THE LOWER CARBONATE AQUIFER AS A BARRIER TO RADIONUCLIDE TRANSPORT

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ABSTRACT

Yucca Mountain is the site of the proposed high-level nuclear repository in the United States. Underlying the repository at a depth of 4256 ft (1.3 km) is an extensive Lower Paleozoic Carbonate Aquifer known to be highly permeable. This paper presents the results of our investigation of the Carbonate Aquifer as a potential pathway for radionuclide transport to the major Furnace Creek springs in Death Valley National Park. Our study culminated in a MODFLOW groundwater model that simulates flow through the Funeral Mountains. The model is supported by our current program of: 1) monitoring well drilling on the northeast flank of the Southern Funeral Mountains, 2) surface and subsurface geologic mapping in the area, and 3) groundwater chemistry analysis from springs and wells in the area. One of the major inputs to the modeling is a water budget analysis of the discharge from the Furnace Creek spring system. Two bounding geologic hypotheses are proposed as contour maps of the base of the Carbonate Aquifer in the Southern Funeral Mountains: 1) a fault plane with a shallow dip that projects a higher elevation for the base of the aquifer, and 2) a fault plane that is more steeply dipping that projects a lower elevation base for the aquifer. The groundwater modeling suggests that both fault planes are feasible. The computed water table has approximately 300 feet of saturated carbonate rock above the higher elevation fault plane through the critical area—the so-called spillway. The more steeply dipping fault plane indicates a saturated thickness of more than 1000 feet through the critical area. The model recreates the flow of the various springs in Death Valley.

INTRODUCTION

Yucca Mountain is the site of the only proposed high-level nuclear repository in the United States. The repository was designed using the philosophy of multiple barriers, both engineered and natural, each of which impede the movement of contaminants. The proposed repository will be in the unsaturated zone above the water table in Tertiary tuffaceous rocks. The principal transporting mechanism for radionuclides is moving groundwater. Underlying the repository at a depth of approximately 4250 ft (1.3 km) is an extensive Carbonate Aquifer known to be highly permeable. Only one drill hole at Yucca Mountain has been drilled into the Carbonate

Aquifer—hole UE-25p1. This hole encountered the Paleozoic Carbonates at a depth of 4256 ft (1300 m).

Up until the 1960s the conventional wisdom in Nevada was that individual basins contained separate and distinct groundwater systems. Winograd, working at the Nevada Test Site in the early 1960s, hypothesized, based on the chemistry of groundwater, that Paleozoic Carbonate rocks that underlie both eastern and southern Nevada integrated the groundwater flow into a much larger system, or systems, than those suggested by the overlying topographic basins. Winograd's prime examples were the major springs in Death Valley that he postulated were the discharge from the underlying Paleozoic Carbonates. Winograd was slow to publish his ideas; however, other investigators quickly adopted his hypothesis (Mifflin, 1968; Winograd and Thordardson, 1975). The idea that the deep groundwater systems in southern and eastern Nevada are integrated through the Carbonate Aquifer is now generally accepted doctrine.

The principal data used to determine the origin of spring discharge in the area of the Amargosa Desert basin are the chemistry of the groundwater. The Carbonate Aquifer groundwater has a distinct chemical signature. The major springs in the Furnace Creek area of Death Valley have the distinct carbonate water chemistry. The groundwater recharges that supply the springs of Death Valley are thought to be principally in an area north of Yucca Mountain. The groundwater is believed to flow southward through the Carbonate Aquifer beneath Yucca Mountain, beneath the Amargosa Valley, and then through the Funeral Mountains to finally discharge in the springs in Death Valley.

Usually groundwater flow paths are based upon hydraulic head data that indicates the hydraulic gradient; however in the case of Amargosa Valley/Funeral Mountain/Death Valley Carbonate Aquifer system there are very few boreholes on which to base hydraulic head information. The UE-25p1 hole, mentioned above, reached the Carbonate Aquifer beneath Yucca Mountain at a depth of 4256 ft. The hydraulic head data from the hole showed that the head in the Carbonate was 65 ft (20 m) higher than the head in the overlying Tertiary Tuffs. The temperature of the groundwater in the deep Carbonate was high—approximately 54^0C (Sass et al., 1988). Bredehoeft (1997) commented on the higher head in the Carbonate Aquifer:

This is a favorable condition for the proposed repository. The upward potential for flow from the deep Carbonate Aquifer protects it from the downward movement of contaminants…. Nothing should be done either: 1) through construction of the repository, or 2) through ground-water development to reduce heads in the Carbonate Aquifer; the higher heads protect the Carbonate Aquifer.

There are few other holes that penetrate the Carbonate Aquifer in the Amargosa Valley flow system. Nye County drilled a series of early warning holes in the vicinity of the community of Amargosa Valley to the south of Yucca Mountain. One of the Nye County wells is believed to have penetrated the Paleozoic Carbonate rocks. The heads in the deepest portion of this well were higher than those usually encountered in the Tertiary Tuffs in the area. The groundwater and head in this well is thought to reflect the Carbonate Aquifer. Other wells encountered groundwater with a carbonate chemical signature.

One wildcat oil well is reported to have reached the Paleozoic Carbonates in Amargosa Valley. This well was plugged and abandoned without hydraulic head measurements or water samples taken from the Carbonate Aquifer. Devils Hole in the Amargosa Valley is a water-filled cave in the Paleozoic Carbonate Aquifer. We have a good water level record for Devils Hole. Nearby Devils Hole are the Ash Meadow springs that discharge from the Carbonate Aquifer.

The Carbonate Aquifer has the potential of providing a conduit for radionuclide transport away from Yucca Mountain. However, the head higher in the Carbonate Aquifer than in the Tertiary Tuffs provides a barrier to the movement of contaminants from the Tertiary Tuffs downward to the Carbonate Aquifer; the gradient in head is upward not downward. The higher hydraulic head in the Carbonate Aquifer in the vicinity of Yucca Mountain could be reduced by groundwater development in the Amargosa Valley. A rapidly growing population in Las Vegas and Pahrump Valley are seeking sources of water; local groundwater in the highly permeable Carbonate Aquifer is an obvious source of great interest. Were contaminants to enter the Carbonate Aquifer in the vicinity of Yucca Mountain they would be transported through the aquifer to the springs in Death Valley.

The purpose of this paper is to summarize the recent Inyo County program; including the results of our deep drilling, and to present a model of groundwater flow through the Carbonate Aquifer in the Funeral mountains. The modeling draws heavily on all the various elements of the Inyo County program.

Inyo County Investigations

Death Valley is in Inyo County, California. Inyo County is concerned with the potential impacts of the Yucca Mountain Repository on its resources, especially its groundwater resources. Since the Carbonate Aquifer provides a potential pathway of transport for radionuclides from the repository into Inyo County, the County has focused its investigations on the Carbonate Aquifer and the associated springs in Death Valley. The U.S. Department of Energy (DOE) has issued a research grant to the Inyo County Planning Department to conduct geological studies in the Southern Funeral Mountains to characterize the relationship of the Carbonate Aquifer and the major springs in the Furnace Creek area of Death Valley National Park. The Hydrodynamics Group provides technical services and technical oversight for Inyo County.

In the past we sampled and chemically analyzed water from numerous springs in the Funeral Mountains (King and Bredehoeft, 1998). The spring sampling was intended to assess the impact of local recharge on the major Furnace Creek springs in Death Valley. In addition Fredrick has mapped in detail the geology of the Funeral Mountains. Much of the range is composed of the Paleozoic Carbonate rocks that makeup the Carbonate Aquifer. We also engaged in a water budget study to better define the Furnace Creek spring discharge. We drilled one observation well in the vicinity of Travertine Spring.

Deep Drilling

Recently Inyo County has engaged in a deep drilling program focused on drilling to the Carbonate Aquifer within the Amargosa Valley just to the east of the Funeral Mountains. A first hole has been drilled—BLM #1. This hole encountered the Paleozoic rocks at a depth of 2440 ft. A highly permeable zone in the Carbonate Aquifer was encountered at 2550 ft. The water from the 2550-foot zone had a temperature of 52^0C—similar to the temperature of the Carbonate Aquifer water in UE-25p1 at Yucca Mountain. The hole was drilled to a total depth of 2900 ft.

The first hole, BLM #1, was difficult to drill with washouts and sloughing material in the Amargosa Desert Basin sequence of sediments. Casing was placed in the hole from the surface to a depth of 2129 ft; the casing facilitated the deeper drilling. Once the hole reached total depth, and the drilling was completed, the hole partially filled with caving to the bottom of the casing. No geophysical logs could be gotten in the bottom portion of the hole. The water level stabilized at a depth of 103 ft below ground surface. This suggested that the hydraulic head in the Carbonate Aquifer is approximately 2180 ft.; this is estimated since we do not currently have an accurate elevation for the site. A water level was obtained in the Amargosa Valley sediments during the drilling; however, the observations during drilling suggested that there were not large differences in hydraulic head between the Carbonate Aquifer and the overlying sediments.

The current proposed DOE work plan is to drill out the caving in the lower part of the hole. Then we will complete the well with casing and a screen in the Carbonate Aquifer. A second well will be constructed in the Kelly Wells Formation aquifer in the Amargosa Desert basin sediments.

A second deep hole is being drilled approximately 3 miles to the northwest of the first hole—BLM #2. The hole was drilled 2700 ft into the lower section of Tertiary-age sediments some distance above the Paleozoic rocks. The Amargosa Desert basin sediments are much thicker in this hole. The intent is to drill this hole deeper when our budget allows.

BLM #1 and #2 wells encountered complex subsurface geological structures. Subsurface conditions at BLM #1 indicate steeply dipping rock units that are brecciaed and highly broken up by faulting. We have done extensive geophysics to try and determine good drilling sites. The geophysics accurately predicted subsurface conditions at BLM #1 well, and indicated the top of bedrock in BLM #2. The drilling is further constrained by land access; much of the land in the area is designated wilderness. Nevertheless, we did reach our target of penetrating the Carbonate Aquifer in the BLM #1 well, and are in close proximity in the BLM #2 well.

Funeral Mountain Geology

A general geologic map of the Furnace Creek and adjoining parts of the Amargosa Desert basins is provided in Figure 1. The Funeral Mountains uplift is bounded by two regional-scale right-lateral strike-slip faults. Strands of the Furnace Creek fault have a northwestward horizontal offset; the offset increases to the northwest and reaches a maximum of 80 km of offset to the northwest of the study area. The furnace Creek fault forms the southwest front of the range and abuts against the Furnace Creek basin.

In contrast, the major southernmost strand of the Stateline fault system is located 2 to 4 km to the northeast of the irregular northeastern flank of the range; the Stateline fault has approximately a 25 km offset. The Stateline fault underlies the active channel of the Amargosa River in the area. The jagged northeastern range-front itself is controlled by several different features, including: 1) three large west-to northwest-dipping extensional faults that crop-out within the range, 2) a network of smaller faults that are peripheral to, and related to the Stateline fault system, and 3) a number of east to southeast-facing, dip slopes of the extensionally tilted fault blocks that comprise the range.

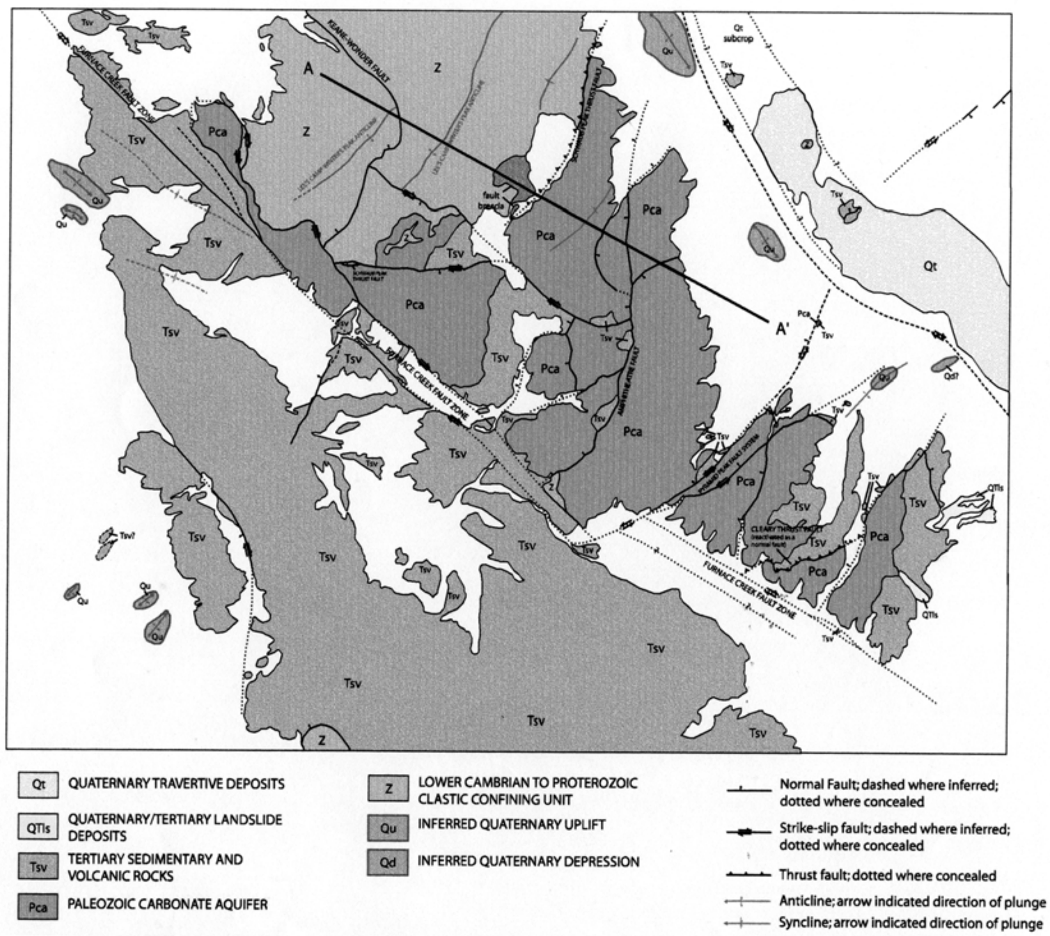


Fig. 1. Geologic map of the southern Funeral Mountains and adjoining areas.

The internal structure of the southern Funeral Mountains includes the extensional faults, noted above, as well as two large thrust faults—the Cleary and Schwaub Peak Thrusts. The extensional faults formed mainly during the 12 to 7 Ma extensional episode of basin and range tectonics in which the mountain range was formed. These dates are based on dated tephras in tectonic sediments deposited and preserved associated with these faults within the range (Fridrich and Miggins, unpub. data). The 25 to 40-degree east to southeast-tilted structural blocks between the major extensional faults are shattered by a plexus of closely spaced, smaller extensional faults, that strike in a wide range of directions, and that form a continuous fracture network that bridges between the major extensional fault zones. Thrust faults formed during the older Mesozoic Sevier Orogeny, and several large folds are present in the range, adjacent to these thrusts. The thrust faults and the related folds are cut and tilted by the much younger extensional faults.

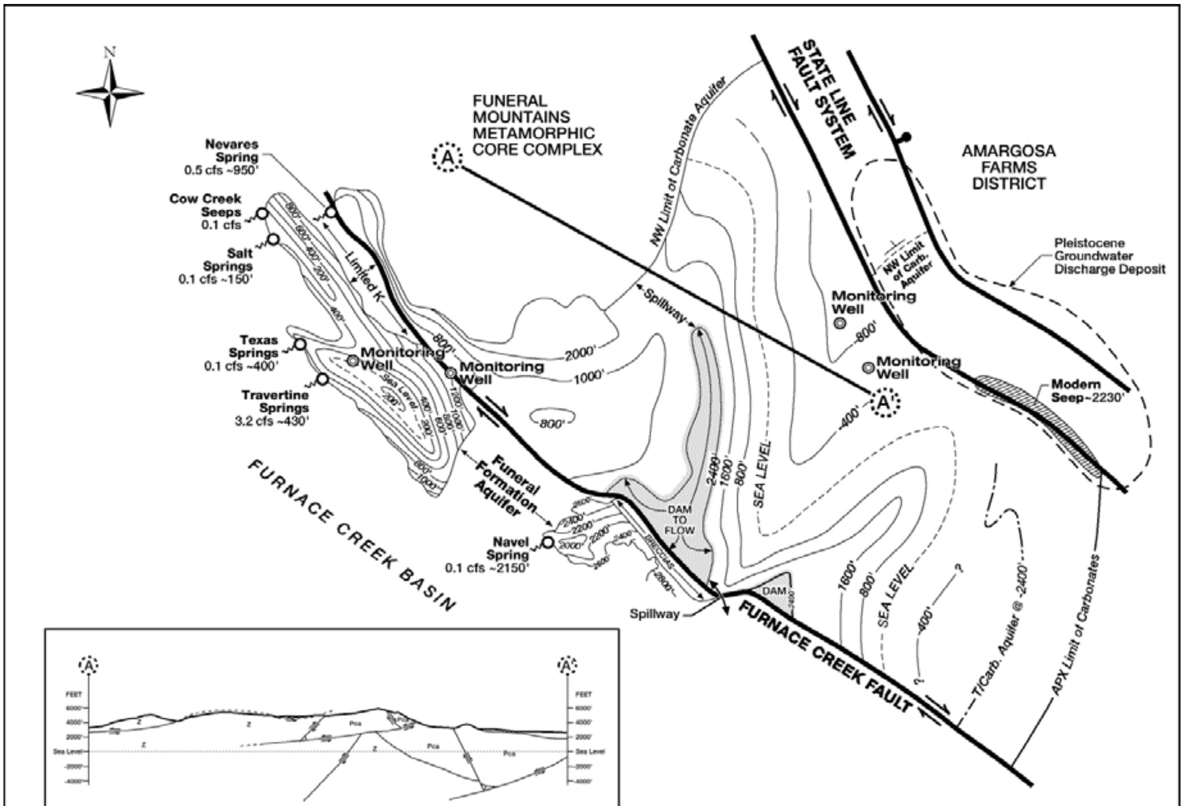
The rocks exposed in the Funeral Mountains include an 8 km thick late Proterozoic to late Paleozoic section of miogeoclinal sedimentary rocks that were deposited when this region was part of the western continental margin and slope of North America that was covered by the eastern edge of the Pacific Ocean. The miogeoclinal sediments overlie an older rock section of sedimentary rocks (now medium-grade metasedimentary rocks) of the Pahrump Group; this Group was deposited during premonitory rifting related to the initial formation of the Pacific Ocean. The Pahrump Group rocks, in turn, overlie 1.7 Ga old crystalline basement rocks, mostly high-metamorphic-grade gneisses and schists. Cenozoic (Oligocene to Quaternary) sediments overlie the Paleozoic miogeoclinal rocks. The rock sequence includes sediments formed before, during, and after the basin-range tectonic extension that formed the mountain range.

The Amargosa Desert basin is a composite of several extensional and strike-slip basins, and is floored by the same miogeoclinal rocks that compose most of the Funeral Mountains. In contrast, the much shallower Furnace Creek basin, to the southwest of the funeral Range, is thought by most workers to be the footwall basin of the Amargosa detachment fault, in which the Cenozoic basin-fill sediments largely overlie the rocks that predate the miogeoclinal section. In the detachment-fault interpretation, the miogeoclinal section was mostly in the upper plate of the detachment, and was transported approximately 80 km northwestward, on the detachment fault, and is now exposed as the Panamint and Cottonwood Ranges (Stewart, 1983). Thus the Cenozoic fill of this basin was deposited directly onto the largely metamorphic lower plate of the detachment fault. Even those workers who disagree with the detachment-fault interpretation agree that the miogeoclinal section is almost completely absent under the Furnace Creek Basin; they ascribe that absence to erosion, rather than to detachment faulting (e.g., Wright and others, 1999). Exposures in the Black Mountains, on the south side of the narrow Furnace Creek basins, show that the miogeoclinal rocks are absent under the Tertiary basin fill, except as small isolated scraps, most of which are blocks of tectonic breccias.

Hydrogeologic Units

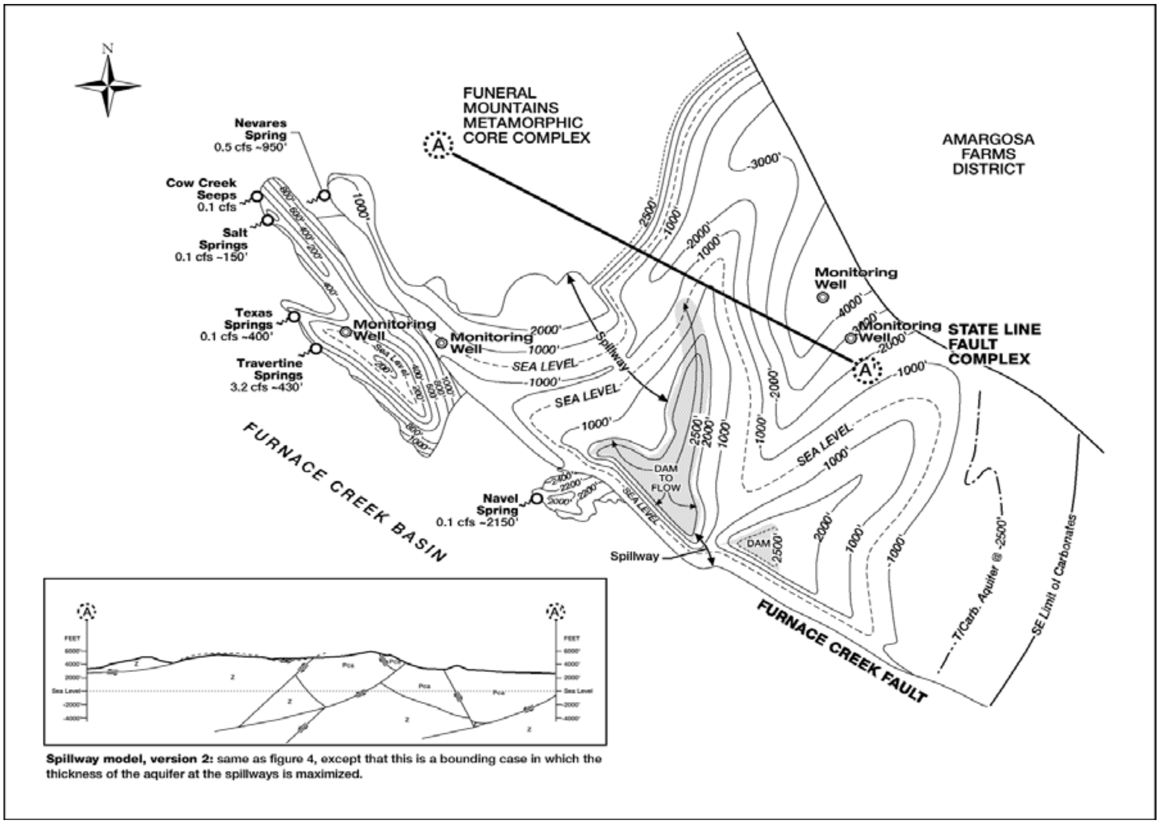
The rocks of the southern Funeral Mountains and of the two adjacent basins can be divided into five major hydrogeologic units. (1) The lower part of the miogeoclinal section consists largely of siliciclastic sedimentary rocks that are generally very low in permeability except where strongly fractured, as in major fault zones. All of the rocks that underlie the lower siliciclastic part of the miogeoclinal section have a similar hydrologic character. Thus, this lower group of rocks as a whole forms the effective base of the aquifer system. (2) The upper part of the miogeoclinal section is approximately 4 km thick (pre-deformation) and consists dominantly of carbonate rocks—limestone and dolomites, with only few and thin interbedded shale and sandstone formations. A large fraction of the plexus of extensional faults that cut the rocks throughout the study area have throws that exceed the thickness of these generally low permeability interbeds. Hence, these structurally dismembered interbeds have insufficient continuity to effectively interrupt ground-water flow through the dominantly carbonate section, which is a highly permeable, fracture-flow-dominated aquifer. (3) The Carbonate Aquifer is locally capped by 170 m (maximum) section of siltstones and shales of the Perdido Formation. It is questionable whether this formation is anywhere sufficiently continuous enough to form a confining unit by itself. However, the Perdido is overlain by the generally low permeability, lower part of the Cenozoic section. Together the Perdido Formation and the overlying Cenozoic rocks form a confining unit over the Carbonate Aquifer. (4) The Cenozoic section is lithologically very diverse, consisting of basin sediments of numerous types. Most parts of this unit are generally of low permeability, but some thin, highly permeable beds are locally present. On a local scale, some permeable beds in this unit are significant aquifers. However, these permeable beds typically can be traced only over short distances; hence, they probably lack sufficient continuity to have a significant impact on large-scale ground-water flow. The sub-alluvial Cenozoic section as a whole can therefore be treated on a large scale as a confining unit. (5) The capping poorly consolidated alluvium of the Cenozoic section is an excellent aquifer, both in the Furnace Creek basin, where it is called the Funeral Formation, and in the Amargosa Desert basin, where it is unnamed and is widely tapped for agricultural and domestic water supply. In the Amargosa Desert basin, the alluvial water-table aquifer is probably connected only poorly with the underlying Carbonate Aquifer, which is confined under a thick section of Cenozoic lakebeds (mostly claystones and siltstones). In the Furnace Creek basin, however, the alluvial aquifer is juxtaposed against the carbonate aquifer of the southern Funeral Mountains, across the Furnace Creek fault.

The rocks that comprise the Carbonate Aquifer extend above the water table throughout most of the southern Funeral Mountains, and are very well exposed at the surface in the range. Based on unpublished mapping, by Fredrick, of the exposed structure and stratigraphy of these rocks, we have constructed two structure contour maps on the base of the Carbonate Aquifer under the range. The major uncertainty in this subsurface interpretation is the geometry of the major extensional faults in the subsurface. High-relief surface exposures of all of these faults show that they are strongly listric—they are concave upward because they progressively flatten with depth. They are moderate- to (rarely) high-angle faults in the highest elevation exposures and their dip declines to low-to- (less common) moderate dips with decreasing elevation. An important, unresolved question is whether the high rates of downward flattening observed on the surface continue at depth, or if the rate of flattening declines and these faults approach near-horizontal dips. We present two alternative structure contour maps on the base of the carbonate aquifer: 1) a bounding case that assumes rapid downward flattening of the faults, and 2) another case that assumes much more gradual flattening with depth. The second (gradual flattening) model is our preferred model because the fault geometry appears most reasonable. The rapid flattening model is, however, one we consider a prudent alternative to consider because one of the major extensional faults, in the easternmost part of the southeastern Funeral Mountains, actually shows rapid downward flattening that is this extreme, in local surface exposures.



Spillway model, version 1: Structure contour map drawn on the base of the Paleozoic carbonate aquifer (northeast of the Furnace Creek fault) and the Funeral Formation alluvial aquifer (southwest of the Furnace Creek fault). Note the two spillways in the central part of the southern Funeral Mountains. In this bounding case, the thickness of the aquifer at the spillways is minimized.

Fig. 2. Structure contour map of the base of the Carbonate Aquifer formed by the fault planes with shallow dips.



Spillway model, version 2: same as figure 4, except that this is a bounding case in which the thickness of the aquifer at the spillways is maximized.

Fig. 3. Structure contour map of the base of the Carbonate Aquifer formed by the more steeply dipping fault planes.

In these two map interpretations of the geometry of the carbonate aquifer, those features that are not dependent on the subsurface fault geometry are the same, and are constrained by the exposed structure and stratigraphy. These common features include boundaries of the Carbonate Aquifer: (1) in the northwestern part of the southern Funeral Mountains, where it is truncated by the northwest-dipping Schwaub Peak Thrust and by a number of other contacts to the west, mostly strike-slip faults that are internal to the range, (2) along the southwestern front of the range, where it terminates against the Furnace Creek fault, and (3) near the southeastern limit of the range, where it terminates against the depositionally overlying confining unit formed by the combination of the Perdido Formation and the overlying basal Tertiary section. Additionally, three isolated bedrock outcrops immediately north of the Funeral Mountains, exposed between strands of the Stateline fault, show that the Schwaub Peak Thrust, the northwest limit of the Carbonate Aquifer, is offset approximately 15 km in a right-lateral sense across the southernmost strand of the Stateline fault. There are additional, but smaller right-lateral offsets of the aquifer boundary across other strands of the Stateline fault, in the southern part of the Amargosa Desert basin. However, as pointed out above, there are very few data to constrain the geometry of the Carbonate Aquifer under this Amargosa basin.

A final element of the two-aquifer maps (Figures 2 and 3) is the geometry of the Funeral Formation aquifer within the Furnace Creek basin. This formation is an important part of the hydrologic system because all but one of the Furnace Creek springs issue from the Funeral Formation, rather than from the Carbonate Aquifer. Nevares spring is the only spring that issues directly from the Carbonate. The outline of the Funeral Formation is largely a function of erosion, except along the fault along the southwest range-front of the Funeral Mountains. At the southeastern limit of the larger mass of the Funeral Formation there is a northeast-striking normal fault within the Furnace Creek basin called the cross-basin fault (McAllister, 1970). Northeast-southwest contractional folding controls the base of the Funeral Formation, which occurred in the Furnace Creek basin mainly between 4 and 2 Ma; this folding is still feebly active today.

On a regional scale, the Paleozoic Carbonate Aquifer extends northeastward at least as far as the east-central border of Nevada. The grouping of springs at Furnace Creek is only one of several discharge areas that lie near to, or at the southern termination of this huge ground-water flow system. Flow in the regional carbonate aquifer is generally to the southwest, and the springs in Death Valley are located at the ultimate southwestward termination of the system. The Funeral Formation provides a very short continuation of the flow system beyond the limit of the Carbonate Aquifer. Where that formation is Furnace Creek Formation is erosionally truncated, there are no adjacent permeable rocks to accept the groundwater, so it discharges onto the surface at the lowest-elevation points along the southwest boundary (Figures. 2 and 3).

From the southernmost part of the Amargosa Desert basin to the lowest-elevation spring in Furnace Creek, the water-table elevation drops by approximately1800 feet. This large decline in head has a straightforward relationship to the geometry of the base of the Carbonate Aquifer under the Funeral Mountains. Under part of the axis of this range, the base of the aquifer is structurally uplifted (Figures 2 and 3). However, there are two areas within this range where the base of the aquifer is lower than the water-table elevation in the southernmost part of the Amargosa Desert basin—our recent BLM #1 well had a hydraulic head in the Carbonate Aquifer of 2180 ft. The uplift under the axis of the range plays a key role in restricting groundwater flow through the Funeral Mountains.

Two lines of evidence support the interbasin flow model under the southeastern Funeral Mountains: 1) the flow from the springs in Furnace Creek is about an order of magnitude higher than the estimated recharge to the Furnace Creek basin and the adjacent southern Funeral Mountains, and 2) the chemistry and isotopic signature of the water that issues from these springs provides evidence that the Carbonate Aquifer under the southern Amargosa Desert basin is the source of the spring water (Winograd and Thordarson, 1975; Mifflin, 1968). Nonetheless, local recharge to the Funeral Mountains probably does contribute approximately 10% of the flow of the Furnace Creek springs.

Groundwater Flow Through the Furnace Creek Mountains

Given the maps of the base of the Carbonate Aquifer, Figures 2 and 3, it is feasible to attempt to model the groundwater flow through the Funeral Mountains. The model needs constraints, and boundary conditions. It was our intent to keep the model as simple as possible; we are attempting to test the feasibility of groundwater flow through the Funeral Mountains.

One constraint on the model is the quantity of the discharge from the springs in the Furnace Creek area of Death Valley. Obtaining a good estimate of the discharge is not as easy as it first appears. There have been several attempts to estimate the total spring flow. The spring flow is a problem to measure because in many instances the spring orifice is not well defined; much of the water flows out in the nearby alluvium. The earliest was by Pistrang and Kunkel (1964). Terry Fisk, of the National Park Service made measurements in 2001 and 2003 (personal communication). We attempted to reconcile the measurements.

Table I. Estimates of the Discharge (cubic feet per second—cfs) of the Furnace Creek Springs.

Springs	Pistrang & Kunkel	Fisk	Our Estimate
Texas	0.8	0.98	1.0
Travertine	3.6	3.09	3.2
Nevares	0.6	0.32	0.5
Cow Creek	0.1	0.10	0.1
Navel			0.1
Salt			0.1
Total			**5.0**

With these data we can set boundary conditions on the model and constrain the flow. The map of the base—Figures 2 and 3 establishes the extent of the aquifer through the Funeral Mountains.

The hydraulic head in the southern Amargosa Desert basin on the northeast flank of the Funeral Mountain is known. BLM #1 has a hydraulic head in the Carbonate Aquifer of approximately 2180 ft. in elevation. There is an area along the Amargosa River indicated in Figure 2 that is perpetually wet; phreatopyhtes are extensive in this area. This appears to be an area of groundwater discharge that overlies the Stateline fault in this area. The area has a ground elevation just above 2200 ft. A hydraulic head of 220 feet in this area of the Carbonate Aquifer is consistent with the elevations of the Ash Meadows springs, Devils Hole, and our BLM #1 head.

The groundwater flow model was created using MODFLOW. As suggested above, the extent of the aquifer was dictated by the geologic mapping of the base of the aquifer—Figures 2 and 3; we use a 1/4 x 1/4 mile square grid to represent the aquifer. The model aquifer includes both the Carbonates in the Funeral Mountains and the adjoining Furnace Creek deposits.

The springs are represented in the model as *drains*. Each drain has an associated elevation. The computed hydraulic head is depicted in Figure 4.

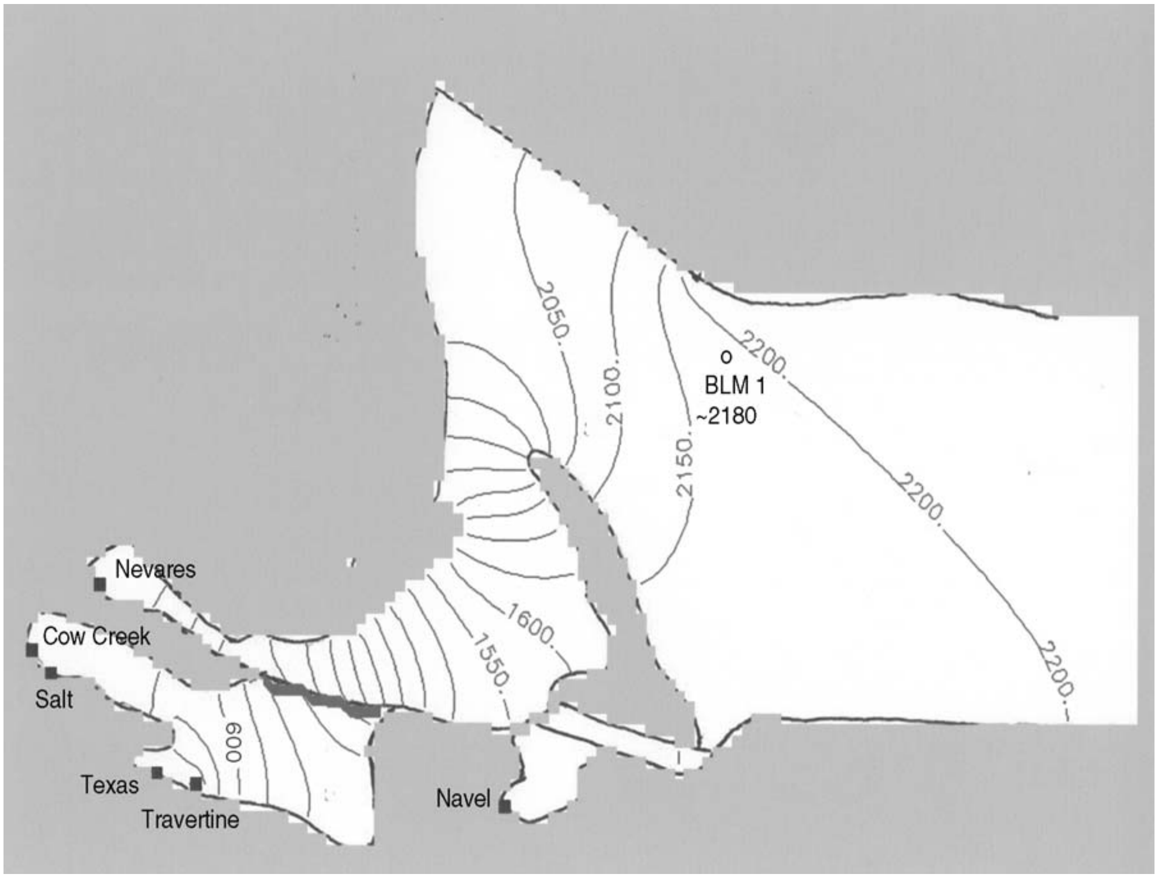


Fig. 4. Computed hydraulic head in carbonate aquifer.

The model as depicted in Figure 4 reproduces the discharge of the various springs quite well:

Table II. Computed Discharge of the Furnace Creek Springs.

Springs	**Approximate Elevation (Feet)**	**Estimated Flow (Cfs)**	**Model Computed Flow (Cfs)**
Navel	2150	0.10	0.11
Nevares	950	0.50	0.47
Travertine	430	3.20	3.26
Texas	400	1.00	0.89
Cow Seeps	150	0.10	0.08
Salt	150	0.10	0.08
Total		**5.00**	**4.89**

The model needs further discussion. We specified a single transmissivity throughout the entire active groundwater domain of the model. The total flow through the system is sensitive to the transmissivity—the best value was 0.022 ft^2/sec.

One hydraulic problem posed by the model is how to force groundwater flow northwestward in the finger of carbonate rock that extends out to Nevares spring. Nevares is approximately 500 ft higher in elevation than Travertine and Texas springs. The model requires a flow barrier to force flow out to Nevares spring; we simulated this barrier along the Furnace Creek fault zone. The model projects a high head drop across the fault—500 to 600 ft.

The model results are consistent with either of the maps of the base of the aquifer—Figures 2 or 3. In the case of the shallower dipping fault plane (Figure 2) the model projects approximately 300 feet of aquifer saturation through the critical area—designated as the spillway on Figure 2. One could calculate an aquifer permeability using the model transmissivity. In the case of shallow fault plane the critical thickness is 300 ft; in the steeply dipping case the thickness is approximately 1000 ft. The viscosity of water at 20^0C is one-centipoise; at 50^0C the viscosity is 0.55 centipoises. Temperature alone makes almost a factor of two differences in permeability. If we assume a saturated aquifer thickness of 300 ft, and water of 50^0C temperature, then the calculated permeability is 1.2×10^{-13} m^2. This compares favorably with the permeability for the Carbonate Aquifer used in the DOE saturated model for Yucca Mountain. Since the aquifer is dominated by fractures it seems more reasonable to treat the system with a single transmissivity.

Modeling the spring discharge is also somewhat problematic. The drain function in MODFLOW requires that one specify both 1) an elevation (which is straightforward), and 2) a resistance to flow (that is not so straightforward). By adjusting the additional resistance in the drain function one can effectively adjust the spring discharge—one can use various rationales to justify this additional resistance in the drain function. It seemed to us that the flow to the principal springs, especially Nevares, and Travertine, should be controlled by the transmissivity of the aquifer. We made the resistance to flow in the drain function sufficiently large that it had no impact to the flow to these springs. We did use the additional resistance in the drain function to adjust the flow to the other springs.

SUMMARY AND CONCLUSIONS

BLM #1 did reach our objective—the Carbonate Aquifer in the Amargosa Desert basin. This deep drilling has established a Carbonate Aquifer water level in our first drill hole BLM #1—approximately 2280 ft. in elevation. Our current DOE Grant Program proposed to complete BLM #1 as a Paleozoic section monitoring well. Hydraulic pump test and water chemical analysis are also proposed.

Our second deep hole in the Amargosa Desert basin, BLM #2, was drilled and cased to a depth of 2700 ft. in the lower section of the Amargosa Formation just above the Carbonate Aquifer.. The hole can be drilled deeper when the budget allows.

Geologic mapping in the Funeral Mountains has provided two possible contour maps for the base of the Carbonate Aquifer in the range. We have created a MODFLOW groundwater flow model that is consistent with the available data and recreates the flow through the Funeral Mountains. The flow model reproduces the spring flow rather well. The model suggests that either interpretation of the base of the Carbonate Aquifer is feasible. The model is very sensitive to the transmissivity of the aquifer; our best value for transmissivity is 0.022 ft^2/sec.

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