows and will return to this matter in a concluding section. W.J. Carr and W.C. Swadley (oral communication, March 1979) have found no evidence for major Quaternary faulting or warping capable of having significantly altered the present regional topography of the area during the Wisconsin. Erosion rates, similarly, appear incapable of so doing in the absence of major faulting. Winograd (1974) summarized the literature on denudation and slope retreat rates in arid and semiarid climates. Average denudation rates of 9-18 cm per 1000 years amount to only 9 to 18 m per 100,000 years.

During the past 100,000 years several pluvial periods are recorded in the sediments of Searles Lake, California and other Great Basin lakes (Smith, 1979, figs. 41-42). The percentage of time occupied by pluvial conditions during the last 100,000 years probably greatly exceeded that occupied by relatively dry periods. Thus, had the pluvial water table(s) stood at significantly higher altitudes than the modern level, ample time would have existed during the Late Pleistocene for the deposition of tufa.

We examine below the following matters pertinent to possible altitudes of the water table (more correctly, the potentiometric level) during pluvial times: (a) the implications of the absence of tufa deposits above 760m altitude northeast of Ash Meadows; (b) clues deriveable from the calcitic veins; (c) inferences from hydrogeologic considerations; (d) possible causes for the present water level in Devils Hole; and (e) position of pluvial water levels in the Cenozoic aquifers. The section closes with an interpretive synthesis of all the evidence and an outline of unresolved matters.

Significance of Tufa Deposits

The absence of tufa deposits in the vicinity of the ridges of Paleozoic rock northeast of Ash Meadows, between the altitudes of about 760 to 940 m, can be interpreted in several ways: (a) all the pluvial springs northeast of Ash Meadows emerged from sediments on the valley floor rather than from sediments adjacent to, or from carbonate rock comprising the low ridges of the area; subsequent alluviation buried all traces of such springs and their deposits; (b) the spring mounds and related deposits of pluvial age were deposited along the periphery of carbonate rock knolls and ridges but they have all been eroded or buried; (c) the pluvial ground waters had a relatively low content of dissolved calcium, magnesium, and carbonate species and thus formed no significant tufa deposits; (d) extensive deposition of stratiform tufa requies a marsh or lake environment a setting which never existed above 790m northeast of Ash Meadows; and (e) the pluvial water tables were never markedly higher than present water table. We devote a paragraph to each of these five possible interpretations below.

Some of the major springs at Ash Meadows, for example Crystal Pool and Big Spring (fig. 1), though deriving their water from the lower carbonate aquifer (Winograd and Thordarson, 1975, fig. 34 and pp. C75-C83), emerge from Pliocene(?) and Pleistocene lake deposits as much as 3 km southwest of the nearest outcrops of the lower carbonate aquifer. Were the water table to have dropped at the sites of similarly located pluvial springs in the search area (fig. 3) northeast of Ash Meadows, it is unlikely that a record of their presence would have survived burial by sediment derived from the nearby ridges. The Ash Meadows discharge area, however, has modern and fossil spring deposits of many types. For example, the prominent tufa mound immediately east of King Spring at Point of Rocks (figs. 3 and 15) is adjacent to the Paleozoic carbonate rocks. Also, stratiform tufa deposits are found at various altitudes overlying lake beds, which overlap the carbonate rock ridges at Ash Meadows (figs. 9-11). Similarly, in Death Valley, the Nevares Spring tufa mound occurs at the base of the topographically lowest outcrop of lower carbonate aquifer in the region (fig. 13). These associations of major fossil tufa deposits with topographically low outcrops of the lower carbonate aquifer have modern spring analogues, for reasons reviewed previously Briefly, it appears unreasonable to require that pluvial springs emerged only from alluvium or lake deposits at some distance from knolls and ridges comprised of the lower carbonate aquifer and that none emerged from the aquifer which would have afforded the most direct discharge to the surface.

The interpretation that the spring mounds and related tufas were deposited adjacent to carbonate rock knolls and ridges but have all been eroded or buried is, of course, possible, but equally difficult to comprehend. Calcium carbonate is relatively resistant to mechanical or chemical weathering in arid and semiarid environments. The existence of extensive tufa deposits in portions of Ash Meadows and Death Valley presently being dissected by erosion negates the likelihood of complete removal of tufa deposited in the search area during the Late(?) Pleistocene. While burial of pluvial springs whose settings were similar to that of Crystal Pool at Big Spring is possible, the erosion or burial of all pluvial tufa mounds and sheetlike tufas deposited adjacent to carbonate ridges in the area of search (fig. 3) appears unlikely.

Harmon, and others (1975) have shown that carbonate ground waters have significantly higher P_{CO_2} (partial pressure of CO_2) and therefore higher concentrations of calcium, magnesium, and bicarbonate in warmer than in colder climates. This relationship is believed to reflect an increase in CO_2 production in soil with temperature (Drake and Wigley 1975). Hence, to the degree that pluvial climates reflected lower temperatures rather than higher precipitation, it is possible that pluvial ground water dissolved significantly less calcite and dolomite than modern water and, in turn, was less likely to form prominent tufa deposits upon outgassing of CO_2 in discharge areas. Brakenridge (1978) postulated a 7^{o}-8^{o}C reduction in mean annual temperature during the pluvials. (Most paleoclimatologists do not subscribe to changes of this magnitude, as will be discussed in a subsequent section.) Such a change, if it occurred, might have resulted in a fivefold reduction in P_{CO_2} (Harmon, and others., 1975, fig. 2) of ground water in a carbonate terrane. However, we do not believe there was a significant reduction in dissolved calcium, magnesium, and carbonate species for the following reasons. First, the pluvial climates were marked presumably by denser vegetation, which should have increased CO_2 production in the soil zones of the principal recharge area the Spring Mountains (fig. 1). This, in turn would have favored increased dissolution of carbonate minerals to counteract the effects of lowered temperature. Second differences in the Ca, Mg, and alkalinity (HCO_3^- + $CO_3^=$) of lower carbonate aquifer water within the Ash Meadows basin are relatively small even though these ground waters range in age from modern to more than ten thousand years (Winograd and Pearson, 1976, table 1). Regionally, these constituents vary, respectively, by maximum factors of about 2,3, and 2; moreover, differences of similar magnitude occur among modern spring waters in the principal recharge area, the Spring Mountains (fig. 1). (The above comparison does not utilize data from well C-1 in table 1 of Winograd and Pearson, 1976; the anomalous chemistry of water from this well coupled with the minor (about 2 percent) input of ground-water flow from Yucca Flat to the Ash Meadows basin justify its exclusion.)

The widespread occurrence of stratiform tufa overlying the Pliocene(?) and Pleistocene lake-beds at Ash Meadows suggests a possible cogenetic relationship, at least locally, between these tufas and the lakebeds. Perhaps an environment of low relief, for example a marsh fringing a lake was necessary for extensive tufa deposition from paleo-ground water discharge in Ash Meadows, whereas discharge into well-defined drainage--as occurs today at all the major springs--did not yield geomorphically prominent fossil tufas. Reconnaissance mapping by Walker and Eakin (1963, pl. 2) indicates that the Pliocene(?) and Pleistocene lake deposits range in altitude from 730 to 790 m at the northern, northeastern and easternmost outcrops surrounding Amargosa Flat (fig. 3). Thus, if the suggested cogenetic relationship is correct and existed during the Pleistocene, stratiform tufa would not be expectable above about 790 m. To the extent the Pliocene(?) and Pleistocene lake was maintained by ground water discharge, the 790 m altitude would also reflect the position of a paleo-water table of the region. We do not dismiss the suggested marsh origin for the stratiform tufas, but point out that the tufa mounds at Nevares and Keane Wonder Spring in Death Valley occur, respectively, about 150 and 240 m above the highest postulated stand of pluvial Lake Manly (Hunt and Mabey, 1966, pp. A69-A72). The tufa mound at King Spring (figs. 15 and 16) though at the same altitude as, and possibly cogenetic with, fringing lakebeds, is clearly distinguishable from stratiform tufas overlying the lakebeds. Briefly, restriction of stratiform tufa deposition to the margins of a Late(?) Pleistocene or even a Pliocene(?) and Pleistocene lake does not preclude the development of tufa mounds at higher altitudes than the lake provided the pluvial water table stood above lake level. If the stratiform tufas at and northeast of Ash Meadows are indeed genetically related to the widespread lakebeds of the region, then their age may extend to middle(?) or perhaps even to early(?) Pleistocene time.

We believe that the fifth explanation (e) is the most reasonable, namely, that pluvial water tables were never high enough during the Late(?) Pleistocene to cause the discharge of water from outcrops of the lower carbonate aquifer between the altitudes of roughly 760 to 940 m in the search area (fig. 3). Discharge from the Ash Meadows ground-water basin during the Late(?) Pleistocene occurred in, and several kilometers northeast of, the Ash Meadows area, but at altitudes apparently only 40 m higher than the highest modern water level (719 m in Devils Hole).

In the absence of uranium-disequilibrium dating of the tufas, we cannot, of course, distinguish tufa of Wisconsin time from earlier Pleistocene tufa. It is likely that ground water discharged from any given tufa mound during several Stages of the Pleistocene. Today, for example, at both Nevares and King Springs modern tufa is being deposited adjacent to, on, and within the porosity of fossil tufa comprising these mounds. Thus, our observations about the absence of tufa above altitudes of 760 m is also suggestive of the maximum altitude of discharge points during older portions of the Pleistocene Epoch.

Significance of Calcitic Veins

Interpretation of the ubiquitous, dense, and finely laminated calcitic veins of the region is a tenuous undertaking in the absence of detailed uranium disequilibrium dating. Most of the veins, particularly those in the Paleozoic carbonate rocks comprising the ridges, occur at altitudes of many tens to hundreds of meters above the present water table in the lower carbonate aquifer; such veins clearly have no relation to present or to pluvial-related ground-water flow. (Permeable strata such as dense fractured carbonate rocks, welded tuffs, or basalt are marked by deep water tables even in humid zones, provided a topography of moderate relief is present. Thus, even if the pluvial climate of the uplands of the NTS region was subhumid, it is unlikely that regional ground-water flow of pluvial age can be invoked to explain the ubiquitous calcitic veins occurring in Palezoic carbonate rocks hundreds of meters above the present water table. These veins were most likely formed below water table prior to the late Cenozoic block faulting; they may also reflect dissolution - precipitation processes in the vadose zone after up-faulting.) The veins sampled at sites 2, 3a, 3b, and 5-7, (fig. 3 and table 1), on the other hand, occur at valley level and fill fractures in alluvium, lakebeds, and adjacent Paleozoic carbonate rocks. Because of their topographic setting, and the age of the rocks they are associated with, these veins are believed to mark the site of pluvial ground-water discharge.

Two calcitic fracture fillings found in Paleozoic carbonate rocks at sampling site 4 (fig. 3 and table 1) are examples of veins apparently having little relation to modern or pluvial ground-water levels despite uranium-thorium dates, of 72,000 and 100,000 years. These samples were collected by W.J. Carr (U.S. Geological Survey, Denver, Colo.) at an altitude of approximately 1140 m (table 1) or about 200 m above the level of the playa in Frenchman Flat. While we tentatively accept the ages, the assumption that this calcitic material was precipitated within a regional zone of saturation during pluvial times is premature.

Sample site 4 is located above the center of a major trough in the potentiometric surface of the lower carbonate aquifer (fig. 1), a trough controlled by a region of extremely high transmissivity (values given in next section). The present potentiometric surface in wells 3, F, Army-1, and Tracer 2 (Fig. 1) to the northeast, north-northwest, southeast and southwest of site 4 is at altitudes ranging from about 720 to 730 m and is about 420 m below the land surface at sample site 4. Thus, major-tectonic-related changes in topography of the area, and (or) accompanying major lowering of ground-water level--due to some combination of increased aquifer transmissivity, reduction in recharge, and lowering of base level since the beginning of Wisconsin time--appear necessary to support the notion that the calcitic veins sampled at this location were deposited by ground water just 100,000 years ago. Neither possibility is attractive. If only uplift were involved, the indicated rate of uplift (420 m in 10^5 years) is roughly 10 times that indicated by three studies cited below. Were the water table 420 m higher (altitude 1140 m) during Wisconsin time, extensive tufa deposition should be evident in the entire region between site 4 and Ash Meadows, and a pluvial lake should have existed in Frenchman Flat. As mentioned previously, there is no evidence for such tufa or lake. A combination of uplift and water table lowering is, of course, also possible. Dissolution of older vein material present at this site (calcite crystals in a nearby vein dated by B. Szabo at $\geq$ 500,000 years) by vadose water followed by its precipitation in an adjacent fracture is an alternate explanation of the 100,000 year date. Clearly, additional work is needed; calcitic veins, particularly in pre-Quaternary rocks, may record successive periods of calcite precipitation and dissolution below and (or) above a regional zone of saturation. Study of the meaning of uranium-disequilibrium ages of such veins is just beginning in the NTS region. Detailed sampling of groups of laminae may be required, in some cases, for an understanding of the age relations within and between veins. For example, periods of hundreds of thousands of years are represented by less than a 10 millimeter thickness of some veins (I.J. Winograd and Barney Szabo, U.S. Geol. Survey, Reston, VA. and Denver, CO, written commun., 1978), while adjacent 10 millimeter thick segments were deposited in a fraction of this time.

The veins sampled at sites 2, 3a, 3b and 5-7, though not yet dated, probably mark pluvial ground-water discharge points. First, these veins fill fractures in alluvium and Pliocene(?) and Pleistocene lakebeds in proximity to Paleozoic carbonate rocks. The vein at site 2 actually passes from carbonate rock into alluvium (fig. 23). Second, the veins at sites 5-7 lie on or near the major northwest-trending lineament marking all the major modern springs at Ash Meadows. The highest of these three veins (sample site 5) is at an altitude of about 750-760 m (table 1). The highest vein cutting alluvium found to date is that at site 2 at an altitude of about 770 m; this vein is about 14 km northeast of the modern spring line. All of these veins appear related to fossil ground-water discharge in the approximate altitude range of 720-770 m, or up to about 50 m above the 1966 water table in Devils Hole (719 meters). The relationship of this discharge to pluvial periods can only be established by detailed age dating. For the purposes of this report we assume that such discharge occurred during Wisconsin time and that the calcitic veins are of a similar age. Should uranium-disequilibrium dating subsequently show that these veins are significantly older than the Wisconsin, then the conclusions of this report may extend to mid-or-earlier Pleistocene time.[1/] In summary, the vein data suggest that pluvial discharge occurred not only at higher altitudes than modern discharge at Ash Meadows, but also at distances about 14 km up the hydraulic gradient.

1/ Since completion of this report Barney Szabo (U.S. Geol. Survey, Denver, Colo., written commun., August 1980) dated the vein sampled at site 7 using uranium-thorium techniques. This vein was deposited between 400,000 and 750,00 years ago.

The suggested 50 m difference in altitude of pluvial and modern discharge areas is virtually identical to the altitude difference between the major modern springs at Ash Meadows. The altitudes of these springs range from about 670 m at Crystal Pool (figs. 1 and 3) up to the water level in Devils Hole, 719 m altitude (Winograd and Thordarson, 1975, fig. 34). The altitude variation among the modern springs is believed to reflect the interaction of geologic structure (that is, the subsurface disposition of the lower carbonate aquifer), Quaternary faulting, topography, the subsurface distribution of cavernous tufa (Dudley and Larson, 1976, p, 47), and local variations in aquifer transmissivity. Thus, it is possible that at the time that ground water discharged from site 2 (fig. 3), discharge was also occurring at the sites of the highest modern springs at Ash Meadows, as well as from still higher, but presently dry, sites, for example the orifice of Devils Hole cavern (altitude 738 ± 2 m).

Inferences from Hydrogeologic Considerations

Independent evidence of possible altitudes of pluvial potentiometric levels in the lower carbonate aquifer between Ash Meadows and Frenchman Flat is available from hydrogeologic considerations. Darcy's Law when written in the following form (Ferris, and others, 1962)

$$Q = TIW, \text{ or } I = \frac{Q}{TW}$$

where Q = discharge (m^3/d)

T = aquifer transmissivity (m^2/d)

I = hydraulic gradient (m/km)

W = width of flow cross section (km)

permits us to estimate the magnitude of rise of the potentiometric surfaces in response to postulated changes in pluvial recharge, provided T and W varied little during pluvial times in comparison to Q. We assumed that W, the width of the flow system did not change significantly during the pluvial periods of interest in this report. We permit T, the aquifer transmissivity, to vary from half to one and a half times its present value in response to possible past (or future) tectonic related fracturing and (or) dissolution of calcite and dolomite along key water-bearing fractures. With W constant and T varying over the relatively small range cited, I, the hydraulic gradient will principally reflect major assumed changes in discharge, Q. The average hydraulic gradient between Ash Meadows and Frenchman Flat is 0.11 m/km (Winograd and Thordarson, 1975, plate I) and the present discharge is about 40 m^3/min. We assume, as an extreme initial example designed to bound our discussion, that the discharge (presumed equal to recharge) during pluvial times was 10 times modern discharge and compute the pluvial potentiometric level in the lower carbonate aquifer beneath Frenchman Flat; the modern level beneath this flat is at an altitude of about 730 m. Because I is proportional to Q, the average hydraulic gradient would increase to 0.73 m/km if T increased by one-and one-half, (while discharge increased ten-fold) to 1.1 m/km if T remained constant, and to 2.2 m/km if T is reduced by half. The distance between Ash Meadows and central Frenchman Flat is roughly 58 km.

Hydraulic gradients of 0.73, 1.1 and 2.2 m/km would result in a rise in potentiometric level in the lower carbonate aquifer of roughly 40,60, and 120 m beneath Frenchman Flat.[2/] If pluvial discharge (or recharge) were 5 times modern discharge the above values would range from roughly 10-60 m.

How realistic are the assumed increases in recharge of 5 to 10 times? As mentioned in the introduction, and as well-summarized by Van Devender and Spauling (1979) and by Wells (1979), major differences of opinion exist regarding to what degree an increase of precipitation or a lowering of temperature resulted in the increased effective moisture regime of the Wisconsin. If a 7°-8°C lowering of annual temperature rather than an increase in precipitation was dominant, as claimed by Brakenridge (1978), then little increase in pluvial recharge may have occurred beneath the major uplands of the area (particularly the Spring Mountains), where recharge today results principally from spring snowmelt with negligible contribution from the deep infiltration of summer precipitation (I.J. Winograd, U.S. Geol. Survey, Reston, VA., oral commun., 1979). On the valley floors, the lowering of annual temperature during the pluvials presumably resulted in increased soil moisture throughout the year with possible attendant periodic recharge through the thick unsaturated zones of the region. An increase in soil moisture would, however, have of necessity, been accompanied by increased density of vegetation to counteract deep percolation. In any event, if Brakenridge is correct, a tenfold increase in recharge appears impossible and even a fivefold increase questionable. Van Devender and Spaulding (1979), on the other hand, argue (on the basis of the fossil plant record in packrat middens) that

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[2/] The computations for an assumed tenfold increase in recharge are as follows:

$(0.73-0.11) \times 58 = 36.0$

$(1.1-0.11) \times 58 = 57.4$

$(2.2-0.11) \times 58 = 121.2$

Late Wisconsin (22,000 to 11,000 years ago) environments south of latitude 36°N were characterized by mild, wet winters and cool summers. If they are correct, and if such conditions extended north to latitude 37°N, a fivefold increase in recharge intuitively appears plausible. Wells (1979), also using the fossil packrat midden record, does not subscribe to the notion of mild and wet winters, though he agrees that cooler temperatures (but not of the magnitude cited by Brackenridge) may have resulted in an effective increase in winter moisture; he also argues for a possible small increase in summer precipitation at the NTS. Snyder and Langbein (1962), in their classical study of a pluvial lake in Spring Valley, Nevada, concluded that an annual precipitation increase from 30 to 51 cm and a reduction in evaporation from 110 to 79 cm was the most probable combination needed to create that pluvial lake in east-central Nevada. Mifflin and Wheat (1979), on the basis of a comprehensive climatologic and hydrologic study, favor a 3°C decrease in mean annual temperature and average increases in precipitation of 68 percent in those regions of Nevada that had pluvial lakes, namely the northern two-thirds of the state. With regards to the pluvial climate of southern Nevada, the work of all the cited authors indicates that semiarid climates persisted on the valley floors with possible subhumid climates on the highest mountains. For example, the packrat midden record discussed by Wells and Berger (1967), Van Devender (1977) and Van Devender and Spaulding (1979) clearly indicates that the widespread xeric juniper woodlands which covered large portions of the region also contained desert species. Mifflin and Wheat (1979) noted that pluvial lakes did not exist in either Yucca or Frenchman Flats and are questionable in other valleys in southern Nevada in which they are purported to have existed. They believe that south-central and southern Nevada remained arid to semiarid on the valley floors, though the "higher mountains received more moisture during the pluvial climates" (1979, p. 42) and in "regions underlain by carbonate rock terrain there was more vigorous or extensive spring discharge......considerably in excess of present discharge" (1979, p. 50). Wells (1979) and Van Devender and Spaulding (1979) believe that the semiaridity of the region during the pluvials was due, at least in part, to its location in the rainshadow of the Sierra Nevada.

For the purposes of this report, we wish to maximize the postulated rise in the pluvial potentiometric surface in the lower carbonate aquifer of the NTS region and we therefore assume that pluvial recharge (and hence ground-water discharge) may have been as much as fivefold greater than modern recharge and that aquifer transmissivity was one-half of the modern value. If so, the water table beneath Frenchman Flat rose about 60 m. If the transmissivity was unchanged the rise would have been about 30 m. The calculations presented above assumed a possible maximum fivefold increase in recharge despite the cited estimates of Snyder and Langbein (1962) and Mifflin and Wheat (1979) that an increase in precipitation only on the order of twothirds (and a decrease in evaporation of one-third) was likely. As mentioned, we did this to maximize the water level changes in the lower carbonate aquifer during pluvial times. Whether or not recharge increases at a lower, equal, or greater rate than a given increase in precipitation depends on several interrelated factors: (a) seasonality and type of precipitation (winter snow versus summer rain): (b) intensity and frequency of summer rain; (c) soil moisture conditions preceding the rainy season(s), itself a function of annual temperature change; (d) thickness and permeability of the soils, particularly those overlying the Paleozoic carbonate uplands (Kafri and Ben-Asher, 1976); (e) place of dominant recharge, that is, uplands versus valley floors; and (f) type and density of vegetation. For example, the flux through thick vadose zones beneath the valley floors of the region is negligible during present climates (I.J. Winograd, in press); however such fluxes might have been important, in comparison with recharge occurring on the uplands, during pluvial climates, particularly if there was a significant increase in the frequency and amount of winter precipitation and a significant decrease in evapotranspiration during the spring months. Because the cited paleoecologic and paleohydrologic evidence indicates that the valley floors were semiarid during the Wisconsin pluvials we assume that significant recharge to the regional carbonate aquifer, then as today, occurred primarily (but not exclusively) on the uplands from snowmelt and ensuing runoff. Accordingly, a somewhat more realistic estimate of water level rise beneath Frenchman Flat during past pluvial climates would utilize a doubling of recharge with a halving of transmissivity. This combination--equivalent to a fourfold increase of recharge at constant transmissivity--results in water level rises of about 20 m beneath the Flat; if the transmissivity was unchanged the rise would amount to only 6 m above modern levels in the regional carbonate aquifer.

The above range of possible rises in potentiometric levels beneath Frenchman Flat were computed assuming a ground water base level of 719 m, the highest water level at Ash Meadow (Devils Hole). In a subsequent section, "Synthesis and Unresolved Matters," higher base levels inferred from the tufa and calcitic vein data are utilized.

The absence of a significant rise in water level beneath Frenchman Flat is not really surprising, for the transmissivity of the lower carbonate aquifer is very high within a northeast-southwest trending band extending from Frenchman Flat to Ash Meadows. Winograd and Thordarson (1975, p. C71-C74) estimated transmissivities in the range of $5x10^4$ to $7x10^4$ m^2/d in the region between Specter Range and Ash Meadows; the high transmissivity permits the aquifer to transmit ground water (modern or pluvial) under extremely low hydraulic gradients; such gradients are common in carbonate aquifer terrane throughout the world.

In summary, the application of Darcy's Law, and assumptions regarding pluvial recharge and transmissivity, enables us to compute a range of water-level rises at various distances from any assumed ground-water base level at or northeast of Ash Meadows.

Origin of Present Water Level in Devils Hole

Some notions on the paleohydrologic significance of present and former water levels in Devils Hole cavern (fig. 3, site 1) follow. The water level in Devils Hole in 1966 (prior to pumping the lower carbonate aquifer for irrigation) was about 15 m below land surface. Fossil water levels several to 6 m above the 1966 level are indicated by horizontal notches visible on the south wall of the cavern (Winograd and Thordarson, 1975, figs. 36 and 37). Nearly vertical, dense calcitic veins, which extend from below water surface to the land surface along a fault zone at the soutwest end of the cavern, may also date from times when water flowed from the mouth of this cavern. One of these veins is shown in figure 19. That a spring once issued from Devils Hole was implied by Hubbs and Miller (1948) and by Miller (1948) on the basis of the presence of pupfish (*Cyprinodon diabolis*) in the waters of the cavern. They implied that upon recession of a middle-to-early Pleistocene lake the fish survived in a spring-fed habitat. With a subsequent drop in water table, the fish population presumably migrated to the depths of Devils Hole. As mentioned previously, Denny and Drewes (1965 p. L30-L31) also implied that a spring once flowed just west of Devils Hole on the basis of the stratiform tufas they mapped west of the cavern (fig. 9 of this report).

If a major spring emerged from the mouth of Devils Hole, what might have caused the decline in water level to a point approximately 15 m below the land surface? And, even in the absence of a spring, what caused the 6 m decline in water level? In consideration of the extremely high transmissivity of the lower carbonate aquifer and of the position of Devils Hole at the discharge (or base level) end of a very large ground-water basin (a minimum of 12,000 km^2), a 15 m or even a 6 m change of water level due to a shift from pluvial to modern climatic conditions appears questionable. Climatic-induced water level changes of meters to tens of meters would certainly be expected in areas up the hydraulic gradient from Devils Hole, as shown in the preceding chapter, but not in the discharge area to which the Ash Meadows ground-water basin is graded. Two alternate explanations of the decline of water level in Devils Hole are outlined below.

That the spring line at Ash Meadows is tectonically controlled, that the area contains Quaternary faults, and that the ridge of Cambrian carbonate rock, in which Devils Hole occurs, is on the upthrown side of the fault zone has been documented by Winograd and Thordarson (1975), Denny and Drewes (1965) and by Healey and Miller (1971). Thus the water level in Devils Hole may have remained relatively constant while the ridge of carbonate rock was uplifted 15 m over a period of a few tens of thousands to over 100,000 years (uplift rate data are summarized on page 80). Additionally, there is a suggestion of possible upwarping of the Ash Meadows area during the Pleistocene. Tufa and calcitic veins cutting valley fill are absent around the western side of the unnamed ridge 6 km east of Amargosa Flat (fig. 3). Paleozoic carbonate rocks comprising the lower carbonate aquifer crop out there at altitudes as low as about 740 m, that is, at altitudes comparable to those having tufa and veins in and northeast of Ash Meadows. The absence of tufa and veins may reflect upwarp of the Ash Meadows area from an altitude which, at the time of tufa deposition, was lower than the cited altitudes adjacent to the unnamed ridge. However, in the absence of an absolute datum, downwarp of the unnamed ridge, from an altitude above that of tufa deposition to the west, is of course, equally possible; such downwarp while explaining the absence of tufa and veins fringing the unnamed ridge would not aid us in explaining the present water level in Devils Hole. Detailed mapping of the stratigraphy of the Pliocene(?) and Pleistocene lakebeds off the region--currently (1980) being done by R.L. Hay (University of Calif., Berkeley), W.C. Swadley, and Will Carr Carr (U.S. Geological Survey, Denver, Colo.)--may yield conclusive evidence of the time and magnitude of the postulated warping in the east-central Amargosa Desert.

The decline in water level may also be explained in the absence of either uplift or climatic change. The land surface at Crystal Pool (about 670 m) and Big Spring (about 680 m)--which together contribute roughly 40 percent of the total spring discharge (Winograd and Thordarson, 1975, fig. 35)--is approximately 10 to 35 m lower than the other major springs, and 40 to 50 m lower than the water level in Devils Hole. We hypothesize that the 6-15 m decline in Devils Hole water level, and perhaps the cessation of spring discharge at some of the mapped calcitic vein and tufa sites, was due to the initiation or increase of flow at the site of Crystal Pool and Big Spring in response to faulting or to orifice enlargement. Resulting fractures would provide a new or more permeable path for ground-water flow from the buried lower carbonate aquifer to the surface. Such a path would result in a major new base-level for lower altitude discharge from the lower carbonate aquifer than offered at springs adjacent to the carbonate rock ridges bordering Ash Meadows on the east. The scenario depicted is analogous to that frequently described for karst areas, wherein the regional ground water level (as recorded by near-horizontal cave passages) responds to a lowering of altitude of master streams cutting such regions (see for example, White and White, 1974).

Combinations of both of the above hypotheses, some also involving erosion, are likely in this region. The above discussion demonstrates the many complexities of deciphering the regional paleohydrology, particularly for time frames (hundreds of thousands of years) during which major changes of regional topography cannot be dismissed.

Pluvial Water Levels in Cenozoic Aquifers

As previously mentioned, beneath some of the valleys of the region a thick tuffaceous aquitard of Tertiary age separates valley fill and tuff aquifers of Cenozoic age from the underlying lower carbonate aquifer. This separation results in different modern potentiometric levels in the Cenozoic and Paleozoic aquifers. In central and north-central Frenchman Flat, for example, the water table in the Cenozoic valley-fill aquifer is about 9 m higher, and in central Yucca Flat about 5 m higher than in the carbonate aquifer; in northern Yucca Flat, where the Cenozoic aquifers are unsaturated (that is, occur above the present water table), the head (potentiometric level) in the tuff aquitard is as much as 40 m above that in the carbonate aquifer (Winograd and Thordarson, 1975, pp C53-C57, and pls. 1 and 2). In contrast, near the distal end of the Ash Meadows ground-water basin (fig. 1), beneath Amargosa Flat (fig. 3), the modern heads in the lower carbonate aquifer are about 9 m higher than in the overlying valley-fill aquifer (Winograd and Thordarson, 1975, fig. 34). The magnitude of head difference between the Cenozoic and Paleozoic aquifers and the resultant direction of water flow between them is a function of the quantity of water moving through the aquifers (itself a function of geographic position within the Ash Meadows ground-water basin), the relative transmissivities of the aquifers and the aquitard, and the subsurface extent of the aquitard. Under conditions of increased recharge during pluvial times the head differences might have been greater or less than those cited dependent upon the relative amounts of water moving through each aquifer sytem, itself a function of geographic position in the Ash Meadows basin. For example, in Yucca Flat we can visualize a greater head difference during pluvial times than that cited, because in this valley the modern downward flux of water through the Cenozoic aquifers (via the tuff aquitard) is a significant fraction (roughly 20 percent) of that leaving the south end of the valley via the lower carbonate aquifer. Indeed, Winograd and Thordarson (1975, p. C56) speculated that the high heads in the tuff aquitard beneath northern Yucca Flat might represent fossil water levels of Pleistocene age. Beneath Frenchman Flat, on the other hand, the modern downward flux is certainly less than one percent of that moving through the lower carbonate aquifer (Winograd and Thordarson, 1975, pp. C92-C94); there a rise in head in the carbonate aquifer might have equalled or exceeded that in the Cenozoic aquifers, despite the high transmissivity of the carbonate aquifer.

We wish to emphasize in the above discussion that our conclusions regarding the magnitude of rise of the potentiometric level in the lower carbonate aquifer during pluvial time does not necessarily apply to the water table rise within the Cenozoic aquifers of Frenchman, Yucca, or Jackass Flats and other valleys. The magnitude of that rise might be determinable, however, by other means, such as a careful study of the grain and interstitial mineralogy of valley-fill sediments cored continuously from the surface to several hundred feet below the present water table.

Similarly, the postulated pluvial rises in the potentiometric surface in the lower carbonate aquifer of the Ash Meadows ground-water basin should not be applied indiscriminately to the widespread Paleozoic carbonate aquifers elsewhere in the eastern Great Basin. Greater or smaller water-level changes are possible elsewhere depending upon the particular hydrogeologic boundary conditions (chiefly topography) and the range and distribution of aquifer transmissivities in each area.

Synthesis and Unresolved Matters

The reader is now aware that pluvial ground-water levels beneath Frenchman Flat are a function not only of the magnitude of pluvial recharge rates, but also of possible changes in aquifer transmissivity with time, and the altitude of the discharge area at Ash Meadows. In table 2 we list these factors and bracket the magnitude of changes in them that we deem plausible during Wisconsin time. Additionally, the thickness of the unsaturated zone beneath Frenchman Flat is also a function of changes, with time, in altitude of the valley floor in comparison with the ground-water baselevel at Ash Meadows. A discussion of these factors and their assigned magnitudes follows.

We have already discussed our reasons for assuming that pluvial recharge might have been perhaps two to as much as five times modern recharge. With regard to transmissivity, we permit a range from 50 to 150 percent of modern, though we do not believe such a change occurred, at least not during Wisconsin time. It can be argued that the transmissivity of carbonate aquifers should, in general, increase with geologic time due to continued dissolution of the calcite and dolomite comprising the aquifer. On the other hand, ground water thoughout the medial and distal portions of the Ash Meadows basin is saturated to slightly supersaturated with respect to these minerals (Winograd and Pearson, 1976). Thus dissolution of these minerals, with a concomittant increase in fracture porosity (and aquifer transmissivity) need not have occurred with time except in the upland recharge areas along the periphery of the Ash Meadows ground-water basin. To further complicate matters, periodic earthquakes in this seismically moderately active

Table 2. Factors affecting altitude of potentiometric surface in the lower carbonate aquifer beneath Frenchman Flat, Nevada during the Late(?) Pleistocene or future pluvials.

Factor	Postulated change with time	Remarks (climatic, tectonic conditions, etc.)
Recharge to Ash Meadows ground water basin (Q)	None	Present climate; steady state conditions assumed, namely, discharge equals recharge
	2X to 5X modern	Past or future pluvial climates (see text discussion)
Transmissivity (T)	None	Present climate
	0.5 to 1X modern	Past pluvial climates (see text discussion)
	1X to 1.5X modern	Future pluvial climate (see text discussion).
Ground water base level in Ash Meadows area	None	Present climate. Base level in lower carbonate aquifer taken as highest head at Ash Meadows; namely, 719 m water level in Devils Hole
	+50 m[a/]	Altitude of calcitic vein at sample site 2 (768 m) taken as highest inferred pluvial base level.[b/]
	-40 m[a/]	Postulated future base level at 677 m altitude.[c/]

a/ Rounded to one significant figure.

b/ Assumes that tectonic uplift is not responsible for the 49 m difference between altitude of vein at site 2 and water level in Devils Hole.

c/ Postulated base level is intermediate in altitude between Crystal Pool (671 m) and Big Spring (683 m); see text discussion.

region might, over geologic time, have served to open new fractures to water flow or to widen existing fractures. Thus, one may postulate either little change or an increase in transmissivity in recent geologic time in the medial and distal parts of this ground-water basin.

With regard to the magnitude of changes of ground water base level in the Ash Meadows region it should be noted that future base levels might be significantly lower (40 m) than the present level (table 2). How lower base levels might form was discussed in the section "Origin of present water level in Devils Hole."

While table 2 lists the factors influencing the rise (or lowering) of the potentiometric surface, still one other factor--namely changes in altitude of Frenchman Flat in comparison to Ash Meadows--would be involved in estimation of the changes in thickness of the unsaturated zone beneath the Flat, a zone presently about 210 m thick beneath the playa. If, for example, the difference in altitude (during the pluvials) between the Flat and the chosen baselevel at Ash Meadows was greater than modern, then the change in thickness of the unsaturated zone would be less than that suggested by the water level rises shown in table 3; if less, then the change in unsaturated zone thickness would exceed the values shown. An indication of the rates of vertical uplift in the region during the late Tertiary and the Quaternary is available from three sources. An isopach map of the valley fill of Yucca Flat (A. Fernald, written communication, January 1980), when coupled with estimates of the start of Basin and Range faulting yields valley-fill sedimentation rates--a rough indicator of uplift rates--on the order of 0.1 to 0.4 $m/10^3$ years, with values toward the lower end of this range more probable. Stewart (1978) presents data suggesting average uplift rates in the Great Basin on the order of 0.2 to 0.4 $m/10^3$ years. Gable and Hatton (1980) suggest uplift rates of 0.2 to 0.6 $m/10^3$ years, with the rate increasing southwestwardly across the study area. Assuming an uplift rate of 0.3 m/10^3 years, a 30 m altitude change might have occurred in Frenchman Flat during the Wisconsin Stage of approximately 100,000 year duration. Such a change is only about one-seventh of the thickness of the modern unsaturated zone beneath the playa in Frenchman Flat. Unfortunately, in the absence of an absolute datum, we do not know if such uplift was reflected principally by elevation of the ridges (relative to a given datum), by depression of the valley floors, or by the elevation of both ridges and valley floors. More importantly, it is the difference in uplift between central Frenchman Flat and Ash Meadows that matters. If both areas were uplifted at the same rate, then the changes in thickness of the unsaturated zone would be identical to the computed changes in water level. We assume hereafter that the present difference in altitude between Frenchman Flat playa (940 m) and at Ash Meadows (roughly 720 m, if water level in Devils Hole is used as datum) did not vary by more than about 30 m between the beginning of Wisconsin time and the present.

In table 3, six combinations (cases I-VI) of factors listed in table 2 have been chosen to bracket expectable past and future changes in water levels in the regional carbonate aquifer beneath central Frenchman Flat. We consider cases I and II to reflect the most likely situation during Wisconsin time and perhaps during future pluvials; this combination of factors suggests a water level rise on the order of 6 to 20 m. Case V, on the other hand, we regard as an extreme example. Here, not only is transmissivity halved, but it is assumed that the ground water base level was at an altitude of about 770 m, that is, that ground water discharged at sample site 2 (fig. 3) during Wisconsin time. As mentioned earlier we do not know the age of the veins at sample site 2 though we strongly suspect they are older than Wisconsin (see footnote, page 64). Moreover, and regardless of age, we also cannot eliminate the possibility that the altitude of these veins may in part reflect tectonic uplift and not solely pluvial climatic conditions. Nevertheless, with this combination of factors, and with the flow path length shown in the table, a water level rise of 90 m would have occurred beneath the playa in Frenchman Flat. Cases III and IV represent intermediate water-level rises. In case VI, we speculate concerning the position of water level during a future pluvial and conclude that the level might be lower, perhaps 10 m lower than the modern one due to a lowering of base level in Ash Meadows (tables 2 and 3). In view of the present topography (namely the integration of the Amargosa Desert and Death Valley) and recent faulting in the region, the postulated future lowering of base level appears plausible. In any event, a future rise in base level appears improbable over a time frame of 10^5 years and thereby suggests that ground water levels (beneath the playa in central Frenchman Flat) during future pluvials might fall in the range of 30 m above (case III) to 10 m below (case VI) modern levels.

Table 3. Postulated Late(?) Pleistocene and future water-level changes in lower carbonate aquifer beneath central Frenchman Flat, Nevada[a]

Case	Combination of conditions listed in table 2	Change in altitude of modern potentiometric surface (meters)[b]		Remarks
		Wisconsin time	Future pluvials	
I	Recharge 2X modern; transmissivity, no change; past and future ground water base-level at 719 m	+6	+6	58 km flow path length between Ash Meadows and central Frenchman Flat. Water level in Devils Hole (719 m) is base level.
II	Recharge 2X modern; transmissivity 0.5X modern; Wisconsin base-level same as case I	+20	—	Flow path length same as Case I. Assumes increase in transmissivity between Wisconsin and Holocene time.
III	Recharge 5X modern; transmissivity, no change; past and future base-level, same as case I	+30	+30	Flow path length same as case I.
IV	Recharge 5X modern; transmissivity 0.5X modern; Wisconsin base level, same as case I	+60	--	Same as for case II.
V	Recharge 5X modern; transmissivity 0.5X modern; Wisconsin (or earlier) base-level at 768 m altitude	+90	—	Assumes ground water discharged at site 2 during Wisconsin (or earlier) pluvials. 43 km flow path to central Frenchman Flat.
VI	Recharge 5X modern; transmissivity, no change; future base-level at 677 m	—	-10	61 km flow path length. Drop in water level reflects 15 m difference between 27 m rise along hydraulic gradient and 42 m drop in base level.

a/ Difference in altitude between playa in Frenchman Flat and central Ash Meadows— roughly 220 m-- is assumed to have varied 30 m or less in last 10^5 years; see text discussion.

b/ Method of computing water-level rise explained in text; values in these columns rounded to 1 significant figure.

Because our uncertainty of the relative changes in altitude between Ash Meadows and central Frenchman Flat, and of the factors in table 2, increases with geologic time, we have focused our discussion on the last 100,000 years, the Wisconsin time. We suspect that the tufa and calcitic veins, probably predate the Wisconsin (see footnote, page 64) and that their altitude may to varying degrees reflect tectonism rather than pluvial-related water level changes. Yet, we utilize such evidence because it leads to a maximization of our postulated water level changes during the Wisconsin pluvials, a maximization warranted by the objectives of this study. To the degree that the key factors discussed varied no more than shown (table 2) during the last few hundred thousand to 1.8 million years, the principal conclusions of this report apply as well to middle and early Pleistocene time.

In conclusion we note that regardless of which combinations of factors is chosen, the NTS region was marked by deep water tables, by attendant thick unsaturated zones, and by long ground-water flow paths during Wisconsin time (and probably older portions of the Pleistocene) much as it is today. This was, and is, due primarily to the combination of high transmissivity of, and low altitude discharge outlet for, the regional lower carbonate aquifer. Similar characteristics are expectable in the Ash Meadows ground-water basin during future pluvials.

Further knowledge of the magnitude of change in ground water baselevel in the Ash Meadows area and of water levels beneath Frenchman Flat during the Pleistocene must await completion of studies of the Quaternary tectonics of the region and of the geomorphic and geochemical history of the Pliocene(?) and Pleistocene lakebeds, tufas, and calcitic veins in the central Amargosa Desert. Information specifically needed includes: (a) the age relationships of the calcitic veins, tufas, and lake deposits; (b) spatial variations in the ages of veins, for example between sample sites 2 and 7; (c) time of dissection of the Pliocene(?) and Pleistocene lakebeds; (d) cause of lakebed dissection, namely by warping, faulting, or integration of Amargosa Valley drainage to that in Death Valley; (e) clues pertinent to the magnitude of vertical displacement, during the Quaternary, of Frenchman Flat playa relative to Devils Hole; and (f) magnitude of pluvial water table rise in the valley-fill aquifers beneath Frenchman and Yucca Flats. Pending completion of these studies, we postulate a southwestward migration of spring discharge during the Pleistocene, from a point northeast of Ash Meadows (sample site 2) to the modern spring lineament, with an attendant lowering of the groundwater base level by perhaps as much as 50 m. We tentatively attribute the southwestward migration to an integration of the Amargosa Valley and Death Valley watersheds coupled with periodic faulting along the modern spring lineament.

CONCLUSIONS

1. A distinction between pedogenic caliche and arroyo-bottom calcrete, on the one hand, and tufa on the other, is feasible in the study area utilizing field morphologic evidence alone.

2. The distribution of calcitic veins filling fractures in alluvium and lakebeds in the area between Ash Meadows and the Specter Range suggests that the potentiometric level in the regional carbonate aquifer may have been as much as 50 m higher (altitude 770 m) than the modern level (altitude 720 m) during a past (but as yet undated) Pleistocene pluvial. At the higher level, ground water would have discharged from outcrops of the lower carbonate aquifer about 14 km northeast of the modern spring lineament at Ash Meadows (fig. 3). An alternate interpretation is that the suggested 50-m water level rise in part reflects tectonic uplift of the veins, and not solely pluvial climatic conditions.

The distribution of tufa mounds or stratiform tufa deposits around the periphery of ridges and knolls of the Paleozoic carbonate rocks adds confirmatory evidence that the potentiometric surface in this aquifer did not rise above 770 m altitude in the Ash Meadows discharge area during Wisconsin time or older pluvials of the Pleistocene.

3. Use of the underflow equation (relating discharge to transmissivity, aquifer width, and hydraulic gradient) and assumptions regarding the magnitude of pluvial recharge, aquifer transmissivity, and altitude of ground-water base level suggests possible rises in the potentiometric level of 6 to 90 m beneath central Frenchman Flat, 58 kilometers northeast of Ash Meadows. During Wisconsin time, the rise probably did not exceed 30 m. Water level rises beneath Frenchman Flat during future pluvials are unlikely to exceed 30 m, and future levels might even be 10 m lower than the modern one, 210 meters beneath the center of the valley.

4. The methods utilized do not permit an estimation of pluvial ground-water level rise in the Cenozoic aquifers beneath the Nevada Test Site, specifically beneath Yucca, Frenchman or Jackass Flats. The water table rise in these aquifers might locally have exceeded that in the regional carbonate aquifer. Detailed mineralogic study of cores of alluvium from Frenchman Flat is a potential means of obtaining information on the position of the pluvial water tables in the Cenozoic aquifers.

5. Utilization of calcitic veins, particularly those in pre-Quaternary rocks, to map pluvial water levels requires caution. Many of the older veins undoubtedly record multiple periods of calcite dissolution and precipitation above and (or) below the water table. An attempt at dating the younger calcitic veins filling fractures in Quaternary rocks at and northeast of Ash Meadows appears warranted. Such dates may provide information on the age of the Ash Meadows discharge area, the possible southwestward migration of the spring line with time, and the relationship of the veins and tufas to the extensive Pliocene(?) and Pleistocene lakebeds of the region.

6. The present 15 m deep water level in Devils Hole need not reflect the shift from pluvial to modern climate, but rather the effects of tectonism (warping or faulting) and (or) the lowering of ground water "base level" which followed integration of the Death Valley and Amargosa Desert watersheds.

7. The information developed in this reconnaissance supports further technical consideration of the Nevada Test Site as a potential repository for either high level or transuranic element radioactive wastes. Deep water tables, attendant thick (up to several hundred meter) unsaturated zones, and ground-water flow paths tens of kilometers in length characterized the region during the Late(?) Pleistocene, and presumably will so characterize it during future pluvials.

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