Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada

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U.S. GEOLOGICAL SURVEY BULLETIN 1790

1988

13. Water-Table Decline in the South-Central Great Basin During the Quaternary: Implications for Toxic Waste Disposal

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Abstract

The distribution of vein calcite, tufa, and other features indicative of paleo-ground-water discharge indicates that during the early and middle Pleistocene the water table at Ash Meadows, in the Amargosa Desert, Nevada, and at Furnace Creek Wash, in east-central Death Valley, California, was tens to hundreds of meters above the modern water table, and that ground-water discharge occurred up to 18 km up the hydraulic gradient from modern discharge areas. Uranium-series dating of the calcitic veins permits calculation of rates of apparent water-table decline; rates of 0.02 to 0.08 m/ka are indicated for Ash Meadows and 0.2 to 0.6 m/ka for Furnace Creek Wash. The rates for Furnace Creek Wash closely match a published estimate of vertical crustal offset for this area, suggesting that tectonism is a major cause for the displacement observed. In general, displacements of the paleo water table probably reflect a combination of (1) tectonic uplift of vein calcite and tufa, unaccompanied by a change in water-table altitude, (2) decline in water-table altitude in response to tectonic depression of areas adjacent to dated veins and associated tufa, (3) decline in water-table altitude in response to increasing aridity caused by major uplift of the Sierra Nevada and Transverse Ranges during the Quaternary, and (4) decline in water-table altitude in response to erosion triggered by increasing aridity and (or) tectonism.

A synthesis of hydrogeologic, neotectonic, and paleoclimatologic information with the vein-calcite data permits the inference that the water table in the south-central Great Basin progressively lowered throughout the Quaternary. This inference is pertinent to an evaluation of the utility of thick (200–600 m) unsaturated zones of the region for isolating solidified radioactive wastes from the hydrosphere for hundreds of millenia. Wastes buried a few tens to perhaps 100 m above the modern water table—that is above possible water level rises due to future pluvial climates—are unlikely to be inundated by a rising water table in the foreseeable geologic future.

INTRODUCTION

Regional interbasin flow of ground water through the thick section of Paleozoic carbonate rocks of the south-central Great Basin has been the subject of numerous studies in the past 25 years (Hunt and Robinson, 1960; Loeltz, 1960; Winograd, 1962, Winograd and Thordarson, 1968; Winograd, 1971; Winograd and Friedman, 1972; Naff, 1973; Winograd and Thordarson, 1975; Dudley and Larson, 1976; Winograd and Pearson, 1976; Waddell, 1982). Flow through the regional carbonate-rock aquifer is directed toward major spring discharge areas at Ash Meadows in the Amargosa Desert of Nevada and toward Furnace Creek Wash in east-central Death Valley, California (fig. 13.1). The flow occurs under hydraulic gradients as low as 0.06 m/km (Winograd and Thordarson, 1975, pl. I), reflecting the high fracture transmissivity of this aquifer. Locally, major hydraulic barriers compartmentalize the aquifer (Winograd and Thordarson, 1968, 1975). A detailed hydrogeologic and hydrogeochemical synthesis of this vast flow system, including potentiometric maps, is available in Winograd and Thordarson (1975).

A variety of geologic evidence indicates that during the Pleistocene the water table in the regional carbonate-rock aquifer at Ash Meadows and at Furnace Creek Wash (fig. 13.1) was tens to hundreds of meters above the modern water table (Winograd and Doty, 1980). The evidence consists of tufas; ancient spring orifices; calcitic veins and cylindrical calcite-lined tubes that mark the routes of paleo ground water flow to spring orifices; and paleo water levels inscribed on the walls of Devils Hole (fig. 13.1), a fault-controlled collapse feature adjacent to the Ash Meadows discharge area. Most of these have been briefly described elsewhere (Winograd and Thordarson, 1975, p. C82-C83; Winograd and Doty, 1980; Pexton, 1984; Winograd and others, 1985). In this study we focus on the calcitic veins as indicators of paleo water tables because they are readily datable using uranium-disequilibrium methods (Szabo and others, 1981; Winograd and others, 1985) This report is an initial step toward a quantification of the observations of Winograd and Doty (1980).

Acknowledgments

We thank D. Stuart-Alexander, W.J. Carr, W.W. Dudley, Jr., W.R. Osterkamp, N.J. Trask, Jr., R.B. Scott, and W.E. Wilson for helpful review comments, and we appreciate the excellent assistance provided by G.C. Doty and A.C. Riggs during the field search for the calcitic veins.

RATES OF APPARENT WATER-TABLE DECLINE

At Ash Meadows, the calcitic veins occur in association with, and adjacent to, a structurally controlled 16-km-long spring discharge area (Winograd and Thordarson, 1975). The veins occur as much as 50 m higher than and as much as 14 km up the hydraulic gradient from the highest water level (altitude 719 m) at Ash Meadows—namely, that in Devils Hole (Winograd and Doty, 1980). Veins AM-7, DH-1, and AM-10 from Ash Meadows and northern Amargosa Flat (fig. 13.1) are, respectively, 11, 19, and 26 m higher than the water level in Devils Hole (table 13.1). (The hydraulic gradient in the region between these veins is extremely small—0.06 m/km (Winograd and Thordarson, 1975, pl. I)—so that for practical purposes the altitude of the veins can be compared directly to the water level in Devils Hole.) Uranium-disequilibrium dating of these veins yields an age of 510±62 ka for the youngest laminae in vein AM-7, 660±75 ka for the youngest laminae in vein DH-1, and 750±52 ka for the center of vein AM-10 (table 13.1). These data permit calculation of the average rates of apparent water-

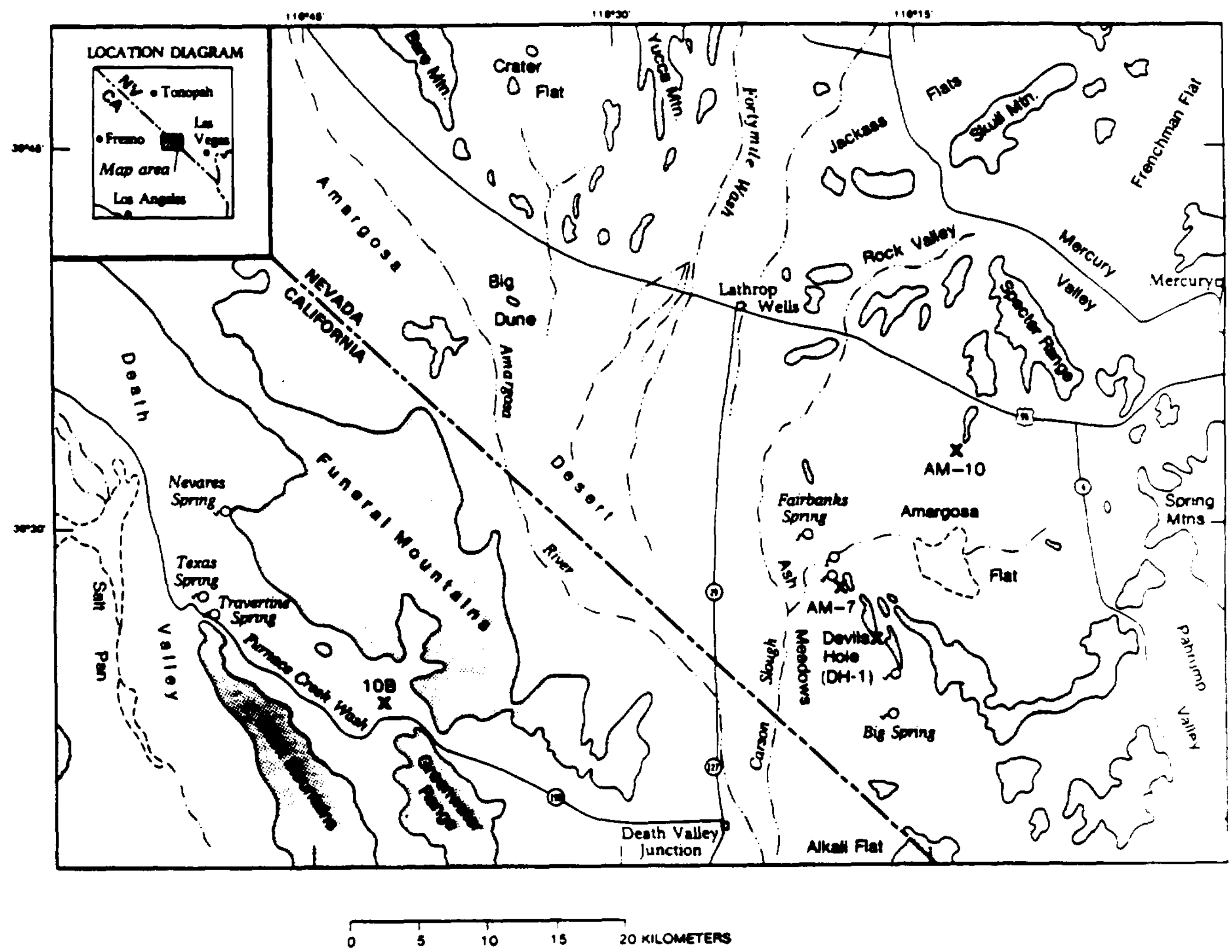

Figure 13.1. Index map of south-central Great Basin, Nevada-California. Uplands shaded; x's mark location of uranium-series-dated calcitic veins discussed in text.

table decline; rates on the order 0.02 to 0.03 m/ka are indicated (table 13.1). These rates are minimum values, first, because we do not know how high above outcrop the sampled veins might have extended prior to erosion; and second, because the youngest laminae in our veins may only record the time of sealing of the vein, rather than the time of cessation of ground-water discharge. Nevertheless, because the numerator (that is the altitude difference between vein outcrop and water level in Devils Hole) in our ratio is so much smaller than the denominator (vein age), any reasonable combination of values yields a very slow rate of decline. For example, if the altitude of vein DH-1 were 20 m higher prior to erosion (a large value considering the present relief on the Pliocene and Pleistocene rocks in central Ash Meadows) and if ground-water discharge ceased 400 ka instead of 660 ka ago, we still calculate an apparent rate of water-table decline which is less than 0.1 m/ka.

The average rates of water-table decline cited above (0.02 to 0.03 m/ka) were calculated (table 13.1, columns 1-5) assuming a constant rate of decline during the middle and late Pleistocene, that is over times 510 to 750 ka long. A more realistic computation of decline rate is one involving three vein pairs that differ in age by only 90 to 240 ka. Such a computation (table 13.1, columns 6-7) yields rates of decline which are 2 to 2½ times as large as the average rates, namely 0.05 to 0.08 m/ka. The paired veins record ground-water flow in the period 510 ka to 750 ka (table 13.1). When these data are arranged by decreasing age and are coupled with the average rate of decline calculated for the past 510 ka (0.02 m/ka, derived from the youngest and lowest vein, AM-7, and the water-table altitude in Devils Hole), we see a suggestion of a possible reduction in rate of water-table decline during the middle Pleistocene; that is, a rate of 0.08 m/ka is indicated for the period 750 to 660 ka, a rate of 0.05 m/ka for the period 660 to 510 ka and a rate of 0.02 m/ka for the past 510 ka. In view of the caveats presented in the preceding paragraph, additional work is clearly in order to verify the suggested change in rate of water-table decline in the Ash Meadows region. In summary, the data of table 13.1 indicate rates of apparent water decline of 0.02 to 0.08 m/ka for the Ash Meadows-Amargosa Flat area.

At Furnace Creek Wash (fig. 13.1), the rate of lowering of the water table during the Quaternary is an order of magnitude greater than the cited rates for Ash Meadows and vicinity. Here a calcitic vein swarm and associated tufa occur at an altitude of about 855 m. Uranium-disequilibrium dating of vein 10B (fig. 13.1) from this area indicates that ground-water flow in the fracture containing this vein ceased about 1,000 ± 100 ka. In the absence of wells or artesian springs, the water-table altitude in the regional carbonate aquifer beneath the vein swarm is unknown, but we can bracket the range of possible water-table altitudes by reference to known water levels both up and down the hydraulic gradient from the vein swarm. The altitude of the water table in the valley-fill aquifer beneath the southern Amargosa Desert, 15-20 km up the hydraulic gradient from the vein swarm, is about 640-670 m (Winograd and Thordarson, 1975, pl. 1), or about 185-215 m lower than the vein swarm (855 m). The altitude of the water table in the regional carbonate aquifer at Nevares Spring (fig. 13.1) in east-central Death Valley, 18 km down the hydraulic gradient, is 286 m or about 570 m lower than the vein swarm. (The water level at Nevares Spring is the highest level known for the regional carbonate aquifer in east-central Death Valley.) Due to the extreme aridity of the region, plus the high transmissivity of the regional carbonate aquifer (Winograd and Thordarson, 1975), the presence of a ground-water mound (a potentiometric high) in the

Table 13.1. Uranium-disequilibrium ages of calcitic veins at Ash Meadows and Amargosa Flat, Nevada, and rates of apparent water-table decline during the Quaternary

[Altitude of vein AM-10 estimated from USGS 1:24,000 Specter Range, SW topographic quadrangle; altitude DH-1 from laser-altimeter survey; altitude AM-7 from average of four aneroid-barometer surveys. Justification for dating the calcitic veins by the $^{234}U/^{238}U$ method in Winograd and others (1985). Average rate of water-table decline assumes constant rate of decline between time of deposition of youngest laminae in vein and the [illegible]; values rounded to one significant figure and represent minimum rates for reasons given in text]

Vein (see fig. 13.1 for location)	Altitude (m)	$^{234}U/^{238}U$ age (ka)	Vein altitude above water-level at Devils Hole (719 m) (m)	Average rate of water-table decline (m/ka)	Difference in altitude (m) and in youngest age (ka) for indicated vein pair	[illegible]
AM-10	745±3	[2] 750±52	26±3	0.03	7, 90 (AM 10-DH 1)	
DH-1	738	660±75 to 890±92	19	.03	15, 240 (AM 10-AM 7)	
AM-7	730±1	510±62 to 620±66	11±1	.02	8, 150 (DH 1-AM 7)	

[1] Values rounded to one significant figure.

[2] Sample came from center of 1-cm-thick vein; given average growth rates (0.3 mm/ka) in other Ash Meadows [illegible] spanned during deposition of this very thin vein is unlikely to have exceeded 50 ka. (We assume the vein [illegible] from the walls.)

carbonate aquifer between the southern Amargosa Desert and east-central Death Valley is extremely remote; that is, we have confidence that the potentiometric surface in the carbonate aquifer beneath the vein swarm at Furnace Creek Wash is intermediate between the cited altitudes in the southern Amargosa Desert and in east-central Death Valley. The uranium-disequilibrium age, in conjuction with the cited vein and water-table altitudes, indicates an average water-table lowering of 0.2 to 0.6 m/ka.

DISCUSSION AND SYNTHESIS

Tectonics, climate change, and erosion in response to tectonics and (or) climate change are obvious potential causes for the observed water-table displacements. A comparison of the cited water-table displacement rates at Ash meadows (0.02 to 0.08 m/ka) and Furnace Creek Wash (0.2 to 0.6 m/ka) with average rates of vertical crustal offsets in these regions seemingly supports tectonism as a major cause for the displacement we have observed at Furnace Creek Wash. In east-central Death Valley, a rate of vertical crustal offset of 0.3 m/ka has been calculated by Carr (1984) for the Black Mountains (fig. 13.1) utilizing the data of Fleck (1970). In contrast, data presented by Pexton (1984, p. 49) on the displacement of a 3-m.y.-old tuff at Ash Meadows indicate relative vertical crustal offset of about 0.01 m/ka, or one-half to one-eighth of the indicated rate of water-table decline at Ash Meadows and vicinity.

Climatic change cannot be discounted as an important auxiliary cause for the documented water-table displacements. Major uplift of the Sierra Nevada and Transverse Ranges during the Pliocene and Quaternary should have markedly and progressively reduced the precipitation reaching the Great Basin during this time. Smith and others (1983, p.23) suggested that 3 m.y. ago, when the Sierra Nevada was about 950 m lower, about 50 percent more moisture might have crossed the Sierra and moved into the Great Basin. Various lines of evidence support such notions. Raven and Axelrod (1977) and Axelrod (1979), using paleobotanical evidence, argued for increasing aridity in the Great Basin, Mojave Desert, and Sonoran Desert during the late Tertiary and Quaternary. They attributed this increasing aridity to uplift of the Sierra Nevada, Transverse Ranges, Peninsular Ranges, and the Mexican Plateau. Winograd and others (1985) described a major and progressive depletion in the deuterium content of ground-water recharge in the region during the Quaternary; the most logical explanation for their data is a progressive decrease in Pacific moisture due to uplift of the Sierra Nevada and Transverse Ranges. And Pexton (1984, p. 43–46, 57), on the basis of studies of sediment depositional environments, believed that the Ash Meadows area became progressively more arid during the Quaternary.

The role of erosion in the apparent lowering of the water table is not known. We assume that in east-central Death Valley, where the rate of vertical crustal offset is large, tectonism dominated both erosion and climate as a factor in water-table change during the Quaternary. This may not, however, be correct for the Ash Meadows region, where the rate of vertical crustal offset is an order of magnitude smaller (see above); here, the erosional history of the bordering Amargosa Desert—a history influenced by climate change and possibly also by tectonism in Death Valley—may have played an important role in the water-table changes we see at and northeast of Ash Meadows.

We should emphasize that the evidence presented by Winograd and Doty (1980), and its initial quantification herein, suggests only an apparent lowering of the water table during the Quaternary at Ash Meadows and Furnace Creek Wash. We do not know to what degree the displacement of veins and tufas relative to the modern water table reflects (1) tectonic uplift of the veins and associated tufas, unaccompanied by a decline in water-table altitude; (2) a lowering of water-table altitude in response to the tectonic downdropping of a region adjacent to the veins and tufas; (3) a lowering of water-table altitude in response to increasing aridity, or to erosion; or (4) some combination of these. Locally, uplift of the veins was probably a major cause for the displacements we observed. For example, the occurrence of the veins at Furnace Creek Wash (site 10B, fig. 13.1) at altitudes higher than the modern potentiometric surfaces to the west and east (see above) strongly suggests that major uplift of the Funeral Mountains and Greenwater Range occurred relative to both Death Valley on the west and the Amargosa Desert on the east. However, a synthesis of regional hydrogeologic, tectonic, and paleoclimatologic information with our observations indicates that a progressive and absolute lowering of the regional water table (more correctly the potentiometric surface) is likely to have occurred throughout the south-central Great Basin during the Quaternary. This inference is based on the following three considerations. (1) The several-thousand-meter topographic relief in Death Valley developed principally during the Pliocene and Pleistocene (Hunt and Mabey, 1966; U.S. Geological Survey, 1984), and the movement of the floor of Death Valley has probably been downward relative both to sea level and to bordering areas (Hunt and Mabey, 1966, p. A153). (2) Gravity-driven interbasin flow of ground water through the carbonate-rock aquifer is widespread in the region today (Winograd and Thordarson, 1975) and is directed toward Ash Meadows and Death Valley. Such interbasin flow of ground water toward Death Valley in all likelihood also occurred during the Quaternary in response to the progressive lowering of ground-water discharge outlets there. (3) The progressive increase in aridity of the region, due to uplift of the Sierra Nevada and Transverse Ranges, would presumably have resulted in a progressive reduction in ground-water recharge.

We are aware that the regional carbonate-rock aquifer is hydraulically compartmentalized by faulting (Winograd and Thordarson, 1975, p. C63–C71) and that, consequently the postulated lowering of ground-water base level in Death Valley during the Quaternary may not have propagated uniformly throughout the region, specifically northeast of the major hydraulic barrier at Ash Meadows (Winograd and Thordarson, 1975, p. C78–C83). Nevertheless, we believe that the combination of increasing aridity and local erosion in the Amargosa Desert during the Quaternary should, in any event, have resulted in a progressive lowering of the water table at and northeast of Ash Meadows.

Yet another mechanism for water-table lowering at and northeast of Ash Meadows that involves neither erosion nor climate change, but rather extensional fracturing, was outlined by Winograd and Doty (1980). They pointed out (p. 74–75) that the major springs at Ash Meadows oasis differ in altitude by as much as 35 m and are as much as 50 m lower than the water level in Devils Hole. Thus, periodic initiation of discharge from new spring orifices (or an increase in existing discharge) in the lower portions of this oasis due to faulting would have resulted in new and lower base levels for ground-water discharge. Implicit in their hypothesis is the belief that the faulting would be of extensional nature, opening new (or widening old) avenues of discharge from the buried Paleozoic carbonate-rock aquifer which underlies eastern Ash Meadows and which feeds all the modern springs (Winograd and Thordarson, 1975). In support of their hypothesis, we note that most of the calcitic veins in Pliocene and younger rocks at Ash Meadows strike N. 40° ± 10° E., that is, nearly at right angles to Carr's (1974) estimate of the direction of active extension in region, namely N. 50° W. This mechanism may also have periodically lowered the water table in east-central Death Valley (fig. 13.1) where the difference in altitude between the highest (Nevares) and lowest (Texas) major springs discharging from the regional carbonate aquifer is about 170 m (Winograd and Thordarson, 1975, p. C95–C97).

Our evidence for water-table decline pertains only to the Paleozoic carbonate-rock aquifer, the "Lower carbonate aquifer" of Winograd and Thordarson (1975, table 1). As mentioned in the introduction, this regional aquifer serves as a gigantic "tile field" which integrates the flow of ground water from perhaps as many as 10 intermountain basins (Winograd and Thordarson, 1975). The water-table altitude in this regional aquifer system presently exerts a major control on the altitude of the potentiometric surface in locally overlying Cenozoic welded tuff and valley-fill aquifers (Winograd and Thordarson, 1975, p. C53–C63, and pl. 1). Accordingly, we suggest further that the progressive water-table decline postulated for the regional carbonate aquifer during the Quaternary was accompanied by a decline in water-table altitude in the overlying welded tuff and valley-fill aquifers of the region.

The suggested progressive lowering of the regional water table throughout the Quaternary does not preclude superimposed and relatively rapid cyclical fluctuations in water level in response to the glacial (that is, pluvial) and interglacial climates of the Pleistocene. Indeed, preliminary data from Devils Hole indicate that the water table in the carbonate aquifer may have fluctuated as much as 10 m in the past 30 ka (A.C. Riggs and B.J. Szabo, oral communication, December 1986). This, in turn, indicates that vein AM-7 (see above), which is only 11 m above the modern water table, would by itself be of limited utility for determination of the postulated water-table decline since the middle Pleistocene. Intensive studies of paleo water level fluctuations are underway in Devils Hole where excellent records of both Quaternary paleohydrology and paleoclimatology are preserved. We hope that these studies will permit us to distinguish between short-term (1–10 ka) and long-term (100–1,000 ka) water-table fluctuations at Ash Meadows and vicinity where the difference between the highest dated paleo water level and the highest modern water table is only 26 m (table 13.1).

IMPLICATIONS FOR TOXIC WASTE DISPOSAL

The cited evidence for an apparent lowering of the water table at Ash Meadows and Furnace Creek Wash and the inference of an absolute lowering of water table in the south-central Great Basin during the Quaternary are pertinent to an evaluation of the utility of the thick (200–600 m) unsaturated zones of the region for isolating solidified radioactive and toxic wastes from the hydrosphere for tens to hundreds of millenia (Winograd, 1981). Important information which must be obtained before using such zones for toxic waste disposal is the magnitude of water-table rise that occurred during past pluvial climates of the Pleistocene; such information would, by extension, provide clues to the likelihood of buried toxic wastes being inundated by a future rise of the water table. Winograd and Doty (1980) and Czarnecki (1985), using worst-case assumptions, suggested possible pluvial-related water-table rises of several tens of meters to 130 m above the modern water table in Frenchman Flat and beneath Yucca Mountain (fig. 13.1). As noted in the preceding section, we have preliminary information suggesting a late Wisconsin water-table rise on the order of 10 m in the carbonate aquifer at Devils Hole. Thus, it appears that solidified wastes emplaced in the thick (200–600 m) unsaturated zones of the region—at levels a few tens to a hundred meters or so above the water table—should not be inundated by a rising water table during future pluvial climates. (The depth of placement within the unsaturated zone would, or course, be chosen to preclude exhumation of the wastes by erosion.) Moreover, if our inference of a progressive lowering of water table during the Quaternary is sustained by ongoing studies of the carbonate rock and other aquifers, then it is likely that wastes buried in the unsaturated zone will in any event become increasingly displaced from the water table in the foreseeable geologic future. That is, the continuing uplift of the Sierra Nevada (Huber, 1981) and Transverse Ranges, and lowering of Death Valley (Hunt and Mabey, 1966, p. A100–A116), relative to surrounding regions, should result in a continued progressive decline of the regional water table in the next 100,000 to 1 million yr (and beyond?) in response to increasing aridity and to lowering of ground-water base level.

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